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1996 Summer Study Task Force
on

Tactics and Technology for 21st Century Military Superiority

Volume 3
Technology White Papers

October 1996

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This document provides technology white papers, some of which were used as supporting material for Volume 1. It does not contain recommendations and findings, nor does it represent the consensus opinion of the Task Force.

Volume 1 is a result of finding new ways to make rapidly deployable forces much more effective than they are today. The report indicates that substantial, possibly revolutionary, improvements in the effectiveness of rapidly deployable forces are feasable. The concepts in the report can be refined, tested and evolved into fielded capabilities over the next two decades. The essence of this new expeditionary force is an ability to mass fire rather than forces. It relies on an ensemble of remote weapons effective against all types of targets; an extensive suite of sensors, information processors and information warfare capabilities to provide situation understanding dominance; a ground force comprised of light agile combat cells that offer few targets for the enemy; a precision logistics capacity that provides the right stuff at the right place at the right time; and a robust information infrastructure that ties this distributed force together. Volume 1 describes potential ways to acheive these capabilities as well as meet other chalenges including command, force insertion and training.

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Foreword

This report of the Defense Science Board Summer Study on Tactics and Technology for 21st Century Military Superiority includes three volumes. Volume 1 provides a summary of the principal findings and recommendations of this Task Force. It represents the consensus view of the Task Force along with supporting analytical results.

Volume 2 contains a set of supporting materials prepared by Task Force panels, or provided as inputs to this Task Force. Each section of Volume 2 is shown with its author(s).

Volume 3 is a collection of papers on relevant technologies. Some papers were prepared by Task Force members. Most were contributed by other experts in response to requests by the DSB Task Force. The author(s) for each paper is shown.

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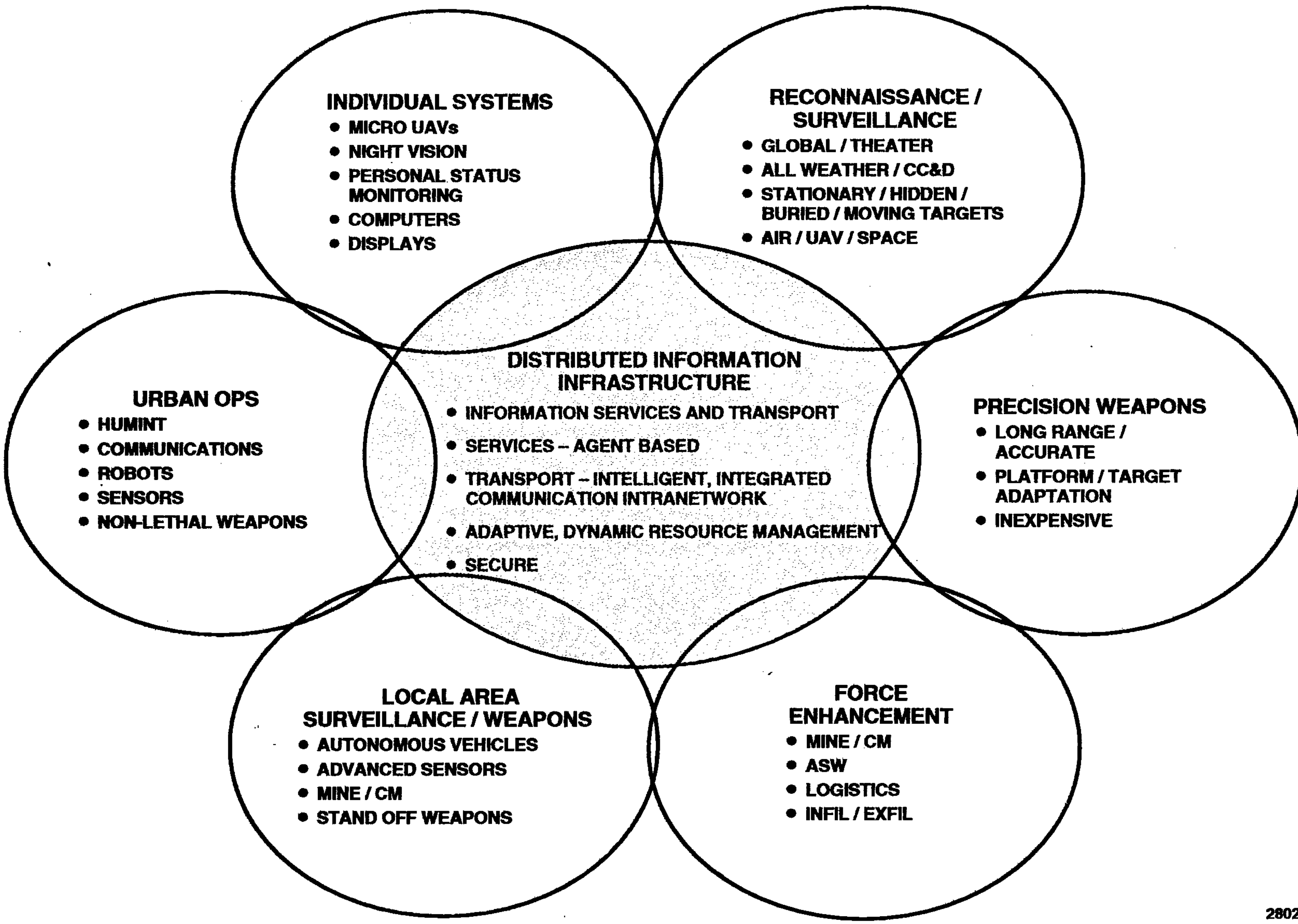

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TACTICAL INFORMATION INFRASTRUCTURE: A VISION FOR THE 21ST CENTURY

ITAD-720-PA-96-096

Prepared by:

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Prepared for:

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TACTICAL INFORMATION INFRASTRUCTURE: A VISION FOR THE 21ST CENTURY

1 REQUIREMENTS/VISION

A force entity must be able to receive or transmit all of the information it needs for the successful and efficient prosecution of its mission. The information infrastructure that supports this entity must be flexible and adaptive. It must allow force structures of arbitrary composition to be rapidly formed and fielded. Furthermore, the infrastructure must adapt to unanticipated demands on it during crises, and to stress imposed on it by an intelligent adversary.

The information infrastructure must allow information to be distributed to and from anyone at any time: its architecture should not be constrained to support a force-structure (enterprise) hierarchy conceived a priori. The information and services provided to an end user must be managed only by the doctrine and policy of the organization, and only when the information and services are in use.

The information infrastructure must support multimode data transport, including land-line, fiber, radio and space-based elements. All of these media must be integrated into a ubiquitous, store-and-forward data internetwork that dynamically routes information from source(s) to destination(s). This data transport segment of the infrastructure must be self-managed, must be adaptive to node or link failure, and must provide services to its users based on quality-of-service (QoS) requests. These services include bandwidths, latency, reliability, precedence, and the like.

The processing component of the infrastructure will include all types of computers, ranging from portable digital assistants to massively parallel processes. These computers will be situated at locations commensurate with their needs for power, environment, and space. All computers will, however, be integrated via the data-transport element of the infrastructure, which will enable them to exchange data dynamically, share computation loads, and cooperatively process information on behalf of the warfighter.

Information services will be provided to a warfighting entity (from a single person to a collection of people, sensors, and/or weapons) by means of intelligent agents—software entities that are autonomous, goal directed, migratory, and able to create other entities and provide services or functions on behalf of a user.

In this concept, the information processing and services component of the infrastructure is tightly coupled to the transport component. Each component exchanges state information with the other, in order to enable the entire infrastructure to adapt to user requirements and stresses imposed on the system by an adversary. This adaptability also enables the infrastructure to change its scale as necessary to support force structure(s) of any size, or to incorporate new processing, network, and communication technologies as they are developed.

Thus, this infrastructure becomes a scalable computing environment. As a user requests information services, with a QoS expectation, the infrastructure dynamically allocates resources to meet the request. These resources include service and application agents, computing cycles, and communication capacity.

This allocation of resources is accomplished against global optimization algorithms, to meet all users' and agents' needs for support. In addition, the intelligent agents proactively provide appropriately packaged information to end users. This information dissemination function includes fusing and filtering information, and sending the right amount to the right user at the right time.

Because the infrastructure *is* the computer, we can now adjust the amount of processing resources given to a force entity, based on constraints such as power, size, and weight. The entities' processor need only provide access to the infrastructure, provide an adequate interface to the user entity, and enable the acquisition and presentation of information to the user. The infrastructure provides the user entity with access to the computing resources it needs to meet its information requirements. Thus, for example, a dismounted infantry person's computer would be dedicated to supporting a rich human-computer interface (with voice recognition, a heads-up display, speech synthesis, and the like). Because this computer provides the user with an access point to the infrastructure, this computer needs only to be able to meet the interface requirements—it need not support the acquisition, fusing, or processing of large amounts of data on its own. The infrastructure automatically provides the computational resources and services needed by the user.

2 THE INFORMATION INFRASTRUCTURE: THE WARFIGHTER'S PERSPECTIVE

Figure 1 shows a warfighter's view of the tactical information infrastructure. In operational terms, this infrastructure comprises local-area networks that provide services to entities on the ground. These transport networks are all store-and-forward, packet-switched data systems that are self managed and adaptive, and provide peer-to-peer data relaying and processing. These networks adapt to changes in the locations (i.e., the mobility) of its end users; they have no centralized nodes or base stations that would enforce the use of a vulnerable star topology; and they automatically route information amongst the nodes (based on real-time assessments of the network connectivity). These local-area networks can support a single person or a force structure of any size (through appropriate subnetting).

Air- and space-borne networks and processors provide data transport and information services among force entities that do not have connectivity on the ground. A flock of autonomous air vehicles (AAVs) provide medium-area networking services. These platforms are cross linked between themselves and the space-borne network, and are linked to the local-area networks. The routers,* depicted as [R] in the figure, understand the entire system's topology and connectivity in real time. In conjunction with the intelligent software agents, the routers make dynamic routing decisions based on this understanding, to ensure that information is transported from all sources to all destinations, as required and at any point in time.

*Routers are currently used in the commercial internetwork.

Information Infrastructure: A Warfighter's View

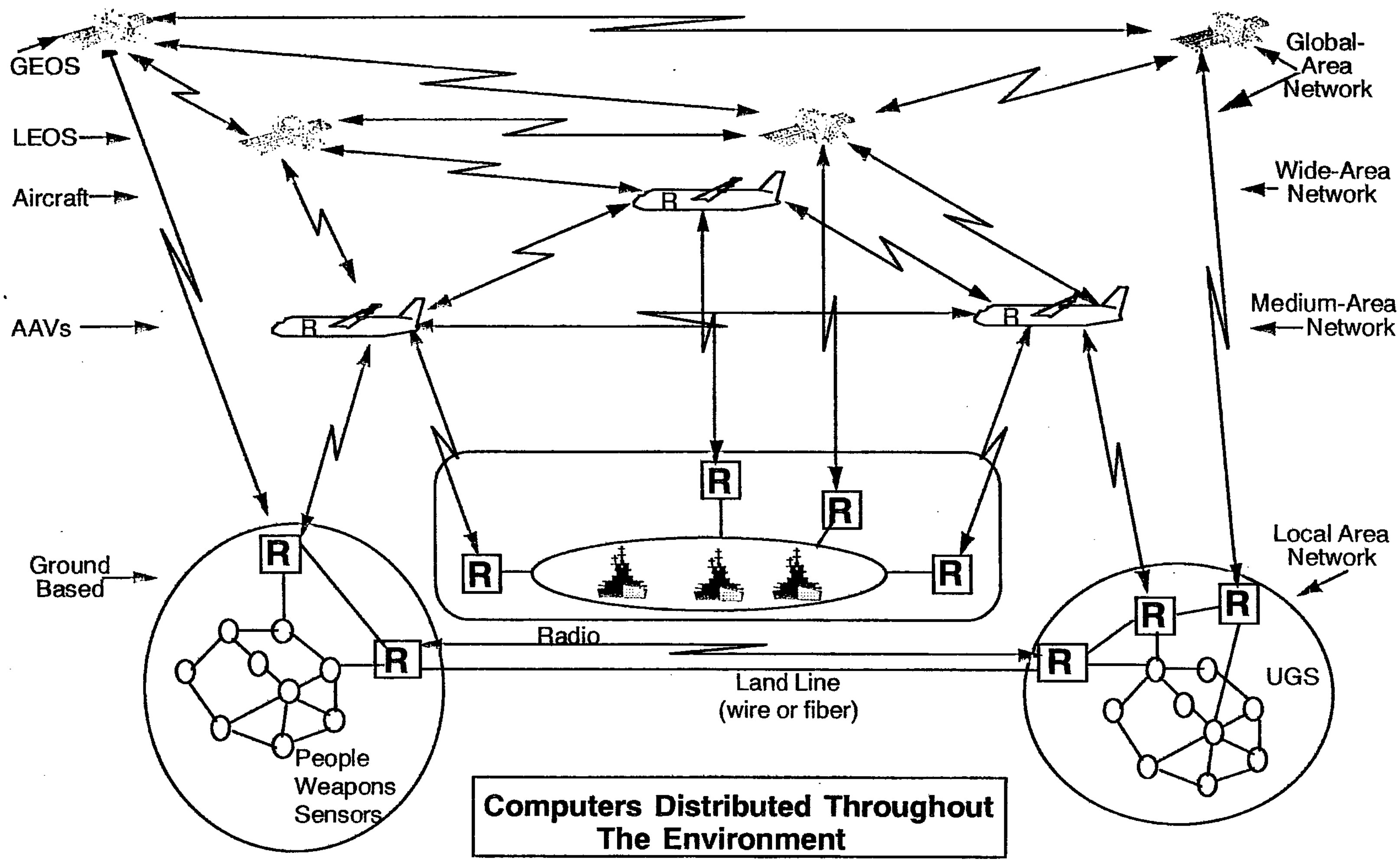


Figure 1

3 INFORMATION INFRASTRUCTURE: A TECHNICAL VIEW

Figure 2 shows a layered diagram of the tactical information infrastructure. This layering is intended to convey the idea that each component of the infrastructure, as depicted, receives services from the layer(s) below it and provides services to the layer(s) above it.

At the center of the diagram is the information transport component. This internetwork (network of networks) integrates networks of all types and sizes, from local (nanonetworks on a person or platform) to global, into a seamless system that automatically routes information between people and/or processors anywhere in the system.

The next layer up represents the computing components distributed throughout the infrastructure. These computers also differ over a broad range of types, purposes, sizes, and architectures. Included in this range are processors embedded in sensors or platforms, personal digital assistants (PDAs), high-end workstations, and massively parallel machines. These processors reside, geographically, at locations commensurate with their size, weight, and power consumption. For example, the higher-end workstations would most likely be situated at command centers; the massively parallel machines would be in sanctuary or CONUS; and the PDAs would be carried by people. All of these machines, however, are integrated into a distributed megacomputer by being interconnected by the information transport component.

The service agent layer comprises software entities that reside on and migrate among the computers integrated into the distributed computing environment. These agents receive state information on available computing and data-transport resources. On the basis of this real-time state information, the agents migrate as necessary to perform the general services they provide to the application agents. Examples of these general services are printed on the service agent layer in Figure 2.

The application service (AS) agents provide mission (domain)–specific services to end users of the infrastructure. Like the other components of this infrastructure, the AS agents receive support from all layers of the infrastructure below them. These AS agents also migrate or replicate themselves across the infrastructure, to ensure the survivability and continuity of domain functions in support of the warfighter.

Finally, at the outermost layer are the end-user entities. These entities (people, sensors, weapon platforms, and the like) are the objects for which the information infrastructure exists: the ultimate sources and destinations of the information that is necessary for the effective conduct of military operations. These entities receive and/or generate (by request or through intelligent dissemination) information of the right type, at the right time, to enable them to effectively execute their mission.

4 TECHNICAL DETAILS

Figures 3 through 6 provide additional details of each of the layers of the information infrastructure shown in Figure 2. In these figures, the reader's attention is directed toward the lists headed "Technology Challenges." Today, the layers of the information architecture are at various stages of maturity. In fact, the maturity of technology tends to decrease from one layer to the next, outwards from the center (as shown in Figure 2).

Information Infrastructure: A Technology View

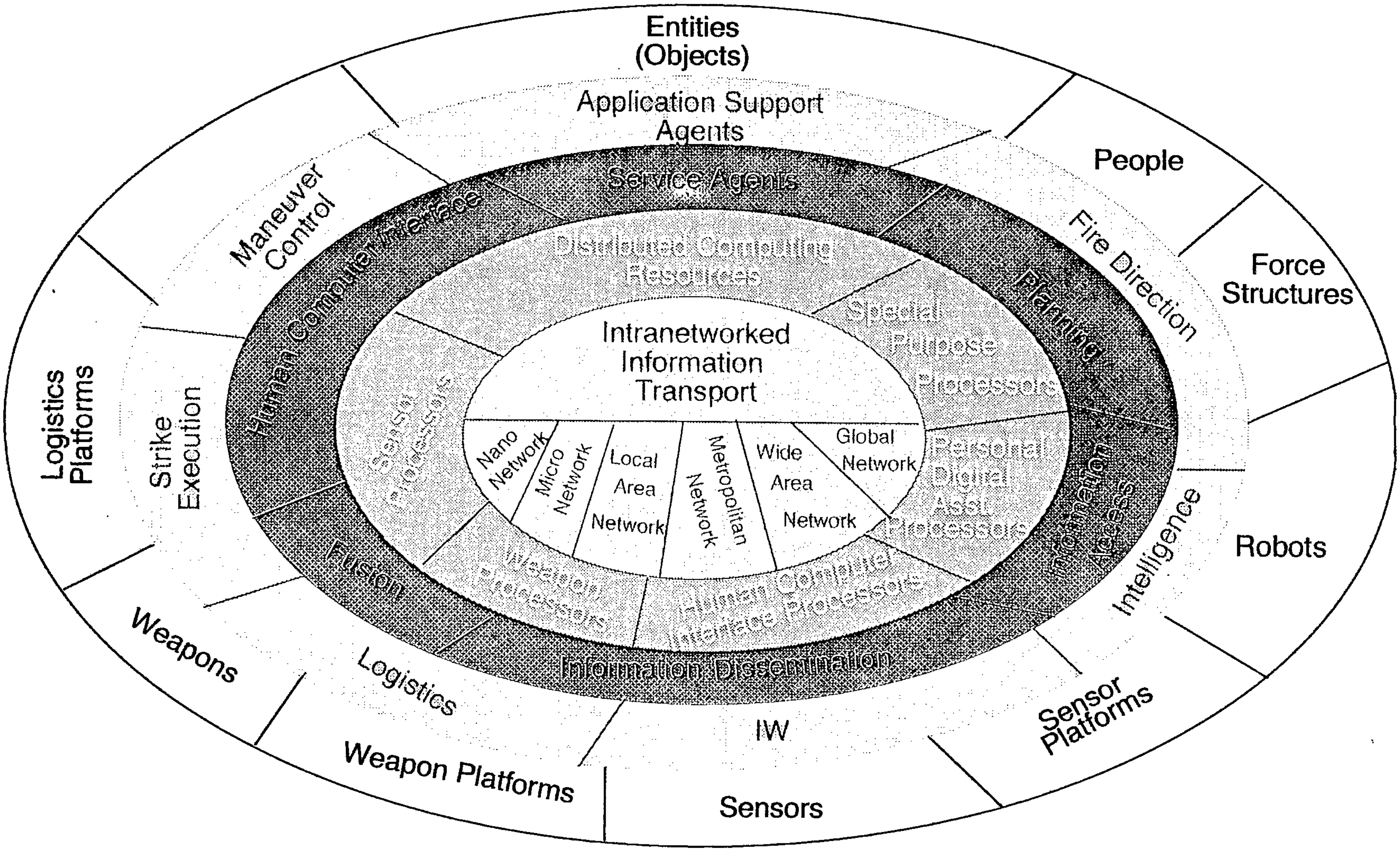
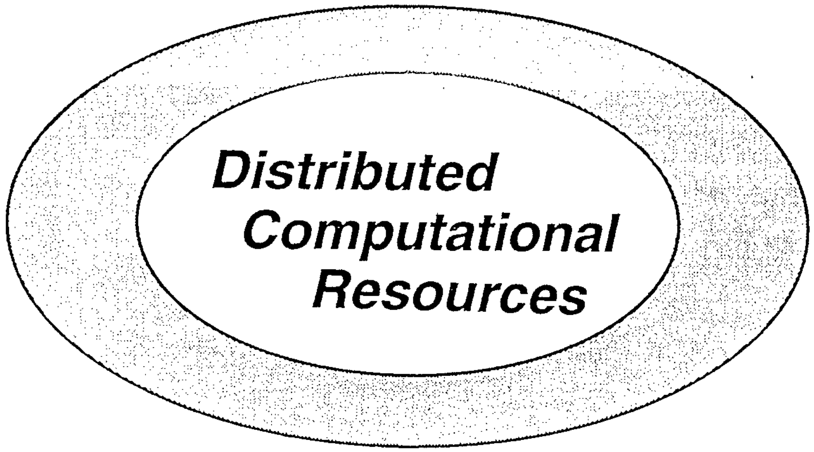


Figure 2



- All resources integrated into a single, virtual megacomputer

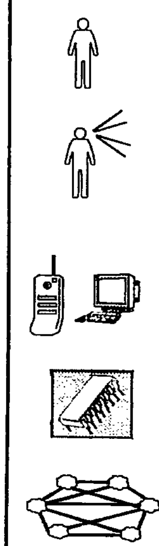
Attributes

- All processing resources are integrated into a distributed collection of cooperative computers.
- Computation resources, in aggregate, provide nearly unlimited computational power.
- Resources are available to all users of the infrastructure at all times under all conditions.
- Resources are automatically allocated/deallocated to meet user's requirements and to cope with adversary.

Technology Challenges

- Heterogeneous processors ranging from massively parallel systems to high-performance, low-volume, low-power units
- Ultra-high-density data storage, RAM and disk based
- Operating systems to provide coarse-grained (distributed) parallel processing
- Algorithms to permit dynamic load leveling, adaptive computation, self management, and reconfiguration
- Algorithms to support dynamic resource management
- Algorithms and protocols that tightly integrate computational resources with transport infrastructure

Vision



- Processors to monitor personal status
- Processor to support user access to infrastructure and to provide HCI (voice recognition; high-resolution, heads-up displays; hearing augmentation, etc.)
- Ultra-high performance personal digital assistants and desktop machines to support end user
- Ultra-high performance processors to support imbedded use (intelligent sensors, controllers, weapons)
- Massively parallel machines to support computationaly complex applications

Figure 3

Software Agents "Services"

- Agent: a software entity that is autonomous, is goal directed, is migratory, is able to create other entities, and provides a service or function on behalf of its owner

Technology Challenges

- Protocols, standards, and environments to support object-based system design and implementation
- Representation techniques for knowledge in object-based systems
- Representation of system resources, plans, and other entities in infrastructure
- Algorithms, protocols, and/or languages for agent definitions, communication, and adaptation

Attributes

- Agents collaborate amongst themselves to achieve goals set by owners. Agents replicate as necessary for efficiency and survivability of services rendered.
- Agents automate human-centric, procedural functions: data acquisition and processing, data fusion, information generation and dissemination.
- Generic services provided include intelligent information dissemination to users, based on their real-time needs and situation.
- Agents provide distributed continuous, adaptive-planning and scheduling services to warfighter. Agents support translation of heterogeneous plan representation and goal sets. Multiple planning approaches are supported through case-based, procedural, evidential and perceptual reasoning.
- Agents support automated, dynamic, adaptive allocation of transport and processing resources.
- Agents provide automated database translation and fusion services.
- Agents provide human sensory augmentation, and support human-computer, multimodal interaction.
- Agents support collaboration amongst themselves as well as collaboration amongst humans. Agents manage the dynamic collaboration environment; others participate in the collaboration process as peers with humans.

Figure 4

Software Agents "Applications"

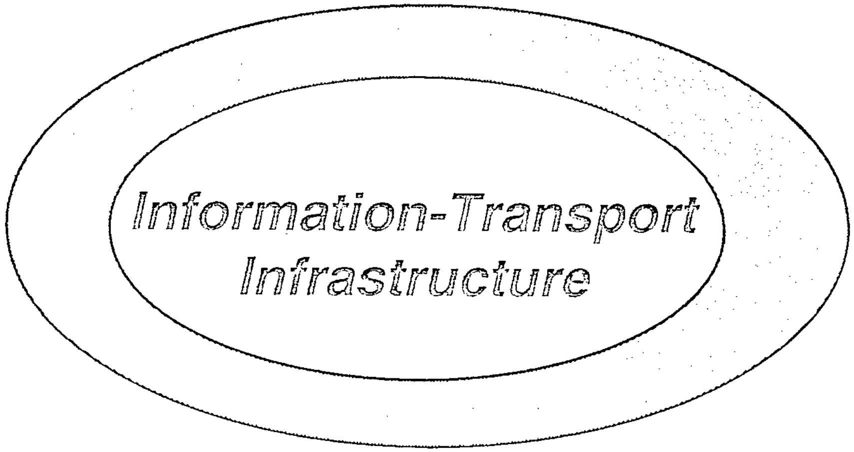
Technology Challenges

- Universal representation of domain knowledge
- Comprehensive, universal language and computational models for declaring agent: attributes, function, domain knowledge, and methods
- Automated techniques for hierarchical decomposition of domain function, processes, and information
- Protocols and algorithms for real-time distributed agent management
- Protocols and algorithms for interagent negotiations and information exchange
- Automated learning techniques to permit agents to adapt to real-world situations

Attributes

- Application agents automatically perform the user-domain-specific functions currently accomplished by people.
- Application agents are goal driven, and have a deep knowledge of their specific domains: process knowledge, information-requirements knowledge and world-state knowledge.
- Application agents broker between each other for sharing information: they negotiate with service agents, as necessary, to achieve these goals.
- Application agents automatically select and perform their functions at appropriate levels of granularity, depending on a specific user's requirements.
- Application agents exchange information and status in order to provide integrated, yet distributed, execution of the domain functions they support.
- Application agents adapt, via learning, to real-world situations. They perform intelligent data and/or information discovery and integration across multiple, heterogeneous databases.

Figure 5



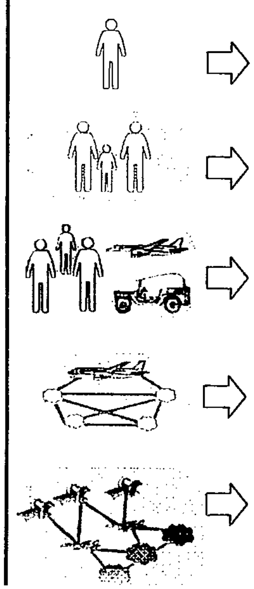
Attributes

- Fully internetworked--**no boundaries between segments or networks**
- Automated management--**self aware**
- Adaptive--**to user needs and stress**
- Flexible--**allows for mix and match of force structure entities**
- Fully integrated--**tightly coupled to distributed computing resources and agents to provide survivable, robust, adaptive, flexible computing and communications infrastructure to the warfighter.**

Technology Challenges

- Autonomous communication platforms and intelligent algorithms to permit robust, highly interconnected transport networks (Flock of Intelligence RPVs!)
- Network algorithms to provide dynamic, real-time, management of waveforms (power, spectrum, FEC, etc.), topology, and bandwidth
- Protocols and standards to permit interoperability between networks
- Distributed algorithms and network protocols to support network and internetwork adaptivity and self management. (Transport support for Mobile Subscribers)
- Algorithms to provide state-info exchange between transport and processing infrastructures

Vision



- Instrumented warfighter (Nanonetwork)
- Collection of instrumented warfighters (Micronetwork)
- Warfighters & organic resources including robots, sensors, weapons (local-area network)
- Force structure including indirect-fire and remote sensor resources (wide-area network)
- Force projection split-base ops, force sustainment, national resources (global network)

Figure 6

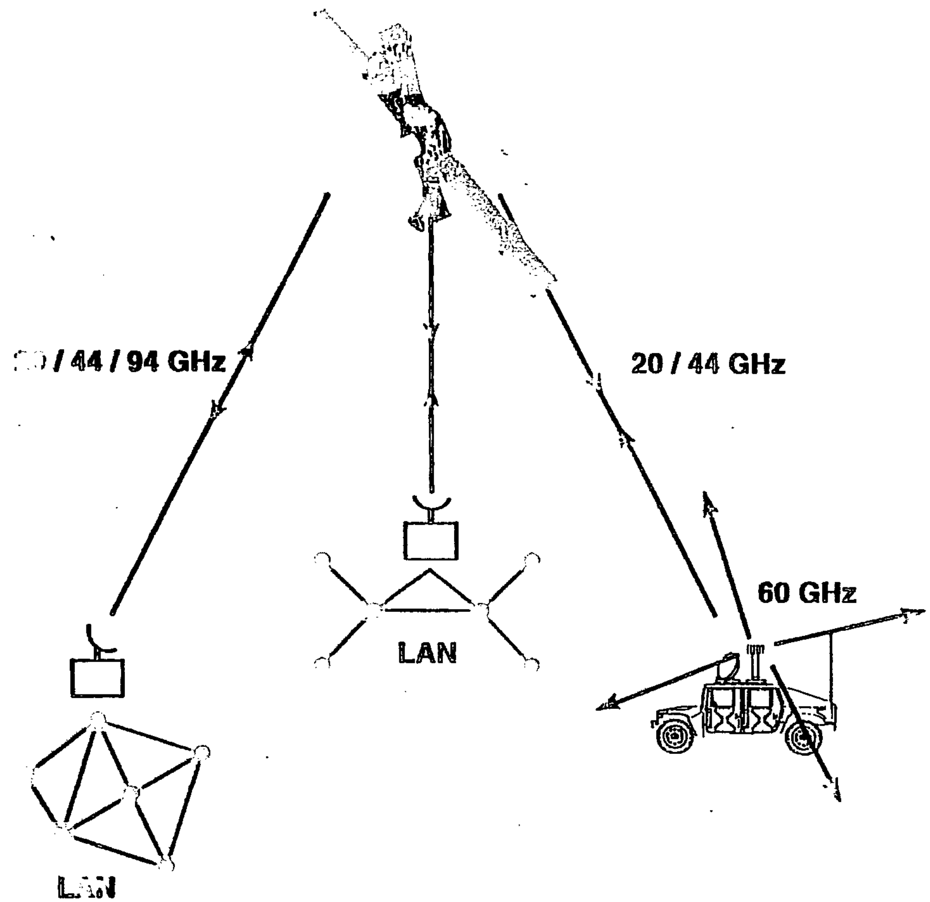
Several DoD science and technology programs are seeking to extend internetwork data transport and intelligent agent technologies. Similarly, the private sector is investing resources to extend radio, land-line, and space-based communications technologies. Although these technology initiatives are making progress, increased focus is needed on the technology challenges identified in Figures 3–6 if the information infrastructure described in this brief concept paper is to be realized by the year 2020.

Furthermore, communication systems must be developed (at the link and physical levels), to provide the raw connectivity needed between the many nodes that compose the tactical information internetwork. The algorithms and protocols mentioned in the figures will turn these communication systems into networks, and ultimately into a network of networks. These raw communication channels must be developed to meet the anticipated information needs of the warfighter. These needs, however, are not well understood at this time: In some instances, users request the transmission of full-motion, full-resolution video to users on weapon platforms, and to and/or from dismounted infantry. Intelligence imagery is also being requested for such end users. Issues associated with information overload, interfaces between humans and the infrastructure, and the true values of various types of information have not yet been adequately addressed. If we are required to provide broadband information products to these types of users, and if we are required to provide protection against jamming threats, the characteristics of the communication networks that support the "last mile" (Figure 7) become very expensive and military unique. Trade-off analyses and evaluations must be completed, and policies must be developed regarding the type, quantity, and priority of the information provided to individual users in weapon platforms and/or on the ground.

5 SUMMARY

Through an appropriate management structure, investment strategy, and focused energy, DoD can realize the vision presented in this concept paper. The private sector has developed the necessary baseline technology, as evidenced in the World Wide Web (WWW) shown in Figure 8. This information infrastructure is a "today" realization of our vision that addresses the emerging information needs of private-sector users. The WWW is an existence proof for DoD—a necessary, if inadequate, development of technology (standards, protocols, and algorithms) that will facilitate the development of an integrated information infrastructure. The WWW is inadequate for direct exploitation as a tactical information infrastructure, because it is insufficiently robust against intelligent adversaries, and cannot support warfighters in unimproved environments. The WWW, as captured in the Joint Technical Architecture (JTA), does provide a starting point.
By implementing the JTA, by focusing a segment of the DoD Science and Technology Program on the technology challenges identified in this paper, and by addressing the security issues noted in Figure 9, we can realize the tactical information infrastructure necessary to achieve military superiority in the 21st century.

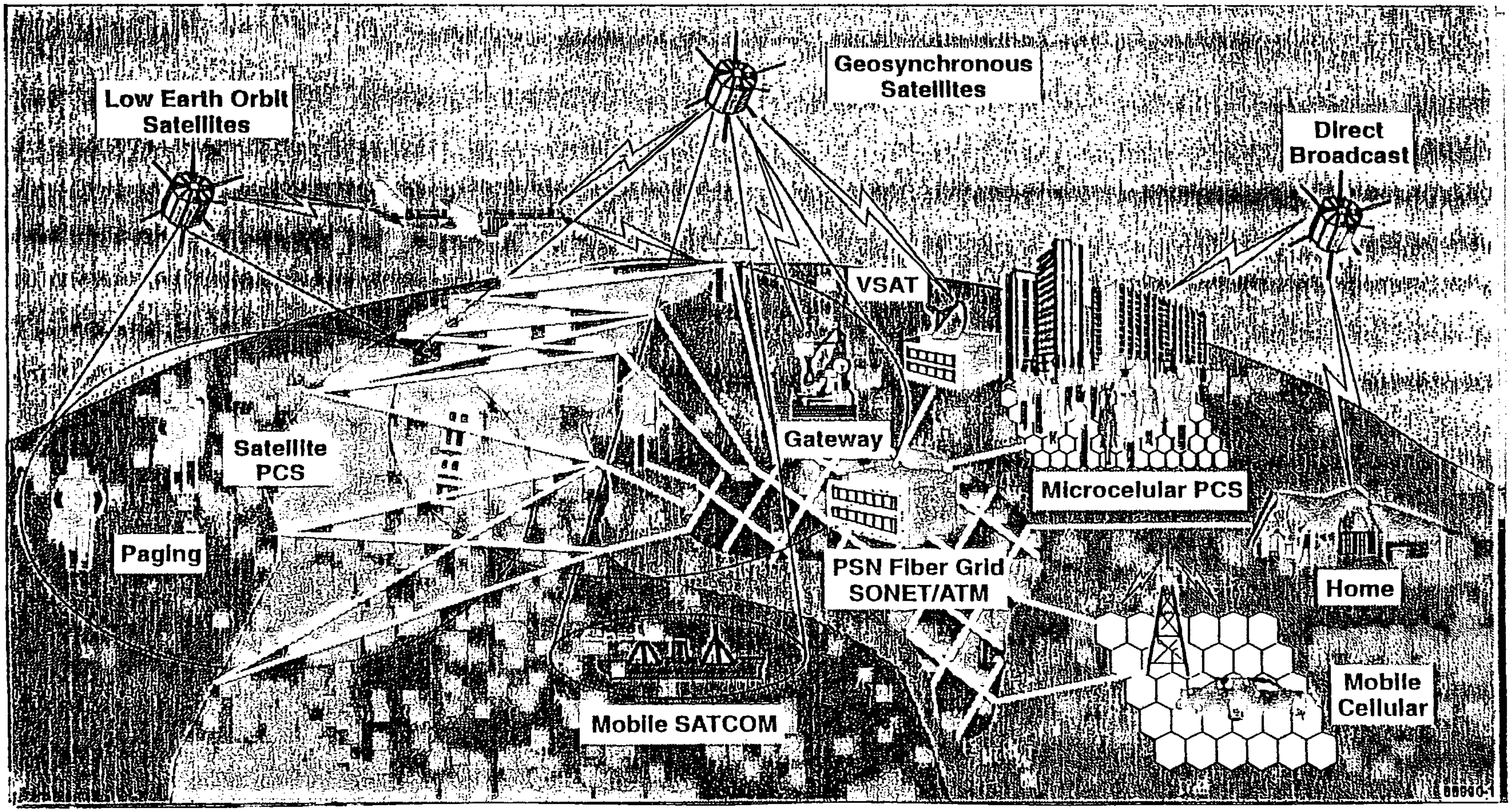
Information Infrastructure Issues: Robust Communication Systems



- AJ via bandspreading and nulling
- Small mobile SATCOM terminals
- 20/40 GHz for theater coverage
- 94 GHz for high speed trunking
- 60 GHz for cross-links
- 60 GHz for ground local-area network
- Phased array antenna for agile multiple narrow beams
- Serves both switched circuits and packet data

Figure 7

Information Infrastructure: An Existence Proof



The World Wide Web Today

Necessary But Not Sufficient

Figure 8

Information Infrastructure: Security

- Issues (Defensive Information Warfare):
  - A new framework and architecture are necessary
    - To allow system adaptability described earlier
    - To permit flexibility envisioned for intelligent software agents
    - To support dynamic user groups
  - Security architecture:
    - Integrated from communication links (TRANSEC) through distributed computers to software agents
    - Developed concurrently and in collaboration with realization of information infrastructure technologies and vision
  - Technology challenges
    - Software agents need security clearances!
    - Distributed algorithms and protocols to support dynamic security policy dissemination and enforcement
      - Data transport routing
      - Dynamic data distribution
      - Dynamic processing--resource allocation

Figure 9

6 RECOMMENDATIONS

The following recommendations should be implemented if we are to achieve our goal of establishing a ubiquitous survivable, adaptive, and scalable information infrastructure for the 21st century. These recommendations are based on the premise that we must, today, integrate our disparate, "stovepipe," warfighters' C4ISR* and communication systems into a baseline integrated information infrastructure for the near term. Our further recommendations are to set in motion a well resourced and focused science and technology program to develop the technologies necessary to realize the information infrastructure envisioned for 2020.

One final observation is that if DoD is to leverage commercial communications technology, DoD must specify the jamming threat we expect, and DoD must establish a policy on the level of jamming vulnerability we will tolerate. Otherwise, DoD and the private sector will continue to be frustrated by our inability to decide how to provide basic communication capabilities at the physical (waveform) and link levels. We can build an adaptive, self-managed network of networks; but locally this internetwork will be no-more robust than the radio communication links we now deploy. How much link-level disruption risk can we (or should we) tolerate? The answer to this question will greatly impact DoD's ability to directly introduce commercial communication technology into our future tactical information infrastructure. With these issues in mind, we present the following recommendations.

1. DoD should appoint a technical architect with authority and responsibility for establishing a baseline (near term) DoD Tactical Information Infrastructure.
2. Responsibility for the DoD Technical Architect should reside with the Under Secretary of Defense for Acquisition and Technology (USD A&T).
3. The baseline TII should be that set in the DoD JTA Version 1.0 to be released in June 1996.
4. The DoD Technical Architect should require that all service and agency C4ISR systems and infrastructures be built in compliance with the JTA.
5. The DoD Technical Architect should conduct a series of trade-off analyses of threat versus risk tolerance versus cost for information infrastructure services. This analysis should address the degree to which DoD can exploit commercial off-the-shelf technologies.
6. The Deputy Director of Defense, Research and Engineering should initiate an aggressive science and technology program to address the technology challenges noted in this paper. This program should be focused on achieving the tactical information infrastructure by 2020. The organizations chosen to execute this program should include DARPA, the Service Laboratories, and the Service Offices of Scientific Research.
7. A series of advanced concept technology demonstrations (ACTDs) should be defined, funded, and executed; these ACTDs should incrementally demonstrate increased information infrastructure functionality, leading to the realization of the vision by 2020. The demonstrated incremental capabilities should be integrated into the baseline information infrastructure established, in the near term, under the direction of USD A&T.

*C4ISR: Command, control, communications, computer, and intelligence surveillance and reconnaissance.

8. DoD and service policies must be established that define the threat our warfighter communication systems will face. These policies should also establish quantifiable antijam and low-probability-of-intercept metrics appropriate for local-, medium-, and wide-area communication links.
9. Modeling and simulations, combined with ACTDs, should be conducted to determine the types, quantities, and time lines of the information and human-computer interfaces required by the warfighter—from the dismounted infantry through unit command centers.
10. DDR&E and the military Services should allocate engineering development resources to apply, extend, and/or develop network communication systems that meet 21st-century multimedia communication requirements.

Information Transfer Support for 21st Century Military Superiority

by

Carl G. O'Berry

Background. The DSB Summer Study Technology Panel tasking for this paper is aimed principally at addressing tactical connectivity issues; however, 21st century tactical communication support can only be properly assessed as a part of a global information transfer continuum which is already developing. It will be in the best interest of war fighters for the DoD to address that global environment in the DoD strategic architecture and to work vigorously in the public policy domain and with commercial interests to expedite its development in a form advantageous to warriors — which should not be viewed as mutually exclusive from national information infrastructure or commercial market interests. In fact, the resultant, largely commercial information transfer utility would benefit *all* consumers by providing close to 100% availability world wide, and multi-task access from a single entry point, or port.

A recent International Telecommunications Union (ITU) task force report directed at building a global infrastructure to meet the information needs of the next century made the following observations:[1]

- Current state-of-the-art fiber optic systems can now transmit the equivalent of 80,000 simultaneous telephone conversations over a single optical fiber and will soon carry 320,000 conversations over a single fiber

- Advances in digital compression have vastly improved the performance and capacity of existing networks by allowing more volume, including data and video, to be transmitted [over single fiber, wire, and wireless links]

- Advances in computer technology will soon offer storage capacity so great that an individual using a hand-held device will be able to carry the informational equivalent of a small library and remotely access many times that amount [of information]

- New digital wireless systems and proposed constellations of telecommunications satellites have the potential to provide telephone and data services to any point on the planet

The ITU task force went on to report that a nascent global information infrastructure (GII) already exists, but that what is needed is *...a superior GII, one that has higher capacity, is fully interactive, faster, more versatile. One that is less expensive to use than existing systems, and more accessible to all the people of the world...*

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[1] Hon Ronald H. Brown, et. al., "The Global Information Infrastructure: Agenda for Cooperation," Washington, DC, 1994.

It is safe to say in April 1996 that more than a *nascent* infrastructure already exists. The rate of fiber optic link growth is indicative of the global demand for greater information exchange capacity, and the marketplace is moving to address that increasing demand. Similarly, space-based communication segments are on the increase and will continue expanding to service the need for instant access to remote areas of the globe, where fiber remains impractical. Moreover, it seems inevitable that all means of information transfer — fiber, terrestrial wireless, coaxial cable, space and laser links — will eventually merge into a single, seamless information system connecting world businesses, governments, public services and private citizens.

Convergence. The increasingly abundant commercial information infrastructure provides rapidly expanding opportunity for the sharing of information of any nature, anywhere, and the still-growing power of computers supplies the potential for satisfying any information transfer requirement instantly, reliably, and securely. These generalized concepts are perhaps more aptly addressed as relating to the *convergence* of information systems and services due to advancing digital technology. A recent futures paper from Motorola discusses convergence at some length, describing the concept as follows:[2]

> The current communications and information revolution is taking place because of digital technology. All information represented by sound and sight can be converted into bits and bytes, be transmitted digitally and reconverted into its original form. That, in turn, serves as a fundamental basis for the convergence of computing, communications and consumer electronics.
>
> Elements of convergence are evident in the current linking of telephone networks and PCs to transmit audio-visual data and provide video-phone facilities. It is important to understand what this convergence will mean and, equally, what it will not mean.
>
> Convergence does not mean sameness. To realize the benefits of the digital revolution, to create a Global Information Society, will depend not on conformity, but diversity and creativity — artistic and technological. The Global Information Infrastructure connecting the world's businesses, public services and citizens will be technologically diverse, using cable, satellite and terrestrial radio. It will have hundreds of operators, thousands of service providers supplying millions of services, and hundreds of millions of users and "publishers" of information.

To be sure, there are technological, political, and economic issues to be addressed in order to gain such capability on a global scale; but the technology is in hand to satisfy the requirement, and the focused pursuit of appropriate public policy, economic incentives, and changes in current cultural attitudes could yield information transfer capabilities far beyond those promised in spectrum auctions, cable-telephone-space system competitions, and often short-sighted architectural visions.

It's necessary, therefore, to examine the elements of *global* connectivity before delving into the tactical interconnection of military forces — the latter being substantially simplified if one can temporarily separate content from structure in the macro sense, then proceed to a more detailed discussion of virtual networking and a potential "system to soldier" information transfer utility.

A Global Infosphere.™ The concepts of National or Defense Information Infrastructures (NII or DII) are usually described in terms of information "superhighways." That metaphor, however, fails to accommodate the requirement for global connectivity as defined by an increasingly digital information transfer environment. Highways are limited in capacity and permit entry or exit at

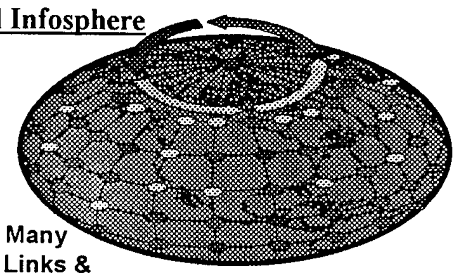
[2] "Convergence and Technological Diversity: A telecommunications futures paper from Motorola," Oct. 26, 1995

only specified points — whereas a true global information transfer environment must be of virtually unlimited capacity and must facilitate easy, affordable access everywhere, for everyone, all the time.

The evolution of the infosphere is hampered by a lack of focus, not by inadequate technology. While industry grows better information *appliances* at an increasing rate, the interconnecting facilities and services tend to lag substantially behind the appliances. The consumer, whether home computer user, office manager, engineer or warrior, has been led to expect far faster and more efficient connection between the tools of his or her trade; but many government and commercial information transfer providers continue to react in classic analog bandwidth terms in response to a requirement that has long since outdistanced such antiquated thinking. In other words, better understanding is required in both government and industry of the waste and inefficiency of specialized networks and classical circuit switching — the currently preferred means of transferring information between geographically separated users and data-hungry information appliances. What's needed is a truly global perspective, where the frequency spectrum, the growing space infrastructure, the broadcast media, and the sum of all wire —classical copper, fiber, or coaxial cable — can be viewed as a *continuum*, every element of which is available for the creation, instantaneously and on demand, of virtual paths for the transfer of digital packets between users anywhere on the earth.

The characteristics of such a global environment are not difficult to delineate. Simply put, the requirement is not for bandwidth, UHF, fiber, wireless or wired; the requirement is for instant connectivity for the purpose of transferring information between authorized parties, human or machine, upon demand, from any point(s) on the globe to any other point(s). Figure 1 serves to graphically describe the requirement. It can, as stated previously, be logically postulated that something like the environment depicted is inevitable — simply because the information transfer demands of an increasingly info-centric world demand it. It can also be postulated that the DoD, with its vast needs and considerable influence, could be a major lever in speeding up the process, should it choose to do so.

Characteristics of a Global Infosphere



- **Millions of Nodes**
- **Every Node a Data Packet Switch**
- **Every Node Connected to Many Other Nodes via Various Links & Operational Modes (RF, Fiber, Coax, Twisted Pair, Laser, Various Waveforms)**
- **Thousands of Node Providers, Distributed Risk of Ownership & Extension**
- **All Information in Digital Form (Packets)**

Figure 1.

All the nodes in such a global environment need not be of the same size or capacity, nor must every node contain all possible operational modes. Every information appliance, from a soldier's backpack or wrist watch to the most sophisticated space system — light switches, dog collars, automobiles, airplanes, tanks, ships and armored personnel carriers — all could contain packet switching nodes. Any node could be made to accommodate to various frequencies and wave forms, and to any wired connection gateway or mode of operation.

The global infosphere can be grown to any required density as the infrastructure expands to support it, in a manner perhaps analogous to the rapid growth of the now ubiquitous *Internet*. As it grows, it will become increasingly robust and survivable, and its resources can be used with increasing efficiency. No "circuit" need exist in such an environment until an information transfer requirement surfaces, at which time a virtual circuit would be created, the transfer would take place, and the resources which constituted the transfer path would be returned to the global "pool" to support other demands — quite unlike the situation in the Persian Gulf, where hard-wired circuits consumed and constrained the utility of all available bandwidth and could be put to use only a fraction of the time (but for which the consumer paid as though they were used *all* the time).

The growth and universal use of a global infosphere would bring with it many advantages of significance to the DoD. Perhaps most immediately important among those would be a high degree of robustness and survivability due to redundancy, and an equally high degree of integrity of the bit stream associated with any transfer transaction. In other words, the more dense the global distribution of interconnection nodes, the lower the likelihood that local or regional disturbances associated with failed network components, jamming, or physical attack would be effective in preventing communication between points in the grid. Similarly, since the likelihood of any two information transfer transactions between the same points in the grid taking the same path would decrease as the infosphere density increases, it would become increasingly difficult for would-be attackers to find — let alone modify or negate — any transfer within the grid.

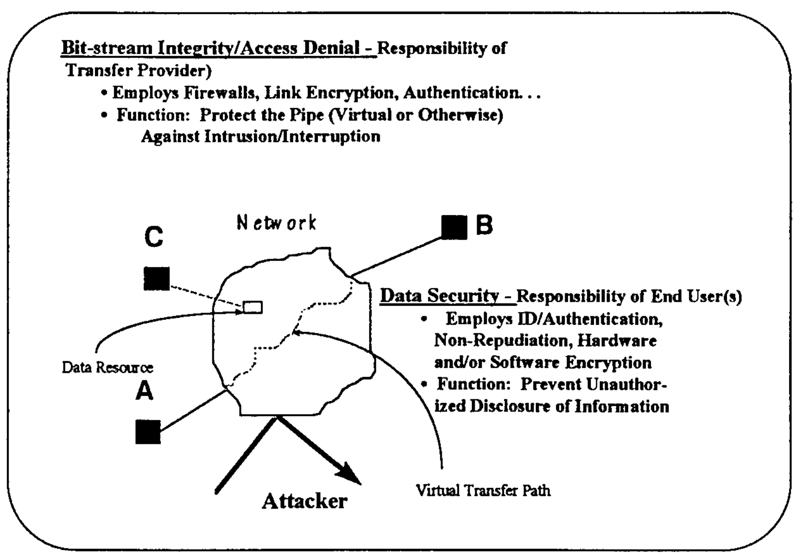


Figure 2.

The issue of protecting information will, of course, continue to be a significant factor in DoD architectures and information transfer objectives. However, information protection activity must also be re-evaluated in the context of the global infosphere. As shown in Figure 2, protection of information should be regarded as a function of two major information transfer domains: first, the protection of *bit stream integrity*, which is a responsibility of the transfer media providers (whether commercial or government); that is, the provider of the instantaneous information transfer pathway must assume responsibility for assuring that the bit stream is protected from interference or alteration or that it is possible to reconstitute the bit stream and its original contents in the event of interruption. Second, the protection of the *content* of the bit stream from unauthorized disclosure, which is the responsibility of the parties to the information transfer transaction (i.e., the humans or the machines calling for the transfer).

The elements of bit stream integrity are network recognition of the threat and appropriate responses thereto, and general resistance to attack. The techniques are straightforward, and may involve fire walls, link encryption, instantaneous path changes, authentication, anti-jamming techniques, and other automated network or human responses to attack, whether from hackers or other enemies of the bit stream. The protection of in-transit information from unauthorized disclosure requires unequivocal identification of the end parties to the transaction, reliable assurance of authorization for the transfer (that is, the sending party must know with certainty that the requesting party is authorized to receive the information), non-repudiation (prevention of denial that the transaction took place and unequivocal assurance that the identified end parties did, in fact, affect the transfer), and the proper degree of packet-level encryption (i.e., the higher the degree of sensitivity, the more robust the encryption methods, such as multiple encryption using multiple keys). Many, if not all, of the listed processes and procedures can be automated, given current and projected technology.

Interoperability. While the DSB Task Force on C^{4}ISR has appropriately pointed out that interoperability is not sacred, but operability *is*, the latter is difficult to achieve without the former. The global environment described above could adequately address interoperability among digital networks and systems, and between the global infosphere and appliances connected thereto, in a manner analogous to the way electrical appliances currently interoperate with electrical power networks. However, functional interoperability among myriad warriors, command levels and war fighting "appliances" will require carefully developed and managed architectures. In fact, it is essential for the DoD to plan and develop a layered architecture for a *single, integrated, global war fighting information exchange environment* as opposed to just trying to interface thousands of legacy systems in an ungainly attempt to achieve "interoperability." Fortunately, tools and methods are available today to achieve that objective; but concerted effort is required on the part of the DoD to develop the necessary global outlook and address the vertical and horizontal integration of architectures such that everyone and everything essential to the successful conduct of combat operations is optimally interconnected.

From Global to Tactical. In most respects, the exchange of information at the tactical level in a world rendered increasingly "connected" by a global infosphere would differ little from strategic connectivity except in possible capacity limitations of the switching nodes available. For example, a soldier equipped with a BodyLAN[3] might not be able to carry a full function multi-mode, multimedia switch; however, he could be equipped with a highly sophisticated sensor/computer suite which could interface via a personal digital assistant [commonly called a "PDA" (which could also be a digital packet switch)] with bigger interactive networks served by larger capacity switches

[3] BBN Tech Watch, "Wearable Networks: BodyLAN Technology Takes Wireless Computing Into New Dimensions," published on the Internet (http://www.bbn.com/techwatch/techwatch.html)

carried on air, sea, land, or space vehicles within reach. In essence, every element of a tactical force, however widely distributed, could interact with all other elements of the force to greater or lesser degrees, depending on the size and weight of the interactive nodes it could carry. Figure 3 is a notional example of such integrated networking. The diagram's center of focus, as previously described, is the virtually integrated sum of all connective media — terrestrial, airborne, and space based. In fact, every "information appliance" depicted here could serve as a node in the global infosphere, carrying one or more digital packet switches — each of which could negotiate nearly instantaneous virtual information transfer paths with other nodes within reach as required.

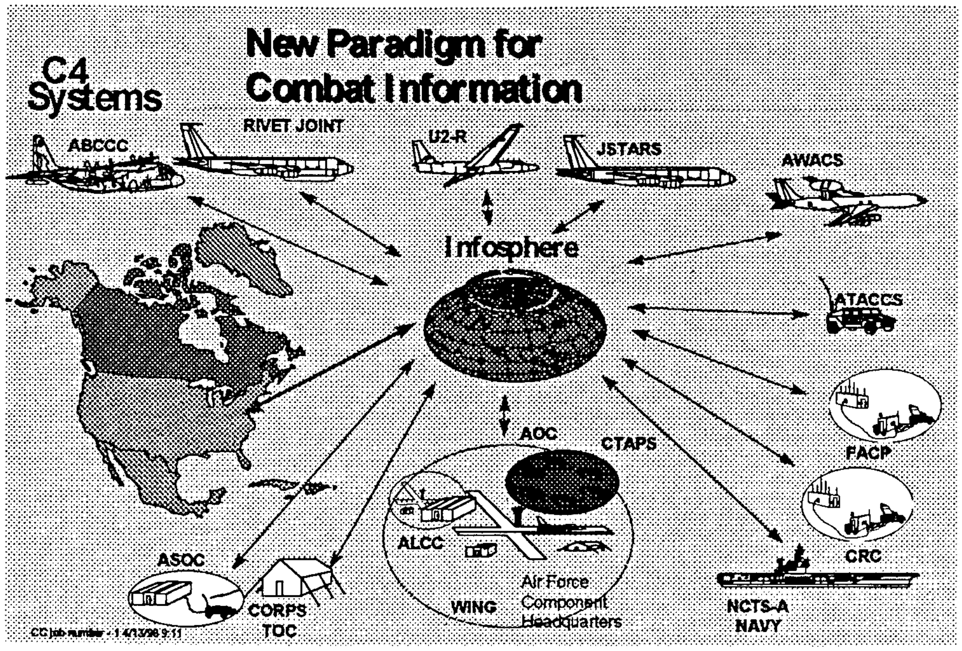


Figure 3.

The Way it is Today. The alternative to a systematic approach like the one shown in Figure 3 is to remain on the current course of data links and point to point circuits as the preferred response to information transfer demands. The principal issues with that "solution" are that it is inordinately wasteful of bandwidth, cannot ultimately provide the volume necessary even for projected *private sector* information transfer requirements, results in unacceptable tethering of resources to fixed points, and is unaffordable. Nor is it affordable — or operationally feasible —

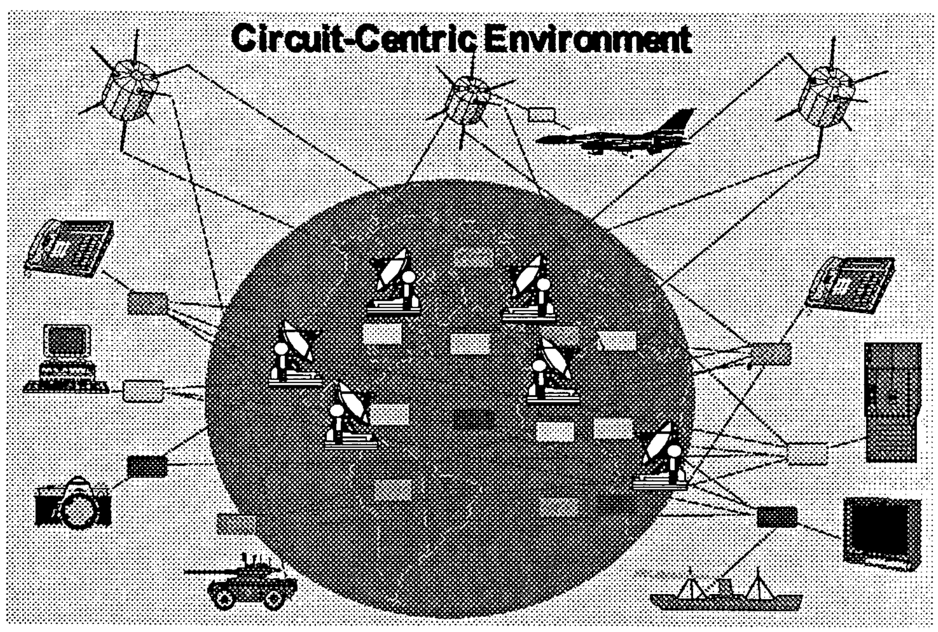


Figure 4.

to continue the past practice of exclusive DoD ownership of extensive information transfer media in the misguided belief that this only way to assure connectivity, survivability, and security of military information.

The move from an analog world to a fully digital environment encompassing the sum of all transfer media will not be easy; but it is absolutely essential. Figure 4 is a notional summation of the situation today, and graphically illustrates the extremes to which architects and system planners must go to nurse every cycle of bandwidth from already overtaxed resources. Carried to its logical extreme, there is not enough bandwidth in the universe to satisfy even today's relatively meager demand. Operations Desert Shield/Storm served to illustrate the problem in real world terms. With the movement of an additional DSCS satellite to the theater of operations and the transport of more than a hundred GMF satellite terminals to the theater, the demand for bandwidth could not begin to be met. Commercial terminals were sent to the Gulf to augment the milsatcom structure; but the demand still far surpassed the available circuits. Yet after action analyses and studies show that almost every T-1 circuit installed in the Gulf was actually used less than 50% of the time. The reason was that once a circuit is installed between two points its bandwidth is "locked in;" it cannot be used for any other purpose; therefore, this precious resource is substantially wasted.

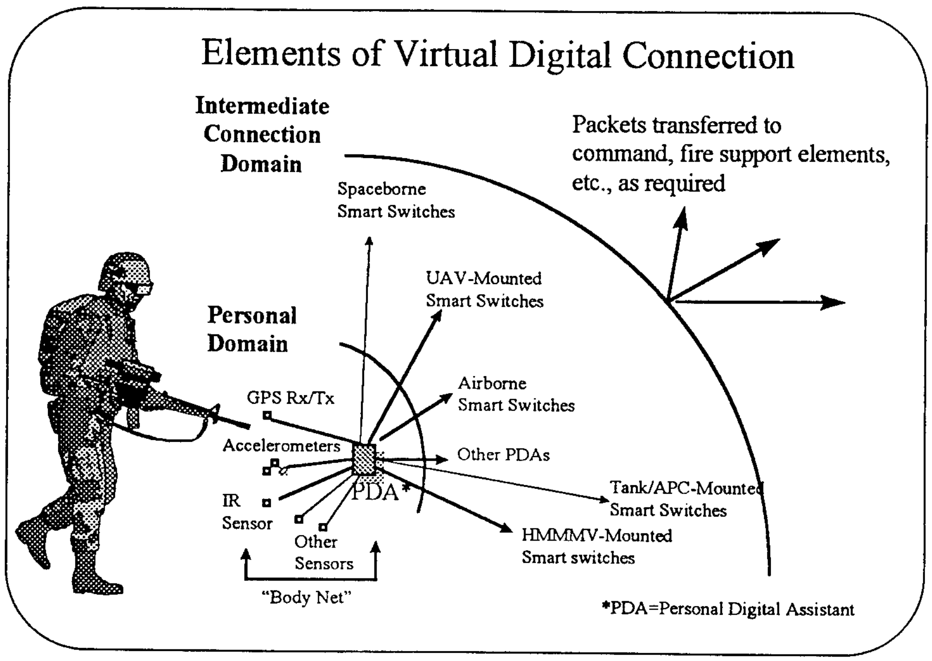


Figure 5.

Connecting the Soldier. How, then, does the information transfer utility described above ultimately connect and serve the individual consumer — particularly one whose need can be characterized as one of persistent and rapid mobility, high information density, and limited transfer interface capacity? If the current projections of combat force structure and weapon systems are even close to the mark, then it is essential that every element of such forces have on-demand access to a responsive, secure, reliable, highly mobile and virtual connective structure. Direct, or "hard-wired," links will not satisfy the multiple element connections envisioned by the 21st century soldier, nor will so-called data links enable the exchange of information needed to optimize a combat environment such as that prescribed by the Air Force Scientific Advisory Board's *New World Vistas* product. Figure 5 more closely depicts the information transfer environment needed. It is essential that the next generation soldier be equipped with various sensors, precise location determination and reporting, and a highly sophisticated computing capability. In effect, such capabilities demand the functional equivalent of the BodyLAN referenced earlier which, in turn, would permit some functions supporting the soldier to be accomplished in a continuous, digitally subliminal fashion, to include position reporting and other analytical data collection, processing, and reporting. A logical extension of this individual soldier picture to fighting vehicles, aircraft, UAVs, and the myriad weapons and command/support elements of combat operations only strengthens the argument in favor of the digitally layered information transfer environment described in the Figures 3 and 5. It must be reiterated that the environment described is not here today; however, many elements are in place, or nearly so, which offer sound starting potential. Today's technology requires only relatively minor development and additional tuning to make a global, highly intelligent information transfer utility available within the next five or so years, and the DoD has the necessary persuasive influence to cause a major effort in that regard, should it choose to do so.

Summary. There are several important points to consider in DSB deliberations concerning the optimization of the information transfer environment for 21st century combat operations:

- The global information infrastructure (GII) must be substantially developed and operated by commercial information transfer enterprises; however, commercial interests and military requirements are *not* mutually exclusive. Warriors may use the GII and still employ special means of communication, such as LPI, AJ, spread spectrum, encryption, and special communication linkages — in addition to conventional commercial means. What is critical to effective use of the GII is that the *form* of all information (i.e., digital, "packetized", employing appropriate compression techniques, etc.) must enable it to move wherever it is needed within the global environment without it requiring translation between connecting systems.

- A system such as that described herein can be constructed such that it has essentially perfect flexibility. Who communicates with whom and what information the parties share should be determined by the appropriate set of tenets (e.g., doctrinally, in the case of the military). In joint operations, the forces of the three Services should be able to intercommunicate without translation between their respective systems. Similarly, infantry forces should be able to communicate readily with fire support, naval, or air forces without having to pass through cumbersome chain of command systems, if that's what the tactical situation demands. Information at all command and staff levels should share common attributes with tactical information, such that communicating up and down the structure is simple and can be readily accommodated by the global grid.

- The vast bandwidth of an emerging, commercially developed global system is already substantially deployed, and will continue to be enriched as the demand increases. Those information transfer resources will be instantly available for military operations, and will permit many information transfer processes to be software driven (like the Speakeasy and other programmable digital devices), thus freeing the DoD from the current constraints of many cumbersome legacy systems and obsolete hardware.

- A major key to successful prosecution of combat operations in the years ahead lies in successful development of a global DoD architecture for virtual digital connection of all legitimate DoD consumers of information, consistent with the GII. Automated tools are available to build and manage such an enterprise-wide architecture.

- Finally, the cost of continuing to strive for exclusive DoD information transfer capabilities is logically and fiscally insupportable. The only reasonable answer to the huge demands of military information exchange is to establish a GII-compatible Defense architecture and, to the extent possible, to leverage the evolution of the GII to the advantage of war fighters.

Recommendations for the DoD. A specific, but not exhaustive, list of actions by which the DoD might leverage the development of the global infosphere to its advantage follows:

- Take an active interest in and seek to hasten the development of public and international telecommunications policy which will motivate governments, industry, and private consumers to pursue the development of the environment suggested here.

- Foster a more profound understanding of the physics and implications of pure digital telecommunications structures. Seek to motivate more rapid extension of Asynchronous Transfer Mode (ATM) technology for both wired and wireless digital information transport and switching.

- Develop top-down, globally structured architectures to address functional, operational, and technical elements of combat operations and provide the Services with the attributes essential to ensure a truly integrated military information infrastructure. The present efforts at "enterprise integration" are failing to achieve the even the limited and transient objective of interoperability between the thousands of DoD legacy systems.

- Foster better understanding of cybernetics and organizational structures, focusing on the potential effects of digital information systems. Many of the operational structures in use today appear to be artifacts of old, slow, and deficient analog information processes. The graphical content in present and future information systems, coupled with increasingly capable automated decision aids should substantially reduce the need for many layers of command and control structure.

- Seek to re-educate the user of information systems such that requirements are stated in terms of *requirements* and not potential solutions. Too often, the consumer tends to ask for UHF, or fiber optics, or T-1 circuits, etc.; whereas a good architecture, accompanied by rigorous underlying analysis of information flow conditions and the attributes necessary to assure those conditions are satisfied, would serve to establish an entirely new frame of reference for user requirements.

- Foster greater understanding , and rapid expansion, of commercial information systems. With few, if any, exceptions, the satisfaction of military information transfer requirements is most likely to come from the private sector.

- Foster and continue to encourage commercial *system* solutions to Defense command, control, communications, surveillance, and intelligence requirements. Despite DoD efforts at acquisition reform, the process of acquiring services and capabilities continues to motivate point solutions, rather than integrated system answers.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

ISSUES IN BUILDING A HETEROGENEOUS NETWORK

White Paper

Vincent W. S. Chan

Issues In Building A Heterogeneous Worldwide Network

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Abstract

In support of the information needs of new warfighting concepts, non-traditional data connectivities need to be established. There are a significant number of developments of new hardware and system concepts to bring more of a data networking approach to military communication. However, there is still much to be done to develop individual systems and integrate them into a seamless web.

Advantage can be taken of the explosive development of commercial products and systems, but there are a number of unique attributes of military communication in the theater grid that will require new solutions and their integration with key existing systems. Among these unique attributes are the need for 1) data collection and relay, 2) instant infrastructure, 3) communication on the move, 4) assured real-time access, and 5) adaptation to the environment.

ATM (among other formats) will be widely used in the worldwide military network infrastructure. In this role, it will have many benefits. However, there are real differences in the requirements of military and commercial communications systems. Furthermore, multiple administrative domains will be involved in the construction and operation of this infrastructure leading to a large degree of heterogeneity. These differences and the heterogeneous nature of the internetwork lead to a number of technical issues which need to be resolved. In this paper we identify a set of critical issues that need to be addressed in future research.

I. MILSATCOM and Global Networking: Brief Overview

The Defense Information Infrastructure (DII) includes wireless (satellite and radio) communications resources. These resources are used to connect various segments of the DII's "fixed" backbone network as well as to provide a deployable theater extension network and serve dispersed users. In this paper we focus on issues in providing seamless connectivity between the wireless resources and the wired resources, as well as among the different wireless resources.

Satellite resources available to the military include the DSCS, FLTSAT and MILSTAR MILSATCOM systems as well as an increasing number of commercial systems. These systems can be vastly different in their capabilities because they were often designed to meet very specific user needs. As a result, providing connectivity between these various systems can be a difficult task. The DSCS system consists of transponder satellites that are primarily used to carry high data-rate circuits from fixed sites and deployed transportable tactical trunking terminals. Most DSCS terminals do not provide anti-jam protection, although some low rate anti-jam terminals do exist. The FLTSAT satellite uses UHF tranponders to serve small mobile users at low data rates. FLTSAT circuits are typically used to provide military radio "push to talk" and specialized tactical data networks. A Demand Assignment Multiple Access (DAMA) system is being established that will use TDMA to increase the user capacity of the FLTSAT system. The MILSTAR system is a processing satellite system that will operate at EHF and provide jamming protection for all of its users (including small terminals). MILSTAR is a circuit switched system that can provide data rates ranging from 75 bps to 1.5 Mbps per user. The MILSTAR system will, at least initially, be used in a similar way to FLTSAT and DSCS to provide dedicated circuits in support of specific functions or ground networks.

Many commercial systems are also used by the military network. Wideband trunks are leased from commercial providers when they are available. Inmarsat is used on ships to provide voice, video and data services. Other systems such as Iridium, Globalstar and Inmarsat-P are being considered for future military use when they come into being. A major concern with the use of commercial systems is guaranteeing access wherever and whenever needed. Commercial systems must not only have available capacity but also legal "landing rights" for use in host countries.

In addition, there are a number of military requirements, such as anti-jam protection and strict and multi-level data security, that are unlikely to be provided by commercial systems. The military also has some specialized functional requirements, such as broadcast radio nets and time-critical delivery systems for missile warning, that are unlikely to be met by commercial systems. Therefore, it is reasonable to assume that MILSATCOM systems will continue to be developed and used alongside commercial systems.

The military also uses a wide variety of terrestrial radio systems (e.g. combat net radios, HF, troposcatter, etc.). One notable system that integrates a variety of services is the Mobile Subscriber Equipment (MSE) network. The MSE network is essentially a "transportable" digital telephone network. While MSE's primary use is for circuit switched voice, it also has packet switched data capabilities. Most MSE switches are connected via line-of-sight radio relay. SMART-T terminals are capable of interconnecting MSE switches beyond line-of-sight with EHF satellite resources.

New techniques for wireless battlefield communication to support highly mobile tactics and an increasing information flow are currently under consideration. These include mobile wireless LANs, satellite, circuit switched cellular networks, and satellite PCS services when available. Connection-oriented and connectionless services will be used. Wireless services will be characterized by: link quality that may be marginal and fluctuating, connections that will be rapidly made and unmade due to user mobility, and a wide variety of formats that will probably evolve. While these new systems will provide a desirable capability, it will be a challenge to integrate them into a general B-ISDN structure such as ATM which is designed around more uniform high quality link conditions.

With so many military and commercial systems in use, questions arise as to how to "inter-connect" these systems in order to provide users access to services across a variety of systems. For example, how would a voice call be made that originates on the commercial telephone network and goes through MILSTAR to a ground terminal situated in the field of operation; or how would a DSCS user communicate with a MILSTAR user. More generally, the question is how can communication services be provided across the various domains of military and commercial systems used by the military. The problem in providing such services is that these different networks operate using different protocols and sometimes provide different (and possibly incompatible) types of services. For example, while a packet data service may be supported by the MSE network, there is no equivalent error-free packet data service provided by MILSTAR; consequently, there is no efficient way to connect the two systems in order to support data services (A circuit switched connection is possible but would not make efficient use of scarce MILSTAR resources).

Military radio communication resources are, for the most part, used as dedicated networks or point-to-point links. In order to realize the kind of seamless connectivity described in the previous paragraph it will be necessary to move toward a networked view of these resource. Such a view would require the availability of communications protocols that are compatible across the different resources and are capable of providing the required services.

As a first step we must identify the services that may be required by the users. Such services may include voice, real-time video, maps and imagery on demand, interactive data services, high rate information broadcast, AJ communications, etc. Certain components of the communications system may not be able to provide certain services. For example, high-rate transmission of video cannot be provided by the relatively low rate EHF satellite systems. Similarly, secure AJ communications cannot be provided by commercial systems. Clearly, not all services can be made available across every available communication resources. It is necessary to identify those components that can support the different services and then to consider protocols that can operate across network components capable of providing the required services.

II. Potential Impact of A Well-designed Research Effort

Background

ATM - Its benefits and design assumptions

The use of ATM technology in the military communications infrastructure should provide a number of significant benefits. The characteristics of ATM (efficient multiplexing and unified switching) should allow the deployment of a cost-effective network while providing a wide variety of services such as voice, video, and traditional data transfer. These are the same benefits expected by the commercial users of ATM technology. Furthermore, the fairly rapid pace of standardization of most aspects of ATM should allow equipment from different vendors to interoperate while the large commercial interest in ATM will ensure a large vendor base from which equipment may be procured. This equipment will be suitable for both private network and public network applications. Finally, ATM is planned as the underlying "bitway" technology used by many domestic and foreign service providers and many of these providers will provide ATM user services at what is expected to be attractive pricing.

Two technology trends were crucial to the development of ATM. First, advances in point-to-point fiber optic transmission technology have provided the ability to transmit higher-and-higher bit rates at very low error rates over long distances. This has led to the widespread acceptance of SONET/SDH as a standard for the lowest transmission layer in the national and international public network infrastructure (and even in some local area networks) while low cost electro-optics have been made available by the popularity of certain consumer products and LANs. Second, the continued advances in the speed and density of CMOS integrated circuits and DRAM density have been impressive. These advances have made possible the low cost, very high performance processing (switching, buffering, and error detection / correction) of short data packets.

These trends led directly to some of the key assumptions behind ATM. Some of these are: 1) point-to-point links, 2) low bit error rates (with statistically independent errors), 3) high speed links, 4) a stable (and relatively reliable) topology of links and switches. While valid for most LAN and public infrastructure environments, these assumptions are not always compatible with all aspects of a worldwide military communications environment.

Some Differences Between the Military and Commercial Communications Environments

While most of the services that must be provided by a worldwide military network are in common with the commercial environment, some, however, are different.

- For example, there are few needs for on-demand multi-gigabit per second flows in today's commercial environment.
- Generally, in the commercial environment, demand for service changes slowly allowing time for reliable fiber optic channels to be installed in time to satisfy that demand. This is not always the case in the military environment where they may be insufficient time to install high quality channels and switching of sufficient capacity. Even when there would be time to install sufficient capacity, finite resources or other requirements may make it difficult to satisfy demand. For example, communications subsystems which have good anti-jam capability or low probability of detection are often only capable of providing a low bit-rate service.
- When a resource, such as bandwidth, is scarce, one or more users may be denied service by the network. Commercial networks try to avoid such a situation by overconfiguring their networks to reduce the probability of blocking and by tracking usage to plan for the installation of additional capacity. Therefore, they rarely need to deal with the issue of dynamically adjusting the behavior of the network to allocate scarce resources to high priority users at the expense of pre-empting others.
- User mobility/roaming is an issue that is only beginning to be addressed in the commercial environment. This has long been a requirement in the military environment.
- Even if mobility were not an issue, the lack of physically secure terrestrial or undersea fiber to every area of operations implies the use of other types of channels, such as RF and free-space optical, to connect to the backbone. These links span many orders of magnitude in link speed as well as bit error rate.
- The level of sophistication of (and resources available to) adversaries in the military environment implies much more attention needs to be paid to all aspects of security in a military network.
- Often, special purpose communications links are needed which must be operated near their margin limits implying the need for extreme efficiency in link usage.

- Finally, in times of crisis, some minimum level of connectivity (availability), service, and performance must be guaranteed. Network operation and allocation of resources may be different when operating in such a mode.

Multiple Network Types, and Multiple Administrative Domains

Today's military communications infrastructure is composed of many systems in various stages of their life-cycle. Because there is a large investment in these systems (people, process, hardware, and software) we must assume that these systems will continue to exist for some time to come. Therefore, despite the desirability of a homogeneous ATM communications infrastructure, this will not occur for a number of years. This implies a period where end-to-end communications will occur over a hybrid (ATM and non-ATM) infrastructure. This will lead, as we will see, to a number of technical issues which must be resolved.

The most obvious way to apply ATM is in backbones. ATM is well suited to this and appropriate channels are most likely to be available there. This may be done with a) government-owned links, b) links leased from commercial providers, c) use of an ATM service from one or more carriers, or d) some combination of the above. Each alternative potentially has different implications on the management, monitoring, security, and routing of the network. The general strategy for resolving many of these issues is to use some form of gateway.

Even in the heterogeneous internetwork model we should not, in general, assume a simple model in which only one ATM network is traversed by a given connection (see Figure 1). So, although we would expect non-ATM links would be primarily used to access an ATM backbone, this would not be their only usage.

Another key issue in this heterogeneous internetwork (HI) environment is the existence of more that one administrative domain [1]. Each network shown in Figure 1 may be administered by a different entity - each with its own local goals, processes, policies, and *capabilities*. This factor will lead to a major set of issues which will need to be resolved for a smoothly operating (and useful) HI.

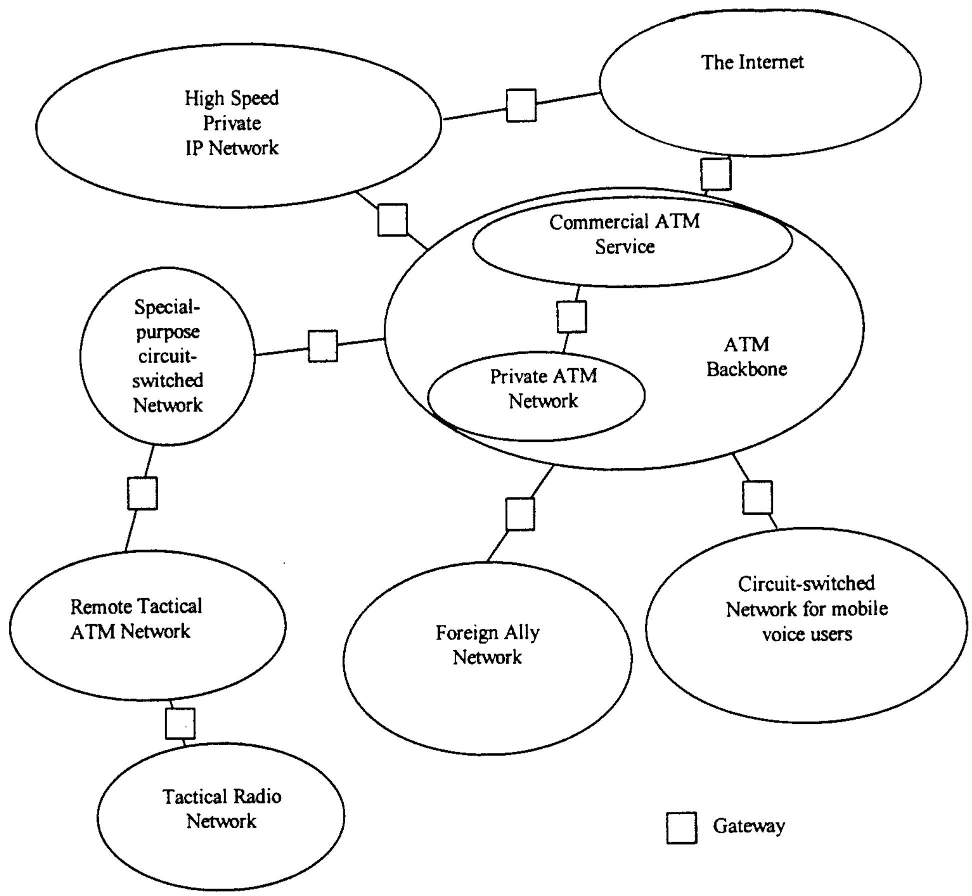

Figure 1

Major Issues in a heterogeneous ATM/non-ATM military network infrastructure

There are several categories of issues which arise in a military HI. We will outline these categories and some of the issues in each.

1. Issues arising from the heterogeneous nature of the internet itself - this heterogeneity takes several forms:
   - The first form affects the types of end-to-end services available across the HI. For example, although the backbone may be ATM and the destination may also be a native ATM station, the source may only be capable of generating a vocoded audio signal into a narrowband RF digital channel. This again leads us to the notion of using gateway devices. For example, the mapping of a service request whose semantics assume voice calls (or datagrams) to ATM flows across multiple networks would likely be the responsibility of the gateway at the joint boundary of the heterogeneous networks. In the case just described, such a mapping seems intuitively straightforward. However, there are other cases where

such a mapping may not even be possible. An example of this might be a request for a guaranteed bandwidth flow which must traverse a best-effort IP network. Furthermore, there are a number of issues to be resolved in the design of gateways which will need to be studied (such as the circumstances for use of translation versus encapsulation).

- In addition to the problem of simply being able to provide a set of useful connections from, say an existing RF voice network to an ATM-based voice end station, there is the issue of resource discovery and naming. For example, how would a user of such a voice network express his desire to communicate with another user who has no "address" on the voice net? How would a user even know whether the other party is reachable from the source network?

- Another form of heterogeneity that must be dealt with arises from multiple administrative domains. Given that two networks are connected via a gateway device implies that they intend to communicate through that gateway. However, not all types of communications may be expected or desired. For example, some networks may not wish (as defined by administrative policy) to allow transit traffic even though they may be connected to multiple other networks. Another example is one in which traffic above certain security classifications may be permitted over only one of several paths to the backbone. Yet another example is one in which the use of certain networks is reserved for periods of high traffic because use of those networks is more costly than others. These types of issues are starting to be addressed in packet networks [2], but this work must also be extended to hybrid (virtual) circuit/packet networks. We believe that how this will be made to work is a major issue that needs to be addressed.

2. Issues arising from the use of non-fiber optic channels within ATM networks - such channels are often slower that fiber links and are also more likely to have different error characteristics.

   - In LEO satellite communications systems, the satellite used to relay traffic to/from the surface changes frequently. Depending of the architecture of the communications subsystem, this may imply frequent changes in the topology of the ATM network. If such changes occur, internal routing algorithms must be run to adjust to the new topology and some flows may need to be re-established by the end user or the network. How this might be done will need study. Alternatively, such a communications subsystem may be connected through a gateway which "hides" such topology changes from the ATM routing algorithms.

   - The trend towards use of links with low bit error rate has led to networks, such as ATM, in which error recovery is done only at the end nodes. This has a number of advantages. However, many types of RF channels exhibit raw BERs which are in the 10^{-3} - 10^{-6} range. Such error rates lead to significant cell loss which in turn leads to end-to-end retransmission with the overall effect of lowering the efficiency of the network. Furthermore, the loss of efficiency becomes more pronounced at larger packet sizes (which are desirable for efficiency in end systems). This phenomenon is well known, but methods to improve the error rate seen by the ATM layer need additional work. Specifically, the obvious approach of using error correction to improve the often bursty error characteristics can be very inefficient for certain links and also lead to bursty residual errors. These are not dealt with by the error detection/correction capabilities of the ATM header error checksum.

- Fading is a significant problem on many expected RF ground - satellite links. These fades may be very severe exceeding 20 dB in some cases [3]. Mechanisms to deal with these fades include using a large margin, adaptive power, FEC, and interleaving. However, these may be costly to employ and, in the case of interleaving, may add excessive delay for the user. The more stringent BER requirements of end-end error recovery implied by ATM make this a more difficult problem to solve. Perhaps the addition of ARQ capability will be necessary on some links to provide acceptable end-to-end throughput and efficiency.

- It would be very desirable to have a demand-based random access RF ATM channel for bursty user services such as some types of data which support interactive applications. However, this is a difficult problem since the small size of the ATM cell reduces the efficiency of the channel with many existing access methods [4].

- We expect that some of the links (especially RF ones) in the HI will be scarce resources. That is, they will be of marginal capacity for the demand placed upon them. In this situation, there will be a higher probability of blocking. Since some military users will have higher priority than others we are led to the notion that some users will get preempted. Also, since ATM is useful for multiplexing a variety of traffic types (e.g., voice, data, and video) we may be faced with a situation where a single high priority video user may preempt tens or hundreds of low rate users. Is this an appropriate sharing model for such ATM links? Should some resources be pre-reserved for certain traffic classes? Does the notion of priority need to be refined?

- TCP is the most widely used transport protocol in the world. In the ATM environment, TCP is defined to operate over AAL5. It is well known [5] that TCP had severe throughput problems on "long, fat pipes" - fast links with long propagation delays. Although some progress has been made to improve TCP, proposed multi-gigabit channels with half-second delays will present severe challenge to the improved TCP even when the error rates are good (when compared to traditional fiber optic error rates). What is the best method to resolve this issue? Further enhancement of TCP?, Forward-Error-Correction?

- Advanced, special purpose communications subsystems are often designed, by necessity, to operate with very small SNR margins. The more stringent BER requirements of end-end error recovery and the additional overhead imposed by the short ATM cells will make the design of these systems more challenging. Perhaps such subsystems should not all be required to carry ATM and a gateway approach would be more effective.

3. Issues arising due to security concerns - It is assumed that one or more forms of encryption will be used in a global HI.

   - If end-to-end encryption is used through an ATM network, the headers of the ATM cells must be kept in the clear to allow for cell switching to be performed. This leaves open the possibility of a traffic analysis attack since an adversary may gain significant information by counting cells to or from certain networks or nodes. Furthermore, unless steps were taken to prevent it, connection requests might be monitored as well.

   - If link encryption is used between ATM switches, an adversary monitoring the channel would be less likely to mount a successful traffic analysis. However, the ATM switches themselves potentially represent a major source of information. Cell counts per VCI may be maintained by the switch and this information might be retrieved by an adversary using standard network management mechanisms. It would seems that some form of strong authentication and authorization is needed for even "innocent" management requests.

     What are the implications of this issue on the use of commercial ATM services in a military ATM backbone? Perhaps some form of traffic aggregation and demultiplexing at the gateways would reduce the information content available to traffic analysis. Perhaps random "phantom" traffic needs to be sent to reduce the effective information content available in an untrusted network - and how would this affect the cost of service from a carrier?

   - Denial-of-service, replay, man-in-the-middle attacks may be mounted using a number of techniques by an adversary with authorization to manage an ATM (or non-ATM) network. This may be problematic when using commercial services.

III. Specific Items to be Explored

To address this very complex problem, the first step is to conduct an in-depth study to enumerate the key technical issues which need to be resolved in subsequent work. In this work, one should attempt to take a holistic approach to deal with issues and produce results which, a) can be applied during the period of migration from the current situation to the heterogeneous internetwork case, and b) used by designers of future communications subsystems.

In this initial study, one should investigate many of the areas covered in the Issues section of this document to determine which are in need of further work. For those areas in need of additional research, detailed list of questions to be subsequently answered by that research should be developed.

1. Heterogeneity-related issues:
   - End-to-end service mapping over an internetwork with disjoint types of service
   - Gateway design issues (performance, translation vs. encapsulation)
   - Resource discovery, resource naming
   - Route establishment
   - Extensions to the work on Policy Routing

2. Non-fiber optic ATM link issues
   - Implications of LEO systems on ATM, alternatives to running ATM directly over such systems
   - Methods to improve the BER seen by the ATM layer on RF and free-space optical channels - coding, adaptive power, interleaving, possible use of link-link error recovery
   - Methods to deal with deep fading on RF channels used to carry ATM
   - Algorithms and mechanisms to provide an efficient, fair, demand multiple-access RF channel for ATM
   - The implications of preemption and user priorities in ATM networks
   - Policies for reservation of resources for classes of users or traffic
   - Quantify the performance degradation of TCP over AAL5 on multi-gigabit, long propagation delay paths - propose solutions
   - Strategies for incorporating advanced, special-purpose small-margin links into an ATM-based infrastructure

3. Security-related issues
   - The implications of various encryption strategies and the associated risks
   - Mechanisms to reduce risks associated with traffic analysis in ATM networks including securing network management, and adding random traffic

Finally, the study should frame a migration plan, consistent with current realities, towards the ultimate goal of a high-service-quality heterogeneous global defense network.

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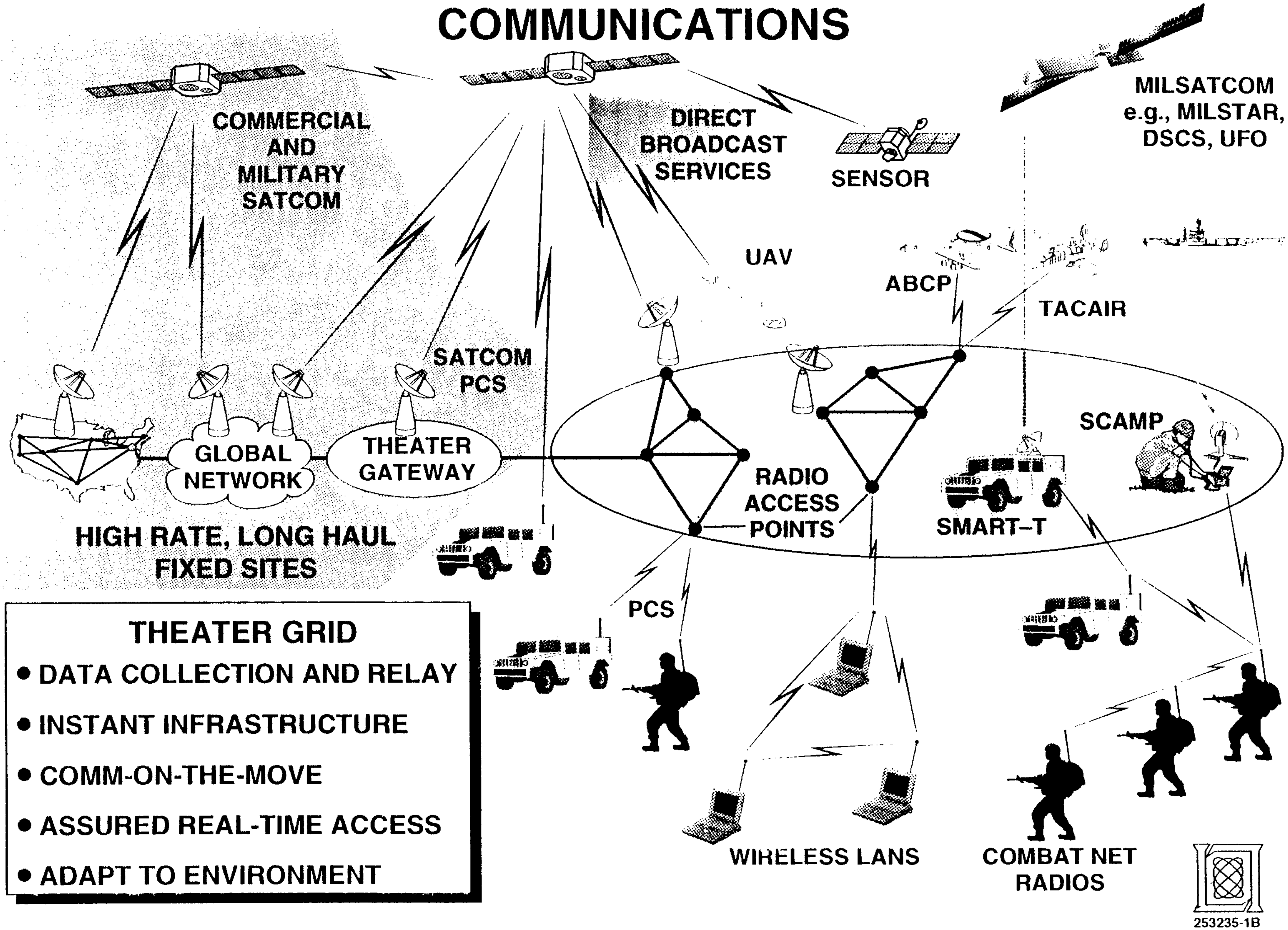
GLOBAL DEFENSE NETWORK–THEATER TACTICAL COMMUNICATIONS



THEATER GRID

- DATA COLLECTION AND RELAY
- INSTANT INFRASTRUCTURE
- COMM-ON-THE-MOVE
- ASSURED REAL-TIME ACCESS
- ADAPT TO ENVIRONMENT

White Paper

Emerging Wireless Technologies --

Applications/Issues for Mobile Forces

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This white paper is intended to address the issues related to the application of commercial wireless technologies for the future US Army small sized forces (typically under 5,000) organized into many teams. These teams are intended to be distributed over a wide geographical region in a non-linear battlefield environment.

1. Objective

The objective of this white paper is three-fold. First, provide a summary and forecast of the state-of-the-art commercial wireless (satellite and terrestrial) technologies. Second, highlight some issue as foreseen by incorporation of such technologies for future smaller and highly mobile forces. Third, discuss potential improvements to make commercial wireless services/technologies more robust and survivable for the mobile warfighter.

2. Technology Trend

2.1 Overview

The rapidly forming global market, along with increased user demand for multimedia capabilities and mobility, has motivated a technology explosion in the wireless area. This trend is forcing a merging in communications, computing, and entertainment to provide new services, utilizing visual (e.g., video on demand), information (e.g., digital library), and personal (e.g., "nomadic" computing) needs. This global telecommunications infrastructure (consisting of both wired and wireless services) is depicted in Figure 1.

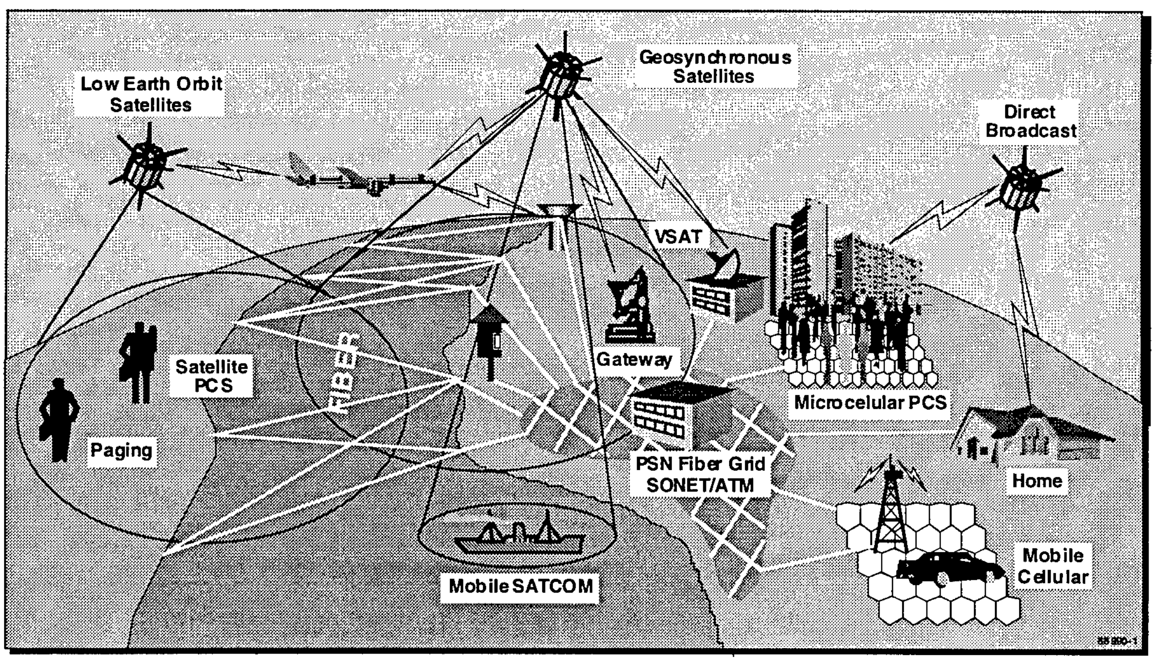

Figure 1. Emerging Commercial Communications Services/Technologies

The trend in connection is to "the person" instead of to "the place". Figure 2 summarizes the technology trends in wireless communications. The near-term timeline delineates the current state-of-the-art, with mid and far terms being forecasts in steps of three to five years each.

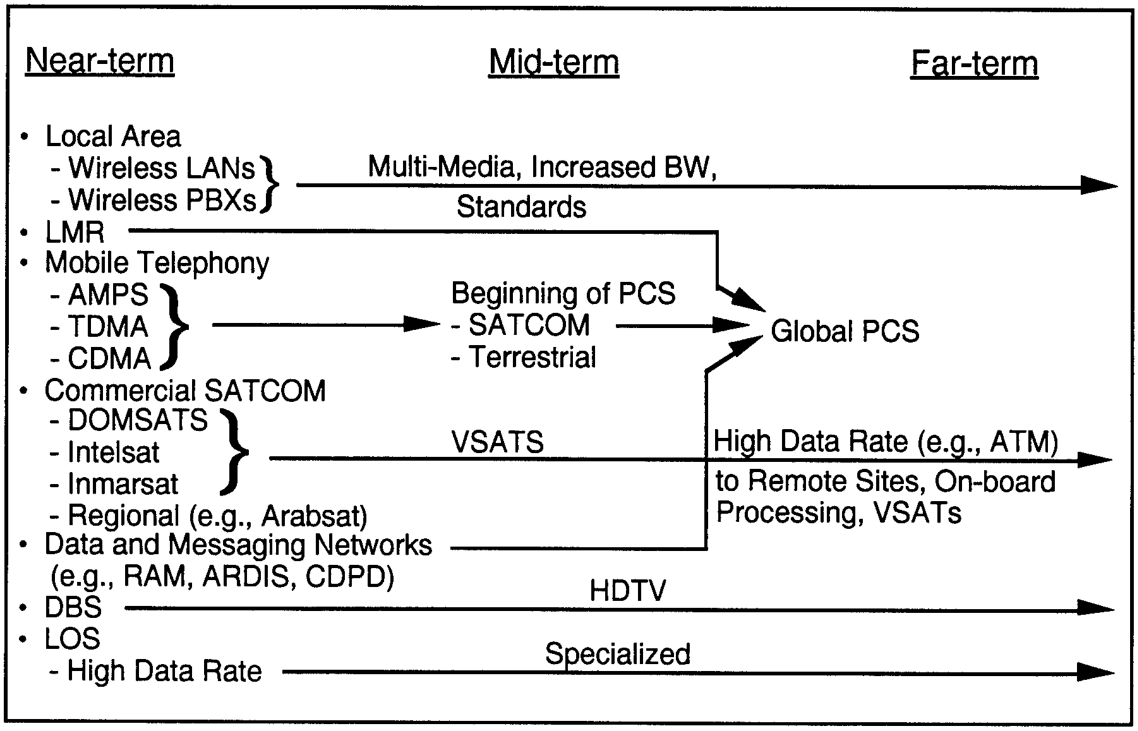

Figure 2. Communications Technology Trend

Wireless LANs are likely to remain distinct technology from the other services. These will continue to be much higher data rate systems which operate in unlicensed bands. Some manufacturers are already developing LAN/PBX systems for wireless offices. These products could be of interest to deployable units.

Land Mobile Radio (LMR) is likely to remain a special-purpose, dispatch-type service. Cellular telephone and the messaging and paging networks will evolve into some multi-service systems. For example, one could use a handheld device that accesses the local terrestrial infrastructure if available, and then uses a satellite-based service if required.

Direct Broadcast Satellite (DBS) will remain a special-purpose service with special terminals. Its primary application will be cable TV-like services and high-bandwidth video such as High Definition Television (HDTV).

Point-to-point Line-of-sight (LOS) microwave will continue to be available for situations not suitable for laying fiber optic cables.

The following sections discuss the technology trends in each area in more detail.

2.2 Wireless LANs

Table 1 summarizes the trends for wireless LAN technologies. Currently, there are a wide variety of wireless LAN products on the market. They typically fall into two categories: (1) spread spectrum waveforms, (2) time division multiplexing. They provide throughputs at Ethernet speeds (10 Mbps signaling rate and around 5 Mbps effective throughput). They are limited in range (maximum of 200 feet in a closed area). Transmission range in open areas could be significantly higher. Although designed for computer-to-computer data transmission, like a wired Ethernet system, voice (packetized) could also be transmitted through this media.

The transmission speeds are also expected to increase to the FDDI rate (about 50 Mbps throughput). This assumes the availability of the frequency spectrum for this higher transmission rate.

Table 1. Technology Trend - Wireless LANs

	Near-term	Mid-term	Far-term
Technology	Ethernet	Ethernet	Ethernet
Service	Data, Voice (packetized)	Data, Voice (packetized)	Multimedia
Throughput	5 Mbps	5-10 Mbps	5- 50 Mbps
Spectrum Availability	Unlicensed Bands	Unlicensed Bands	Unlicensed Bands
Coverage	Local, Deployable	Local, Deployable	Local, Deployable

2.3 Wireless PBXs

Table 2 summarizes the trends for wireless PBX technologies. The current demand for wireless PBXs is due to the lower cost (as compared with cellular) of wireless phone service within a building. The current technologies are based on either time division multiplex access or spread spectrum. The ranges are limited to coverage within a building (typically 30 feet per relay cells). These wireless products are designed to interface to standard PBX systems (as an adjunct). They currently use the Industrial, Scientific, and Medical (ISM) bands which are unlicensed. The current products are designed for voice and the trend is for provision of data interfaces at the hand-held units. The far-term trend is for multi-media at Personal Communication Services (PCS) bands with interoperability with PCS systems.

Table 2. Technology Trend - Wireless PBXs

	Near-term	Mid-term	Far-term
Technology	TDMA or Spread Spectrum	TDMA or Spread Spectrum	Compatibility with PCS
Service	Voice	Voice/Data	Multimedia
Throughput	4.8-32 kbps	4.8-32 kbps	4.8-32 kbps
Spectrum Availability	Unlicensed Bands	PCS Bands	PCS Bands
Coverage	Local, Deployable	Local, Deployable	Local, Deployable

2.4 Land Mobile Radio (LMR)

Table 3 summarizes the trend for LMR technologies. LMR continues to be the communication system of choice for on-base and logistics communications. It operates in half-duplex, push-to-talk mode. While most other commercially available systems may become part of PCS, LMR is likely to be around as a separate entity for a while.

Most LMR systems are proprietary and do not interoperate. Even systems made by the same vendor may not work together. However, these systems are made to be deployed at various UHF/VHF bands (150, 400, 800 MHz ranges), which provides for cost-effective government acquisition of government-specific systems.

LMR can be implemented in full-mesh mode, using simple repeaters in a talk-around mode, or using trunking to provide enhanced capacity and internetworking capabilities. Its inherent broadcast capability is somewhat unique among commercial systems.

LMR (including trunked LMR which switches channels as directed by the base stations) is inherently fixed-channel narrowband signaling. It will never provide even modest AJ, and would be easily jammed. Systems are already implemented with voice encryption, so COMSEC is available.

Table 3. Technology Trend - Land Mobile Radio (LMR)

	Near-term	Mid-term	Far-term
Technology	25 KHz Analog FM, 12.5 KHz Digital	12.5 KHz Digital	6.25 KHz Digital, 3.125 KHz Digital
Service	PTT* Voice/Data	PTT* Voice/Data	PTT* Voice/Data
Throughput	2400 - 4800 bps	2400 - 4800 bps	2400 - 4800 bps
Spectrum Availability	Licensed Bands	Licensed Bands	Liicensed Bands, PCS Bands
Coverage	World-wide	World-wide	World-wide

*PTT = Push to talk

2.5 Mobile Telephony

Table 4 summarizes the technology trends for mobile telephony. Mobile telephony (or as it is commonly referred to as cellular telephone) is and will continue to be the most widely used commercial two-way (full-duplex) wireless communication service. Currently FCC has allocated 50 MHz band in the 800 MHz region for the cellular system (both AMPS and Narrow CDMA). In the U.S. (and also WARC recommendation), PCS allocation in the range of 1850-1990 MHz is being made available.

From the present till around the year 2000 we can expect most of the commercial service providers to transition to digital service, thereby increasing capacity. It is likely that both time division multiple access (TDMA) and code division multiple access (CDMA)-based services will proliferate, with the older analog (AMPS) technology being the only interoperable mode. Long term we can expect these systems to provide modes compatible with PCS systems. In addition, broad CDMA systems may also become a commercial option. It could provide, in addition to high quality voice (32 kbps) and high speed data (64 kbps), a video capability as well.

Data services can be provided either using circuit-switched or packet-switched methods. The standards for circuit-switched data over the digital channels are still in flux. cellular digital packet data (CDPD) is an emerging packet-switched standard (and technology) that coexists with voice users on a mobile telephony system.

Many of the small, rugged mobile telephony systems are well suited to military use. Some low-capacity small base stations are available for haul-around type use. Large capacity base stations and associated mobile telephone switching offices tend to be large and expensive at present but the prices are decreasing.

Table 4. Technology Trend - Mobile Telephony

	Near-term	Mid-term	Far-term
Technology	2:1 30 KHz FM (AMPS) 3:1 TDMA (IS-54) 10:1 CDMA (IS-95) Cellular Digital Packet Data (CDPD)	TDMA CDMA CDPD	Digital PCS Waveforms
Service	Full-Duplex Voice, Circuit-Switched Data, Packet-Switched Data	Full-Duplex Voice, Circuit-Switched Data, Packet-Switched Data	Full-Duplex Voice, Packet-Switched Data
Throughput	4800 - 9600 bps	4800 - 9600 bps	4800 - 9600 bps
Spectrum Availability	Licensed Bands	Licensed Bands	Licensed Bands
Coverage	CONUS/Europe/ Pacific Rim	Most Industrialized Nations	Possible World-wide Service

2.6 Satellite-based PCS

Table 5 summarizes the technology trends for satellite-based PCS. The primary innovation promised by these systems is voice and data communications capability between small hand-held devices anywhere in the world. Voice and low-rate data are the main services to be offered. There will likely be 2-3 of these systems launched in the next 2-5 years. Although near global-to-global coverage is planned, some service providers may reduce orbit populations to stress coverage to more populated and wealthy portions of the earth.

These satellites will be susceptible to in-beam jamming. However, some of the designs use very small spot beam antennas to maximize signal power, thereby making jamming more challenging.

World-wide frequency allocations are likely for these systems. However, different waveforms will prevent much (if any) interoperation between systems. Interoperability will be provided by gateways.

For areas not serviced by the commercial systems, DOD could simulate satellite functionality using satellite "packages" carried on UAV platforms over the deployment area.

Table 5. Technology Trend - Satellite-based PCS

	Mid-term	Far-term
Technology	Beginning of LEOSATS	LEOSATS, MEOSATS, GEOSATS
Service	Voice, Data, Position Tracking	Voice, Data, Position Tracking
Throughput	2400 - 9600 bps	2400 - 9600 bps
Spectrum Availability	Licensed Bands	Licensed Bands
Coverage	CONUS/Europe/ Pacific Rim	Possible World-wide Service

2.7 Commercial SATCOM

Table 6 summarizes the technology trends for geosynchronous commercial SATCOM. Commercial SATCOM has become a consistently growing industry with an increasing user communications demand that forces the FCC and the ITU to continuously allow more orbital slots to accommodate new launches. The contiguous US is covered by tens of C-band, Ku-band and hybrid C/Ku-band domestic satellites (DOMSAT). Other countries typically have their own satellite systems that provide regional coverage. They include Eutelsat, Arabsat, etc. There are also international systems such as Intelsat and Panamsat that provide worldwide coverage. Each satellite carries an average of 30 transponders and each transponder can support more than 10 duplex T-1 trunks. Typical services offered include fixed satellite service (FSS), very small aperture terminal (VSAT) service, broadcast satellite service (BSS), and mobile satellite service (MSS). FSS services are typically point-to-point high data rate trunking that requires each terminal to be equipped with a large size antenna (e.g., 5 - 11 meters). VSAT terminals on the other hand can have antennas 1 meter or more in diameter.

Despite of much satellite resources, only limited Ku-band capacity is available for lease because there are many applications such as VSAT services that have become significantly popular worldwide.

The mentioned systems however do not provide coastal and ocean coverage to support ship-to-shore and ship-to-ship connectivity. Inmarsat can support these requirements and also aeronautical communications.

Vulnerability is typically a problem for many commercial communications satellites. They are not designed to operate against moderate electronic jamming. DOMSAT and Intelsat satellites have their spacecraft control and command links encrypted to survive against spoofing. The trend for satellite communications is towards the use of small terminals for thin-route traffic. Further, the demand for video transmission (cable TV programming and HDTV) is requiring high power direct broadcast satellite systems with very small receive terminals. Very high data rate fixed services are expected to transition to terrestrial fiber links.

Table 6. Technology Trend - Commercial SATCOM

	DOMSAT	Intelsat	Inmarsat	Regionals
Services	FSS, MSS	FSS, BSS	Aeronautical Maritime	FSS, BSS
Throughput	Multiple T-1s	Multiple T-1s	<=56 kbps	Multiple T-1s
Spectrum Availability	C and Ku	C: Worldwide Ku: Limited	L and C Available Worldwide	Regional
Frequency Band	C, Ku, Ka	C, Ku	L	C, Ku
Terminal Size (m)	C: 2.4 - 11 Ku: 1.2 - 9	C: 2.4 - 11 Ku: 1.2 - 9	0.5 - 3	C: 2.4 - 11 Ku: 1.2 - 9
Coverage	CONUS	Worldwide	Ocean, Coastal	Regional

FSS = Fixed Satellite Services, MSS = Mobile Satellite Services,
BSS = Broadcast Satellite Services

2.8 Direct Broadcast Satellites (DBS)

Table 7 summarizes the technology trend for commercial DBS systems. DBS is a satellite-based system that distributes digital programming to residential subscribers. Relaying via Ku-band commercial satellites, services provided in the near term include direct broadcast television, pay-per-view movies, sports and specialty programs, cable television, and high quality digital service that can accommodate HDTV. In the mid and far-term, DBS service providers plan to support high data rate dissemination and two-way communications for "pull" services.

A typical DBS spacecraft has sixteen 24-MHz transponders. Each transponder carries 4 to 6 program channels for a total of approximately 80 program channels.

Table 7. Technology Trend - Direct Broadcast Satellites (DBS)

	Near-term	Mid-term	Far-term
Coverage	North America, Europe, Japan	North America, Europe, Pacific Rim	World-wide
Throughput	~4.5* Mbps and Analog	~4.5* Mbps	~4.5* Mbps and Higher for HDTV
Spectrum Availability	Licensed Bands	Licensed Bands	Licensed Bands
Services	Cable TV, HDTV, Video Rental	Cable TV, HDTV, Video Rental	Cable TV, HDTV, Video Rental
Terminal Size	18 inches	18 inches	<18 inches
Frequency Band	Ku	Ku	Ku, Ka

*Per Channel

2.9 Data and Messaging Networks

Table 8 summarizes the technology trends for commercial data and messaging networks. The primary wireless data networks are ARDIS and RAM, though the many paging networks could be included as well. These are digital modulation, narrowband systems. In the far-term these data-only services may well become obsolete if such services become available from PCS providers.

The networks are generally well designed to locate and communicate with member radios in half-duplex mode. These radios are generally designed to be sufficiently frequency agile to operate over wide ranges of possible frequencies. These are narrowband systems that use paging channels, so EW vulnerability is moderate to high. COMSEC should be straightforward.

These are proprietary systems, so base-station equipment costs are difficult to determine. It is reasonable to assume ARDIS or RAM-like base options cost less than mobile telephony base stations, but more than LMR base stations. A military deployment system might license the technology from one of these systems.

Table 8. Technology Trend - Data and Messaging Networks

	Near-term	Mid-term	Far-term
Technology	25 KHz Digital	25 KHz Digital	Digital PCS Waveforms
Services	Paging (very-low rate, one-way) Circuit-Switched Data Packet-Switched Data	Paging Circuit-Switched Data Packet-Switched Data	Paging Circuit-Switched Data Paket-Switched Data
Throughput	2400 - 9600 bps	4800 - 9600 bps	4800 - 9600 bps
Spectrum Availability	Licensed Bands	Licensed Bands	Licensed Bands
Coverage	CONUS	CONUS/Pacific Rim	World-wide Service

3. Application of Emerging Commercial Wireless Technologies for Small Mobile Forces

The previous sections discussed the state-of-the-art in wireless technologies and their technology trends in the next ten years. These technologies can be categorized in three groups: (i) geosynchronous SATCOM, (ii) satellite-based PCS systems, and (iii) LOS wireless technologies (includes both wireless LANs and cellular systems). It is anticipated that the DOD's emphasis on geosynchronous SATCOM is going to increase as additional world-wide resources become available. The primary users, however, will be at higher echelons. Small and rapidly mobile forces require access to small and low-weight communications resources, and terminals allowing communication with geosynchronous terminals are typically (>1 meter) large. One exception will be the receive only capability of DBS-like services where typically a 0.4 meter dish could be used by a small mobile force to receive INTEL and other Theater data.

The emphasis of the remaining discussion will be on satellite-based PCS and LOS wireless LAN/cellular systems. Figure 3 delineates some of the basic needs of a highly mobile warfighter force. As shown, global connectivity, assured access, good quality of service, and protection are the minimal needs. In addition, it is anticipated that on-demand, high data rate receive capability (e.g., INTEL) will be required.

- Global/distributed connectivity
- Protection (COMSEC, AJ/LPI/LPD, as needed)
- Assured, real-time access
- Quality of service (e.g., low BER)
- On-demand, high data rate receive capabilities

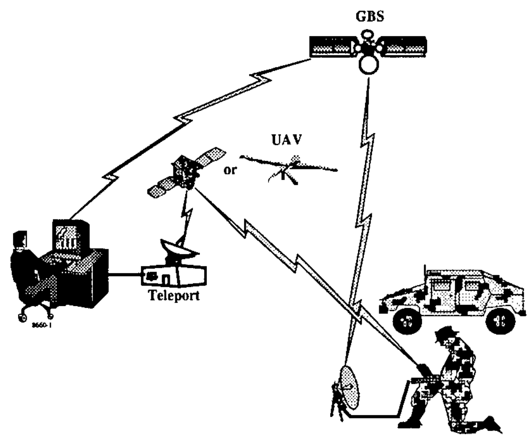

Figure 3. Basic Mobile Warfighter Communications Needs

Figure 4 shows pictorially how such commercial wireless resources could be used by a small mobile force.

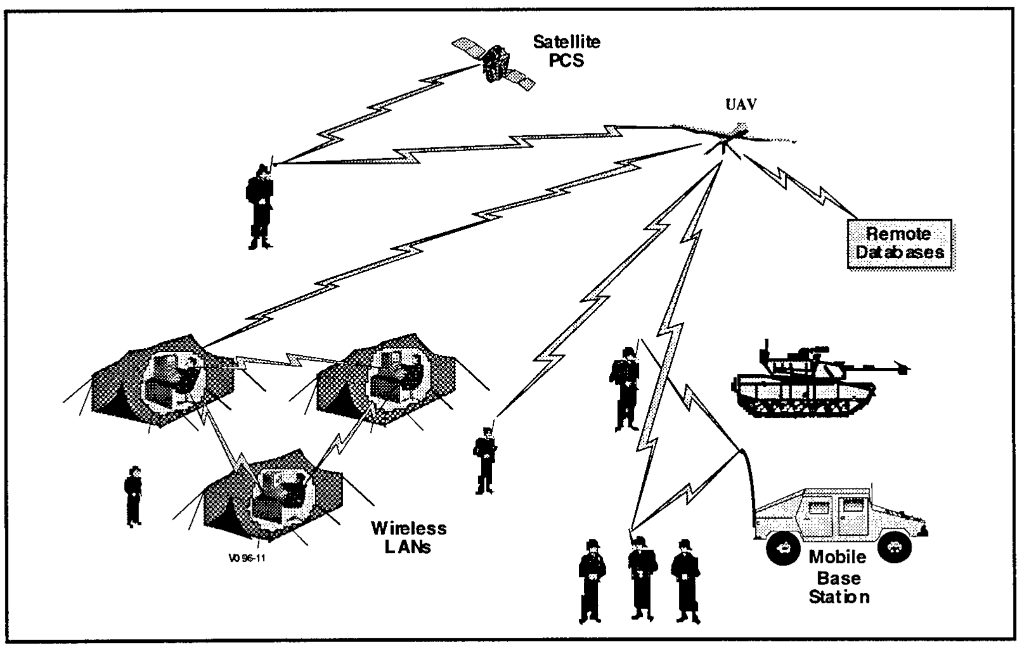

Figure 4. Representative Warfighter's Use of Commercial Wireless Services/Technologies

As indicated in Figure 4, there are three main components, namely satellite-based PCS services, mobile cellular telephony, and wireless LANs. As discussed previously, by year 2000 a respectable global satellite-based PCS system is anticipated. The most likely candidates are the Iridium and the Globalstar systems. Transmission data rate is expected to be at around 9600 bps with higher rate transmissions (e.g., 64 kbps) possible with modifications.

As shown conceptually, UAV platforms could also be used to carry satellite-based PCS payloads allowing redundancy, significantly lower handset power utilization, and/or higher data rate transmissions due to lower propagation losses. Since the networks are digital, end-to-end secure transmission is feasible. Crosslinks as in Iridium and/or gateways located at friendly sites can also prevent denial of service.

Another wireless communications asset shown in Figure 4 is the digital cellular systems. Either the CDMA or the TDMA cellular technologies will be available for extending tactical communication through mobile base stations. As in the satellite-based PCS case, end-to-end security is feasible.

Lastly, wireless LAN systems can be used to rapidly reconstitute an Ethernet network. Throughput rates higher than Ethernet are anticipated for the far-term.

4. Issues

The ever growing world-wide communications infrastructure provides low cost opportunities for DOD. However, it must be noted that by the very nature of a "global" network, these assets may also be used by our adversaries for their civil and defense needs. Although end-to-end encryption will provide the security that DOD needs, there are other robustness and survivability issues that must be fully understood. Figure 5 highlights some issues related to the warfighter's use of commercial wireless services/technologies.

- **Possible surge capability limitation, if not leased a priori (assured access?)**
- **An array of regulatory restrictions (e.g., host nation frequency approvals)**
- **Denial of service (through gateway or spacecraft TT&C*)**
- **Minimal AJ and LPI capabilities**
- **Limited commercial terminal battery life**
- **Restoration priority and dynamic resource allocation**
- **Survivability of commercial hardware (e.g., ruggedization)**
- **Integration into tactical environment**

TT&C = Telemetry, Tracking and Control

Figure 5. Warfighter's Use of Commercial Wireless Services/Technologies - Issues

A key issue is how much capacity is available when hostilities starts if resources are not leased a priori. Friendly countries and major commercial users may become competitors for capacity when hostilities start. Another issue is the array of regulatory issues that need to be ironed out prior to any deployment (e.g., host nation frequency approvals).

Another key issue is the possible denial of service through a Government's PT&T (Postal, Telephone and Telegraph). This issue can be avoided by configuring networks through gateways in friendly countries and the use of satellite crosslinks (e.g., Iridium).

Commercial systems are also inherently susceptible to jamming and have limited LPI capabilities. In the case of satellite-based PCS systems, limited AJ protection is possible due to small and moving spot beams. Increased AJ and LPI features could be provided by incorporating UAV platforms with more directional antennas (including the handset). Further, to deny the adversary the geolocation information about our forces, a combination of the crosslinks (e.g., Iridium) and/or tactically located gateways could be used.

Other areas that warrant improvements are the low battery life and ruggedization of the equipment. Finally, integration into the tactical environment (interfaces to legacy systems) is worthy of detailed planning.

These commercial wireless assets can augment the existing military systems in an effective way, however there are inherent survivability and robustness issues that must be examined and fully understood. Innovative ideas, such as the use of UAVs (incorporating commercial wireless technologies), can significantly increase the survivability of such commercial assets. Figure 6 highlights potential improvement to make commercial wireless services/technologies more robust and survivable for the mobile warfighter.

- **A priori capacity allocation for surge capabilities**
- **US control and integrated network management**
- **Redundancy through UAVs**
- **Modified antennas and RF (payload on UAV and terminal) for better AJ/LPI**
- **Improved power sources (e.g., terminal batteries)**
- **Selective ruggedization, as required**
- **Selective development of tactical/commercial gateways**

Figure 6. Warfighter's Use of Commercial Wireless Technologies - Implications

5. Conclusions

Based on the vast growth in the commercial telecommunications infrastructure and technologies, it is given that commercial technologies (e.g., cellular, ATM, DBS, and PCS) will be an integral part of military communications systems. DOD will use commercial systems/services to supplement military communications systems. However, commercial services and technologies, by their very nature of being market driven, may not always provide the robustness/survivability features that a mobile force may require. DOD should incorporate innovative ideas (e.g., UAV platforms, network management, and new antennas and RF designs) to utilize the emerging commercial wireless systems/services.

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THEATER TACTICAL COMMUNICATIONS

White Paper

Dr. Charles W. Niessen

THEATER TACTICAL COMMUNICATIONS

With increased emphasis on information flow in the battlefield to support modern warfare, there is increased need for better, more responsive communications systems to provide it. While emphasis is properly on the end user, the warfighter, much of the support information he needs will flow into the tactical theater from outside. Therefore, world-wide communications and information transfer is vital to the United States defense posture and to the conduct of military operations. Communications must provide for a surge of connectivity to developing theaters of operation as well as timely access to data-bases around the world. Within the tactical theater, all units must be interconnected with respect to voice and data traffic; isolated communication systems will not meet the needs of today's forces.

Communications services in the foregoing spirit are not generally available today. Enhancements are needed to provide wide bandwidth data relay from intelligence collection sensors (both National and Theater) to analysis and fusion centers, and from there to warfighters at all command levels. Sensors can be located on spacecraft, on airplanes (including UAVs), and on the ground (including Unattended Ground Sensors -- UGS). There needs to be a mechanism for the warfighter to request (and receive) information that is specific to his immediate needs, as well as general information that is broadcast uniformly to the forces. (The Global Broadcast Service -- GBS -- is being developed to provide this capability.) Communications to/from forces on-the-move needs to be upgraded to provide assured access (communications availability), robust service (protection from jamming and information warfare), and full connectivity (to the disparate existing communication systems).

Experience in a variety of contingency operations (Desert Storm, Haiti, Bosnia) have revealed some of the shortcomings of existing tactical military communications systems. A major deficiency is in the ability to provide a rapid surge of communications service to support the entry of forces into a conflict and to maintain connectivity among them during rapid maneuvers that result in physical separation of force elements. The main factors in these deficiencies is that current systems overly rely on bulky equipment that must be sea- or air-lifted into a theater (at a time when logistics are under the most stress) and/or that operate only over line-of-sight distances. It is further compounded by the poor mobility of many of these communications assets; set-up and tear-down times are inconsistent with the rapid maneuvers that are the key to modern tactics. Two simple examples should illustrate these points. In the permissive entry into Haiti, forces landing at Port Au Prince had initial connectivity out of theater only through line-of-sight radio links to the USS Mt. Whitney (just off-shore) and from there via Satcom to CONUS. Forces entering simultaneously at Cape Haitian (in the North) were separated by mountains from Port Au Prince, so line-of-sight communications between these forces was not possible; only limited UHF Satcom was available for this purpose. In Desert Storm, the well-known "end-run" of our armor to engage Iraqi forces was carried out with almost no long-range communications. Because of the speed of our armor, all of the line-of-sight relay equipment that provides the bulk of Army MSE (Mobile Support Equipment) connectivity was left in the dust, along with all of the SHF Satcom equipment. The only connectivity to these forces during the actual battle engagement was two UHF Satcom voice channels. Of course, the communications support was eventually re-established in both Haiti and in Desert Storm, but it was not available at the critical times.

The experiences outlined above identify several specific needs and suggest the technologies to support these needs. An important need is for Satcom terminals to be as mobile as the forces they support. Since UHF Satcom is extremely limited in capacity (and vulnerable to disruption), it does not make sense to rely on it for the needed connectivity. Operation at SHF (through DSCS) or EHF (through Milstar) is needed. The Services are investing in more mobile SHF & EHF Satcom terminals (Fig. 1) that are transported mounted on a HMMWV with set-up times of less than 30 minutes (vs. hours for previous terminals). Through line-of-sight links to these Satcom terminals, local troops will be provided access to the MSE backbone. But even 30 minutes set-up may not always be sufficient; armor can move beyond line-of-sight in this time period. What is needed is true on-the-move communications. For this purpose, the Army has identified the need for a Radio Access Point (RAP) on a tracked vehicle that serves as a relay node for local troops using standard line-of-sight radios (such as SINCGARS). However, the non-line-of-sight connectivity from the RAP to the MSE backbone is more of a problem. In particular, if SHF/EHF Satcom is to provide this connectivity, the RAP will need an on-the-move microwave antenna system. This might be accomplished by a steerable dish antenna, but the stabilization of pointing while the RAP is moving rapidly over rough terrain is a serious design challenge. Alternatively, the antenna could be an electronically-steered phased array. The technology for implementing such an antenna is just now becoming available; substantial development effort is need here. Although phased array antennas have been studied (and even built) in the past, they tended to be bulky, expensive, and hard to integrate onto a platform. Today optical fiber technology can be used to ease the implementation of phased arrays (Fig. 2) by remoting the phasing hardware from the array of antenna elements, and microwave/millimeterwave MMICs are becoming available for array transmitter elements. This class of work should be pursued.

Another class of Satcom terminals that is needed is true man-portable units. Today that is restricted to UHF terminals; however, the Army has just let a substantial production contract for SCAMP EHF terminals that will connect through Milstar to provide assured, AJ access, yet weigh only about 30 pounds. They can be carried in a back-pack and set up in 5 minutes. These terminals are ideal for use by Special Forces, but can be carried easily at any force level without burdening the logistics transport system as do truck-mounted terminals. Thus this kind of man-portable terminal can provide support for long range connectivity even during early entry into a theater. The technology for reducing this type of terminal in both size and weight should be pursued; a 10 pound EHF terminal is a reasonable goal. (Fig. 3)

Introduction of new Satcom terminals into theater communications inventory will provide substantial benefits. However, there is a large inventory of non-Satcom communications equipment that depend primarily on line-of-sight links. This limitation is serious, but can often be overcome by the use of radio relays positioned to be within line-of-sight of users who are not within line-of-sight of each other. Traditionally, these relays can be positioned on high ground to extend coverage substantially -- if that high ground is in friendly hands. Alternatively, experiments have been performed with the relay equipment aboard aircraft; the added height provides even longer range relay function.

With the advent of High-Altitude, Long-Endurance Unmanned Air Vehicles (HAE UAV) such as the Tier 2+ (Global Hawk), the opportunity for a truly long-range radio relay platform is at hand. From a cruise altitude of 65,000 feet, the UAV is within line-of sight of ground radios at ranges out to 150 miles or more (depending on terrain) and to even longer ranges to other airborne platforms. From this vantage point, forces that would otherwise be out of touch due to terrain blockage or rapid maneuvering can be connected by relay through the UAV. Since many types of equipment could be relayed through the UAV, it would also be desirable to provide on-board gateways and interconnections that would extend the connectivity and utility of current tactical communications equipment. And since the Tier 2+ is being procured with a Ku-band Satcom terminal on-board, this could be used to provide out-of-theater connectivity. A simple example of this interconnection would be the relay of SINCGARS VHF radio traffic through the satellite link to a CONUS-based CINC. The satellite link could also be used to relay JTIDS and EPLRS force location data for display at remote command centers.

The concept for an Airborne Communications Node (ACN) is based on utilization of the Tier 2+ UAV, modified from its SAR/EO surveillance sensor payload configuration (Fig. 4). This concept was examined in a DARPA Summer Study during 1995 and received much support from Service representatives participating in that study. The ACN concept (Fig. 5) provides theater-wide communications as well as reach-back connectivity to out-of-theater sites in CONUS or elsewhere through direct satellite communications links. The payload would operate with equipment currently fielded by the Services as well as provide new classes of service that are not yet deployed (such as theater-wide broadcast of intelligence and other data, handheld radios modeled after commercial cellular systems, and paging service).

A summary of the communications services that the ACN could provide is given in Fig. 6. The essential service is for range extension and relay between users that are not within line of sight of each other but are all within line of sight of the ACN. The need for an ACN relay could be because of intervening terrain or simply because of rapid maneuvers the units have gone beyond line of sight. The ACN can also provide connectivity to overcome the limited amount of comm gear that can be provided in early entry situations due to inadequate air- and/or sea-lift capacity. The ability of forces to have the freedom to maneuver and still maintain connectivity allows new operations concepts to developed. This beyond line-of-sight communications is essential to new amphibious assault techniques being planned by the Navy and Marines.

Because of the Satcom terminal on the ACN, users in the tactical theater can be provided with reachback connectivity to remote command centers using only their normal line of sight radios, with the ACN acting as a gateway. This is particularly important to forces that do not have have access to Satcom terminals on the ground, such as during early entry or rapid maneuvers.

The ACN can also carry equipment to implement new services in conjunction with new ground equipment. Because the ACN is a single point serving many types of communications equipment, it can also provide gateways to allow connectivity between users that otherwise would not be able to communicate directly. In some cases this connectivity can be implemented in the UAV by simply switching baseband or IF signals between different pieces of equipment; in other cases is may be necessary to reformat digital messages to translate between different digital transmission protocols.

The Global Broadcast System (GBS) is planned to disseminate battlefield awareness data to users through small (18 inch diameter) microwave terminals modeled after direct broadcast TV. The ACN can supplement this service by broadcasting some of this data to users that are on the move and only have an omnidirectional antenna that cannot directly receive the GBS signal. For example, by broadcasting at a 1 GHz frequency with a 50 watt transmitter on the UAV, a 1.5 Mb/s data rate can be received through a simple antenna.

A theater paging service can be implemented on the ACN using commercial-type pagers and a 30 watt transmitter carried by the ACN. This would allow alerting users that are temporarily out of contact with communications service that a message is waiting for them. It could also be used to alert selected groups of users to impending attack from theater ballistic missiles or chemical/biological weapons.

The commercial technology behind cellular radio service could be adapted to military use by implementing a base station on-board the ACN. This would allow small, inexpensive handsets to be used for voice and data service. Development of the airborne base station would be required, however, since commercial base stations are not packaged for airborne use and do not have the circuit capacity or antenna pattern required. Planned LEOSAT systems such as Iridium are closer to the model of the needed ACN base station.

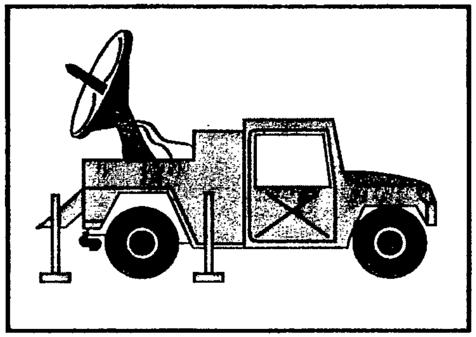
The ACN could also be used to control and read out Unattended Ground Sensors (UGS). From a 65,000 foot altitude, the ACN could reach 150 miles or more to such sensors positioned well behind enemy lines. From this vantage point, the ACN could send command signals to the UGS field and receive reports from the sensors. This information could then be relayed to intelligence centers in or out of the theater over other communications links carried by the ACN.

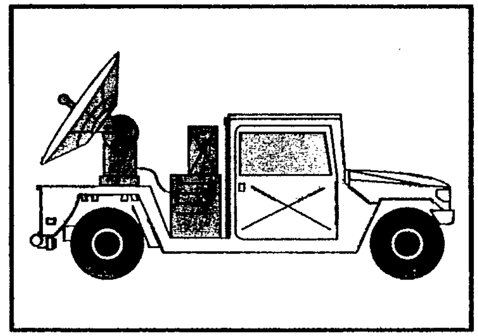
Fig. 7 shows the technical concept of the ACN. Examples of the equipment and services that could be carried on the ACN are shown, together with the communications controller that implements the interconnections among the various equipment, including out-of-theater connectivity provided through a Satcom terminal.

During the 1995 DARPA Summer Study, communications needs, sizing, and priorities were established by representatives of the Services, and the utility of the Tier 2+ as a communications platform was determined by showing how it can meet the communications deficiencies experienced in recent conflicts. Evaluation of communications equipment that is available for use on the ACN was completed; it was determined that a communications payload with significant military utility would fit within available weight and power limits of the Tier 2+. Payload integration issues were also identified. DARPA intends to carry this ACN concept through to an ACTD to evaluate its real-world utility.

This paper has discussed initiatives that should be undertaken to provide communications access to forces in contingency operations that are not available today due to limitations in available logistic support, to lack of mobility of the communications infrastructure, and to rapid maneuvering. These encompass small, light-weight Satcom terminals, Satcom antennas for forces on the move, and the use of a UAV-based communications node. Additional work is needed to assure the interconnection of all theater communications assets. Voice and (particularly) data must be able to flow freely wherever needed on the battlefield. Because of the current disparate communications systems in use, significant work in development of gateways and in development of networking protocols is necessary to achieve the desired goal.

ARMY SATCOM TERMINAL MOBILITY





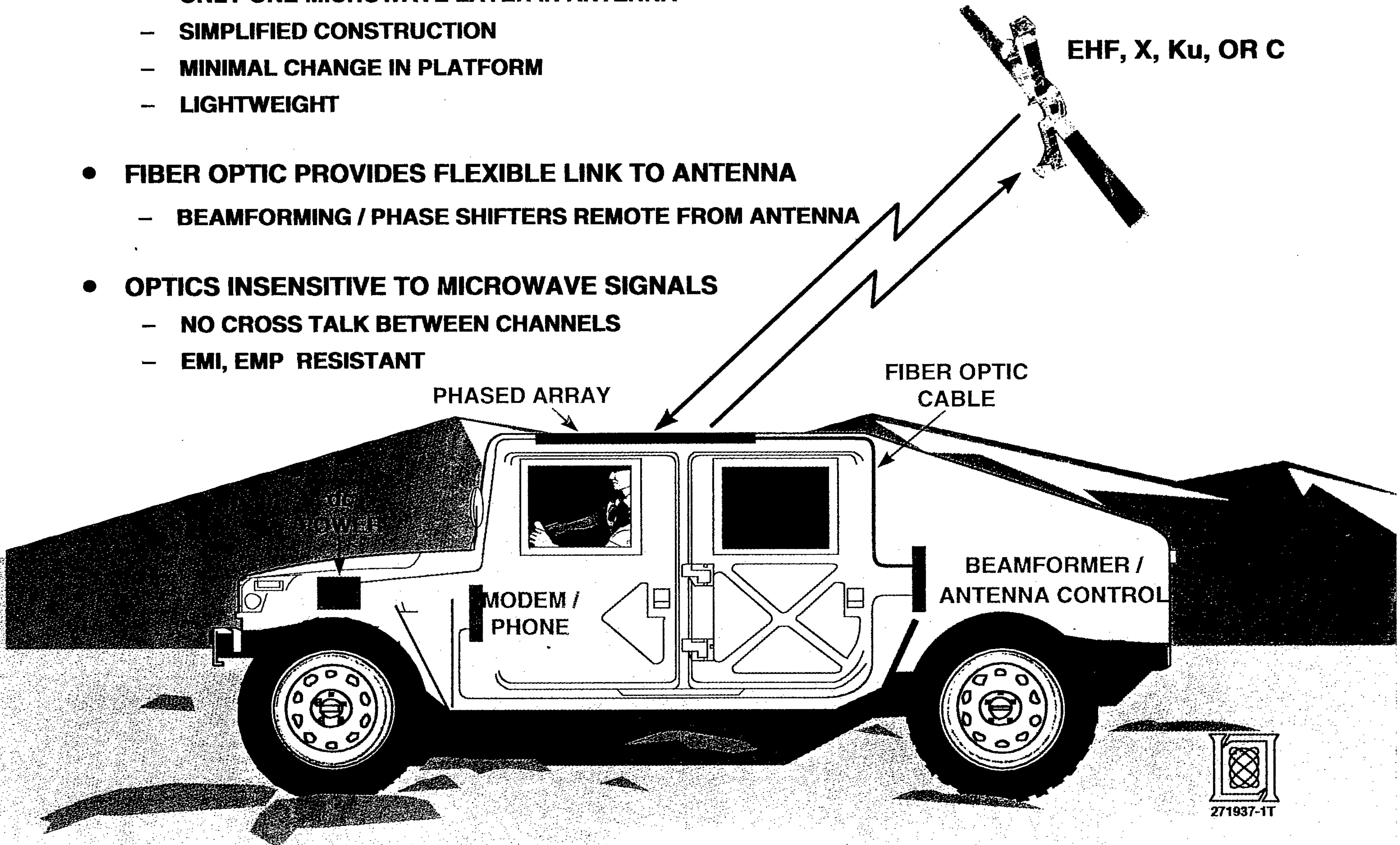
TERMINAL	STAR-T	SMART-T	SCAMP
FREQ BAND	C, X, Ku	EHF	EHF
DATA RATE	8.2 Mbps	1.5 Mbps	2400 bps
AJ	NO	YES	YES
WEIGHT	< 3000 lbs	< 3000 lbs	31 lbs
MOBILITY	ON HMMWV	ON HMMWV	MANPACK
SETUP	30 min	20 min	5 min
INTERFACE	MSE SWITCH	MSE SWITCH	SINGLE USER, VOICE & DATA

271792-7P

Figure 1

PHASED ARRAY FOR COMM ON THE MOVE

- THIN, LOW-PROFILE ANTENNA
  - ONLY ONE MICROWAVE LAYER IN ANTENNA
  - SIMPLIFIED CONSTRUCTION
  - MINIMAL CHANGE IN PLATFORM
  - LIGHTWEIGHT
- FIBER OPTIC PROVIDES FLEXIBLE LINK TO ANTENNA
  - BEAMFORMING / PHASE SHIFTERS REMOTE FROM ANTENNA
- OPTICS INSENSITIVE TO MICROWAVE SIGNALS
  - NO CROSS TALK BETWEEN CHANNELS
  - EMI, EMP RESISTANT



EHF SATCOM TERMINAL TECHNOLOGY

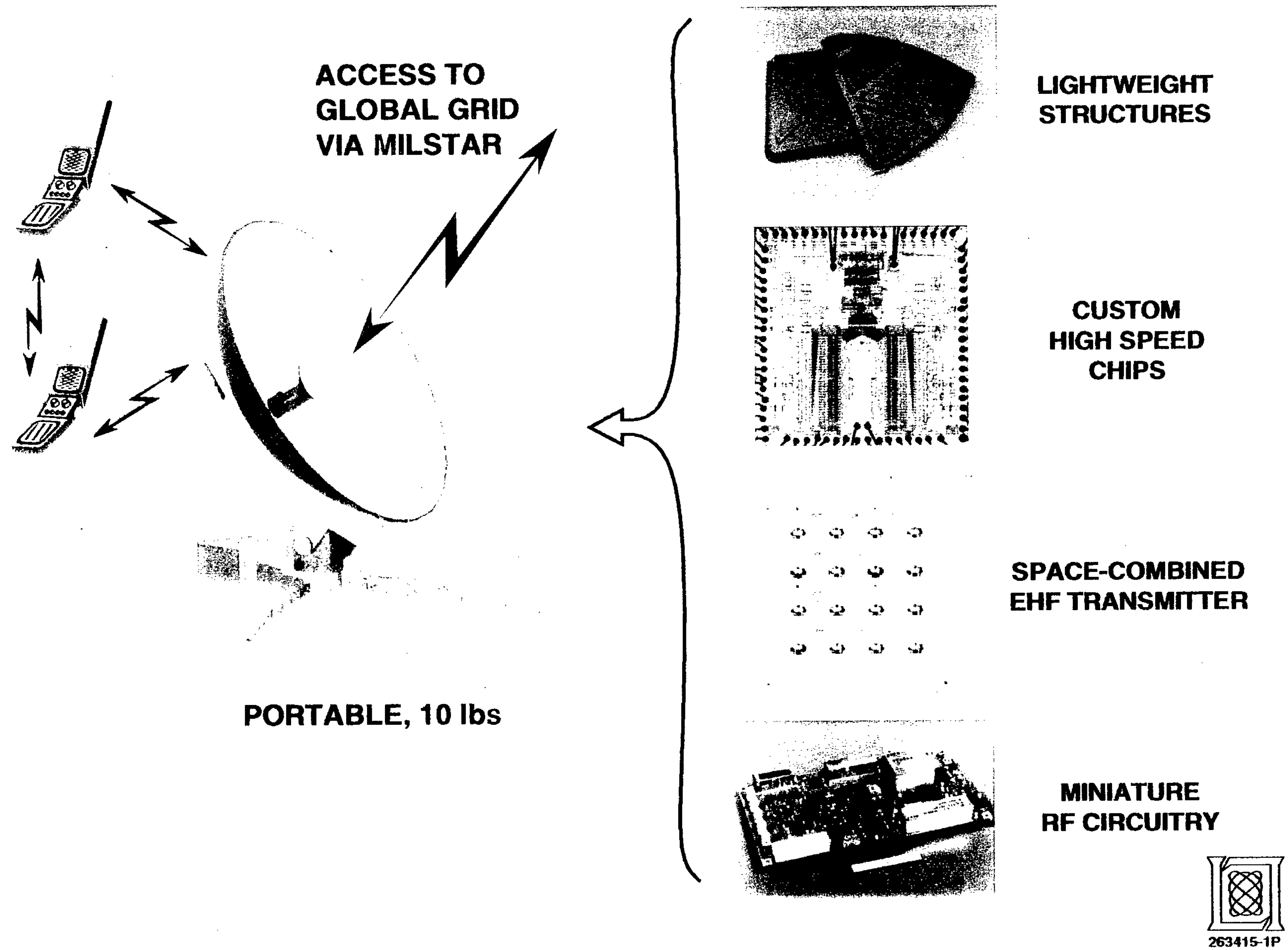
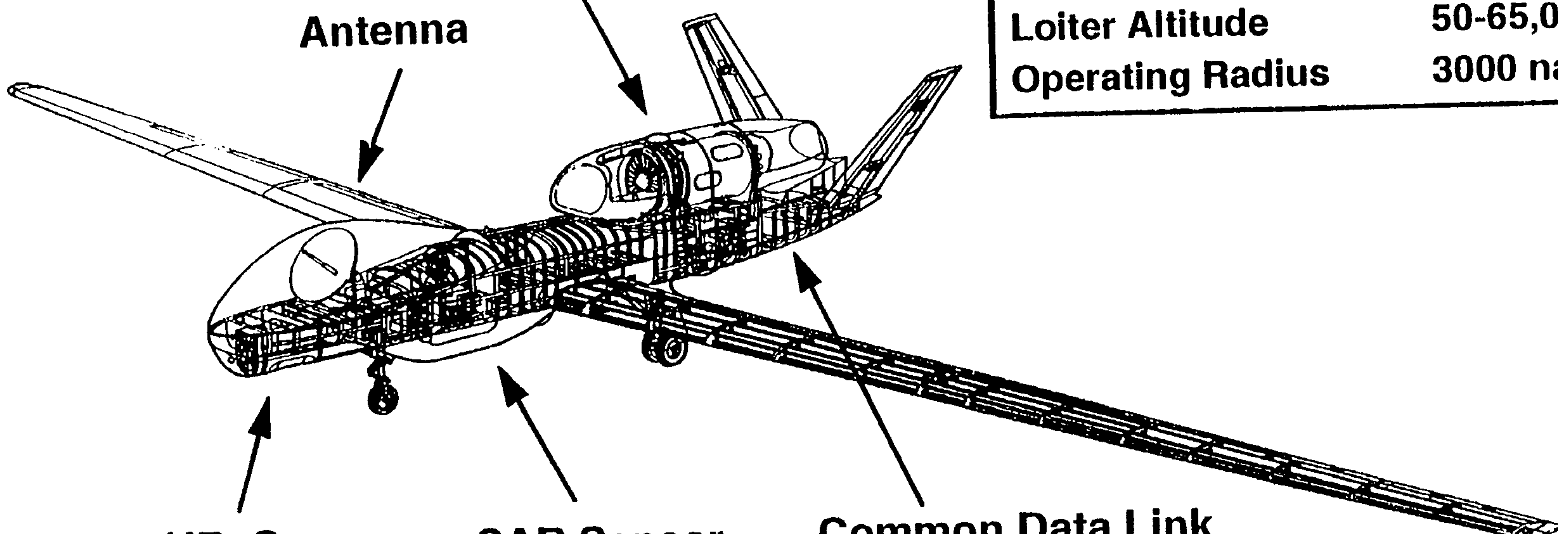


Figure 3

HAE UAV Tier II+ Air Vehicle (Sensor Payload)

Wing Span	116.2 ft.
Length	44.4 ft.
Height	15.2 ft.
Design Gross Wt	24,390 lb.
Installed Payload Wt	1,864 lb.
Mission Duration	24 hrs on station
Loiter Altitude	50-65,000 feet
Operating Radius	3000 nautical mi.



Remove for ACN Payload;
Makes 900 lbs, 6 kw Available

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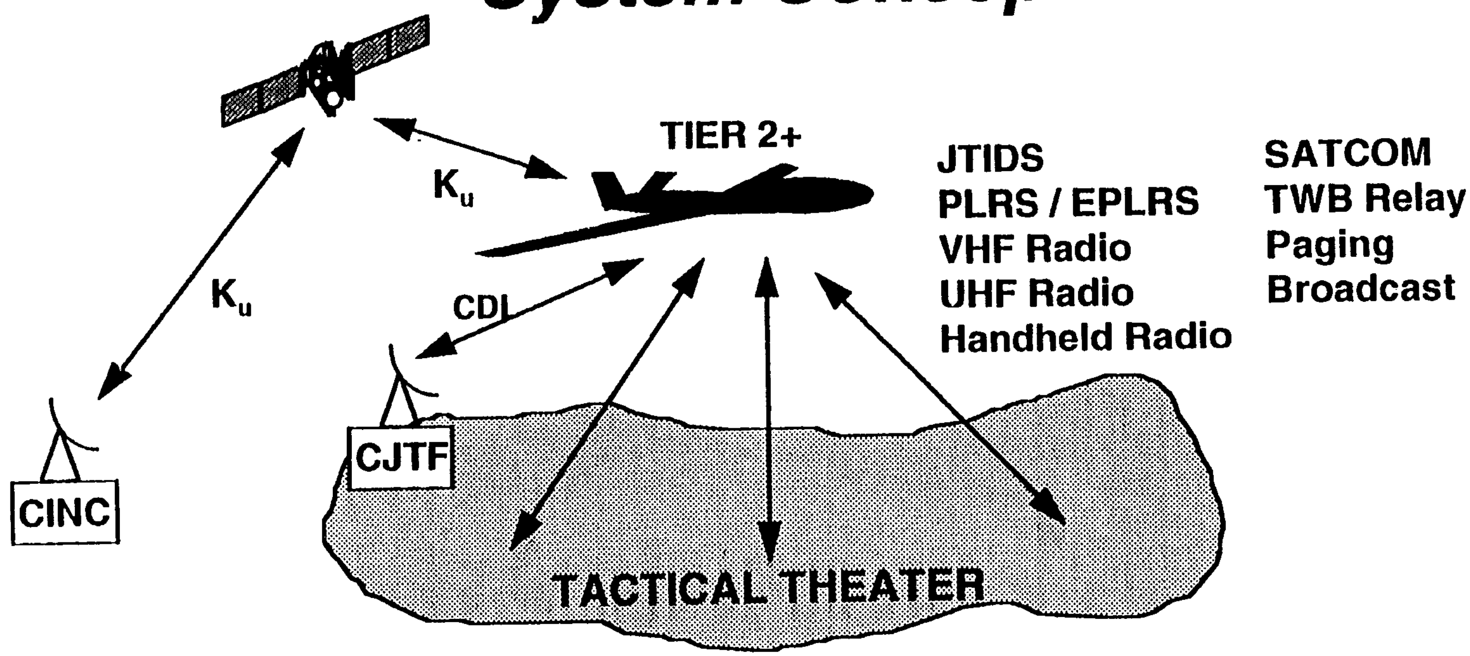
14

Figure 4

Airborne Communication Node System Concept



- **65,000 Ft. Altitude Provides Line-of-Sight Extension Up To 150 mi Radius**
- **Self-Deployment Provides Comm Connectivity to Developing Theaters World-Wide Without Need for Large In-Theater Assets**

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Figure 5

Communications Services Needed in Contingency Operations

- **Range Extension and Relay Beyond Line-of-Sight to:**
  - Overcome Terrain Blockage
  - Support Rapid Maneuvers
  - Overcome Limited Transport, Limited Mobility
  - Support New Operations Concepts
- **Reachback Communications via ACN Satellite Relay**
  - Users Reach ACN via LOS Radios; Relayed Out of Theater by ACN
  - For Forces On-the-Move and Early Entry without Satcom Terminals
- **New Classes of Service**
  - Broadcast to Forces On-the-Move (omni antenna)
  - Theater Paging System
  - Handheld Radios Using COTS Cellular / LEOSAT Technology
- **Gateways for Interconnection of Dissimilar Radios**

Figure 6

ACN Technical Concept

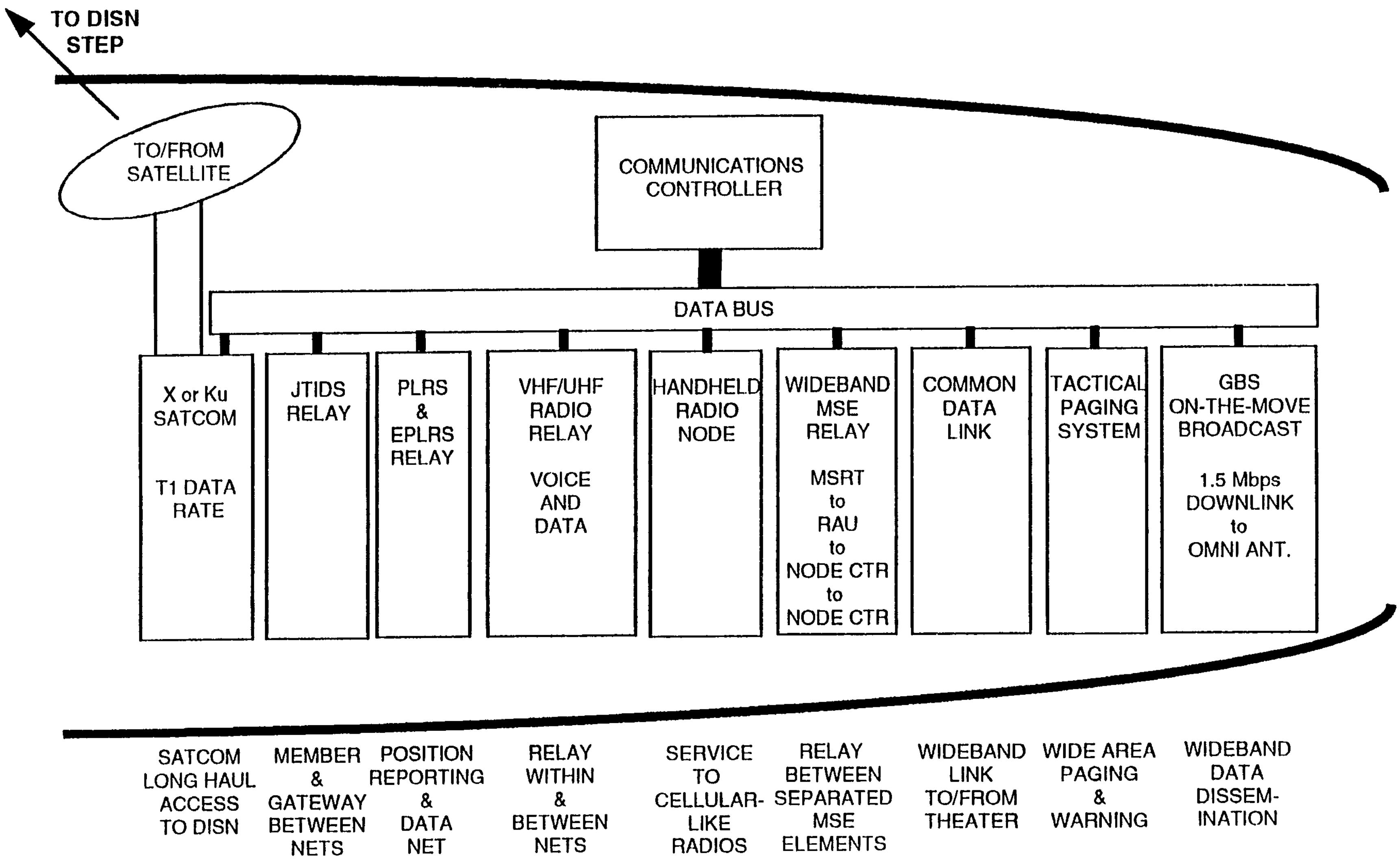

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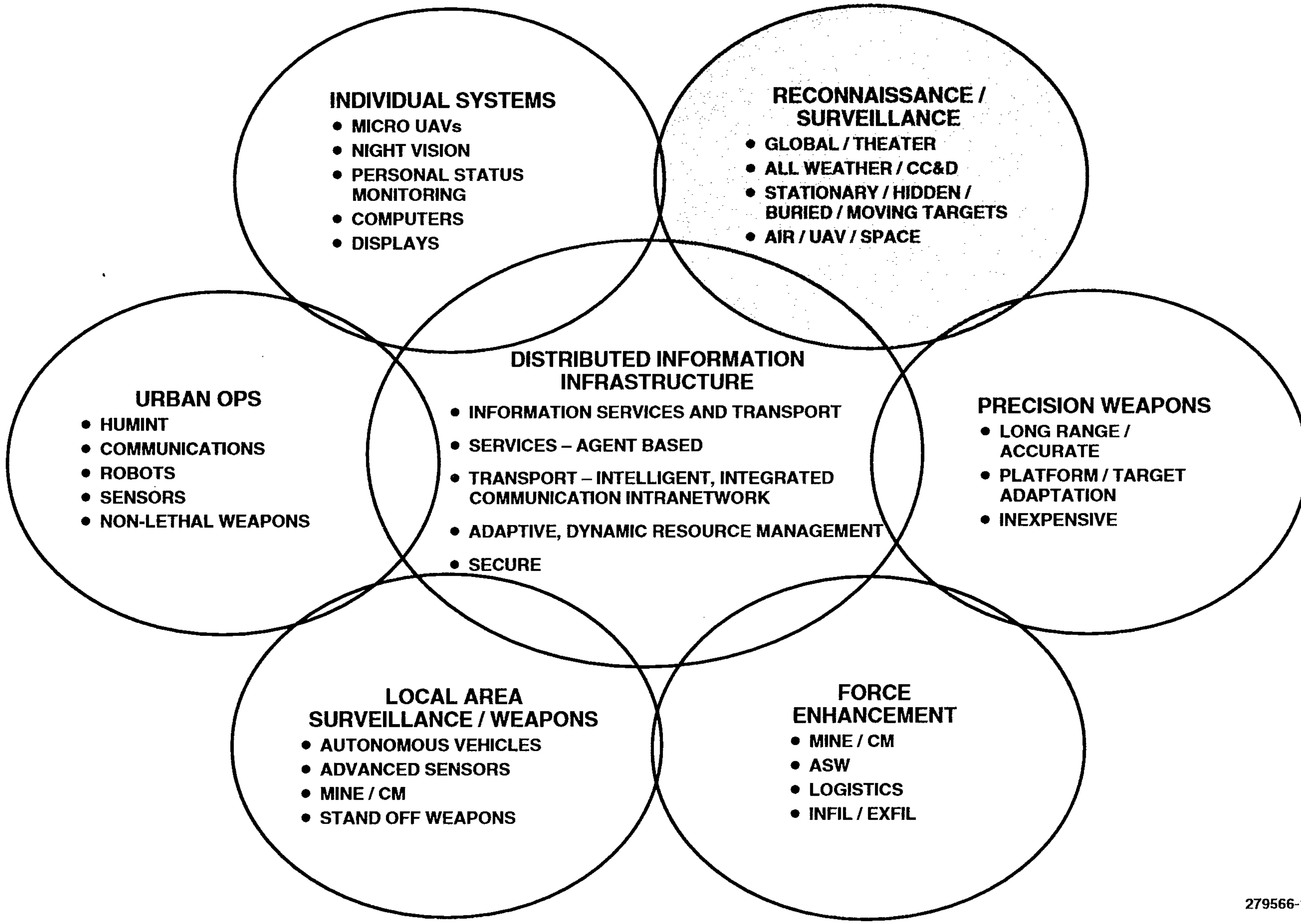
Figure 7

TACTICS AND TECHNOLOGY FOR 21st CENTURY MILITARY SUPERIORITY

TECHNOLOGY CONCEPTS PANEL



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UAV-BASED SENSING FOR SURVEILLANCE AND TARGETING

White Paper

Michael Gruber

UAV-based Sensing for Surveillance and Targeting

M. Gruber

INTRODUCTION

The need for situation awareness has always been key to operations by military forces, and it will particularly crucial for operations with small forces. While many factors contribute to an effective capability to provide the war fighter with the information that he needs to execute his mission, an essential element is the ability to gather data on enemy operations, movements, force structure, tactics, weapons and sensors etc.. Depending on the scope and tempo of the operation, these data may need to be obtained over wide regions and at frequent intervals to accommodate the dynamics of a rapidly evolving battle or other enemy action. Furthermore, it may be necessary to establish situational awareness without the benefit of pre-deployed assets or the time to deploy such assets in reaction to an enemy's aggressive actions. UAV-borne sensors, with associated processing and communication systems to extract the relevant information and disseminate it to the user, represent a powerful tool in the arsenal of capabilities that will be needed by small forces in future conflicts.

In addition to their function as surveillance assets, UAV-based sensors will also be crucial in providing the targeting information that will allow small forces to bring to bear remote weapons on enemy targets. In this case, the ability to locate targets with high precision and to communicate this information in a timely manner to the shooter is of paramount importance.

Because of their extended time on station, long endurance UAVs can provide essentially continuous coverage of a region of interest. Operating at high altitude and close to, or within enemy territory, they are also less vulnerable to terrain masking as well as SAMs than manned platforms. In this paper we will focus on the use of UAV sensors for long range (i.e. >50 km) operation. In addition, UAV-based sensors can also play a significant role across the whole spectrum of potential small force operations (e.g. see the discussion of micro-UAVs). In this paper, however, we will focus on long range UAV operation (i.e. ranges greater than 50 km).

1. Major Sensors

Sensor suites for the UAV include electro-optical (EO), IR, ESM and radar. In addition, a UAV will carry communication systems, both to transmit its own sensor information to users on the ground or in the air, as well as to serve as communication relays for the dissemination of other information to overcome line-of-sight limitation or preserve covertness. Of these sensors, radars are central to provide the long range, all weather capability that will be needed for broad area battlefield surveillance, tracking and targeting that will be required for the envisioned small forces operation in the future. When conditions permit, EO/IR systems can provide image data that can greatly contribute to the identification of targets and damage assessment. ESM can serve to detect and locate enemy emitters, provide intelligence data, and cue other sensors to locations of interest. Several additional white papers will cover the communication and EO/IR areas. The discussion below focuses on radar sensors.

1.1 Tier II+ UAV Radar

The need for long range, all-weather surveillance, tracking, and targeting in support of small forces operation in a number of proposed scenarios dictates the incorporation of microwave radars in future reconnaissance systems as the principal sensor. The desire for long endurance and the ability to penetrate enemy territory without putting personnel and costly aircraft at risk has focused attention on relatively inexpensive Unmanned Air Vehicle (UAV) reconnaissance systems. Tier II+ represents an example of the new generation of such systems which are aimed at providing significantly improved performance at a significantly lower overall cost. The challenge in the radar area is to develop and fully exploit technologies and design concepts in future UAV radar systems to go well beyond the expected Tier II+ performance which we will briefly summarize to provide a framework for the discussion of potential future radar sensors.

Tier II+ will make available major new capabilities in wide-area surveillance, chief among them is its ability to provide high search rate (40,000 nmi^2/day), medium resolution (one meter) SAR stripmap images, and high resolution (one foot) SAR images in spotlight mode (2 km by 2 km spot). It will also have an MTI mode which can search a ±45° sector in two minutes or less. In addition to the radar, an EO/IR sensor is available to provide imagery at search rate similar to that of the radar when conditions permit.

The Tier II+ radar being built by Hughes Aircraft Company under subcontract to Teledyne Ryan has a mechanically steered antenna that limits its ability to rapidly steer the radar beam to regions of interest and interleave modes. Thus it is expected to operate in only one mode at a time, e.g., the stripmap SAR must be interrupted when either spotlight SAR or MTI is desired. In a highly dynamic, rapidly evolving conflict it would be desirable to maintain simultaneous MTI and SAR coverage. While an MTI mode is inherently designed to achieve relatively rapid revisit rates through its "windshield wiper" coverage, the SAR revisit time is limited by the search rate that can be achieved in stripmap mode. Thus, although Tier II+ will be of great value, future needs will be for systems with improved performance and substantially greater capability in such areas as search rate, MTI resolution and revisit time, radar resource scheduling flexibility. In addition, to find targets that may be masked by foliage will require fine resolution at low radar frequencies and the ability to recognize interesting targets from their images at these frequencies. These capabilities can be realized by fully exploiting currently available technologies and technology growths (i.e. in processing throughput and memory), supplemented by focused technology developments where necessary - primarily microwave and high speed digital front-end data conversion and data processing technology where commercial interests are not likely to provide the necessary incentive for technology developments.

2. Performance Objectives

2.1 Fully Polarimetric SAR Imaging

Results of investigations into Automatic Target Recognition (ATR) and Automatic Target Cueing (ATC) techniques applied to SAR images indicate that fully polarimetric radar measurements lead to major improvements in algorithm performance. Fully polarimetric image data may prove to be essential for achieving the combined high probability of detection/recognition and low probability of false alarm required to allow the confident operational use of these techniques - a key prerequisite to realizing a true theater wide-area, timely surveillance under dynamic battlefield conditions.

2.2 Improved Modes of Operation

A radar for airborne reconnaissance will have two basic modes of operation: Synthetic Aperture Radar (SAR) for imaging of terrain and stationary targets, and some form of Moving Target Indicator (MTI) for detecting, tracking and imaging of moving targets. Because of the different requirements for these modes (in terms of parameters such as dwell time, PRF, bandwidth, etc.), surveillance radars typically operate in only one mode at a time. For example, if such a radar switches to the MTI mode for some period of time from the stripmap SAR there will be a discontinuity in SAR coverage. To maintain continuous surveillance of both stationary and moving targets , the ability to simultaneously operate in multiple modes is highly desirable. Exploiting the synergism between these complementary modes can further enhance surveillance effectiveness, e.g. providing continuity in keeping track of a target when it is moving (via MTI) and when it stops (via SAR), or maintaining the ID of a stationary target derived from SAR data when the target moves, by correlating SAR and MTI location data. Only electronic beam steering offers the speed and flexibility to support such a concurrent, multimode radar operation.

2.3 Extended Area Coverage

There are two aspects to the radar range coverage which, although related, have different operational implications. The first of these is the maximum range at which the radar achieves an operationally useful performance level. A longer range is desirable because it provides a greater standoff distance from hostile forces as well as greater reach into hostile territories without violating sovereign air space. The second aspect of radar range coverage is the area illuminated by the radar and processed by the remainder of the system which directly determines the search rate, a primary system performance measure. For a fixed elevation beamwidth antenna a compromise solution must be selected between broad coverage at short range, requiring a wide beam, and antenna gain at long range where a narrower, higher gain beam is desirable to minimize radar power requirements. Such a compromise is unnecessary in a 2-D phased array radar, leading to a much more efficient and flexible overall system design.

Increased search rate in the SAR mode can also be achieved by illuminating a large area with a broad transmit beam and employing multiple high-gain (narrow) receive beams to cover the illuminated area. This approach circumvents inherent limitations of single-beam systems imposed by ambiguities (PRF) while achieving greater sensitivity.

An agile beam phased array radar can provide the larger aperture and beam shaping flexibility required to optimize sensitivity and achieve large scan sectors without the need for the large swept volume required for a mechanically steered antenna.

2.4 Improved Resolution

The performance of ATR and ATC techniques using SAR images improves as the resolution of the image improves. At present the large amount of data and processing that are required by high resolution (~1 ft) wide-area imagery has restricted its use to the "spotlight" mode for SAR, typically covering an area of only ~ 2 km x 2 km. Such limited range coverage has allowed the use bandwidth reduction techniques such "stretch" processing to cope with the large bandwidth signals required to achieve this resolution. As more efficient algorithms are developed and processor capabilities improve, increased high resolution radar area coverage will be required to fully exploit these improvements. Thus, processing approaches, such as the use of high speed digital radar signal processors, not constrained to the limited range interval possible with current techniques will be necessary to achieve the coverage that is needed.

2.5 Foliage Penetration

The majority of airborne radar reconnaissance objectives are best met with radars operating at X-band or possibly Ku-band. However, an important operational objective, foliage penetration, can only be achieved using a low frequency radar, typically in the UHF band. The primary mode of such a radar is stripmap SAR, although an MTI capability could enhance its operational utility. These radars are characterized by very large fractional bandwidths, raising unique problems for the antenna, transmitter and receiver, and signal processing. Because the maximum operating frequency is comparatively low, the opportunity exists to leverage developments in high speed digital technology to explore a digital RF radar approach for reducing cost and improving performance.

3. Future Radar Systems

3.1 UAV Radar

A key limitation on the SAR stripmap search rate achievable with Tier II+ is the processing throughput that can be realized on-board the UAV within the weight, power, and above all, cost constraints. The planned processor for Tier II+ will have a throughput of ~10 GFLOPS to support a SAR stripmap image swath width of 10km. Growth in processing technology combined with highly parallel processor architectures, together with improvements in software tools that increase processor efficiency can be expected to support a tenfold increase in the SAR area coverage rate achievable with a UAV radar system. Furthermore, progress in the area of automatic target cueing and recognition will be able to support on-board image data pre-processing to reduce the load on the data link to the user ("intelligent data compression").

In addition to improving stripmap SAR search rate, the use of a solid state phased-array radar having multiple receive beam channels will also make possible simultaneous SAR and MTI surveillance thus providing essentially continuous coverage of both stationary and moving targets. This capability can be used to exploit the synergism between these two modes: for example, information on a target or target group, once acquired by either mode, can be maintained continuously to provide up to date and robust situational awareness to forces in the field and tactical planners, i.e., the desired "birth to death" tracking of targets. In particular, the rapid beam steering possible with solid state T/R modules can be used to subdivide a radar pulse and steer energy sequentially in different directions during transmit. The multiple receive beam channels can then be used to receive the return echo. Direct Digital Synthesis (DDS) of waveforms, a technology that finds widespread use in existing and planned systems, provides the flexibility to generate the necessary composite waveforms for the transmit pulse.

Wide bandwidth, large aperture array radars require time delay steering when scanning off-boresight. To meet this requirement at reasonable cost, such arrays are typically divided into subarrays, and time delay steering is only applied at the subarray level. Analog delay lines can be used for this purpose but typically need continuous real-time calibration to preserve the necessary phase coherency across the array. DDS generation of waveforms at the subarray level avoids this problem and simplifies the implementation of the required time delay steering, making phased arrays with their attendant advantages over mechanically steered antennas the approach of choice in the future. On receive, high speed A/D conversion at the subarray level accomplishes the same for the receive beams. In addition, bringing the signal into the digital domain at RF provides for flexible signal processing to accommodate the variety of waveforms required to optimize radar resource allocation.

A notional UAV radar system incorporating the concepts and technologies discussed above is shown in Fig. 1. The primary SAR imaging and MTI radar is at X-band. A separate radar at UHF for foliage penetrating (FOPEN) SAR imaging and MTI is also shown. A separate white paper discusses this capability in more detail.

The X-band radar system consists of a 1-D active array radar aperture and separate, fixed beam receive antenna for the SAR stripmap as shown. This receive antenna supports continuous SAR stripmap imaging without the need for the more costly alternative of additional receive beams in the active array. By partitioning the transmit pulse into subpulses with waveforms appropriate to the various radar modes, and transmitting these subpulses at the proper beam positions, the radar can obtain simultaneous stripmap SAR, MTI and SAR spot mode coverage. Subpulse energy (pulse length) can be allocated to optimize radar sensitivity. The coverage obtained for the principal modes, SAR stripmap, SAR spotlight, MTI, and FOPEN is shown in Fig. 2.

In addition to providing surveillance information for situational awareness, a UAV radar system will need to provide accurate targeting data to support the use of remotely launched weapons. With the aid of GPS and advanced navigation systems, the location of the UAV can be accurately determined. Calibration of the radar system will also allow accurate location of targets in range and angle relative to the UAV. Precise designation of target position for inertial guided weapons also requires accurate data on terrain height (within a few meters). If such data are not available, interferometric SAR (IFSAR) derived from successive SAR imaging passes may be used in critical areas. Again the shows a conceptual application of a future UAV radar system of the type discussed above to the surveillance of a notional region of interest for small forces, e.g., support of an amphibious ability to achieve large area coverage and to flexibly allocate radar resources is important.

Fig. 3 operation. In this case an area of ~100 km by ~100 km would be continuously monitored with MTI and SAR. MTI scan time is of the order of 1min or less. Because stripmap SAR imaging is carried out simultaneously with MTI, the entire region will be imaged by SAR every ~ 15 min. on average as the UAV follows a race-course trajectory. Specific areas where targets of interest are detected by SAR can be monitored with the MTI mode for any movement of these targets between revisits of the SAR. Change detection (as discussed in the ATR white paper) can be also used for successive SAR images to monitor stationary objects (including false alarms) and detect when targets stopped or moved away from a site. Moving targets that have been identified using moving target imaging or on the basis of other data (e.g., 1-D high resolution range profiles) can also be handed over to SAR when MTI determines that the target has stopped (e.g., isn't just temporarily obscured by terrain or trees). Having continuous and essentially simultaneous and high revisit rate coverage for both MTI and SAR thus greatly enhances the ability to gather information that supports a high level of situational awareness as well as the ability to engage targets whether stationary or moving.

3.2 Space Based Radar

In the far term, a space based radar (SBR) system may prove superior to an airborne system in satisfying some of the surveillance requirements. Space systems provide quick reaction world wide access and have generally better survivability than airborne systems. However, because of the extreme ranges involved, SBR systems would be necessarily large and costly, hence unlikely to incorporate all of the features (such as foliage penetration) that are realizable on a UAV. Applications that require continuous coverage would also be costly to implement from space because of the large number of spacecraft that would be needed to provide that coverage from reasonable operating altitudes. For these reasons, space based systems are unlikely to completely replace airborne systems.

As an example, an SBR system consisting of 15 to 20 satellites at an altitude of about 1500 km could provide sufficient (but not continuous) coverage for surveillance. Each spacecraft might weigh about 7500 lb and carry a radar having a 3 × 16 meter phased array antenna radiating about 3 kW rf. The SBR would operate in both SAR and MTI modes and be capable of covering a 10,000 km^2 area in about 100 seconds. The SAR mode would cover the area with 3 meter resolution, or smaller areas with finer resolution. The MTI mode would be capable of detecting targets having 10 m^2 radar cross section moving at a radial speed of 3 m/s.

Implementation of such a system would require an antenna capable of multiple receive beams formed using time-delay steering in order to support the SAR coverage and resolution requirements. Image formation at the finer resolutions would require digital processor thruput rates far in excess of those that are currently available. The MTI mode would require the use of a displaced phase center antenna (DPCA) or other space-time adaptive process to achieve the required subclutter visibility. Technology development requirements for both UAV and SBR are discussed in the next section.

4. Required Radar Technology Developments

In principle, currently available technologies can support many of the UAV radar performance goals discussed above. However, they cannot do so within the constraints of acceptable weight, power, volume, and, especially, cost. Hence technology developments need to focus on achieving improvements in future systems in a cost effective way by tailoring these developments to the specific requirements of airborne reconnaissance radars and to take advantage of their unique characteristics.

On the other hand, technology sufficient to support the SBR performance goals is not uniformly in hand. In particular, many of the technology developments that would be useful in reducing cost for the UAV radar are necessary for implementation of the SBR. The developments required for each application are similar in nature, so that a technology program could be aimed at the UAV implementation in the mid term and the SBR implementation in the long term.

These technology developments are divided into two principal areas, phased array radars and radar signal processing..

4.1 Phased Array Radars

Electronically steered active phased array radars offer the greatest performance potential and flexibility. Solid state active (or hybrid) arrays promise higher reliability and fault tolerance, lighter weight, and greater ease of integration compared to other approaches. It is also the approach that can best meet the performance goals outlined above, given a phased array's ability to:

(1) rapidly steer the beam, in any direction to support both SAR and MTI modes, individually and, with multiple beamformers on receive, concurrently,

(2) adjust the beam shape to best match the angular coverage required (both in azimuth and elevation),

(3) form multiple, simultaneous receive beams to achieve greater high resolution SAR coverage rates and extend the maximum range beyond that possible with single beam radars,

(4) allow partitioning of the antenna aperture into subarrays to meet requirements for different modes (e.g. Displaced Phase Center Antenna (DPCA) for MTI processing) as well as support adaptive beamforming techniques for interference (ECM) suppression,

(5) provide fully polarimetric capability using appropriate radiating element designs,

(6) be build with a modular architecture that uses basic building blocks (subarrays) that, once developed, can serve as common elements for a broad range of radar systems, thus helping to reduce design and manufacturing costs for new systems.

The driving cost element for solid state phased array radars is the T/R module. Two approaches to reducing the cost of such radars is thus to reduce either the number of T/R modules required or their unit cost. A hybrid approach where one high power T/R module feeds a number of radiating elements, each of which has a low-loss, low-power, and, most importantly, a low cost phase shifter for beam steering would substantially reduce the number of T/R modules required. Alternatively, the low power required may permit the entire T/R function to be implemented on a single MMIC (Monolithic Microwave Integrated Circuit), with the attendant cost savings.

4.1.1 Single Chip T/R Module

The low power requirement at each radiating element offers the opportunity to reduce cost by reducing the complexity of the electronics associated with each such element. Single chip T/R modules were a goal in the early stages of this technology development which was abandoned because the low yield experienced at the time and the increasingly higher module power required to meet candidate radar system sensitivity objectives made this approach unattractive. However, even these early attempts yielded modules with 1-2 W peak power output. This approach should be re-examined in light of the improvements in materials as well as manufacturing techniques which have occurred since that time. In addition to providing all the required functions on a single chip, a key challenge is the need to achieve high module efficiency in order to keep DC power and cooling requirements low. Particular emphasis will have to be placed on achieving low power consumption in the receiver.

4.1.2 Low -Loss Phase Shifters

A key requirement for the hybrid phased array approach is a low-loss phase shifter. An approach for obtaining such phase shifters at X band takes advantage of Low Temperature Grown (LTG) Gallium Arsenide (GaAs) microwave switches. Phase shifters fabricated with these devices are expected to achieve 2-dB insertion loss. It is expected that these losses could be further reduced to less than 1 dB with additional development. In particular, computer simulations carried out at Lincoln Laboratory indicate that phase shifters using LTG GaAs microwave switches can handle 1-W peak power and weigh of 0.2 to 0.5 oz. Using a single T/R module, such as the ones which have been developed for X-band by a number of companies (for example, Texas Instruments, Westinghouse, and Raytheon) to feed a 16-element subarray with this type of phase shifter at each element could result in a cost savings of a factor of four compared to using a T/R module feeding each element.

Other approaches to achieving low-loss, low-cost and light weight phase shifters may be feasible. For example, the use of compact, low-loss ferrite phase shifters in monolithic configuration using high temperature superconductor printed circuits has been suggested. Of course, the implication on total system design and cost needs to be assessed when considering various alternatives. Such an assessment should be the first step in any development in this area to identify the most promising approaches.

4.1.3 Subarray Building Block

A technology program to achieve a suitable low cost radar design will focus on a radar architecture that allows the use of a common, low-cost, mass-produced building block to serve as the key element for radar designs to meet a variety of system performance requirements. This building block will consist of a subarray of radiating elements, with associated electronics and circuitry to generate and distribute microwave power to the radiating elements, receive the radar return signal, provide for steering and shaping (via phase control) of the radar beam, and include provisions for calibration, alignment, and status monitoring.

Simplifying the electronics required at each radiating element creates the opportunity to develop a highly integrated, compact subarray design using a "tile" configuration for the antenna. Such an antenna consists of a multilayer structure to accommodate the radiating elements, phase shifters or T/R module chips feeding the elements, and corporate feed networks to distribute the transmit and receive signal to and from the array. Approaches to implement such a subarray are currently being explored in industry using Low-Temperature Co-fired Ceramics (LTCC) and High Density Interconnects (HDI) technologies. These efforts can serve as a jumping off point for developments directed specifically at the airborne surveillance radar problem.

To assemble a radar using the kinds of building blocks described above will require the distribution of microwave and other signals from some central signal generation and control subsystem. A distribution network using optical fibers offers a lightweight, low loss, stable and low-cost approach which will also reduce the cost of platform integration because the much less stringent mechanical, thermal and EMI shielding requirements of fibers compared to other alternatives, such as coaxial cable.

An important consideration for very wideband, large scan angle, narrow beam (large aperture) radars is the requirement for time-delay steering. The modular architecture postulated here for future phased array radars is well suited to satisfy this requirement. Time delay units, for either a single subarray or a group of subarrays, can be implemented as part of the central control subsystem. Direct Digital Synthesizers (DDS) can be used to generate not only the required waveforms but also provide for the necessary time delay. DDS technology is maturing rapidly; the key challenge will be to achieve low cost, by reducing the number of chips required to carry out this function and building affordable generator modules which, just as the subarrays themselves, can serve as common building blocks for a variety of radar designs, including radars at different frequencies and for other applications.

4.2 Radar Signal Processing

On receive, the signals from each subarray, or a group of subarrays, can be digitized for further processing by digital beamformers (possibly using adaptive or space-time processing for interference suppression), with time delay of the signal being accomplished as part of the digitizing process. By transforming the microwave analog signals from the output of the subarray into a time sampled digital signal, phase, amplitude and time correlation of signal between subarrays are easily preserved, a crucial requirement for making the antenna operate as one coherent large aperture and achieving the desired resolution and radar beamshape.

The large time-bandwidth products encountered for high resolution SAR systems makes digital signal processing the most attractive approach for such functions as beam forming and match filtering, which have traditionally been carried out in microwave analog hardware. Rapid progress is being made in this area in the commercial arena, where Digital Signal Processing (DSP) chips are expected to reach throughputs in the several hundred mega FLOPS. Dedicated processing chips or chip sets to carry out common signal processing functions such as FFTs are, and will be achieving several times the DSP chip throughput. The focus of technology developments in this area should be to investigate processing architectures that optimize the application of these basic chips to the radar signal processing problem, and develop the necessary custom chips (ASICS) to implement these architectures.

SUMMARY

Advanced wide-area surface surveillance radars, together with advanced automatic target recognition and automatic target cueing techniques which take full advantage of the data provided by these radars, promise to bring a greatly enhanced operational capability to the theater in the future. Developments of the technologies discussed above would provide the foundation for realizing this promise in future system designs.

Figure 1:

STRAWMAN UAV RADAR SYSTEM

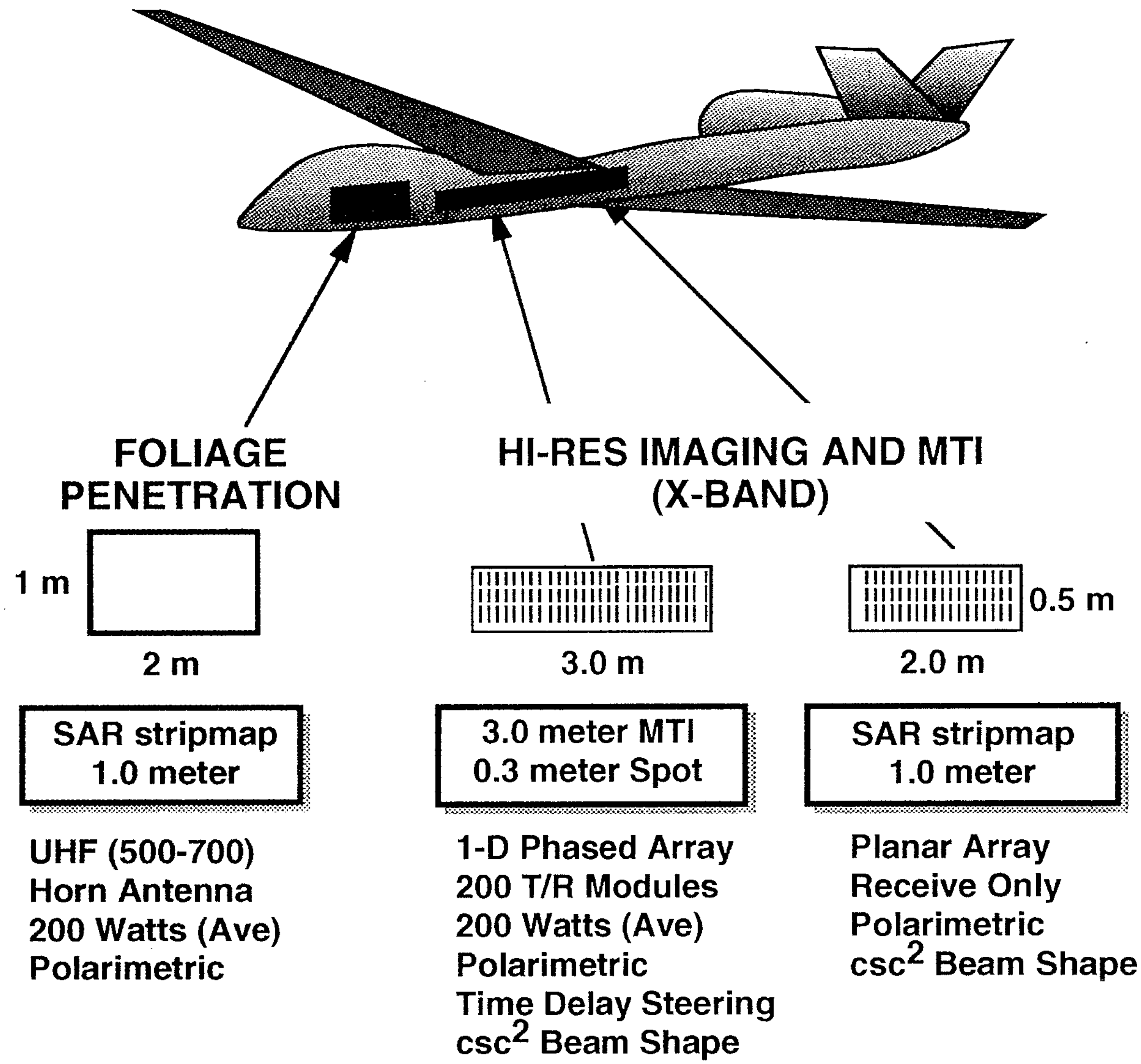


Figure 2:
NOTIONAL UAV RADAR COVERAGE

STRIPMAP SAR - MEDIUM RESOLUTION WIDE AREA IMAGE
STRIPMAP FOLIAGE PENETRATION (UHF)
SPOTLIGHT SAR - HIGH RESOLUTION LOCALIZED IMAGE
MOVING TARGET INDICATOR

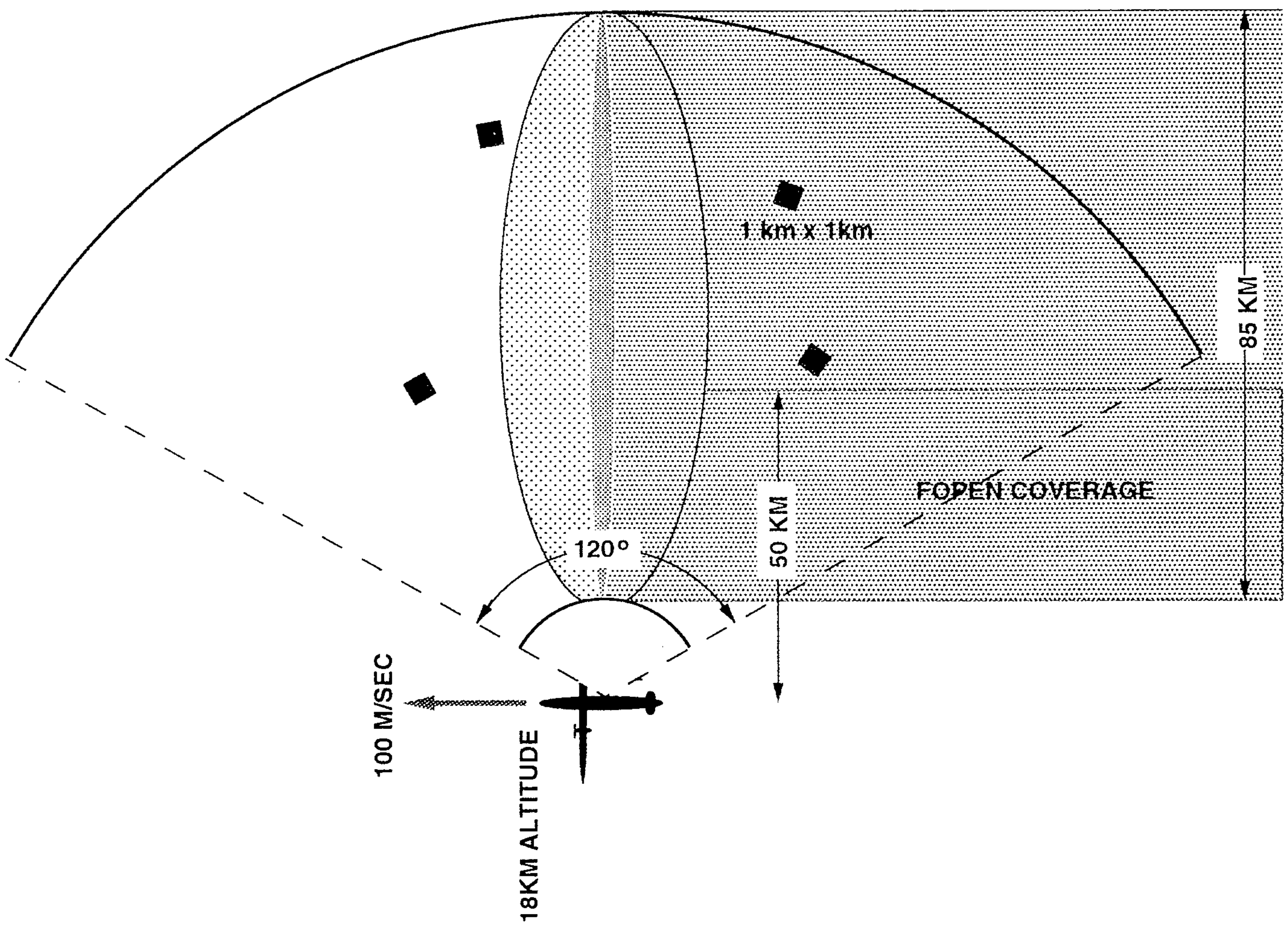


Figure 3: Example UAV Radar Surveillance Region

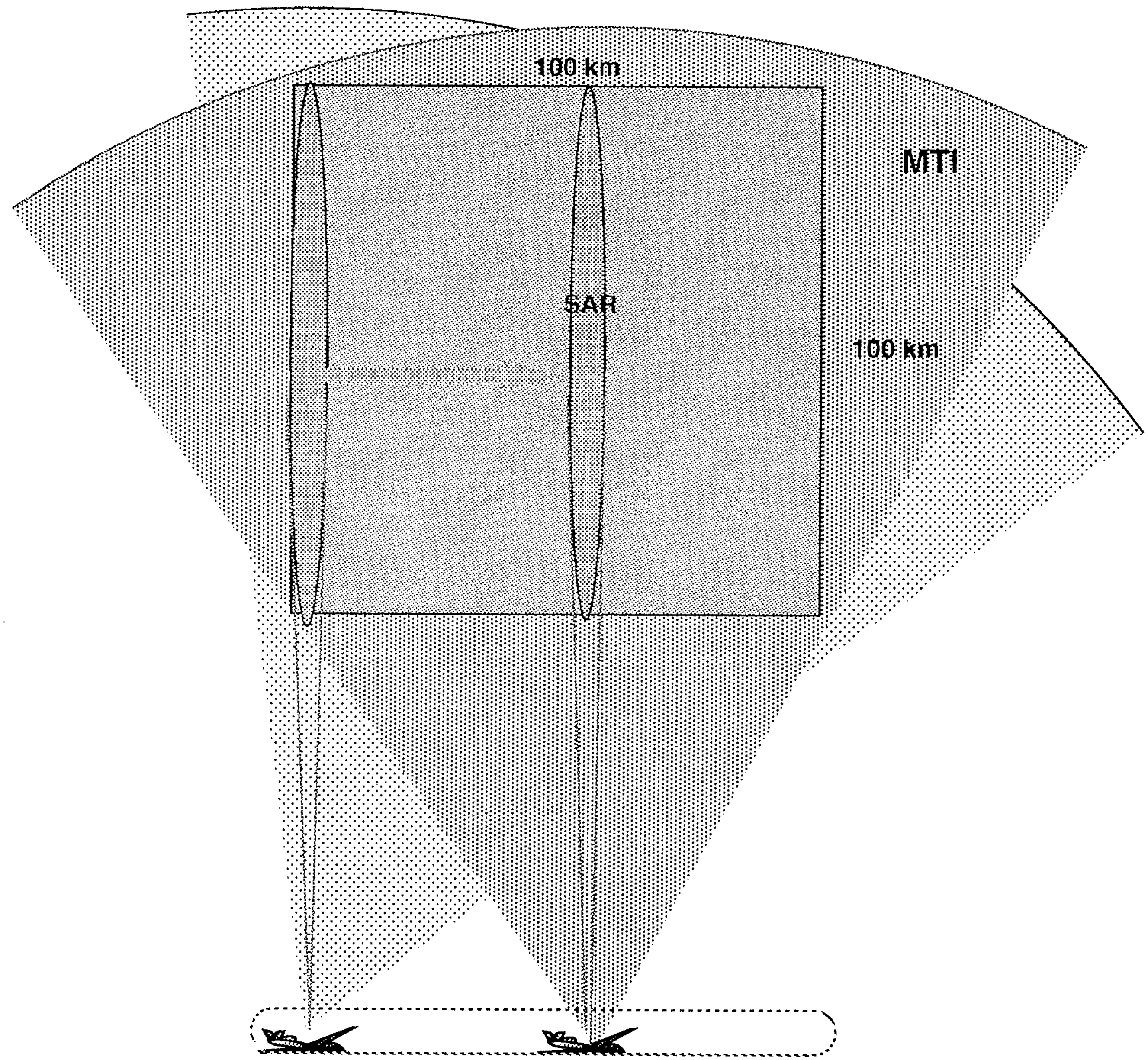
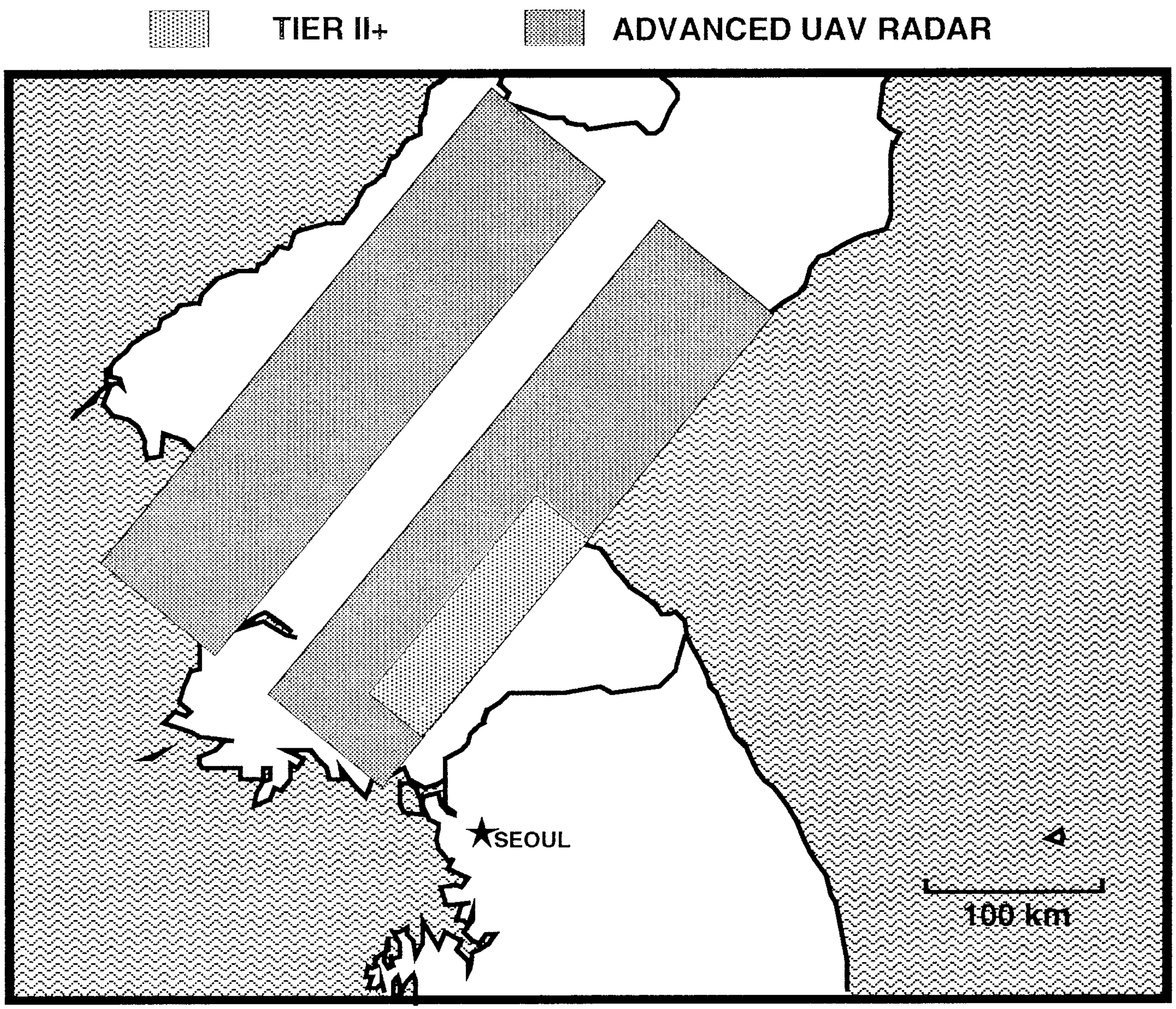


Figure 4:

SAR AND COVERAGE COMPARISON

AREA COVERED IN ONE HOUR



MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

EO SENSOR TECHNOLOGY FOR 21st CENTURY GROUND FORCE SUPPORT

White Paper

M. Cantella, D. Harrison, R. Hull, and B. Kosicki

EO SENSOR TECHNOLOGY FOR 21st CENTURY GROUND FORCE SUPPORT

WHITE PAPER AUTHORS: M. Cantella, D. Harrison, R. Hull, B. Kosicki, edited by D. Kostishack, R. Parenti, A. Waxman

I. Introduction:

Electro-optical sensor systems and technologies will play an increasingly important role in supporting ground forces in carrying out military operations in the 21st Century using relatively small force groups. This white paper describes a number of EO sensor technology concepts and applications that should have significant impact in carrying out these demanding operations. In order to identify the most important and appropriate technology concepts, a top- down approach was taken starting with the five proposed military action cases of: Halting a combined arms attack, Securing territory, Operations in Urban settings, Extended offensive operations and Force extraction. A list of more than ten operational capabilities were identified to support these five cases and many operating functions and needs were determined in response to these required capabilities. Technical approaches were identified to support these functions and needs; and, four classes of EO sensor types were called out to categorize the many technology concepts that would be important to these approaches. The matrix in Table I indicates the relationship of the most important technologies and concepts with the four classes of applicable EO sensor types.

As this top-down approach evolved, it became apparent that just about all of the appropriate technology concepts addressed EO sensor applications for relatively small basing platforms including soldier, small UAVs, small Unmanned Ground Vehicles and other compact deployment systems. A few interesting technology applications also applied to remote, larger platforms which would include aircraft (manned and unmanned) and spacecraft. It also became evident that Electro-optic imaging systems, operating across a multitude of spectral bands (visible through long-wave IR), will proliferate in use throughout ground forces as well supporting airborne (low and high altitude) and spaceborne platforms. Such sensors will provide electronic vision enhancement for the soldier and airman, enhancing personal situational awareness and tactical efficiency. However, there is an enormous opportunity here to literally create a whole picture which is greater than the sum of its parts. By integrating GPS positioning and image/video transmission/reception capabilities into the soldier's electronic vision system, small team special forces will be able to share one another's imagery for enhanced awareness of the battle space, i.e., realtime battlefield intelligence. Taken to a larger scale, through the inclusion of distributed, hierarchical image intelligence fusion centers, the distributed imagers moving through the battle area will be able to provide data to create a realtime Integrated Battle Space Visualization capability. Selected imagery will be tied to status maps which integrate all-source intelligence and support broadcast to certain units. Battle commanders will be able to perform a virtual "fly through" of the battle space for realtime planning purposes. Post-battle replays will integrate

TABLE-I

EO SENSOR TECHNOLOGY FOR 21st CENTURY GROUND FORCES SUPPORT

Technology/Concepts	Sensor Types: **Small** Small Platforms Soldier, UAV, UGV	**Large** Remote Platform, Air and Space Craft	**Smart** Enhance Perception, Automomous	**Smart Weapons** Local and Remote Platforms
-- SINGLE CHIP CAMERA	X			
-- MINIATURE OPTICS	X			X
-- MULTI-RESOLUTION FOV	X			
-- INTEGRATED OPTICS	X			
-- COMPACT SOLID-STATE COOLING	X			
-- UNCOOLED IR FPAs	X			
-- COMPACT IMAGE PROC.	X		X	X
-- COMPACT HYPERSPECT.	X			
-- COMPACT FISHEYE FOV	X		X	
-- COMPACT SHORT PULSE LASER ILLUM.	X			X
-- LARGE, HIGH PIXEL COUNT FPA		X		
-- HIGH SENS., HYPER-SPECTRAL		X		
-- SEGMENTED OPTICS		X		
-- LASER RADAR		X		
-- NEUROMORPHIC SENS.	X		X	
-- ON/NEAR FPA PROC.	X		X	
-- FLASH DET. FILTERS	X		X	
-- COMPACT SS LASERS	X			X
-- HIGH RESOLUTION MINI-SCOPE				X
-- OPTICS DETECTION/AUGMENT			X	X

his EO visualization with known vehicle and soldier trajectories through the digital battlefield for "lessons learned." An investment in R&D is essential and should begin immediately, to realize the hardware and software technologies required to support an Integrated Battle View capability for future conflicts.

The following provides a brief, high level description of a number of technology concepts with emphasis on specific applications and utility to small forces operations for essentially two types of basing, small and large platforms.

II. EO Sensor Technology Concepts for Small Platforms:

These concepts mainly address sensor applications in support of soldier or small vehicle based systems. They are presented in sections representing specific sensor functions of interest with some description overlap.

A. TARGET AND WAYPOINT LOCATION DESIGNATION:

The success of future warfare fought with a "small force" depends largely on the ability to ascertain the situation associated with planned objectives and then direct appropriate resources from a remote location. The backbone of the " small force" is depicted by the twenty-first century warrior concept. This warrior can operate independently in a hostile environment with equipment-enhanced hearing and sight. Navigation aids, threat warning, and various forms of communication are essential to mission success.

Direction of remote resources directly by a soldier or from a vehicle or ground installation can be accomplished rapidly and unambiguously with a laser location-marking system. This system has high precision, does not require optical line-of sight to the remote platform, and can minimize exposure of personnel. Remote resources that contain the laser sensor include aircraft, unpiloted air vehicles, and missiles. Operational utility of the system includes remote-platform navigation, drop-zone location, and target designation.

One of the best ways to implement such a system is to combine it with communication links. One link is used to trigger the laser on demand from the remote platform only when this platform is in the vicinity. This minimizes the number of shots needed to designate the location, so laser battery-power is conserved, and detection of the laser or communication links by an enemy is minimized. When the laser fires, a second communication link is used to synchronize an image-gated sensor on the remote platform. This synchronization greatly enhances sensor sensitivity by reduction of background exposure and permits a multiplicity of simultaneous, unambiguous engagements in the battle space. There is inherent immunity to countermeasures and low probability of fratricide, especially if IFF techniques are incorporated in the schemes for communication.

The key electro-optical components in the design of a laser location-marker system are a high-efficiency laser and a high-sensitivity, gated, imaging sensor. The laser should be eye-safe and operate in the SWIR spectral band. Emissions of approximately 200 mJ within a pulse width of 5 microsec would provide excellent performance. Laser design could be tailored to this function and perhaps include a dual-use, laser rangefinding mode. The imaging receiver should contain an SWIR narrow-band filter and a staring type of focal plane array (FPA) with approximately 10 microsec image-gating capability. This device could be developed by extension of modern FPA technology.

Designate & Forget Targeting Algorithms

Smart imagers should be integrated into munitions to support a target designate and forget capability. Following momentary target designation by a (possibly remote) soldier using a laser tagging method, a maneuverable munitions should be able to lock onto the visual/thermal appearance of a spatially resolved target. Using real-time feature extraction, 3D geometrical transformations, and image space to 3D projective transforms, smart weapons will be able to lock onto and home into targets selected in the field, without requiring constant active designation, thereby protecting the soldier's location. It will also provide UAVs a means to deliver precision munitions in congested urban environments, effectively working together with the soldier on the ground. Hence, each soldier can be in command of a personal UAV air force for surveillance, targeting and munitions delivery.

B. OTHER ACTIVE SENSOR CONCEPTS:

Optical sensors, either visible or infrared, provide the most easily interpretable information for human observers. When a laser is added to provide active imagery, the information content can include range (coarse for fire control, fine for target recognition), Doppler for both moving target detection and identification, vibration sensing for ID, and range gating to overcome obscurants, such as smoke and haze. Mapping functions can be implemented for robot scout vehicles, to provide ingress and egress paths or to find recently implemented obstacles. When combined with the usual reflectance and thermal images produced by passive sensors, such multidimensional images have been shown to provide high probability of detection and recognition with low false alarm rates for automated target recognition procedures.

In non-imaging operation, active sensors can and have provided target designation functions and range-finding. One can imagine that infrared laser sensors could provide combat identification of friendlies in a covert manner, especially during close-in or mixed battle encounters.

In order to make such sensors feasible for proliferation on the battlefield of the future a number of technology developments must occur. To save weight and power mechanical scanners must be eliminated. This can be accomplished through the development of highly sensitive detector arrays combined with solid state laser development. The current generation of solid state lasers has become considerably lighter in weight and more efficient in the use of electrical power through the use of diode pumping to replace flash-lamp pumping. Further developments needed are to move the wavelengths of operation to the eye-safe region, which are wavelengths greater than two microns. Highly sensitive, low noise detectors also need to be developed for this spectral region. Uncooled operation of both detectors and lasers will be required to make miniature sensors possible for use either as man-portable instruments or for use on micro-UAV's. On-chip image processing must be developed. Active and passive imaging functions must be incorporated into single module sensors.

Identification of friendlies in mixed battle situations can be provided by laser interrogators, which can be highly covert when compared to radio-frequency or even millimeter wave devices.
Techniques based on finding patterns imbedded in uniforms when laser illuminated, or development of fluorescent materials should be developed. The IFF function can be combined with range-finding or with target designation to keep the number of separate sensors within bounds.

C. NIGHT VISION, HIGH SENSITIVITY:

It is paramount to realize that, as we advance the soldier's vision enhancement capabilities, our adversaries are doing this as well. A good example is night vision capabilities. To "own the night" is an important tactical advantage our forces currently enjoy. However, our adversaries can currently purchase Gen II intensifier tubes, and soon there will be available Gen III tubes and uncooled thermal IR imagers in the commercial market place. Despite export restrictions, smuggled goods will be able to supply small elite guard units with advanced night vision technology. It is necessary to support revolutionary technologies to restore and maintain our forces' ownership of the night. Such technologies are now just emerging in the form of electronic low-light visible and uncooled thermal imagers which support realtime digital image processing and communications. Solid state imaging technologies will lead to robust and inexpensive night vision systems available to all forces.

Technologies which support enhanced visual perception and eye safety for soldiers on the battlefield (including urban battles) will be critical for small force success. To operate in a dangerous urban environment in battle, it will be essential for each soldier to have Electronic Vision

Enhancement Goggles (and weapon sites) able to see through and cue in day, night, fog, rain, snow, dust, and smoke. Through the miniaturization and integration of low-light CCD and thermal imagers, computing electronics, displays, GPS, broadcast/receive electronics, low power IC technology, and all important lightweight battery technology, the soldier will be able to see through the cloak of darkness and obscuration and even see around the corner (through the sensors of a mobile ground robot or a fellow soldier). He will be able to "shoot/launch" a smart mobile micro-robot imaging sensor (and listening device) into a building and view (hear) the interior before entering. He will be able to see overhead views provided by micro/mini-UAVs. Overall situational awareness will be greatly expanded, and remote commanders will be aware of the situation from the perspective of the soldier as it evolves in realtime, leading to safer and more effective small force operations in urban areas.

Simulations of low-light-level imaging systems have shown the need for read noise down to at least 0.1 electrons/pixel. The reason for such a low noise requirement in this type of system is that frequently multiple reads are needed for a single image to be assembled. Therefore, although the photon noise itself is at least a few electrons, it is still important to maintain this ultra low noise of the system. Important application areas are any in which the number of photons is severely limited, such as night vision, certain spectral measurements, or very fast framing. New application areas may open up for single-photon imaging systems which are also very small, compact and rugged. Improvements are possible both by pressing the current state of the art in reduction of the size of output nodes, and also by radically new types of structures which are very low in input capacitance.

D. ENHANCED PERCEPTION:

Multi-resolution Field of View Imagers and Displays:

Today's night vision goggles and thermal imagers present the user with a very restricted field of view (40 degrees or less), necessitating constant head scanning to increase field of regard. Motivated by the design of the retina, imaging sensors can also exploit multi-resolution optics and imager layouts to provide very wide fields of view to the user. The wider field of view can be sampled at lower resolutions, with central fields of view sampled at high resolution, all presented on intermediate resolution displays (implying geometric compression of the widest field of view). Development of conforming wide field displays/visors will support the display of this sensed data, as well as other intelligence and maps, and protect the soldier's eyes from laser and chemical attack.

Multi-spectral and Data Fusion Algorithms:

Advanced EO systems on the soldier and providing surveillance support from the air, will be multi-spectral. For example, dual-band (visible and thermal IR) electronic night vision goggles are just now being explored. Experimental multi-band IR imagers are already flying. Such multi-spectral imagers can support color night vision for enhanced situational awareness, clutter suppression for enhanced targeting, and can penetrate obscurants. They can also be used to localize chemical plumes passively, and work in coordination with active illumination probes (e.g.,tunable lasers) to better localize chemical and biological agents. All such capabilities require both multi-spectral sensing and processing algorithms. As we move to hyperspectral imagers (essentially imaging spectrometers), environmental sensing for chemical and biological agents will be feasible on a large scale in realtime. However, they will require the development of adaptive band selection algorithms and integrated spectral pattern recognition capabilities, directly into the imaging cameras. The sensors will not only produce images in select bands, but also chemical composition maps of the viewed scene in realtime.

The technology of providing for compact, accurate hyperspectral imagers will be important both for small, real-time (eg, vision) imagers, and also for large, slower surveillance imagers. There are two different and possible separate application areas; first, low-light level, where photons may not be discarded; and second, applications in which the number of photons is not the limiting factor, but the number of spectral channels is very stressing. In the first application, it may be possible to closely integrate a dispersive element onto an area imager so that it becomes a linear imager with the second dimension containing the spectral information. Although such devices have been constructed in the past, compact and rugged integration of the optics with the imager will make it useful in hand held operations. The second application may be served by integration of many narrow-bandpass filters or interferometers fabricated integrally on area detectors. For example, a programmable interference filter can allow successive imaging frames to be taken each with a specific wavelength. Again, close integration and replacement of mechanical components with electronically switched components will make the use of such systems practical for the field. Application areas are to enhance target recognition, for example to improve discrimination between friend or foe, focal plane arrays for small UAVs and to enhance vision.

E. ULTRA COMPACT EO SENSOR IMPLEMENTATION:

An imager for a microsensor must be highly integrated into its overall system to be practical. Current production high performance imagers are usually very large or have few integrated functions on the imager's silicon. Very high quality visible imagers are being made by several vendors (mostly Japanese) with small physical size (~ 0.25 inch diagonal), but these all require support chips much larger than the imager itself, on the order of 1 Watt of power for TV-like operation. There are few integrated imagers available commercially; all are relatively large and have poor performance compared with the best non-integrated imagers.

High performance integrated microminiature imagers have been proposed using two different technologies - conventional CCD/CMOS imagers and active pixel sensors. The technologies each have a set of advantages and disadvantages, which must be carefully weighed during system trade studies. Table II compares the performance drivers and their impacts on each technology.

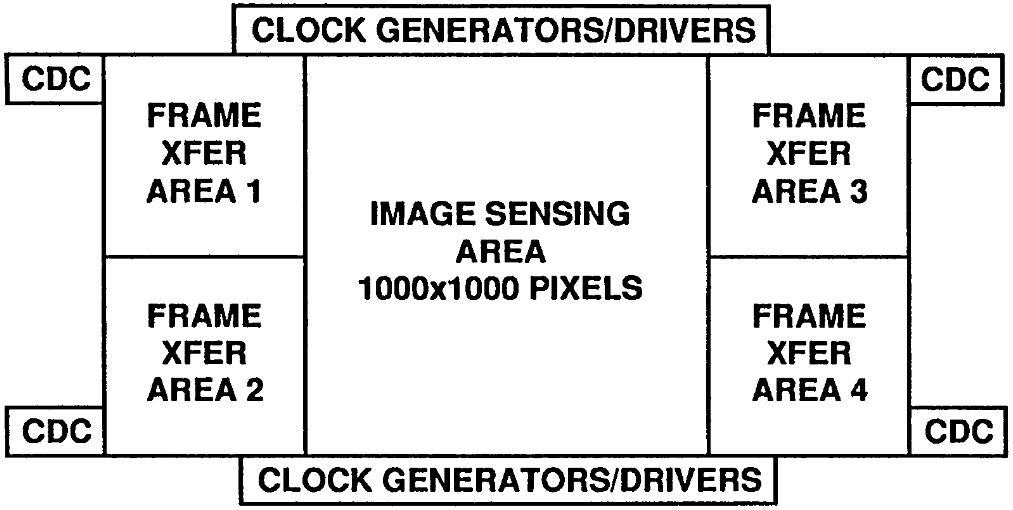
CCDs have the current major advantage that several vendors have been able to make high performance, low noise imagers with frame rates up to several kHz. The next technology addition is to incorporate timing, analog processing and digital conversion to an imager without compromising its noise and image quality. Work is currently in process to add a charge to digital converter to an imager, eliminating the need for external analog processing and its associated system complexity.

An example of an integrated CCD sensor is shown in Figure 1. This imager uses a frame transfer area to add shuttering while preserving the maximum pixel area for high sensitivity. This example, part of a point design for a microUAV, was designed to allow 2 frames per second of high resolution ground imagery from a low altitude air vehicle. Power and system simplification were prime requirements for the design. All analog processing has been eliminated, with the detected charges converted directly into digital by a charge-to-digital converter (CDC). The clock drivers and most of the timing functions have been added to the imager chip. AS a result, nearly all functions have been migrated to the CCD silicon, eliminating external wiring runs, saving power and simplifying the operating requirements. Fewer wires mean fewer interface drivers and less work keeping track of system resources, a savings in both system hardware and in system design.

Active pixel sensors (APSs) have the advantage that they can have adaptive resolution and processing at the photosite prior to readout. Current performance lags that of CCDs, but progress is being made to resolve some of the performance shortfalls. The lower fill factor of an APS photosite is being addressed two ways - with microlenses concentrating the light onto the photosensitive area and with higher resolution lithography, reducing the overhead area required by the active electronics in the photosite. Some combination of the two is likely to yield the best systems solution.

A good system example for an APS is for a focal plane with temporal sensing; i.e. with a high pass filter in the photosite. Such an imager would provide outputs only when there was a scene change, either by the creation of light (muzzle flash) or when there was movement in the field of view. By restricting outputs to changes, the sensor would require a low bandwidth communications system, sending few messages of just the

Figure-/ , microUAV Point Design



- 5 μm PIXELS, 8x12 mm BAR
- 4 500x500 FRAME STORAGE AREAS
- 0.5 MHz PIXEL RATE PER OUTPUT PORT, MAX
- 4 OUTPUT PORTS FOR FRAME RATE OF 2 Hz, MAX
- POWER ESTIMATED TO BE 4 mW @ 1/2 FRAME/SEC

- BACK-ILLUMINATED PROCESS FOR HIGH QUANTUM EFFICIENCY
- SCALED DARK CURRENT RATE OF <500 ELECTRONS/SEC @ ROOM TEMP
- FRAME TRANSFER TIME UNDER 0.2 msec ALLOWS INTEGRATION TIME AS SHORT AS 1 msec
- WELL CAPACITY ESTIMATED AT 25,000 ELECTRONS
- NOISE <10 ELECTRONS @ 1 msec INTEGRATION
- INTEGRAL CLOCK GENERATOR, CHARGE-TO-DIGITAL CONVERTERS (CDC) FOR ALL DIGITAL INTERFACE
- 4 BITS SELECTED FOR OUTPUT BY COMMAND

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locations of interest. Shape processing might also be incorporated, operating only when the imager has detected change, allowing the sensor to send messages of change locations with a partial identification of the new object.

TABLE II COMPARISON OF CCDS WITH ACTIVE PIXEL SENSORS

PERFORMANCE DRIVER	CCD	APS
Noise	< 10 electrons	~ 50 electrons
Fill Factor	Nearly 100%	<50 %
Pixel size	<7 Fm to >30 Fm	>20 Fm
Integration of system functions	Just starting	Inherent
Subframe read	Difficult	Easy
Frame Rate	> 1 KHz (small imagers)	> 10 KHz (adaptive size)
Power		

Compact, high efficiency solid-state cooling

Efficient cooling of focal plane arrays, particularly in the infra red but also in the visible, is required for more compact, rugged high performance imaging systems. Currently available thermoelectric (TE) modules provide a lightweight, compact, rugged, highly reliable, and vibration-free means of cooling for a variety of applications. Somewhat low efficiency is their main drawback for use in the vicinity of room temperature. For low-temperature use they are limited to temperatures >160 K because the best TE materials (Bi2TexSe3-x alloys) are not capable of efficient heat removal below ~180 K. The availability of a reliable long-life cooler operating at cryogenic temperatures below ~80 K could have a major impact on many important military infrared surveillance systems and on systems employing high-Tc superconductors. An improved and cost-effective TE cooler could allow the replacement of present-day commercial Freon-based refrigerators and air-conditioners and eliminate their associated environmental problems, which could be particularly important for compact, high performance IR systems. For such applications, the coefficient of performance COP (ratio of heat pumped to input power) of a TE module is approximately proportional to the TE figure of merit ZT of the material used for the thermocouples. Only a factor of 2 to 3 improvement in ZT would enable the achievement of cryogenic temperatures and give the required efficiency improvement for wide-spread use near room temperature. However, although there is no fundamental limit to the value of ZT, the state-of-the-art ZT ÷ 1 has remained unchanged for about 30 years, since the days of extensive TE materials research in the 1950's and 1960's.

In recent renewed efforts to improve the state of the art of thermoelectric cooling materials, there has been considerable interest in the concept of creating quantum-well superlattices of heavy-atom materials to increase thermoelectric properties through enhanced Seebeck coefficients and carrier mobilities as well as reduced lattice thermal conductivities. Theoretical calculations have shown a very large increase in the Seebeck coefficient of a single quantum well as the thickness of the well is decreased, because of the large density-of-states per unit volume that occurs for small well widths. However, realization of this will require considerably more materials research, such as developing a good wide-gap lattice-matched barrier material for Bi1-xSbx quantum wells.

Compact Image Processors:

Image processing will be required on every imaging sensor, and hence, on every soldier. Processing will be necessary to enhance contrast, adaptively control sensed dynamic range, fuse imagery across sensors (e.g., visible and IR for color night vision), detect flashes (e.g., sniper fire or laser attack), detect moving objects, cue for targets, and perform image compression and reconstruction to support image broadcast/reception. Such realtime processing today requires power-hungry DSP chips. It will be important to develop highly integrated ASICs for image processing (they already exist for JPEG compression, though other approaches are preferable). It is absolutely critical that extremely low-power IC technology be developed, with transistor switching occurring at 0.1 volt or less in order to minimize battery power requirements. Note that electronic vision enhancement goggles will be used constantly. It is equally important that size and weight be minimized, not only at the chip level, but at the functional module level. Thus, 3D integrated circuit technologies (stacked thin film ICs, Z-axis interconnects, and thru-wafer optical interconnects) must be pursued vigorously.

Neuromorphic Imagers:

Motivated by biological imaging systems, the integration of image processing local to each sensing pixel aims to reduce the overall discrete circuitry required for smart sensors. Limited progress has been demonstrated to date. However, simple useful functions can indeed be integrated into sensitive imagers that aim to reduce bandwidth requirements to go off-chip to further processing and display (e.g., temporal filtering for change/flash/motion detection, contrast enhancement, and adaptive dynamic range compression). Equally motivated by biological imaging systems, is the need to send image signals in parallel at every pixel out the back of the sensor to a next processing layer. Functional neuromorphic layers can be developed, such that the insertion of additional layers adds functional capability to a sensor (e.g., flash detection, fog penetration, multisensor image fusion).

On/Near Focal Plane Processing

The technology area of on/near focal plane processing can include any elements which perform logical, linear or non-linear functions to photocharge on the focal plane or at a very close proximity. Therefore, many different technologies fall under this classification; on the one hand, very simple processing elements such as micro-amplifiers associated with each pixel; on the other hand, more distributed and moderately complex analog circuits which are able to perform reasonably complex operations to detected charge.

There are several reasons for undertaking the added complexity of on focal plane processing; first, to enhance the fundamental performance of the device, eg, to improve the noise; second, to reduce power/size of the device; and third, to improve the flow of data from the imaging plane through the system, eg, to remove bandwidth bottlenecks or to reduce latency time. On/near focal plane processing includes processing elements on either the device, or very close to the device, in the same package, so that signal bandwidths are not degraded by the loads imposed by driving package pins, and size and also drive power can be minimized.

Some examples of rudimentary processing elements are the in-pixel amplifier, which can provide for very low noise, random access imaging devices, and an electronic shutter built into the device, which provides the ability to divert photoelectrons from the storage wells to a discard drain. We have data which shows that a non-linear shutter element provides the ability to reduce the photon shot noise, and thereby improve the signal to noise ratio of high background, low contrast signals. Examples of more complex processing are edge detection of an image, and compression of a signal with large dynamic range into a nominal 7 or 8 bit image which is the limit that can be displayed on a display device.

F. ENEMY FIRE SOURCE DETECTION:

As a countermeasure for sniper fire directed to troops carrying out their mission in relatively confined areas, active/passive IR sensors can be used to generate an optical "fence". The passage of incoming rounds, bullets, mortar shells, artillery, through the fence would be detected and their trajectories backtracked to pinpoint the location of the source of the incoming fire. In the 1970's a counter-mortar sensor was demonstrated that could accurately backtrack mortar shells. The sensor was extremely covert, in that a passive long wave infrared sensor created the "fence" , and a laser was fired only a few times (usually only two or three times) to range on the rounds in flight.

The combination of several accurate azimuth, elevation and range measurements was sufficient to solve the trajectory for an accurate origin. The problem in the 1970's was the bulkiness of the laser and the associated power supply that drove the flash lamps. The present generation of solid state lasers is considerably more compact and efficient and the entire concept is ready for another look. Moving to the eye safe spectral region would be advantageous for testing and training, and would provide protection for neutrals in an actual battle situation.

Hemispherical Sensors for Event Cueing

In order to maintain optimal efficiency, small military forces must have a keen awareness of their surroundings. When troop density is low, as will be the case when a small group is attempting to occupy an extended geographical region, each soldier must be responsible for self-protection from threats that may be directed from any angle. A helmet-mounted hemispherical sensor coupled with appropriate computational hardware could offer additional protection by providing an automated capability for motion and/or flash detection.

To minimize interference with normal activities, a helmet-mounted sensor would need to be light, expendable, and exhibit a very low profile. These requirements clearly necessitate large uncooled detector arrays, as well as novel optical designs that exhibit low distortion characteristics over extremely wide fields-of-view. Plastic elements would clearly be preferable to glass, and it may be possible to significantly reduce aberrations by applying binary-optics overlays on the surfaces of conventional refractive elements. A successful development program would require a coordinated investigation of detector technology, refractive material selection, optics design optimization, and the development of specialized data processing for high-bandwidth imagery.

III. EO Sensor Technology Concepts for Larger Platforms:

In the future, small force operations will depend more than ever on remote EO sensors located on relatively larger platforms including airborne and space-based systems. These sensors will require long range, high sensitivity, high resolution and multi- spectral capabilities which will drive FPA and optics design requirements.

The technology of producing large, many-pixel FPAs will be needed to support remote platform, aircraft and spacecraft surveillance in the future. In the past, these types of FPAs were frequently either TDA arrays (long in one direction, but with a modest total pixel count) or were composed of a tiled array of staring imaging devices, each of which was relatively small in size. One problem with the former type is that the sensitivity of the detector suffers because light is not being used most efficiently; on the latter, the seams between devices can cause discontinuities and blind spots in the image. Recently, the technology has matured to the point that ultra large silicon CCD imaging arrays are possible (> 10 MPixels). As wafer size increases and materials quality improves, it is anticipated that even larger, more defect-free imagers can be fabricated. Also, it is possible that these large arrays can be segmented in a way that utilizes all the silicon for continuous imagery, but allows multiple readouts so that the data may be output in a reasonable time.

Segmented Optics for Reconnaissance Satellites

The cost of deploying high-resolution optical satellites is largely driven by the weight and dimensions of the primary collector. Ground resolution is fundamentally limited by diffraction effects, and to achieve a ground resolution of d from a viewing range, R, the aperture diameter of a system operating at wavelength, l, must exceed lR/d. Although the intelligence community has deployed a suite of very expensive orbiting sensors capable of sub-meter resolution, these data are highly classified and typically unavailable to field commanders responsible for small-scale tactical maneuvers. For this reason, there is a strong interest in the development of light-weight, expendable satellites suitable for rapid-deployment missions directed by mid-level military officers.

One novel approach to cost reduction is the use of segmented telescopes that can be compactly folded within an inexpensive launch vehicle. Through the use of Fourier-domain renormalization, it is possible to achieve near-diffraction-limited imagery from an aperture containing as little as 10% of the area of a filled circular collector. Although the viability of the applicable data processing algorithms has been demonstrated, a more extensive research effort is essential to optimize the mechanical design of the telescope and overcome the problem of phasing the segments of the deployed structure.

IV. SUMMARY:

Considerable, detailed information is available for all of the technology concept and application topics included above which deal with technology status, payoff and objectives and options for future development.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

UAV OPTIONS

White Paper

William R. Davis

4/2/96

UAV OPTIONS

W. R. Davis

1. Introduction

This white paper considers a wide range of UAVs from the current large, high-altitude vehicles under development, mid-sized UAVs like those used in Desert Storm, to extremely small, micro vehicles which will soon be possible as technology advances. The paper is organized by UAV subsystem including potential payloads. In each case an assessment is made of current technology and what improvements and new capabilities will become available as we move into the 21st century.

2. Configurations and Performance

A very wide range of UAV sizes and configurations could conceivably be available to support 21st Century conflicts. Figure 1 shows one approach to comparing UAVs, in terms of payload weight versus wingspan. The plot shows vehicles ranging from Tier II+, the largest UAV currently under development for DOD applications, down to micro UAVs which would have payloads of around 1 g and wingspans of 7 cm or less.

To date, UAV development has concentrated largely on fixed wing vehicles carrying optical or SAR payloads for reconnaissance missions. The larger-payload vehicles like Tier II+ and Tier III- fly at high altitudes (12 to 20 km) to increase survivability, endurance, and sensor aerial coverage. They use turbofan propulsion. Mid-size vehicles such as Tier II, Pioneer, and Exdrone operate at middle altitudes (1 to 8 km) and are best matched to internal combustion engine/propeller propulsion systems. Smaller vehicles would provide advantages where simple logistics, local control and covertness are needed, but they have not yet been developed. They would most likely operate at very low altitudes (down to 100 m or less) to ensure adequate sensor performance.

Vehicle true airspeeds range from up to 150 m/s, for turbofan-powered vehicles, down to 10 m/s for the very smallest vehicles which must fly just fast enough to overcome local winds. Endurance can range from 40 hrs plus for Tier II+ to as small as 30 min for small, locally-controlled vehicles. On-station loiter time can be traded for range, with a vehicle like Tier II+ having a ferry range of over 25,000 km.

Technology improvements in aerodynamics and propulsion will enhance UAV performance as we move into the 21st Century. For the larger and mid-size vehicles there will be small incremental improvements in turbofan and internal combustion engines, and small aerodynamic improvements as analysis tools mature and unique aerodynamic configurations are invented. So far, the larger vehicles have been built with high aspect ratio wings for endurance at altitude. Depending on the mission, other configurations may be advantageous. Essentially any manned aircraft could be converted to a UAV with a suitable autopilot and sensors. In fact, studies are currently underway on unmanned tactical aircraft (UTAs) which would derive weight and maneuverability benefits by virtue of eliminating the pilot and associated support systems.

While largely ignored, small UAVs down to about 50 cm wingspan could be built using today's technology. Combining model airplane technology with available internal combustion engines, such vehicles would provide good performance and carry practical payloads. Electric propulsion is also possible with currently available batteries, but endurance would be limited.

Recent studies have shown that micro vehicles are feasible. Here one challenge is providing adequate performance in the low Reynolds number aerodynamic regime for which there is limited experimental data. Lift, drag and propeller performance can be degraded in this regime; on the other hand, micro vehicles derive a benefit in that their volume-related mass decreases more rapidly than wing area as size decreases. For electric propulsion advances in battery technology are required to provide adequate power and energy densities, but these improvements can be expected during the next decade. Internal combustion engines are more efficient, and they are currently under development and will be available over the next several years, as will microturbines which could provide thrust or electric power.

Fixed wing configurations may not be the best for applications which require close-in surveillance or data gathering. Rotary wing vehicles which hover have been built, e.g. the Lear Puma, and are being considered for tactical applications. Hover capability is particularly intriguing for small and micro vehicles where the ability to fly vertically as well as fly forward faster than wind speeds (the hummingbird analogy) would be particularly useful for urban warfare. Hovering could be achieved through various means such as rotating wings, ducted fans, or even ornithoptry. The ability to hop or perch could also be useful. Hovering vehicles are less efficient than fixed-wing flyers and will always have smaller payload to total weight; however with expected improvements in propulsion technology for micro vehicles, they may become practical over the next decade.

3. Payloads

UAVs have the potential for carrying a wide variety of payloads. A representative list is given in Table 1. Included are rough estimates of payload masses based on current systems and estimates of what could be developed using near-term technology.

For other than close range applications, SAR and MTI radars are the most practical for surveillance because they can see through weather. Advancing technology will result in improved performance and lighter weight for future systems.

Optical imaging provides critical information when there are no obscurations, and it is particularly applicable to the small, covert vehicles which operate below cloud cover. Imaging sensors can also be combined with laser designators for targeting smart weapons. For most applications, inertially stabilized optics are required to compensate for vehicle motion and vibration. Advances in focal plane array technology, mechanical coolers, electronic packaging, and inertial sensor miniaturization will result in improved performance and lower weight. For the smallest vehicles unstabilized optics will be necessary, at least initially, to save weight. Such sensors will need short integration times or shutter speeds to avoid the effects of vehicle motion. Advances in chip fabrication technology, e.g. combining pixels and CMOS readout circuitry on the same chip, will make very small cameras available in the next few years: as small as 1 g for visible imagers, and 15 g for MWIR imagers.

UAVs, particularly those operating at high altitude, offer the potential for relaying communications, either to connect communicators on the ground or to relay data through satellites, and for gathering signal intelligence. Advances in electronic packaging will continue to reduce the weights of such systems. Antennas whose size is constrained by wavelength and aperture requirements will continue to be drivers for vehicle integration, especially for the smaller vehicles. On-board power will also be a driver. Another important communications relay application in the future will be the control of low flying vehicles which, by virtue of the terrain or urban environment, must operate beyond the line of sight of their local operators.

The detection of nuclear, biological and chemical (NBC) contaminants in the atmosphere is particularly suited to UAVs, which permit wide-ranging sampling without risk to personnel. This application requires flying at mid to low altitudes where such contaminants will be found. It is desirable to use small vehicles to reduce their vulnerability to detection and attack and to reduce cost. The simplest approach, which is applicable to the smallest vehicles, is simply to gather samples in evacuated collection bottles and return them to a ground site for analysis. However, on-board detectors are desirable to provide timely alerts and to avoid the need to handle contaminants. NBC detectors are currently under development, and their weight will decrease as the technology advances.

Other types of sensors, such as acoustic, seismic and magnetic, are applicable to small vehicles, particularly those which can deposit payloads on the surface where detection of personnel and ground vehicles is important. Such sensors are already available in small packages and could be attached to small UAVs which parachute or crash onto the surface. Small UAVs could also deliver "stick-on" RF or laser sources providing homing targets for smart weapons.

Weapons carriage and delivery is another UAV mission. Tier II+ is already being considered to carry weapons for theater missile defense. UAVs could carry most weapons now carried by manned aircraft. The ability to use large numbers of small, cheap UAVs to deliver weapons depends on the technology for building lightweight, but effective warheads.

4. Flight Control and Navigation

Larger UAVs can use state-of-the-art inertial sensors and autopilots for flight control, even if advanced airframes are inherently unstable. For very small and micro UAVs flight control is more challenging. Flight control sensors and control surface actuator weight limitations require advancements in micro electro-mechanical systems (MEMS) technology, although such advances are expected over the next few years. Small vehicles are also subject to gust upset, which may drive aerodynamic design and control system requirements.

Operators of early UAVs used images from on-board video sensors for navigation purposes. Modern UAVs must fly autonomously to selected waypoints, and GPS is the most logical choice for navigation. This can be supplemented with inertial guidance in the event of GPS outage or jamming. GPS also provides precise guidance, especially when operated in the differential mode, for target location and weapon guidance. GPS is problematic for very small vehicles because of weight limitations. Miniaturized GPS electronics are now under development, but GPS antenna size is fundamentally limited by the L-band operating wavelength.

Several other approaches are feasible, especially for small UAVs. For short ranges, the UAV can be tracked from the ground using a tracking antenna which determines angle and range via a telemetry link. Another is to use time-speed-distance calculations, or dead reckoning, to navigate autonomously, although this requires estimating the winds aloft. This limitation is avoided by using an inertial measurement unit on board. Very small IMU components will be available soon as a product of MEMS research. One could also envision UAVs with sufficient computational power to navigate autonomously using automatic recognition of scenes from on-board optical or SAR sensors.

5. Command and Data Links

Large UAVs provide the flexibility to carry a variety of communications equipment for command links and data transmission. Tier II+, for example, has several air-to-ground and satellite links for both functions. This equipment can be large: the Tier II+ Ku-band satellite link requires a 4-ft dish to transmit data at 50 Mb/s. Moreover, data rates will continue to increase rapidly as higher performance optical focal plane arrays and SARs are developed. Direct UAV-to-satellite links have the advantage of being difficult to jam and providing the ability to control vehicles from ground stations thousands of miles from the UAV operations.

Small UAVs will continue to be limited to control via ground-to-air links until antenna apertures and equipment power requirements shrink sufficiently to support satellite communications. Local links are particularly important for such vehicles which have the potential for supplying real-time data to units as small as individual squads. The small size of micro vehicles will drive communications to high frequencies (20 GHz and beyond) to keep antenna sizes within the physical dimensions of the vehicles. With the availability of custom MMIC technology the on-board electronics can now be shrunk to the sub-gram level for communications links of about 1-10 km. High frequency systems also permit the ground station to operate with small, man-portable antennas. In fact the entire ground station for a micro UAV could consist of a collapsible tracking antenna of 13-60 cm diameter and a laptop computer for data display and navigation calculations. Air-to-ground links are susceptible to jamming, but spread spectrum and other techniques are available and could be implemented at small cost in weight and power.

Small UAVs provide the important advantage of getting close to the action and providing detailed data on what is going on over the next hill, beyond trees or around buildings in an urban environment. Unfortunately these obstacles are an impediment to practical line-of-sight communications. For these applications vehicles need to either operate autonomously and bring data back for later review, or use an overhead relay to maintain real-time communications. The overhead relay could be another small UAV, but it may have to be larger than the micro vehicles it controls because of the requirement to carry directional antennas to achieve the gain needed for the relay function.

Ground stations can be a large and costly logistics constraint for UAVs. Long range UAVs like Tier II+ and Tier III- with satellite links have the advantage of using fixed ground stations which do not have to be moved into the theater of operations. Current tactical UAVs, however, need van-sized ground stations which require significant airlift capability to reach the theater and are then difficult for small mobile units to transport in the field. With advances in electronic miniaturization, high frequency communications and automation, the potential exists to significantly reduce the size of such units in the future.

6. Survivability

As with manned aircraft, UAVs are susceptible to attack by surface-to-air or air-to-air missiles at all altitudes and by anti-aircraft artillery at low altitudes. For large, high altitude UAVs there are two approaches: stealth technology (Tier III-), or countermeasures (Tier II+). The stealth approach is expensive and can put significant constraints on airframe design options. The countermeasure approach may or may not be successful. Towed RF decoys will work against most current radar guided missiles, but new seeker technology will eventually beat this countermeasure. As with manned aircraft defense, there will be a continuing evolution of seeker capability and corresponding countermeasure technology. The inability of current UAVs to maneuver rapidly at altitude is another limitation.

Mid-sized UAVs, operating at lower altitudes, are vulnerable to shoulder-fired IR missiles and artillery. Current vehicles in this class do not now carry countermeasures. Here the very small and micro vehicles have a distinct advantage in that they will be very difficult to detect and target. A micro UAV the size of a bird will have a correspondingly small radar cross section. As a result its radar return will be lost in the clutter or its low airspeed will result in it being below the radar's minimum detectable velocity. The micro UAV's small IR signature will also make it nearly impossible to target with IR seekers.

Micro UAVs provide an additional advantage in that they are also covert to most other means of detection. With electric or muffled combustion engine propulsion their acoustic signature will be very small, and their visual signature may be indistinguishable from birds. A narrowband, directional receiver could be used to detect their communications links, but low probability of intercept and spread spectrum techniques would be effective countermeasures.

However, small, low-altitude UAVs which are visible to troops on the ground could provide a psychological advantage. It may be demoralizing to the enemy to know they are under observation with a UAV which cannot be shot down with rifle fire or IR missiles.

7. Summary

Tier II+ and Tier III- are representative of the large, high altitude UAVs we will see into the early 21st century. Incremental improvements in airframe and engine performance will be possible, but these vehicles will benefit primarily from weight savings and performance improvements associated with advances in electronics and sensor systems. As long as they are survivable, they will provide an important means of supplying quick-reaction wide area surveillance, communications relay, SIGINT, or even weapons delivery without the need to ship equipment or operators into the field.

Mid-sized, intermediate-altitude UAVs have an important function for local area surveillance, atmospheric sampling and other missions. Such vehicles will also benefit in advances in electronics technology, and they need to be survivable as well. One of the biggest challenges is to limit the logistical overhead of support equipment and ground stations, so they can reach the field expeditiously and keep up with rapidly maneuvering troops.

Micro UAVs have a particular advantage for close-in missions where local control and covertness are important. Advanced versions which can hover or deposit themselves at precise locations offer further advantages. They also have the potential for being inexpensive in quantity as a benefit of the micro-fabrication and MEMS technology which will be required to make them feasible. Technology development is required in several areas including batteries, combustion engines, flight control sensors and actuators and subminiature electronics. The integration of the micro vehicle's systems will also be a technology challenge requiring new thinking on how to build flight vehicles. These technologies are maturing, and micro vehicles will be practical in the next two to ten years if sufficient development resources are applied.

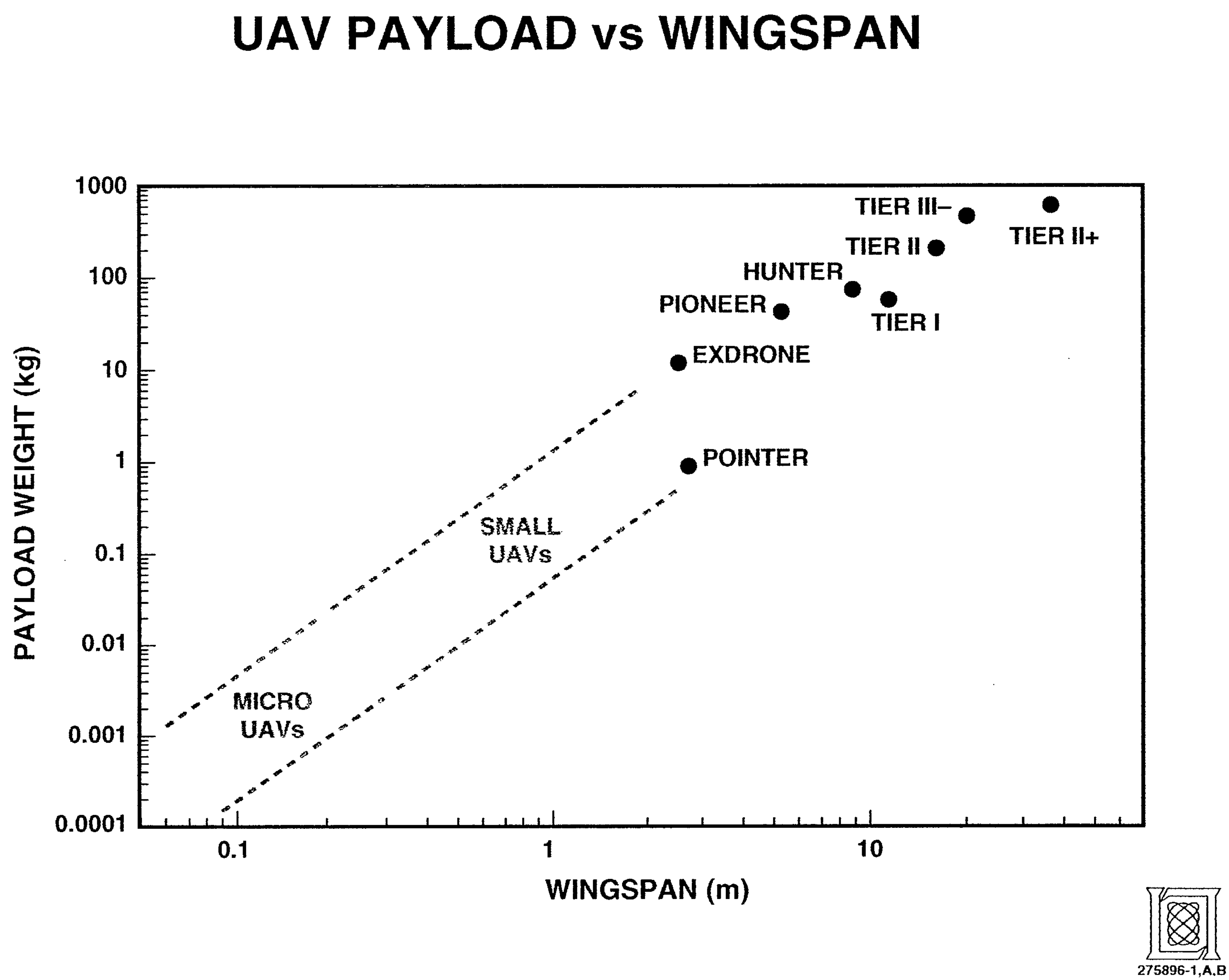
UAV PAYLOAD vs WINGSPAN
PAYLOAD WEIGHT (kg)
1000
100
10
1
0.1
0.01
0.001
0.0001
WINGSPAN (m)
0.1
1
10
TIER III–
TIER II+
TIER II
HUNTER
PIONEER
TIER I
EXDRONE
POINTER
SMALL UAVs
MICRO UAVs
275896-1,A,B

Figure 1

Table 1

UAV Payloads

	Approximate Mass (kg)
• SAR, MTI	15 - 250
• Visible / IR Imaging - Unstabilized	0.015 - 10
• Visible / IR Imaging - Stabilized	2 - 200
• Communications Relay	5 - 500
• SIGINT	5 - 500
• NBC Sampling	0.01 - 1
• NBC Detection	5 - 25
• Acoustic	0.001 - 1 (bracketed: Acoustic, Seismic, Magentic)
• Seismic	
• Magentic	
• Weapons	1 - 500

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

FOLIAGE PENETRATION RADAR SYNTHETIC APERTURE RADAR CONCEPT

White Paper

Michael F. Toups

Foliage Penetration Radar Synthetic Aperture Radar Concept

M. F. Toups

1. Example Scenario

The US is to deploy and gain control of a large region. The weather in the region is generally poor. The area has extensive forest covered areas in which troop concentrations may be hidden.

2. Introduction

The use of a synthetic aperture radar (SAR) to detect targets hidden in forest regions is a technology that is rapidly approaching the maturity required to field an operational system. A foliage penetration (FOPEN) SAR would offer the user a variety of advantages that are not available from other types of sensors. First, the sensor is an all-weather sensor that can operate either during the day or night. Second, unlike traditional higher frequency SARs, it can detect targets which are obscured from view by intervening foliage. In this paper, a possible application scenario and system design for a FOPEN system will be explored.

3. System Concept and Application Scenario

A FOPEN system will mitigate several vulnerabilities of traditional radar and electro-optical sensors. In particular, it will be able to detect targets:

- obscured by foliage.
- masked (from traditional SARs) by tree line layover.
- obscured by (high-frequency) radar scattering camouflage netting.
- obscured (from electro-optical sensors) by smoke or weather.

These capabilities make a FOPEN sensor an important adjunct to the existing radar and electro-optical sensors that are being developed for the Tier platforms.

This section presents a brief overview of the system concept. A more detailed description will be presented in Section 4. The basic system concept is to utilize a FOPEN SAR on a UAV platform such as a Tier II, Tier II+, or Tier III-. For this white paper, the use of a Tier II (Predator) platform with a FOPEN SAR system to perform a cued search will be postulated. The data from the FOPEN SAR would be down-linked to the ground via satellite datalink.

The data would be exploited using a FOPEN modification to the SAIP system. The information obtained would then be disseminated to the battlefield commanders by the GBS system. These systems are current ARPA ACTDs and are described in Section 3.1.

The situation for which a FOPEN sensor will have the most utility will be in a cued search of a limited area. The cues could come from a MTI sensor or from an intelligence asset. The FOPEN sensor would be used to locate enemy troop concentrations in forested areas. This sensor will be most useful for finding vehicle-sized and larger targets (including buildings) hidden in foliage. An additional utility of a FOPEN sensor is its ability to map trails and roads that are hidden within a forested area. The idea would be to use the FOPEN sensor to gather intelligence about enemy forces and their locations rather than to deliver weapons to a target. (This latter option is not ruled out, but may be limited by the ability of current weapon systems to be directed to an obscured target.)

It should be noted that this scenario is less stressing than the "traditional" scenario commonly visualized for a FOPEN sensor. Most of the work in the past has been related to finding a single (or small group) of high-value targets (such as TELs). The problem is fundamentally easier if one is interested in finding concentrations of vehicles.

3.1. Related ACTDs

The readiness for a FOPEN system as a near-term future system is demonstrated by its planned use in an FY1997 advanced concepts technology demonstrator (ACTD). In addition, there are two other ACTDs which will result in systems that should be a part of the FOPEN system architecture. The first is the Semi-Automated IMINT Processing (SAIP) ACTD which is designed to utilize automatic target recognition to reduce the workload of an image analysis. The second is the Battlefield Awareness and Data Dissemination (BADD) ACTD.. This ACTD is designed to disseminate information gathered form a variety of systems (including the SAIP system) to the soldiers in the field to increase their fighting effectiveness. These efforts are described in more detail in Section 0.

4. Components and Design Details

4.1. FOPEN SAR Specifications

The system postulated in this paper will be 0.5 meter resolution polarimetric SAR within the VHF/UHF-bands (either UHF/high-VHF or low-VHF/UHF) and have a 2 km swath width. The system will be capable of imaging continuously during the flight of the UAV. The specifications of the system are based on hardware that is implementable in 1997. This design is basically the same as that of the FOPEN ACTD which is proposed for FY1997. As the technology for computing hardware and communications bandwidth advances in succeeding years, it will be possible to increase the desired swath width. A hypothetical FOPEN sensor design is presented in the following table.

Table 1: Hypothetical FOPEN Sensor Design

Platform	Tier II (Predator)
Altitude	10 km
Speed	50 m/s
Range Swath	2 km
Frequency Bandwidth	400 MHz (20-420 MHz or 100-500 MHz depending on low-VHF antenna feasibility)
Polarization	Polarimetric
Resolution	0.5 m × 0.5 m

4.2. UAV Platform

The system will utilize an existing UAV platform. Due to the high desired depression angles that will force closer standoff ranges, this sensor is a good candidate for implementation on the Tier II (Predator) platform. The recommendation is that the initial system be implemented on a Tier II platform for use as a cued-area sensor. After experience is gained from that system, a Tier II+ or Tier III- implementation could be designed.

4.3. Datalink and Datalink Requirements

By utilizing on-board image formation and an on-board initial ATR stage, it is possible to reduce the data rate down to a value that can fit on a T-1 satellite communications link. By performing the image formation off-board, one can remove the processing system weight and power constraints that limit the available swath width. Unfortunately, the fastest datalink proposed to be available near-term, the common data link (CDL), requires a ground "tether" and limits the swath width to a value less than that which can be achieved by on-board processing.

5. Implementation Risks and Challenges

The risks to successfully fielding a FOPEN system fall into two categories. The first, which will be discussed in Section 5.1, are the risks associated with implementing the required hardware on the UAV. The second, which will be discussed in Section 5.2, are related to achieving the desired performance of the system. The first category of risks are, at this point in time, fairly low due to recent advances in the state of the art in computer and radio-frequency hardware. The second category of risks are due primarily to the immature status of FOPEN ATR at this point. These risks can be mitigated by additional FOPEN ATR development and evaluation. Data to support this activity has been collected during 1995 using the P-3 UWB SAR.

5.1. Hardware Risks and Challenges

The risks associated with hardware development is summarized below:

- SAR Hardware: low risk except low-VHF antennas
- position measurements for motion compensation: moderate risk which can be mitigated using auto-focusing techniques
- computing hardware: moderate risk for small swath widths
- data link: low-moderate risk assuming on-board processing and preliminary ATR
- size and weight constraints of UAV: moderate risk.

Basically, other than for low-VHF antennas, the hardware required is currently implementable. The computing hardware requirements for on-board image processing limits the available swath width for very near-term systems. However, it is possible (as is expected to be demonstrated in the Counter CCD ACTD) to field such a system.

5.2. Technical Risks and Challenges

The major near-term risks to implementing such a system are related to the immature state of FOPEN ATR algorithms. At this point in time, FOPEN ATR algorithms have not been adequately demonstrated. The lack is due mainly to the limited work that has been done in this area. At this time, work is just beginning to develop and evaluate the types of algorithms that would be required for a successful FOPEN ATR. Additional development is required for FOPEN ATR. Due to datalink bandwidth limitations, it will be necessary to perform image formation and some preliminary ATR on-board the UAV.

6. Appendix I: Review of Current FOPEN Understanding

This appendix presents a brief summary of some of the recent work that has been performed in the FOPEN area. During the past six years ARPA (sometimes in conjunction with the Air Force Wright Laboratory) has performed a number of experiments utilizing a variety of sensors and sites to investigate foliage penetration. The initial FOPEN experiment and analysis that was jointly funded by ARPA and the Air Force Wright Laboratory utilized the NASA/JPL AIRSAR, a polarimetric UHF, L-, and C-band SAR with a 4 meter resolution.[1] Due to the successes of this experiment, further experiments,[2,3] as detailed in Table 2, have been performed using the SRI International FOLPEN SAR, the Swedish National Defense Research Establishment (FOA) CARABAS SAR and the X-, L-, C-band NAWC P-3 SAR. In addition, ground based measurements have been made using the MIT Lincoln Laboratory Ultra-Wideband Rail-SAR.[4] Based on information gained during these experiments, it was desired to collect airborne high-resolution polarimetric UHF/high-VHF data. To meet this need, the NAWC P-3 was upgraded to have a polarimetric UHF/high-VHF mode with 0.33 meter range by 0.66 meter cross-range resolution.

Table 2: Recent FOPEN Experiments

YEAR	LOCATION	FOREST TYPE	SENSORS
1990	MAINE	MIXED NORTHERN	JPL AIRSAR
1992	MAINE	MIXED NORTHERN	SRI, P-3 XLC
1992	PUERTO RICO	RAIN FOREST	SRI
1992	SWEDEN	DECIDUOUS	CARABAS
1993	PANAMA	RAIN FOREST	SRI, CARABAS
1993	MAINE	MIXED NORTHERN	SRI, CARABAS
1993	AUSTRALIA	RAIN FOREST	JPL AIRSAR
1994	CALIFORNIA	REDWOOD FOREST	SRI
1995	NORTH CAROLINA	MIXED	P-3 UWB
1995	MAINE	MIXED NORTHERN	P-3 UWB
1995	CALIFORNIA	VARIOUS	P-3 UWB
1995	MICHIGAN	MIXED NORTHERN	P-3 UWB

6.1. FOPEN Phenomenology

6.1.1. Propagation Phenomenology

The first issue regarding propagation is whether one can form a focused image of targets obscured by foliage. The second issue is attenuation of the corresponding target signature. The effect of foliage-induced amplitude and phase fluctuations on the ability to form sub-meter resolution images was investigated initially through the use of narrow-band "tone generator" measurements.[1] Due to the favorable results from these measurements, FOPEN experiments were performed using meter and sub-meter resolution sensors. These experiments have demonstrated with actual SAR imagery of foliage-obscured corner reflectors that it is possible to form focused sub-meter resolution images of foliage-obscured targets.[2]

Data from the experiments listed in Table 2 were utilized to measure two-way foliage-induced attenuations[3] by comparing the return from foliage obscured corner reflectors with that of reference unobscured corner reflectors. In Figure 1, results using data from the collections in Panama and Maine are presented. The two-way attenuations are plotted as cumulative probability distributions. As an example of how to read these curves, the Maine L-band curve shows that 80% of the corner reflectors had a two-way attenuation of less than 20 dB. This data shows that the attenuation decreases with decreasing frequency. It is expected that frequencies at the UHF-band and below, where attenuations less than 10 dB have been observed, will support FOPEN applications. Hence, this favors systems that operate in the VHF or UHF-bands. One can see that similar attenuation results were measured in both the rain forest of Panama and the boreal forest of Maine.

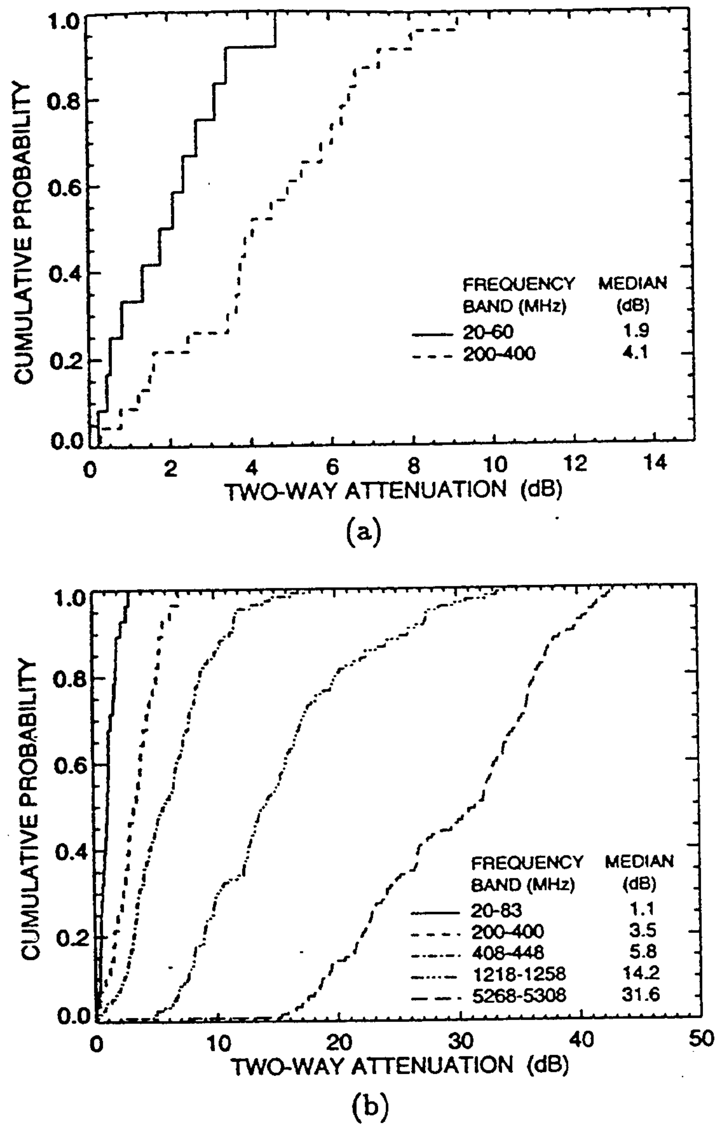

Figure 1: Two-way attenuation distributions from (a) Panama and (b) Maine.

6.1.2. Clutter Phenomenology

The backscatter from forest regions were analyzed[3] to understand the properties of the clutter. The clutter properties are important since the targets will have to be distinguished from the tree clutter by ATR algorithms. In Figure 2, the foliage backscatter are plotted as exceedance distributions. For example, at UHF 10% of the clutter pixels have a backscatter coefficient greater than 0 dB. It has been observed that, for frequencies above 200 MHz, the mean forest backscatter is relatively insensitive to frequency and has a backscatter coefficient of -8 dB. However, for the low-VHF band, the forest backscatter coefficient drops quite dramatically to -18 dB. This is not unexpected since the wavelength is large compared to most of a tree's constituent parts. For the backscatter results, like the attenuation results, one again sees that the measurements from the rain forest of Panama and the boreal forests of Maine were similar.

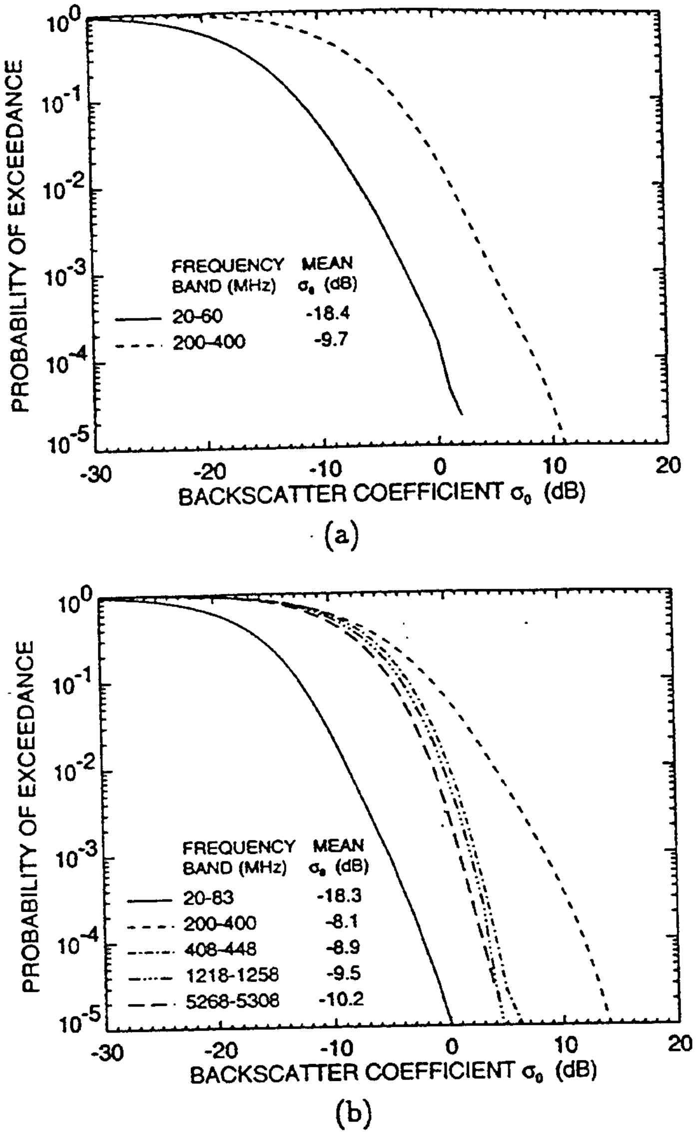

Figure 2: Backscatter coefficient exceedance distributions for forest clutter from (a) Panama and (b) Maine.

One interesting feature to note is that the data for the UHF/high-VHF (200-400 MHz) data has a higher tail to the distribution than the UHF (408-448 MHz) data. This is due to the higher resolution of the former system (1 meter) versus the lower resolution of the latter system (4 meters). At the higher resolution, the tree trunks are being resolved in the imagery and are bright point-like objects. However, note that the mean backscatter value is not altered by this higher resolution.

6.1.3. Target Phenomenology

Target signatures are currently being investigated to understand the properties of the target signatures which allow them to be distinguished from clutter. In addition, as will be described in the next section, the broadside flash is an example of an exploitable feature. It should be noted that due to the wide integration angles of FOPEN sensors, this feature is much more likely to be seen than in more traditional frequency sensors.

6.2. FOPEN ATR Status and Performance

FOPEN automatic target detection and recognition ATD/R capabilities are currently limited to simple prescreening algorithms in conjunction with false alarm mitigation techniques. To date, detection has been demonstrated with moderate false alarm densities (1 to 100 false alarms per square kilometer). The detection techniques that currently hold the most promise are matched-filter processing for exploiting the broadside flash, use of polarimetric statistics, and high-definition vector imaging. The false alarm mitigation techniques that currently hold the most promise are change detection, area delimitation, and group detection.

6.2.1. Matched-Filter Processing for Broadside Flash Exploitation

In the UHF frequency band, targets exhibit a phenomenon called the "broadside flash." The broadside flash refers to the increased radar cross-section of targets observed from cardinal angles. This phenomenon results from the dihedral-like response of the ground-target interaction. Matched filters can be derived to exploit this phenomenon in either the signal-history domain or the image domain. Such matched filters have been shown to reduce false alarm densities by roughly a factor of ten for targets oriented perpendicular to the radar line of sight.

6.2.2. Polarimetric Signatures

With the recent acquisition of polarimetric P-3 UWB SAR data, the exploitation of polarimetric signatures are likely to provide a reduction of false alarm rates that can be achieved by only using single-channel data. Studies are currently underway to understand how to best exploit this information.

6.2.3. High-Definition Vector Imaging

High-definition vector imaging (HDVI) refers to a class of algorithms that exploit modern spectral estimation (super-resolution) techniques for discriminating targets from clutter. These techniques can be matched to various signatures that can be found in the radar data. For each desired signature, an image is created. The pixel values are a measure of the target similarity to the desired model. A set of signatures can be used to create an image of vectors. Work has been done on using the following signature models: point target, broadside flash associated with different vehicle lengths, and polarimetric signatures of dihedrals at various orientation angles. Further development of high-definition vector imaging coupled with appropriate exploitation should lead to reductions in false alarm densities compared to more conventional techniques.

6.3. False Alarm Mitigation Techniques

A variety of techniques designed to reduce false alarm rates are being utilized in the SAIP system. These techniques also have utility for a FOPEN system. The techniques as they can be applied to FOPEN will be briefly described in the following subsections.

6.3.1. Change Detection

The SAIP system is using object level change detection to reduce false alarm rates for targets in the open using a X-band SAR. An object level change detection algorithm would be able to reduce false alarm rates for a FOPEN SAR. A successful object level change detection algorithm would probably require a low false alarm rate for the stage which defines the objects of interest. Hence, object level change detection may be best done after classification.

At this time, work is just beginning on understanding FOPEN change detection algorithms. Some initial work has been done using a pixel level change detection algorithm. This algorithm is an adaptive technique which was originally developed by J. Nanis and G. Hogan[5] for use on K_a-band data. Work is currently underway to quantify the performance of this algorithm. Figure 3 shows a pair of images from the Grayling 1995 FOPEN experiment using the P-3 UWB SAR. This sensor is a polarimetric 0.33 meter by 0.66 meter resolution UHF/high-VHF SAR. The two images shown here are for the HH polarization channel at a 30° depression angle.

The pixel level adaptive change detection algorithm was applied to the data shown in Figure 3. Work is currently underway to quantify the results by generating a curve of detection performance versus false alarm rate. Anecdotally, it is possible to detect approximately 26 of the 33 targets.

6.3.2. Area Delimitation

Area delimitation utilizes prior knowledge of the environment to focus the search to regions that are likely to contain the targets of interest. Area delimitation is often based on analysis of trafficability of the area under surveillance. Terrain that is not navigable need not be processed. For example, one need not search a swamp for heavy tanks.

6.3.3. Group Detection

Group detection is useful for targets that operate in groups, such as tank companies, rather than individually. Group detection exploits the fact that clutter false alarms tend to be randomly distributed; thus, multiple false alarms are less likely to occur in a clustered manner. However, a group of targets is likely to yield a series of detections within a small region. There are two major advantages to using group detection to targets which occur in groups. First, isolated false alarms can be eliminated. Second, the target detection threshold can be increased because group detection remains effective even when the probability of detection for individual targets is lower. This is due to the fact that not all targets need to be detected in order to detect the group. For targets that occur in groups, the overall false alarm density can be dramatically reduced from that of single target detection.

6.4. Areas of Active Research

FOPEN phenomenology at this point is fairly well understood. The areas that are being investigated further are directly related to FOPEN ATR development and performance. In particular, the high-resolution and polarimetric properties of clutter and targets are being investigated.

The major area of research needed to support a FOPEN system is FOPEN ATR algorithm development and evaluation. Data collected during the 1995 FOPEN experiments with the P-3 UWB SAR will aid that activity. This is a crucial area of needed research for fielding a FOPEN system.

Another area of research is RFI/Jamming mitigation. Depending on the RFI/Jamming environment, this may require some receiver design work.

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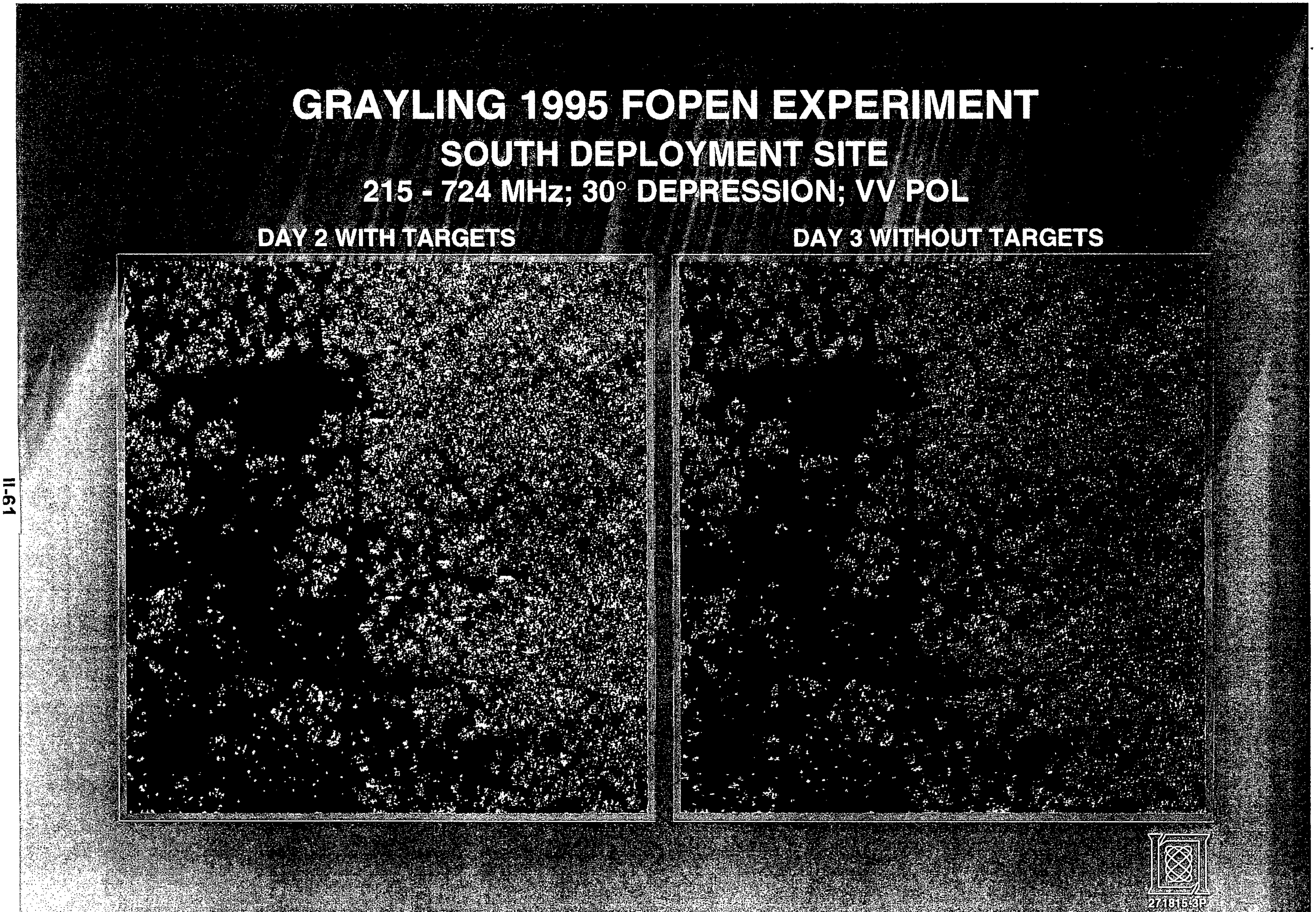
GRAYLING 1995 FOPEN EXPERIMENT
SOUTH DEPLOYMENT SITE
215 - 724 MHz; 30° DEPRESSION; VV POL
DAY 2 WITH TARGETS
DAY 3 WITHOUT TARGETS
271815-3P

Figure 3

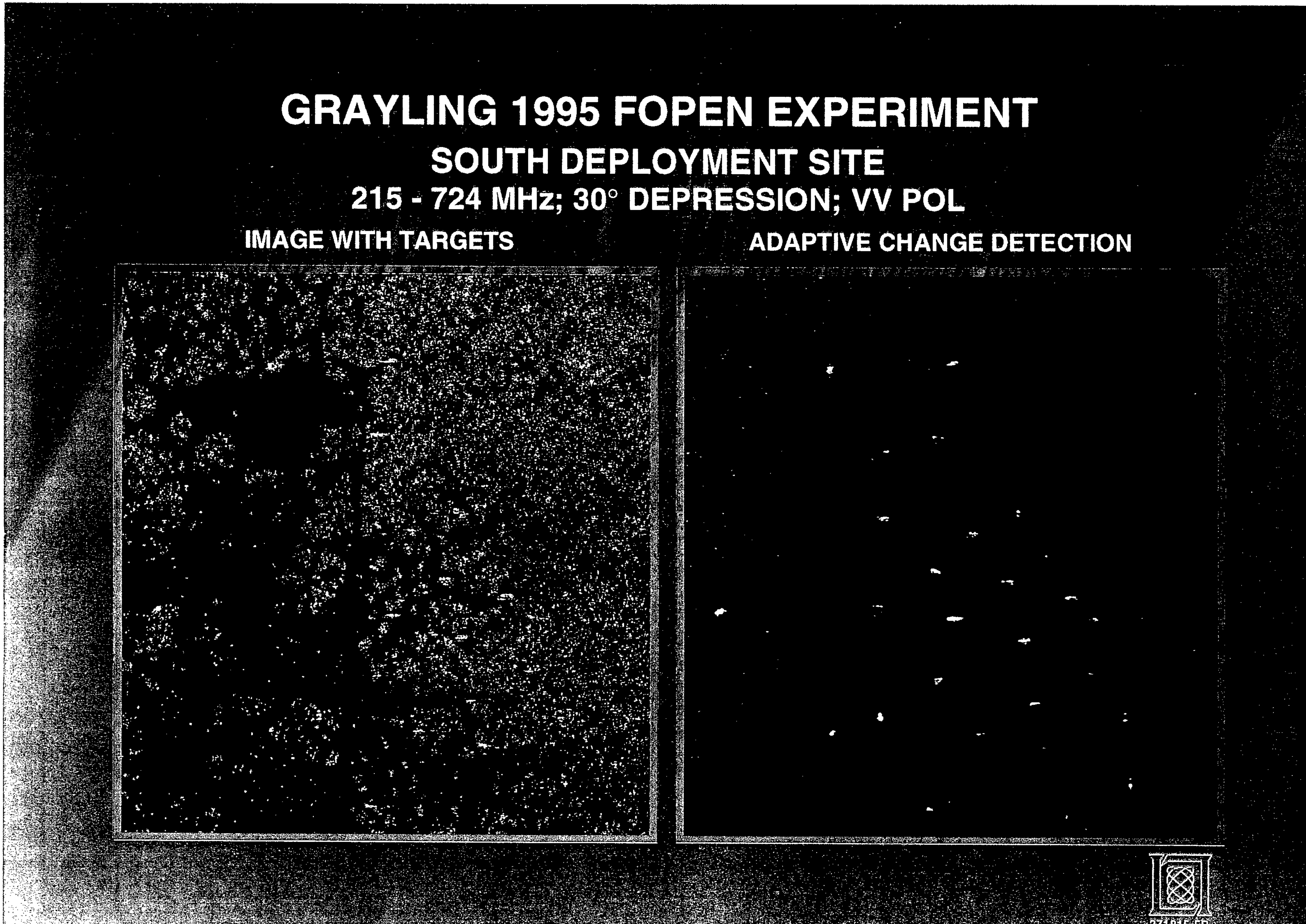
GRAYLING 1995 FOPEN EXPERIMENT
SOUTH DEPLOYMENT SITE
215 - 724 MHz; 30° DEPRESSION; VV POL
IMAGE WITH TARGETS
ADAPTIVE CHANGE DETECTION
271815-6P

Figure 4

UWB SAR As A Mine-Field Cueing Systems

White Paper

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I. EXAMPLE SCENARIOS

1) US is landing forces on foreign beach for surprise attack on enemy (maybe in a friendly country, which has been occupied by enemy forces). The beach will potentially be mined. It would help the US forces to know, from a stand off distance, which areas are mined, to either avoid those areas or to clear before landing troops.

2) US is to deploy to and gain control of, a wide area in which hostile militia-type forces have deployed mine fields widely. The area is generally cloudy. The movement of the US forces will be limited to roads and open fields.

II. INTRODUCTION

This white paper considers a stand off Synthetic Aperture Radar (SAR) system, on a low altitude UAV, to search and detect minefields. The objective is to provide advanced warning to the ground troops for safe route selection, or aid in mine clearing afford by providing the cue to a relatively small area which can then be searched for individual mines using short range (possibly hand held) sensors. The paper is organized as follows:

Section III will outline a strawman sensor/platform description for all weather day/night minefield cueing. Technology shortcomings, outstanding issues that needs to be addressed in development of operational capability will be summarized in Section IV.

Appendix A presents a summary of state of the art in mine and minefield detection, in particular in all weather applications, hence focusing on radar sensors.

Appendix B provides a list of current UWB SAR systems and some of the ongoing Government programs that are relevant to the development of minefields cueing radar.

III. STRAWMAN MINEFIELD QUEING SYSTEM

Sensor Platform

Architecturally, the minefield cueing system should consist of an airborne SAR linking data to either a central multi-purpose Semi-Automated IMINT processing (SAIP) system, which exchanges its output data with a large dissemination network via the Battlefield Awareness and Data Dissemination (BADD) direct broadcast system, or to a local ground station directly serving the specific ground forces in consideration.

The sensor platform should be a UAV because it is likely to fly in harm's way. In the near term, predator (Tier II UAV) would be ready, with relatively short altitude (7.5 km), low speed (50 m/s), and limited coverage rate (less than 1 sqkm/s). Tier II+, with larger altitudes and coverage rates, and Tier III-, with low observable property, could be used in the future as they become available.

Data Link

Data link from the sensor platform to the ground station could be through T1 and T3 satellite links which give longer stand off ranges for the UAV deployment. T1 link bandwidth is currently limited to 1.5 Mb/s, hence, on-board image formation and Automatic Target Cueing (ATC) would be required. However, current processor technology does not have the real time processing and memory capabilities for image generation with the desired resolution (about a foot) and ground swath (> 1 Km). T3 link can provide capability to link raw data to a ground processing station for about 2 Km swath with the Predator's 50 m/s velocity, and for about 0.5 Km swath with the faster Tier II+, assuming 1 foot by 1 foot resolution.

If a relay platform within lign-of-sight to the sensor platform is available, then, a common data link can be used which allows larger coverage rates without the need for on-board processing.[1]

Sensor Parameters

Sensor frequency is driven by the desire to maximize target radar cross section (RCS), minimize clutter, need to penetrate ground for buried mines, and resolution requirements for sufficient target detection, false alarm rejection capability. Lower frequencies are needed for ground penetration, higher frequencies are needed for both maximizing RCS of smaller surface mines as well as for higher resolution.

Because of the small sizes of land mines (10 - 30 cm), submeter resolution will be needed. Although encouraging results were obtained with 1 m resolution SAR in detection of anti-tank mines, which are about 30 cm, detection of smaller anti-personnel mines will require higher resolution. Also, target RCS is at resonance, hence peaks at lower UHF band for surface and buried anti-tank mines, while for small mines, such as anti-personnel VALMARA mines which are at or near surface, RCS is higher at upper UHF or L-band.

Sensor polarization is also driven by the target and clutter phenomenology. Results to date indicate slight advantage in using vertical polarization. This is mainly because of the Brewster angle effect in electro magnetic wave penetration in to the ground. V-polarized waves penetrate earth surface better at Brewster angle, and leads to larger RCS for buried mines.

[1] These tradeoffs are presented in various charts, and other written material and can be made available with some afford, if there is interest.

Considering these observations, the strawman mine detection radar is an ultra wide band (UWB) SAR with 1 foot range and cross range resolution, operating with V-polarization over the frequency range 200 - 800 MHz. Such a sensor can be built with current technology, as evidenced by the currently operating systems, listed in Appendix (B).

Table 1 lists the parameters for a strawman mine detection SAR system.

IV. OUTSTANDING ISSUES

The following is a list of critical technology areas that needs more development to improve operational minefield detection capability.

1. Real time on board processors and memory.
2. Wide band antennas compatible with UAV's.
3. Wider bandwidth satellite links, link antennas, suitable for small UAVs.
4. Research on target and clutter phenomenology along with advanced imaging techniques to optimize system parameters, for the specific task of mine detection.
5. Development and testing of automatic algorithms for the detection of mines and minefields in variety of clutter.
6. Investigation of advantages of fusion of SAR data with other sensors (EO, IR, magnetic etc.) either airborne or ground-based, for false alarm mitigation and better detection performance.
7. Mitigation of RF interference, frequency management issues, as in all applications of UWB SAR, where a large part of RF spectrum, which is crowded with TV, radio and cellular phone transmissions, is utilized.

Table 1
Strawman Mine-Field Cueing SAR Parameters

Platform	Predator
Altitude	7500 m
Speed	50 m/s
Frequency	200 -800 MHz
Polarization	VV
(On Board Processing Assumed to Become Available)	
Link	T1
Algorithm Suit	CFAR Detection/Size Filtering/Group and Density Requirement
Resolution	30 cm x 30 cm
Coherent Integration Time	~ 12 min
Total Power	1 kW (Processor Driven) (~ 20 W if raw data can be linked to ground station)

APPENDIX A

State of the Art in all Weather Mine Field Detection

The task of locating buried mines has generally been carried out using short range, ground based sensors [1,2]. While ground-based sensors can be fairly effective, they lack a wide area overage capability. Ideally, the search and detection of minefields would be accomplished using an airborne sensor capable of rapid, wide area surveillance. Recently, airborne systems utilizing passive IR and laser sensors have been developed and tested with fairly encouraging results against conventional surface minefields [3,4,5]. The current US Army mine detection technology program outlined in [6] includes airborne passive and active IR sensors as well as various ground-based systems.

Detection of buried minefields through wide area surveillance presents a greater challenge. Also, for time-critical battlefield applications, there is a need for an all weather stand-off sensor. The recent advances in ultra wideband radar technology make ground penetration (GPEN) Synthetic Aperture Radar (SAR) a promising candidate for a minefield detection sensor suite.

Imaging radar capabilities have improved significantly over the last several years. In 1990 when the "Project Ostrich" mine detection tests was carried out, the participating SAR systems, NASA/JPL C-, L-band UHF polarimetric SAR and the Navy P-3 L-band polarimetic SAR, had maximum resolutions of 4 m x 4 m and ~2 m x 2 m respectively and results were discouraging [7]. More recently, in 1993, experiments with the SRI FOLPEN II SAR with 1 m x 1 m resolution at UHF, with horizontal polarization only, showed detectability of buried metal anti-tank under relatively dry soil conditions. At the time this white paper is being written, in 1995, new ultra-wide-bandwidth (UWB) SAR systems are being tested with fully polarimetric capability and with increasingly higher resolution. One of these systems is the ARPA funded Navy P-3 UHF-upgrade SAR built by ERIM, which has a resolution of 0.3 m in range x 0.6 m in cross range. The other, the ARL Boom SAR, is a UWB ground-based system, with fully polarimetric capability and a maximum resolution of 0.15 m x 0.15 m.

These new sensors, with ground penetration capability, and with frequencies and resolutions matched to the sizes of land mines, present significant potential utility as part of a mine field detection sensor suite.

An example of UWB airborne low-frequency SAR demonstration is provided by the ground-penetrating (GPEN) radar experiment that was carried out using VHF/UHF SAR that was built and operated by SRI at Yuma, AZ, in June, 1993. [7] The target deployments included metallic anti-tank mines (M-20), plastic anti-tank mines (M-80), and anti-personnel mines (Valmara); these mines were deployed in a 200 by 200 square meter area of relatively-low clutter. One-meter resolution imagery was processed for this area. The M-20 mines were metallic disks approximately 1 foot in diameter and 5 inches high.

Figure 1 shows the SAR image of the minefield.

More than 10 dB T/C was achieved for both the surface and shallow-buried M-20 mines (Figure 2).

The plastic M-80 mines were 1 foot square and 4 inches high. The dielectric constant of the M-80 mines is roughly 2 to 3, which is similar to the dielectric constant of the desert soil; thus, detection of these plastic mines was not expected.

An Automatic Target Recognition (ATR) algorithm for minefield detection was developed and tested on an image of the GPEN site. [8] This ATR algorithm detected many of the surface and buried M-20 mines and detected the buried and surface minefields, with 3 false minefield cues in a 4-square-kilometer area of SAR imagery (Figure 3 (a) and (b)).

The Valmara mine is about the size of a soda can mostly plastic, with only about 2 inches metal top. thus, it was not expected that the 1 m x 1 m resolution SRI SAR would have high enough resolution to detect these targets. However, predictions indicate that Valmara anti-personnel mines would be detectable with a 1/2 foot resolution SAR. Preliminary results from recent tests with and ground based SAR system (Boom SAR) developed by ARL which achieves 15 cm x 15 cm resolution over 40 to 1000 MHz are encouraging [10]. Sample imagery of an anti-tank minefield and a row of Valmara are shown in Figures (4) and (5).

APPENDIX B

Relevant Existing SAR Systems Government Programs

Over the years, there have been several developments in SAR technologies and system developments in the United States. Some of these technologies and systems may be reconfigured or combined to form an entire or a part of the minefield cueing system. The following lists some of the relevant airborne SAR systems and their respective performances.

1. ARL Boom SAR. It is a ground base VHF/UHF ultra wideband impulse radar. The radar system is mounted on a self propelled boom of 150 feet tall when fully extended. It operates in the 40 - 1040 MHz band, is fully polarimetric with 15 cm by 15 cm resolution.

2. Sandia's VHF/UHF/Ku/Ka band SARs. It operates in several frequency bands, from upper VHF to UHF and, Ka and Ku bands; it is fully polarimetric with resolution better than 1 foot.

3. The SRI FOPEN II SAR. It is a VHF/UHF ultra wideband impulse radar with three VHF/UHF frequency bands (100 - 300, and 200 - 400, and 300 - 500 MHz); it is horizontally polarimetric, with 1 meter resolution. [12]

4. The SRI FOPEN III SAR. It is a VHF/UHF ultra wideband impulse radar; it is fully polarimetic with 1 meter resolution.

5. The NAVY/ERIM P-3 SAR system. UHF radar on the system operates from 200 - 900 MHz; it is fully polarimetric with 0.3 m x 0.6 m resolution [13]. The system also operates at X-, C- and L- bands although not simultaneously with UHF. The resolution of these higher frequency channels is 1.5 m - 2 m.

Example of the several Government programs addressing SAR-sensor development for obscured and surface-object detection include ARPA's FOPEN, AFWL's RADCON, ARL's FOPEN, and ARL/DIA GPEN Radar programs.

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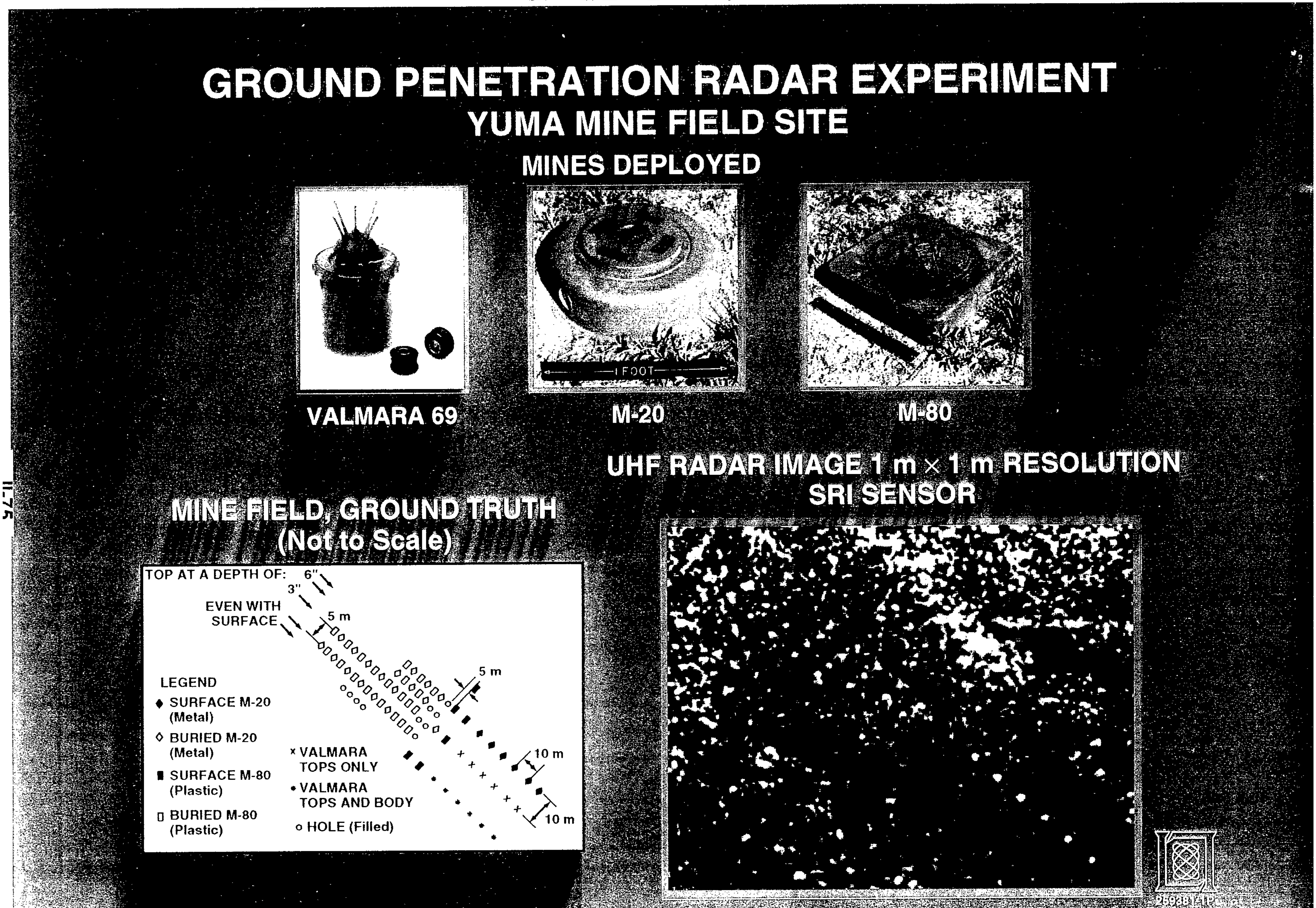

GROUND PENETRATION RADAR EXPERIMENT
YUMA MINE FIELD SITE
MINES DEPLOYED
1 FOOT
VALMARA 69
M-20
M-80
UHF RADAR IMAGE 1 m × 1 m RESOLUTION
SRI SENSOR
MINE FIELD, GROUND TRUTH
(Not to Scale)
TOP AT A DEPTH OF: 6"
3"
EVEN WITH SURFACE
5 m
5 m
10 m
10 m
LEGEND
SURFACE M-20 (Metal)
BURIED M-20 (Metal)
SURFACE M-80 (Plastic)
BURIED M-80 (Plastic)
VALMARA TOPS ONLY
VALMARA TOPS AND BODY
HOLE (Filled)

Figure 1

1993 YUMA GPEN EXPERIMENTS
M-20 MINES, SRI SENSOR, 300 MHz

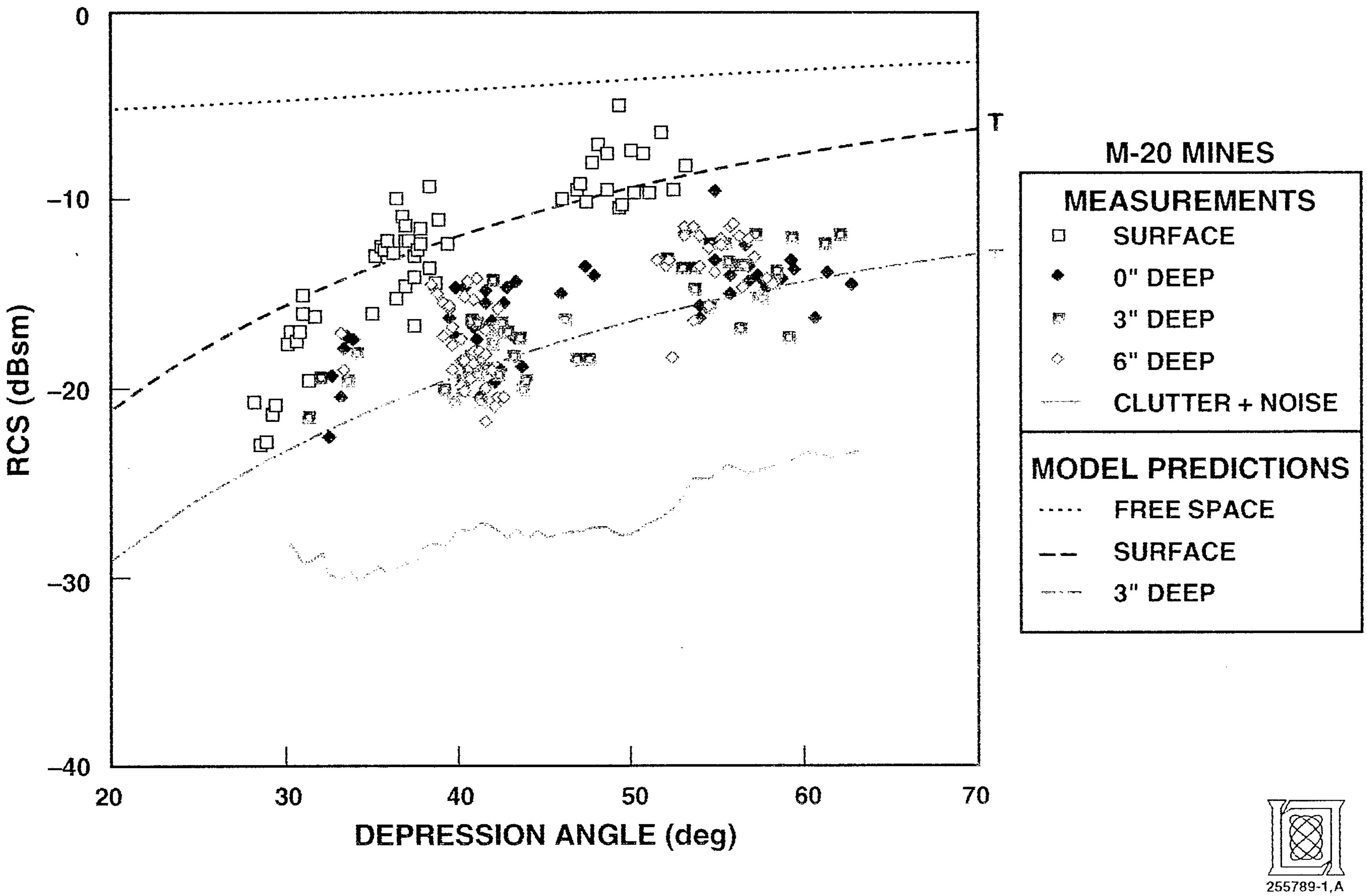
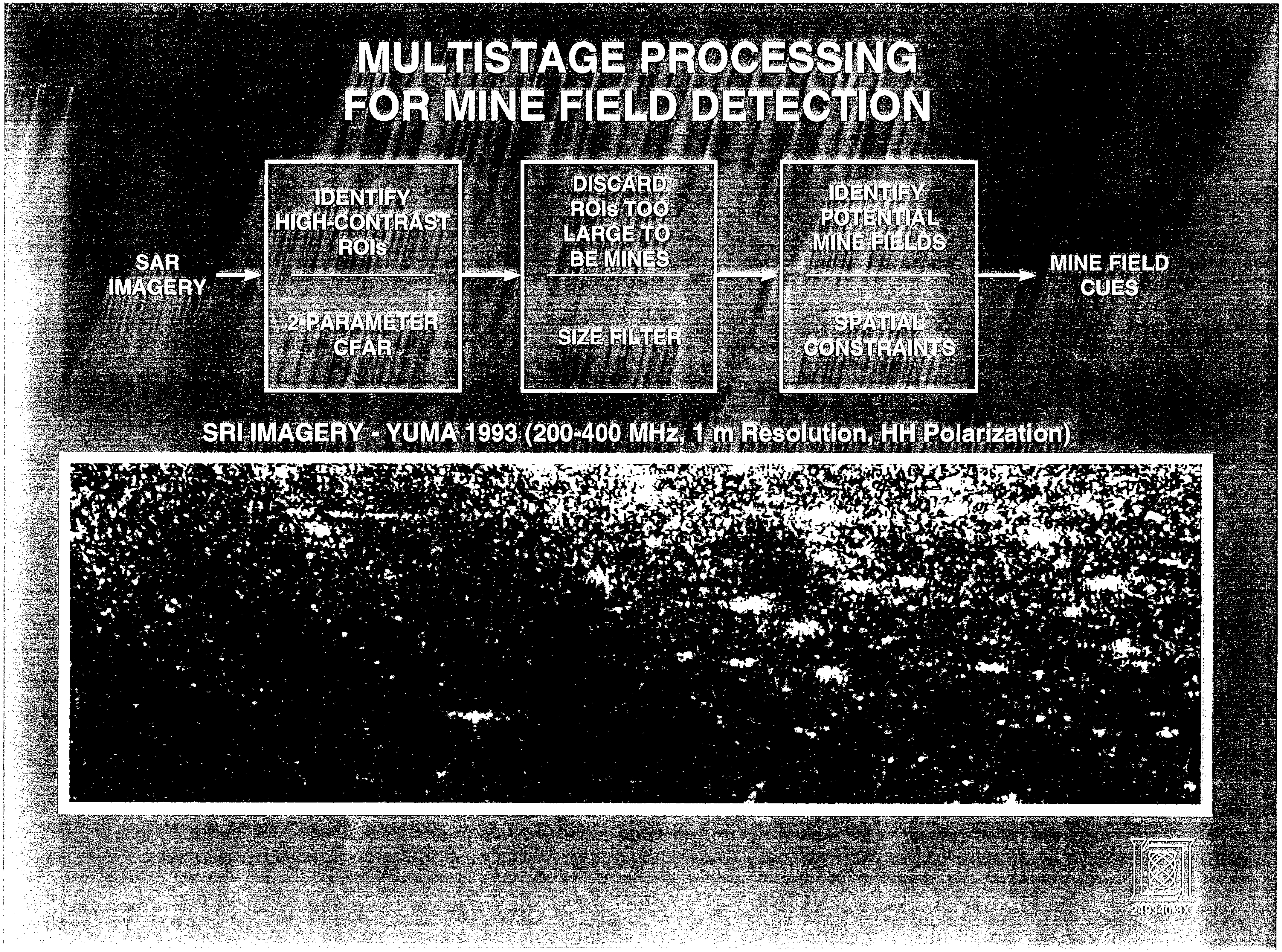
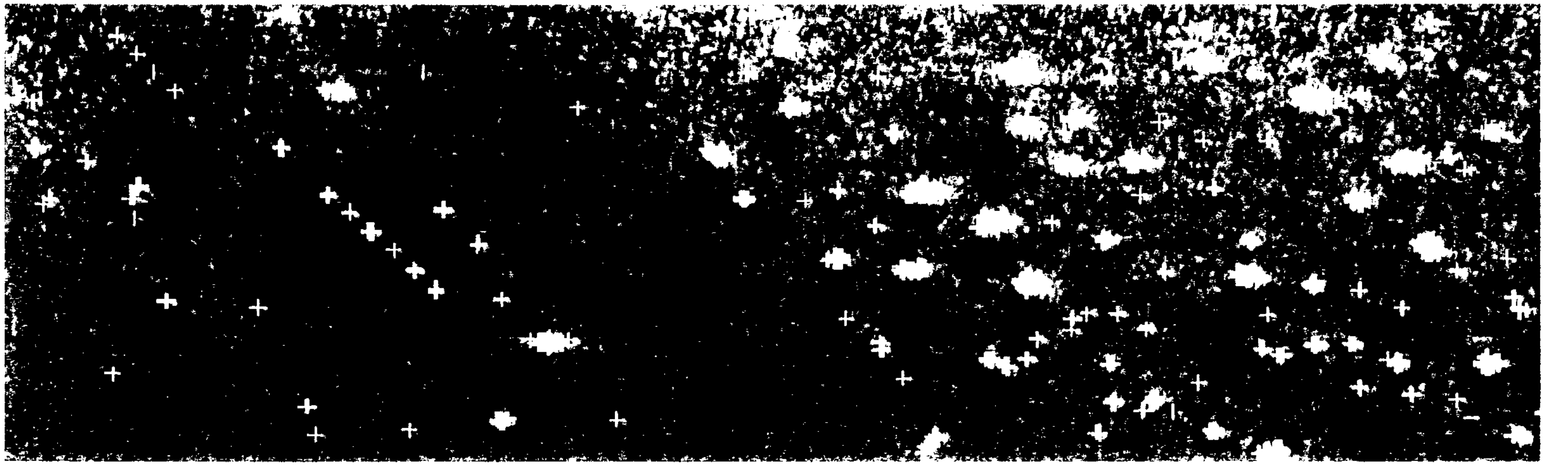


Figure 2



SRI IMAGERY Fig. 3(a)

CFAR DETECTIONS



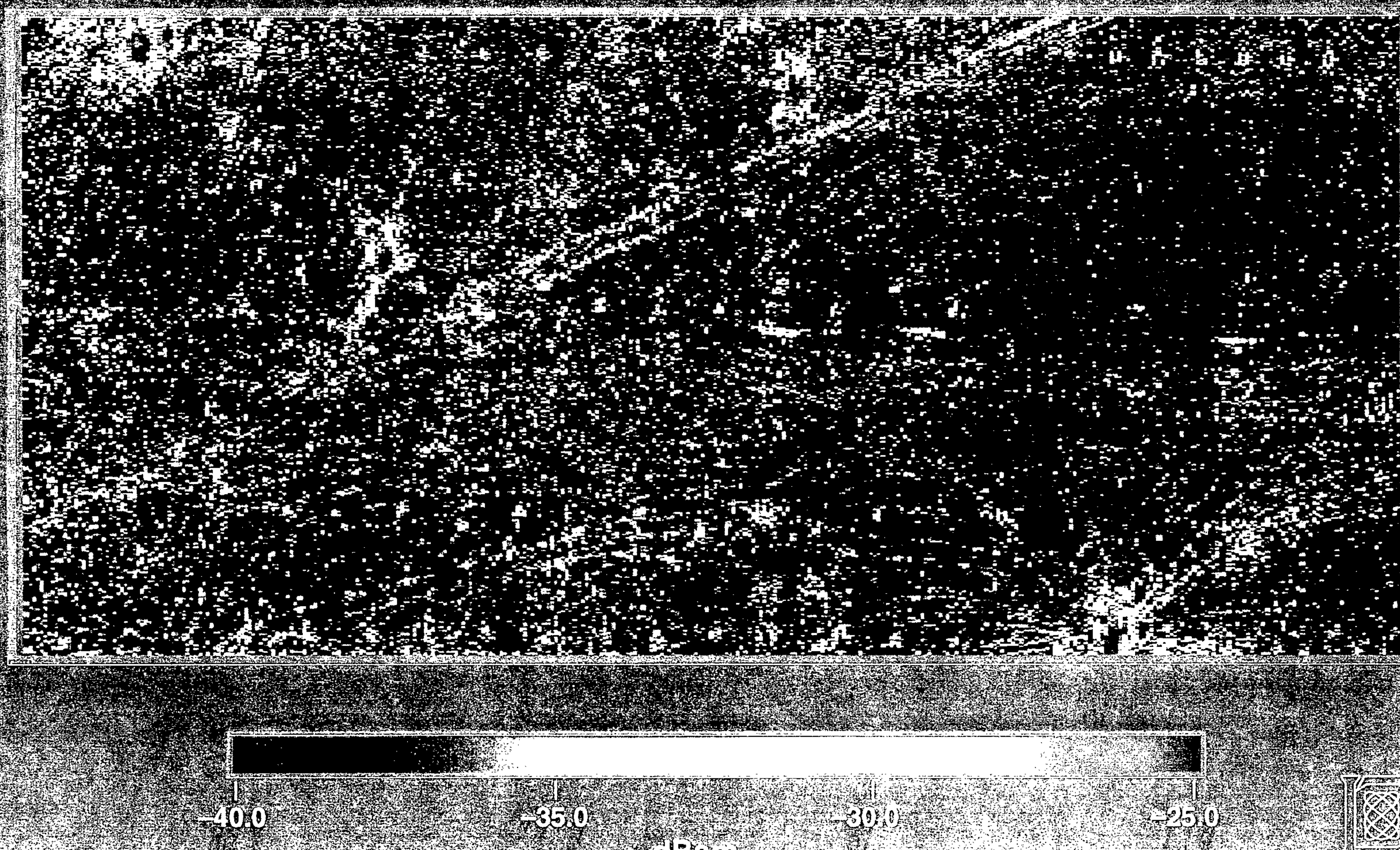
POTENTIAL MINE FIELDS

248915-2P

Fig. 3(b)

1995 YUMA GPR EXPERIMENT

PHILLIPS DROP ZONE, BOOM SAR, VV – POLARIZATION, 28 m × 81 m
40 – 1040 MHz, 15 cm × 15 cm RESOLUTION, M-20 MINEFIELD



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AUTOMATIC TARGET RECOGNITION (ATR) FOR RAPIDLY DEPLOYABLE, OUTNUMBERED FORCES IN WIDE-AREA ENGAGEMENTS

White Paper

Jonathan Schonfeld

AUTOMATIC TARGET RECOGNITION (ATR)
FOR RAPIDLY DEPLOYABLE, OUTNUMBERED FORCES
IN WIDE-AREA ENGAGEMENTS

White Paper
MIT Lincoln Laboratory
17 May, 1996

Motivation

A relatively small and rapidly deployable force, facing a much larger adversary in a wide-area engagement, cannot meet or manage its information needs without technology for automatically extracting information from imagery. The ratio of intelligence data to personnel is high; there is a premium on real-time intelligence exploitation since there is little "reinforcement mass" to absorb surprise actions by the enemy; targeting must be precise because a small force may not have the luxury of wasting ordnance; and exploitation facilities must be compact and modular to facilitate deployability.

Fortunately, automatic target recognition (ATR) technology equal to this challenge is now emerging from the laboratory in response to broad budgetary and policy pressures. The inexorable drawdown of the military intelligence analyst (IA) population, the advent of low-cost, very-high-pixel-rate imaging systems such as the Tier II (Predator), Tier II+ (Global Hawk) and Tier III- (Dark Star) unmanned air vehicles (UAVs), as well as the national preoccupation with tactical-ballistic-missile (TBM) mobile launchers, all require the same ATR performance as do the rapidly deployable, outnumbered forces that are the focus of the Defense Science Board Study on Tactics and Technology for 21st Century Military Superiority.

Vision of the Future

In the future (Figure 1), humans and ATRs will collaborate to manage and make best use of information. In this future, large numbers of highly capable wide-area airborne imagers will, with the help of onboard ATR screeners, send imagery of moving and stationary targets, in the open and under trees, to the ground over inexpensive, low-rate datalinks. ATRs will enable such sensors to quickly decide, under time-critical circumstances, when additional information is urgently needed from other sensors on other platforms, and to adaptively reconfigure sensor schedules accordingly. Compact, highly transportable ground stations equipped with ATR will enable small cadres of analysts to comprehend wide-area sensor output. Soldiers in far-flung locations will be equipped with personalized ATRs that can "ride the network" for suitable data and suitable computational horsepower to meet customized needs. Users everywhere will have tools for quickly correcting ATR errors, and for teaching ATRs to recognize new targets and adapt to new backgrounds, on the fly.

Figure 2 suggests the schedule on which various basic ATR capabilities will mature, organized by target disposition. Automatic detection and recognition of stationary targets in the open is making its way into prototype systems now, backed by decades of experience with human exploitation of high-frequency synthetic aperture radar (SAR) imagery. Automatic detection of moving targets in the open has been commonplace for some time with high-frequency ground-moving-target-indicator (GMTI) radars like Joint STARS. Techniques for imaging moving ground targets with radar are being perfected now; within several years they will be implemented together with ATR in operational systems to provide the capability to automatically recognize moving ground vehicles in the open. Target motion is a great boon to ATR: A moving target is hard to camouflage, its configuration is highly restricted (doors are closed, missile rail is stowed...), it's easy to detect (GMTI), and its direction of motion dictates its orientation.

Automatic detection and recognition of stationary targets fully obscured by foliage, using UHF or VHF SAR, will become available in the longer term. Sensor design today is not mature, techniques for mitigating radio frequency interference (radios, TV stations) are developmental, and viable ATR algorithms have yet to demonstrated with existing experimental sensor. Automatic detection of moving targets fully obscured by foliage is not in the inventory today, but requires no conceptual breakthrough. In principle it could be done with the E2C as it exists today. Automatic recognition of moving targets fully obscured by foliage is entirely unexplored today.

As for partially obscured targets: Detection of the unobscured parts is possible today. Recognition from partial information is an active research area.

State of the Art

<u>ATR and Sensors</u>

ATR performance is strongly sensor-dependent. Performance is sensitive to the quantity of raw information collected by the sensor. Information-bearing sensor degrees of freedom include resolution (i.e. numbers of pixels per target), spectral diversity, polarimetric diversity, geometric diversity (number of different angles from which a sensor can look at a scene), and number of antennas (two for vertical-interferometric SAR, which generates terrain elevation) per collection platform. Performance is sensitive to the wavelength of imaging radiation and how it's generated/processed. Currently, ATR for SAR is more mature than ATR for infrared or visible focal-plane imaging in large part because target-to-background contrast is much stronger in SAR imagery, and because the complex, coherent nature of SAR imagery leads to highly effective superresolution techniques. ATR for short-wavelength SARs (X-band and higher frequency) is currently more mature than for the long-wavelength SARs (UHF and lower frequency) now in development for foliage penetration.

Developments of the last several years have changed how we think about SAR resolution. Until very recently, SAR imagery was always formed by applying fast

Fourier transforms (FFTs) to raw radar signals. The resolution nominally attributed to a SAR sensor is based on expectations derived from such FFT-based image formation. However, thanks to the advent of superresolution techniques such as High Definition Imaging (HDI), developed at MIT Lincoln Laboratory, one can now form SAR imagery at least twice as finely resolved as with FFTs (Figure 3). Such Superresolution techniques are more computationally costly than FFT-based techniques, but not beyond the capabilities of modern COTS computer hardware; in any case, if SAR data is appropriately prescreened, superresolution processing need be applied only to a small fraction of the total radar data stream.

Present and planned DoD airborne radars have few degrees of freedom, because of expense. There are no operational multi-band SARs, no polarimetric SARs, and no multiple-phase center SARs capable of vertical (elevation) interferometry. Sensor degrees of freedom increase cost in at least three ways: by increasing the complexity of the sensor itself, by increasing processing complexity, and by increasing the cost of data transmission associated with an obvious increase in raw sensor data. In the future, ATR will help mitigate these costs: With more sensor degrees of freedom, ATR onboard the sensing platform becomes more effective, enabling more effective onboard imagery screening; if screened imagery only is downlinked, then pressure on the downlink is relieved. Thus, there is an ATR-driven trade between sensor degrees of freedom, and communications.

False-Alarm Mitigation

ATR algorithms need are not stand alone. If ATR algorithms label non-target objects as targets, other types of automated algorithms can be invoked to mitigate such "false alarms." Change detection algorithms can screen out objects whose locations never change (not likely military vehicles); terrain-delimitation algorithms can screen out objects in locations inhospitable to target vehicles; force-structure-assessment algorithms can screen out collections of vehicles whose topographic arrangement bears no resemblance to what's known about enemy deployment practices. In the case of moving targets, tracking with moving-target-indicator (MTI) radar can dramatically narrow that ATR uncertainty by providing vehicle bearing, and therefore aspect angle relative to the imaging sensor.

Fusion of target-recognition evidence from multiple sensors, possibly on multiple platforms viewing a scene from multiple viewing angles, could be a powerful false-alarm mitigator. In the future, with the maturing of mathematical schemes for adaptively tasking large numbers of distributed sensors, and with continued apprehension about high-value moving targets that could flee between successive passes of single sensors, multi-sensor, multi-platform fusion will become commonplace.

ATR and Computing

ATR for SAR, complete with false-alarm mitigation and selective application of superresolution (see above), today requires 10-20% of the computation resources required to form FFT-based SAR imagery. Thus, ATR presents only a modest additional computational burden to any facility already equipped to form SAR imagery. This isn't just about ground stations: Onboard SAR image formation is a baseline specification for the Tier II+ UAV.

Mission-Driven Specifications for ATR

It has taken a long time to begin inserting ATR into operational surveillance systems in part because of unrealistic specifications. ATR is now making its way into prototype systems in large part because the development community has come better to understand ATR's proper place in *end-to-end* system concepts, and to understand that performance requirements are strongly mission-dependent.

For example, until recently it was taken for granted that ATR to support wide-area search should tolerate no more than one false alarm per 1000 sq km (at 90% probability of detection), to make best use of attack-aircraft resources cued by the ATR. We now understand that this applies to the *total* system consisting of ATR *together with* image analysts that screen automatic target nominations. In such a total system, the specification on the ATR per se is no more than one false alarm per image analyst per two minutes (a reasonable minimum verification time). In the case of the Tier II+ SAR stripmap -- 100 sq km per minute -- this amounts to requiring no more than one false alarm per 100 sq km -- *a factor of ten easing of the earlier specification* -- to render the entire imagery stream exploitable by no more than two people. (For narrower-area sensing -- e.g., for the Tactical Endurance SAR (TESAR) onboard the Tier II (Predator) Medium-Altitude-Endurance UAV, which collects SAR stripmap imagery at 35 m/s with a sub-kilometer swath, or for continuous monitoring of limited-area sites -- the specification can be much less demanding than one false alarm per 100 sq km.) A two-man exploitation team would be consistent with the flexibility and deployability needed for small-force operations.

This level of performance has already been demonstrated with the automatic target recognition algorithms in the DARPA/DARO/OSD-funded Semi-Automated IMINT Processing (SAIP) ACTD system now being integrated at Lincoln Laboratory for delivery to Edwards AFB in November 1996. Figure 4 shows "Receiver Operating Characteristic" (ROC) curves for the SAIP ATR applied to a search for SCUD-B transporter-erector launchers (TELs) over 74 sq km in upstate New York and Suburban Boston for Tier-II+-like SAR imagery (single-polarization, nominal resolution 1 m), superresolved using HDI. Clearly, false alarm rates near the required one per 100 sq km are achieved at very high (95%) detection probabilities. ROC curves for tactical targets (tanks, howitzers) are shown in Figure 5. The tactical ROC curve shows significantly more than one false alarm per 100 sq km under Tier II+ conditions, even with HDVI processing. However, false-alarm-mitigation strategies such as change detection, terrain delimitation and force-structure assessment -- all in the baseline SAIP system -- will reduce the false alarms to desired levels. An example of the false-alarm-reducing potential of target-grouping algorithms is portrayed in Figure 6, which shows ROC curves for a simple target-detection algorithm with and without reasoning about how tactical targets in significant numbers tend to group.

False-alarm specifications when ATR screens imagery onboard a UAV for conserving downlink bandwidth can be much more liberal than when ATR is used on the ground to cue human analysts. In the downlink case, much larger numbers of false alarms are tolerable as long as the downlink isn't saturated. This is the premise of the DARPA-funded "Clipping Service" program, which will stage demonstrations of increasing complexity over the next several years.

As Figure 7 indicates, ATR performance would benefit greatly from polarimetry, which is not now a standard part of military remote imaging. As indicated earlier, such performance gains could pay for themselves by enabling communications-system economies.

Robustness

It has also taken a long time to begin inserting ATR into operational military systems because of fears that ATR, once deployed, would be a kind of "idiot savant," capable of recognizing only objects matching training vehicles rivet for rivet. Developments of the last several years have gone a long way toward dissipating such fears.

For example, in "template-matching" ATR reference images of targets are averaged over a few degrees of viewing angle to counteract over-selectiveness. The benefits of this are evident in Figure 8, which shows "confusion matrices" of statistics for mistaking different targets for one another using the baseline SAIP ATR. One sees the system correctly recognizing two serial numbers of a common vehicle as two examples of a single type of object, and also -- with less perfect but still respectable performance -- correctly recognizing a common vehicle with and without baggage again as two examples of a single type.

Computer programs are now being developed that will enable ATR users *in the field* to correct persistent ATR errors "on the fly" and to quickly make an ATR system cognizant of new targets or new background ("clutter") environments that may not have been foreseen by algorithm developers in the laboratory/factory.

Algorithmic methods for contending with target variability due to such factors as articulation (e.g. rotatable tank turret) and partial obscuration are also in development and are expected to be ready for serious military application in five years or so. For targets, such as tanks, that travel in sizable groups, articulation is not as problematical as one might naively imagine because a substantial fraction of a group is likely to be in a recognizable articulation. For targets, such as mobile missile launchers *in transit*, whose articulation is highly constrained, variable articulation is not a concern at all. (Of course articulation, partial obscuration, and, for that matter, camouflage, concealment and deception (CC&D) are challenging for humans as well.)

To be sure, the full range of objects to recognize on a modern battlefield can be broader than what any single ATR system might be "trained" for. Thus, soldiers may want more or different kinds of information than is screened on their behalf by sensor ground stations. Thus, we foresee a future in which individual soldiers equip their portable computers with individualized "itinerant" ATR algorithms that can travel over a tactical communication network to borrow FLOPS from more powerful ground-station computers for customized target searches.

Summary

The missions envisioned by the Defense Science Board Study on Tactics and Technology for 21st Century Military Superiority -- small units engaging large forces over broad areas -- *require* automatic target recognition technology. Fortunately, major trends within DoD are pushing ATR in ways that suit such missions well, both by making effective use of existing and planned sensors, and by opening the prospect of cost-effective increases in sensor capability.

Figure Captions

Figure 1	ATR Vision.
Figure 2	ATR maturity schedule.
Figure 3	Example of SAR Superresolution.
Figure 4	ATR ROC curves for TEL search with SAR. "MSE 1.0m" and "MSE 0.5m" refer to ATR performance with FFT-processed 1m - resolution and 0.5-m resolution imagery, respectively. "HDI 1.0m" refers to ATR performance with imagery that would have had 1.0-m resolution if FFT processed, but while instead has been superresolved.
Figure 5	As in Figure 4, mutatis mutandis.
Figure 6	Illustration of SAR ATR false alarm reduction (tactical targets) exploiting target-grouping behavior (no super-resolution).
Figure 7	Illustration of SAR ATR sensitivity to resolution and polarization (no superresolution) for tactical targets. "HH" refers to transmitting and sensing horizontally polarized radiation only. "PWF" refers to "polarization-whitened filter," a technique for optimally combining all combinations of transmitted and sensed polarizations.
Figure 8	Confusion matrix from representative multi-target SAR ATR experiment. Entries in black refer to testing on training data Entries in red and blue refer to testing on data not used in training. The second T72 had barrel-like fuel tanks mounted on the rear.

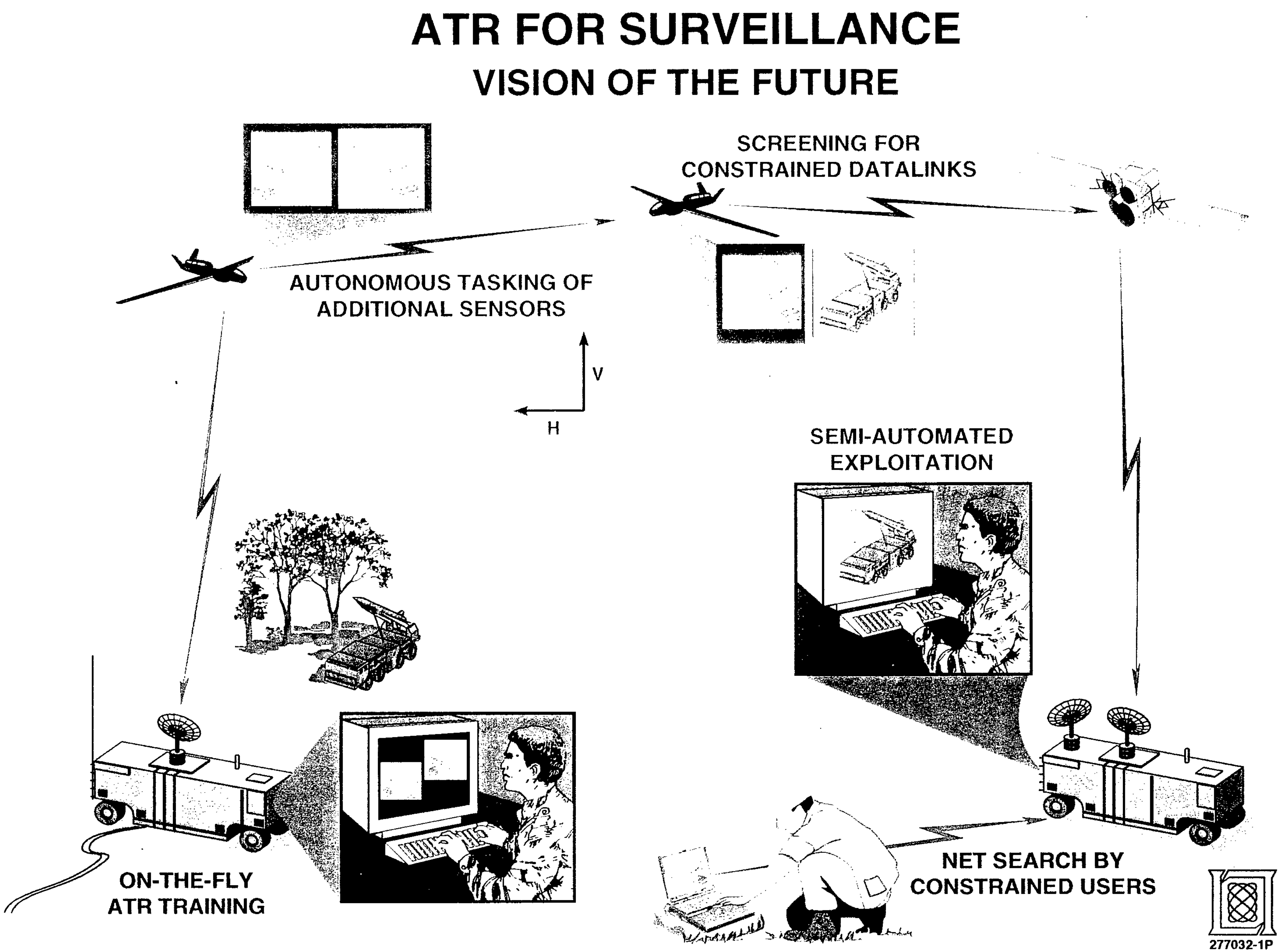
ATR FOR SURVEILLANCE
VISION OF THE FUTURE
SCREENING FOR
CONSTRAINED DATALINKS
AUTONOMOUS TASKING OF
ADDITIONAL SENSORS
V
H
SEMI-AUTOMATED
EXPLOITATION
ON-THE-FLY
ATR TRAINING
NET SEARCH BY
CONSTRAINED USERS
277032-1P

Figure 1

SURVEILLANCE CAPABILITY
PARSED BY TARGET

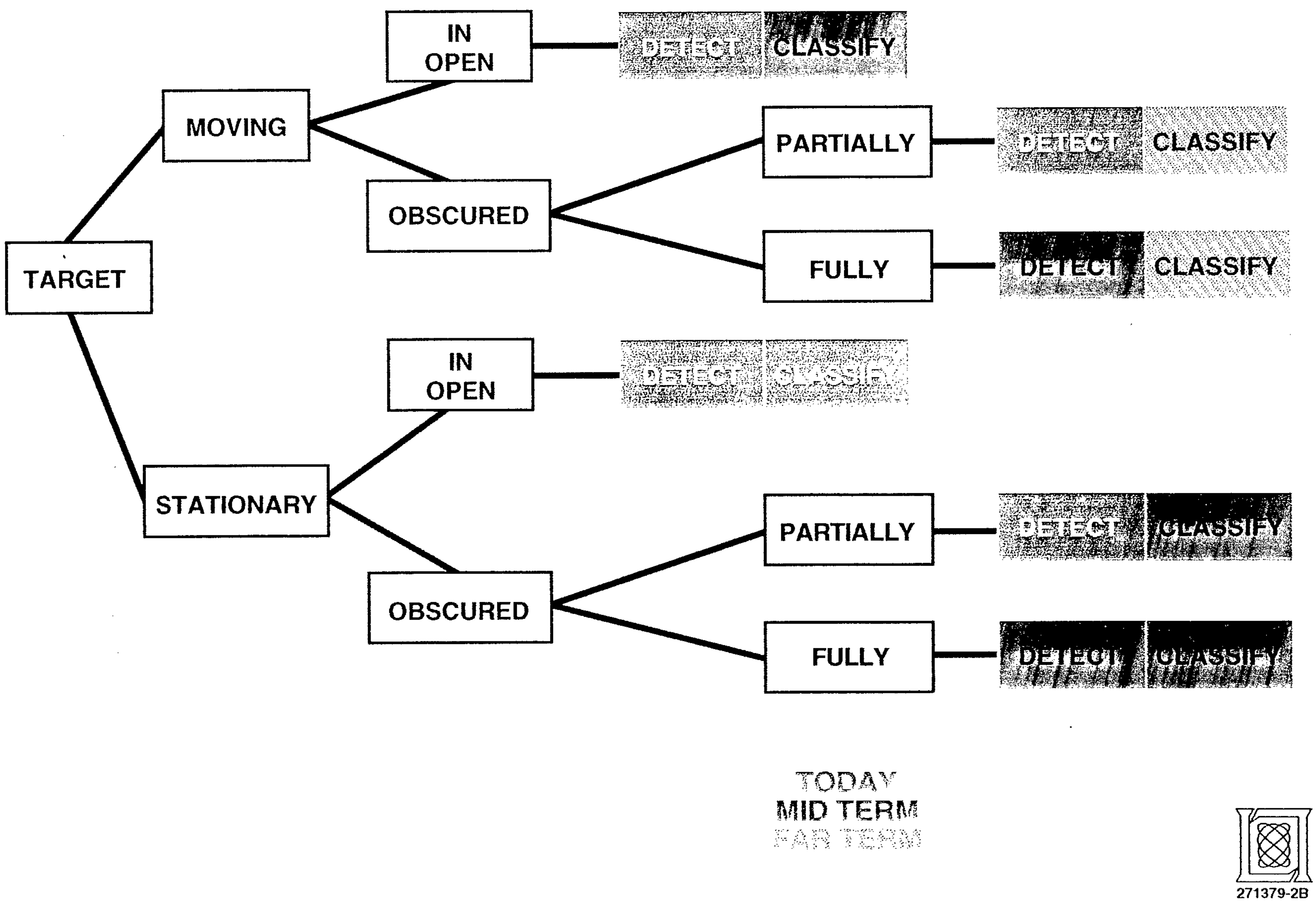

Figure 2

CONVENTIONAL vs HDI IMAGE COMPARISON

HH POLARIZATION, 1 m × 1 m RESOLUTION

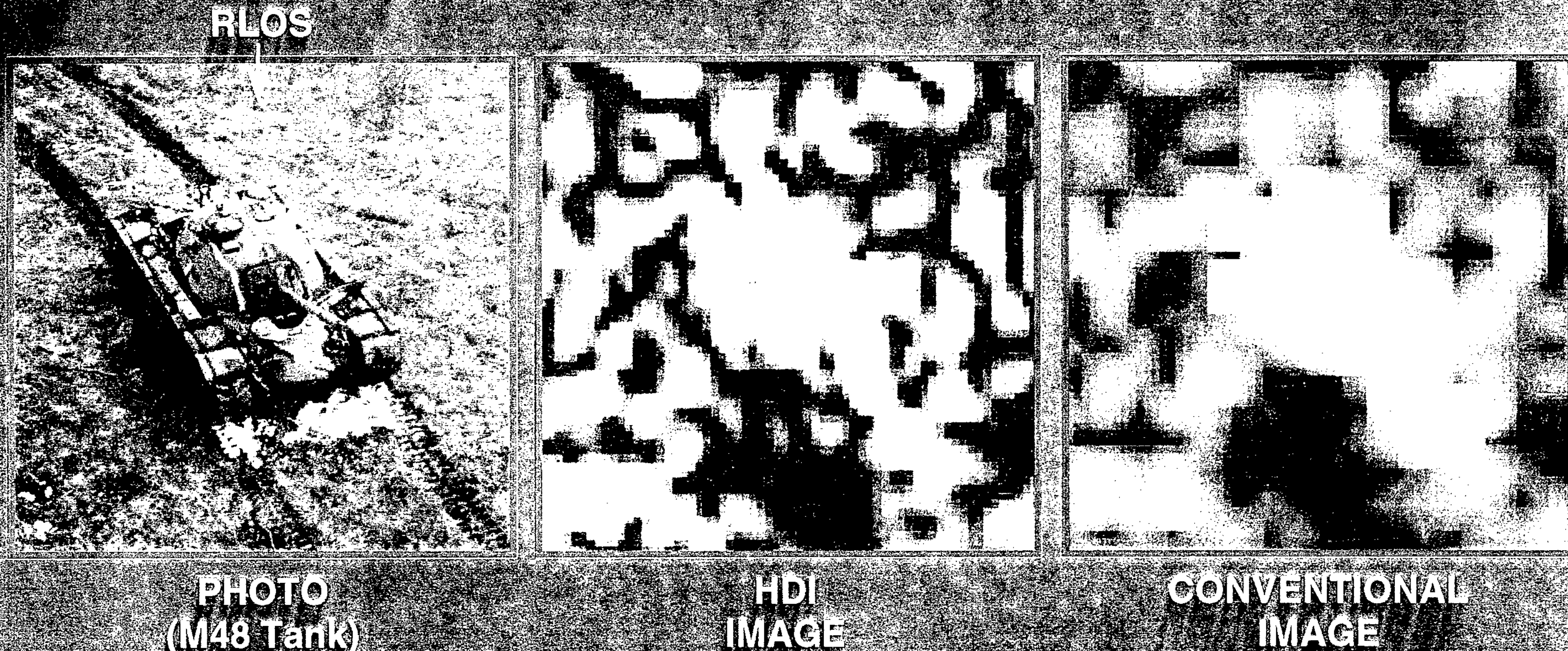

Figure 3

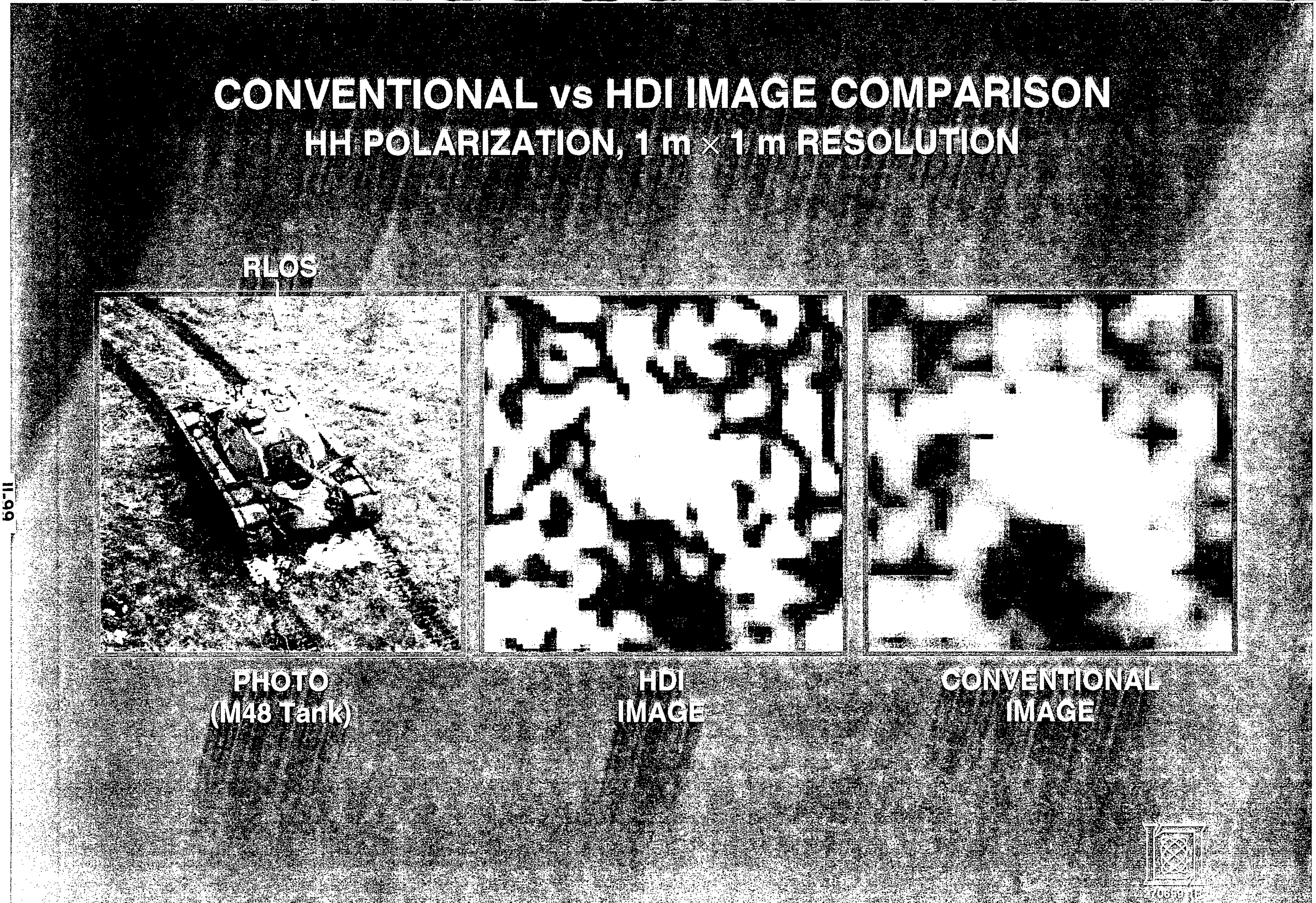
CONVENTIONAL vs HDI IMAGE COMPARISON
HH POLARIZATION, 1 m × 1 m RESOLUTION
RLOS
PHOTO
(M48 Tank)
HDI
IMAGE
CONVENTIONAL
IMAGE

Figure 3

PERFORMANCE OF ATR ALGORITHM SUITE

TEL TARGET, STOCKBRIDGE / AYER CLUTTER (74 km^2)

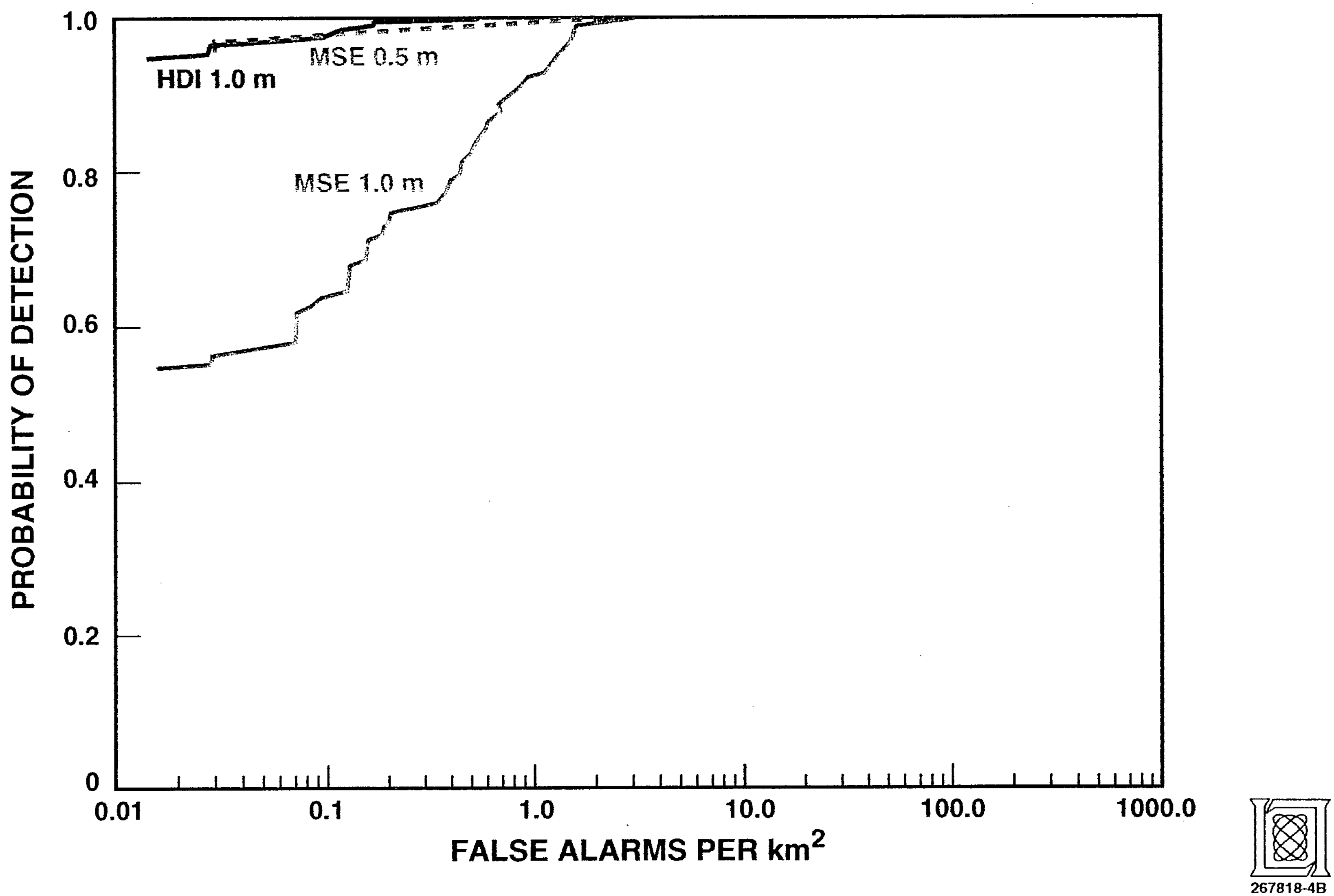

Figure 4

END-TO-END PERFORMANCE OF ATR ALGORITHM SUITE

TACTICAL TARGETS, STOCKBRIDGE / AYER CLUTTER (74 km^2)

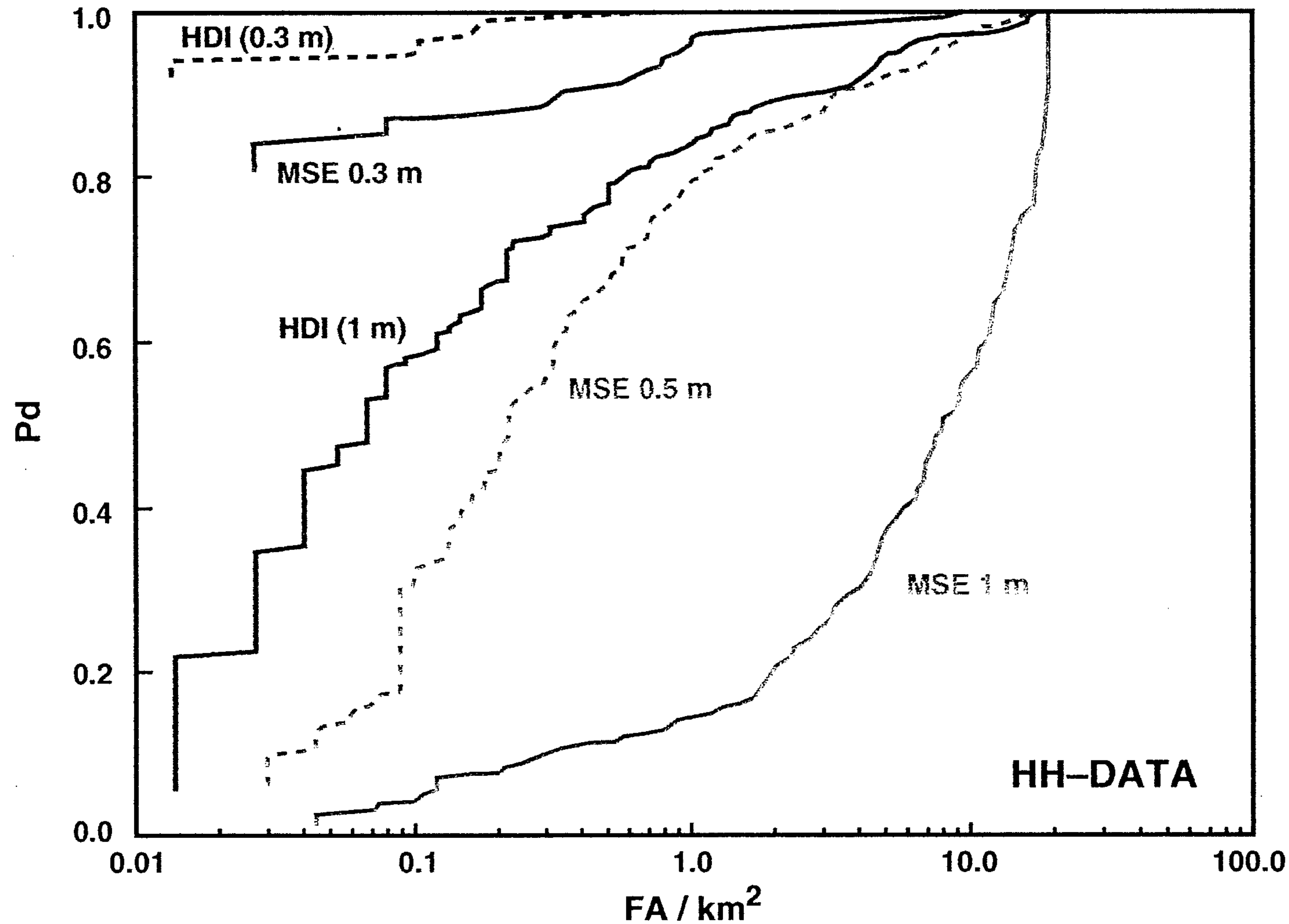

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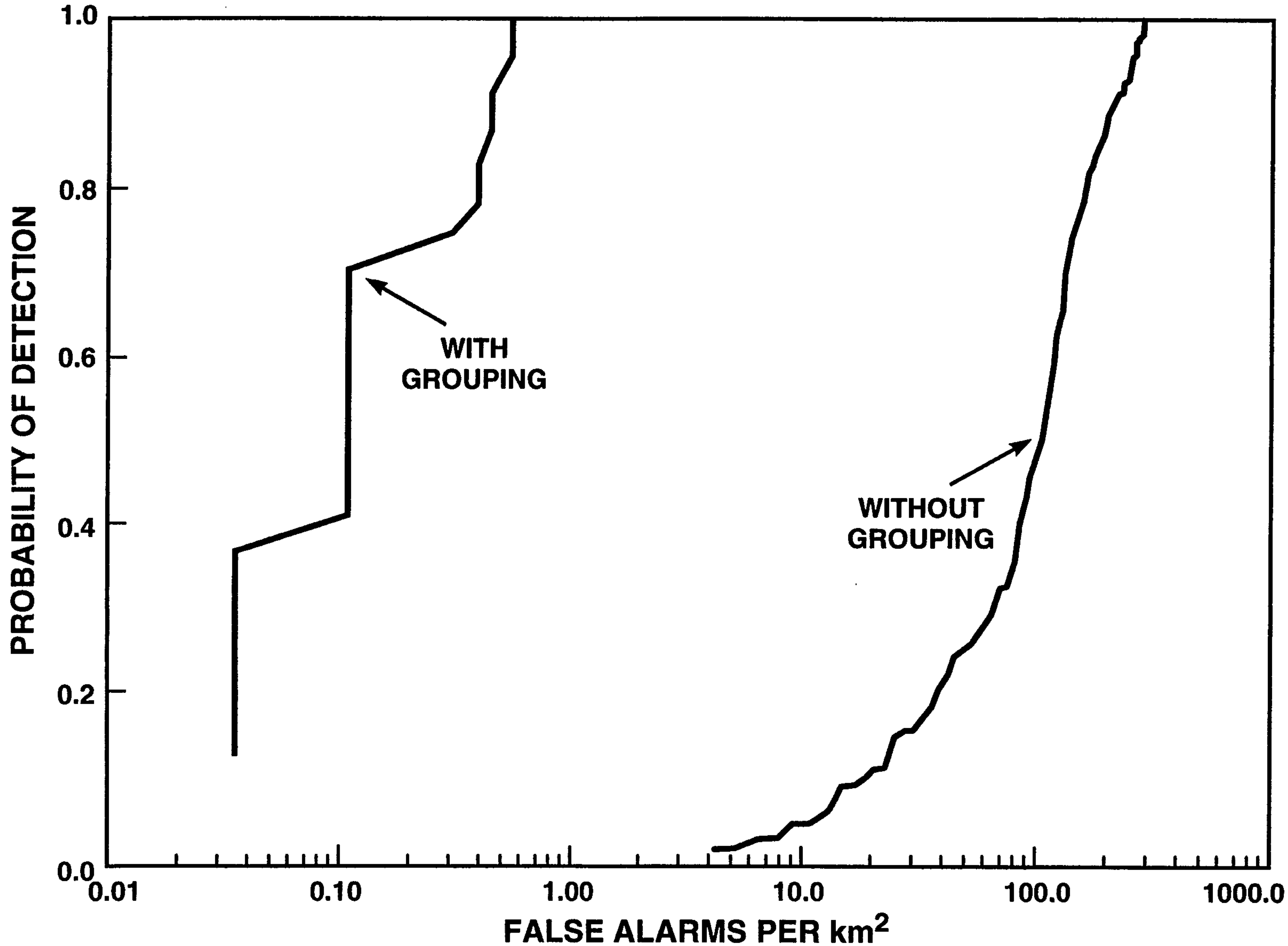
Figure 5

DETECTION PERFORMANCE IMPROVEMENT USING GROUPING

HH-DATA 1 m × 1 m RESOLUTION



254702-1

Figure 6

SAR/ATR DETECTION PERFORMANCE

POLARIZATION AND RESOLUTION COMPARISON

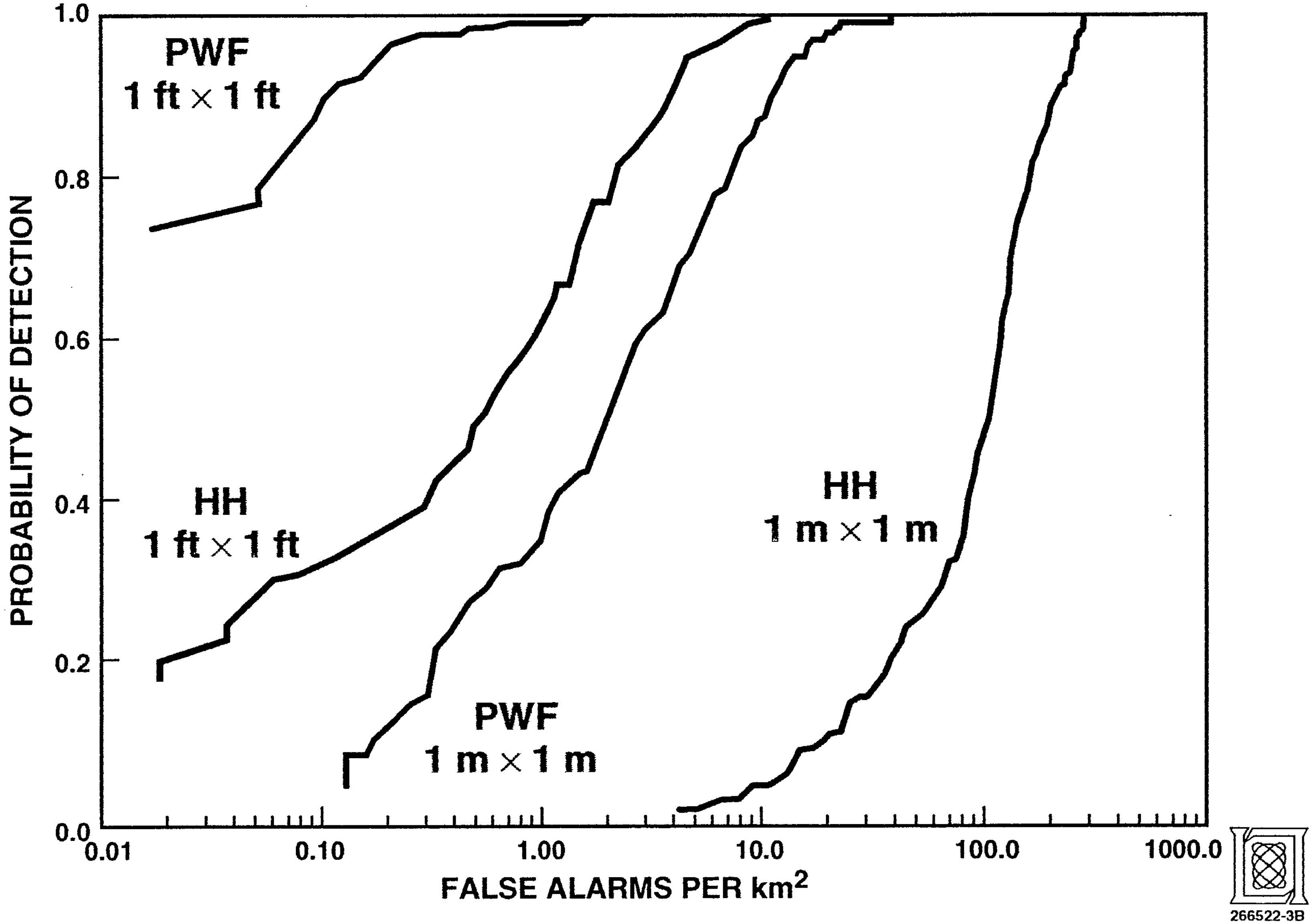


Figure 7

CLASSIFIER PERFORMANCE RESULTS
MSTAR TARGET SET
HH-POL, X-BAND DATA

	NUMBER OF TARGETS CLASSIFIED AS										
	BMP2	BTR60	BTR70	M109	M110	M113	M1	M2	M548	T72	UNKNOWN
BMP2	256										
BMP2	235	1				1		8		7	3
BMP2	237	1						11		4	3
BTR60		255									1
BTR70			256								
M109				256							
M110					256						
M113						255					1
M1							256				
M2								256			
M2				4	5			233		4	9
M2				2	5	1		239		4	5
M548									254		2
T72										256	
T72					3		8	3		217	24
T72				1			2	1		241	6
HMMWV	29	8	1	9	3	115		14	3	1	61
M35	1			3	3	1			5		242

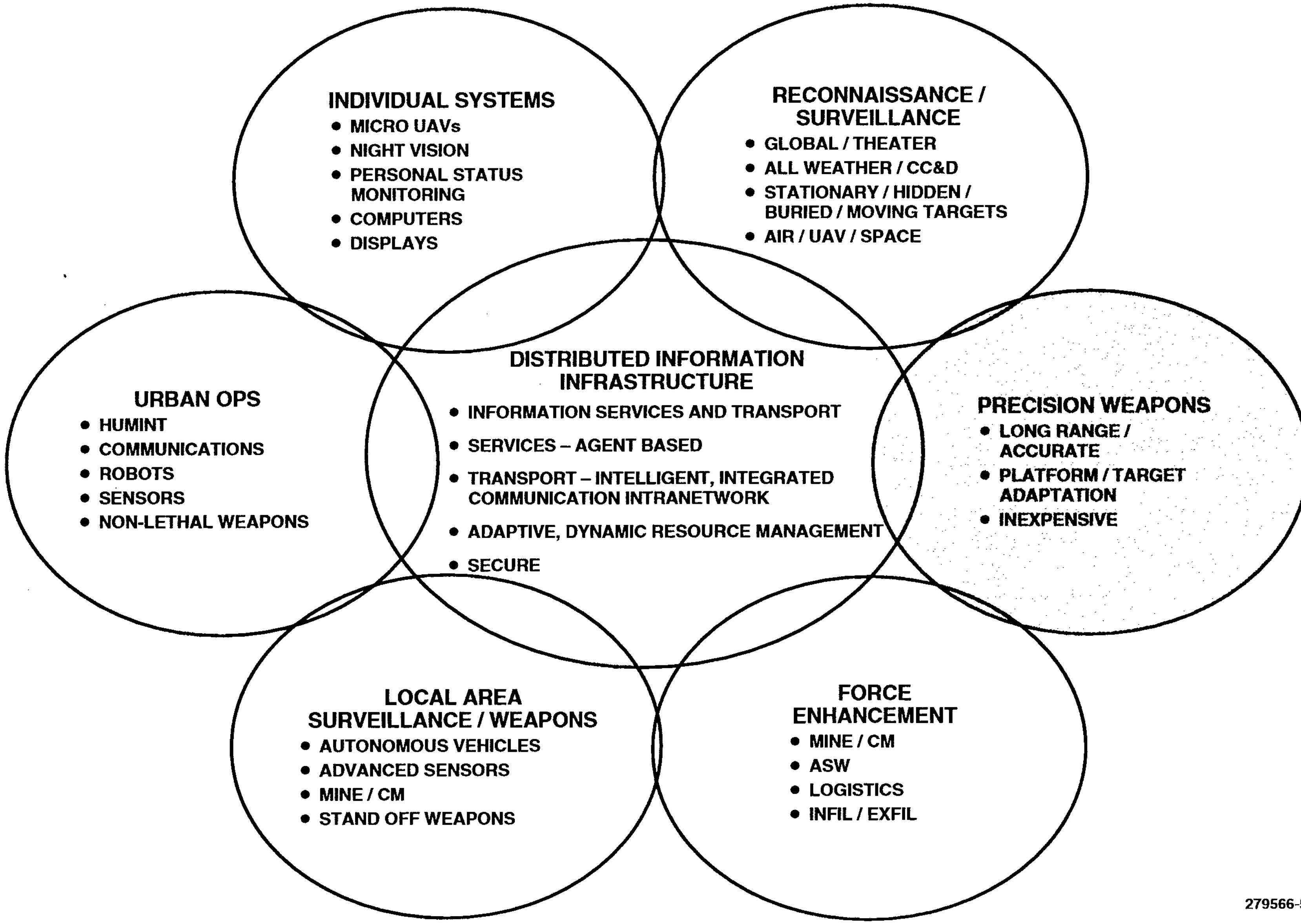
■ INDEPENDENT TEST DATA ■ CONFUSOR VEHICLES (Not in Training Set)

277031-1B

Figure 8

TACTICS AND TECHNOLOGY FOR 21st CENTURY MILITARY SUPERIORITY

TECHNOLOGY CONCEPTS PANEL



279566-5T

POTENTIAL FOR LONG STANDOFF, LOW COST, PRECISION ATTACK

1996 Defense Science Board Study

MAY 1996

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ABSTRACT

The potential for long range, low-cost, conventional precision attack against stationary, fleeting, and slow moving targets in jammed environments has been radically improved by the advent of cheap GPS/inertial guidance. Missions include deep strike, interdiction, offensive counterair, preassault neutralization, anti-armor, close ground-combat support, and ocean surface warfare. To counter the deficiencies of current weapons for these missions, a set of performance and affordability objectives for a new weapon to support the mission areas is formulated, the full spectrum of weapon mechanizations is evaluated, and a strawman (existence proof), low-cost, GPS-guided, rocket-boosted MaRV conventional precision attack weapon is configured.

The weapon concept consists of a common, warhead-tailorable, maneuvering reentry throwbody mounted on either one or two stages of a standardized booster module to allow flexibility of weapon range and basing. The standardized booster module, consisting of a common casing and two interchangeable nozzles (to allow different expansion ratios), is configured in two one-stage and two-stage combinations to produce four attack weapon variants. The variants (compatible with existing launchers) include a theater ground launched weapon (500 km), a theater air launched weapon (1,000 km), a regional sea launched weapon (1,910 km), and a regional air launched weapon (2,750 km). Flyaway cost is estimated at <$100K for the single-stage surface and air-launched theater weapon and <$150K for the longer range two-stage regional weapon at the end of 5,000 unit production runs. Production runs of 100,000 units would cut end unit cost in half.

A $135M ACTD-like program is proposed which calls for a two-year $75M development, one-year $34M flight test and one-year $26M operational service trial. Development emphasis will focus on hypersonic submunition dispensing and lethality, MaRV design and flight control, and carbon-cased, thrust vectored, solid propellant booster production cost. The existing DARPA $15K GPS/inertial package (GGP) would be harvested along with current production submunitions to minimize risk and cost.

Beyond this near-term capability, three areas of impact accuracy subsystem performance improvement (3 m CEP) could offer either effective attack of structural or deep underground targets, or a factor of ten reduction in overall weapon size against non-structural point targets, hence a further factor of three in flyaway cost beyond the previous factor of ten improvement over current strike weapons. These subsystem improvements are guidance accuracy (2 m CEP, in the form of improved GPS ephemeris signal data), countermeasure resistance (20 second loss of signal before impact, in the form of better nulling antennas and clocks), target localization accuracy (1 m CEP, in the form of better geodesic maps and

surveillance image registration or long baseline emission intercepts). Warhead lethality and propellant specific impulse (by application of improved chemical energetics) could reduce weights somewhat, but no near-term energetics technologies offer significant improvements except for slight reductions in weapon volume.

TABLE OF CONTENTS

1.0 BACKGROUND

Tactical strike operations against surface targets are currently employed in seven indirect fire missions, depending on the phase of the hostilities and target proximity to own forces:

Figure 1-1
LONG STANDOFF PRECISION ATTACK MISSIONS

- deep strike
- interdiction
- offensive counterair
- preassault neutralization
- anti-armor
- close ground-combat support
- ocean surface warfare

The potential tactical target types are listed below:

Figure 1-2
TACTICAL TARGETS

Structurally Hard
- deep underground leadership
- C^2/weapon bunkers
- ammunition storage
- aircraft shelters
- runways
- shallow POL
- rail lines
- trestles
- bridges

Stationary Armor
- isolated tanks (parked)
- tank column (choked)
- isolated APC (parked)
- APC column (choked)

Moving Armor
- massed tanks
- massed APC

Stationary Soft
- parked aircraft
- hangars
- surface POL
- SAM sites
- portable C^3
- surveillance radar sites
- isolated parked trucks
- truck columns (choked)
- parked train
- ships/subs in port
- port facilities
- camped personnel & supplies

Moderately Protected Forces
- entrenched troops
- urban resistance

Moving Ocean Vehicles
- ships

The weapons currently employed for these purposes include: air-launched short-standoff ordnance, regional cruise missiles, ship guns, shore-based artillery, armored vehicle guns, low accuracy tactical ballistic missiles, short range unguided rockets, and man-portable and mounted weapons. However, these methods of target nullification suffer from at least one of the following shortcomings:

Figure 1-3
CURRENT DEFICIENCIES IN LONG STANDOFF PRECISION ATTACK

- high in cost per target nullified,
- vulnerable to defensive weapons or counterstrike,
- slow in response,
- non-surgical in collateral damage, and
- tactically alerting in application.

The ideal means of tactical strike would have the following six attributes:

Figure 1-4
DESIRABLE TRAITS FOR LONG STANDOFF PRECISION ATTACK

Affordable Cost - $30K-$100K flyaway cost even in short 5,000 unit production runs for an economic ratio against low cost tactical targets (e.g., trucks).

Rapid Response - <2 minute response for close ground combat support from 200 km standoff; <10 minute response for coordinated tactically surprising strike from 1,000 km standoff.

Countermeasure Resistance - geodetic targeting with jam resistant, high-grade GPS/inertial guidance instead of deception-sensitive target feature homing.

Launcher Compatibility - modularly sized to fit all tactical and strategic aircraft, ground MLRS, and VLS-equipped ships.

Assured Lethality - tailorable ordnance loads with hypersonic (i.e., high kinetic energy), selectable terminal approach path to cope with the full spectrum of soft to hard, point and area, stationary and moving targets.

Moving Target Accommodation - terminal phase update by third party surveillance or smart submunition ordnance load to cope with moving targets.

High Survivability - long standoff (200-3,000 km) for sanctuary, high fast transit for enroute immunity, and stealthy, evasively maneuverable terminal phase for final defense penetration.

Minimal Collateral Damage - <20 m CEP in GPS jammed environment to allow effective use of small <250 lb ordnance loads and to permit close approach to juxtapositioned friendly forces or politically sensitive enemy assets.

Surprising Arrival - Distant launch and stealthy, hypersonic transit to reduce or eliminate target-reactive passive damage-limitation measures.

Treaty Compliance - <500 km INF treaty-limited ground launch and unambiguous shape differentiation for long standoff launch from "non-strategic" aircraft.

These attributes appear to be within easy reach.

2.0 WEAPON DERIVATION

2.1 COMPETING WEAPON DELIVERY OPTIONS

Rapid delivery of warhead to Theater (500-1,000 km) and Regional (2,000-3,000 km) ranges can be achieved by a variety of mechanizations as seen in Figures 2-1 and 2-2. Included are rocket propelled missiles (exo-release buses, MaRVs, and hypersonic glide vehicles), cruise missiles (scramjet, ramjet, supersonic and subsonic turbine, and reciprocating engine propeller) and guns (pure and hybrid). These differ in cost, delivery efficiency, warhead-target tailorability, speed, countermeasure resistance, enroute and terminal phase survivability, launch source burden, and subsystem commonality among variants.

Comparison of the several competing weapon delivery schemes should consider the following issues:

- flyaway cost, weight, and size per payload weight to reveal basic delivery efficiency at each range (theater, regional) for volume limited, weight limited, and dollar limited designs
- warhead weight fraction per throw weight to differentiate structural and control weight penalties inherent in the various delivery vehicle airframe concepts
- warhead coverage efficiency against soft, hard, and mobile targets at each of the ranges to highlight the terminal phase dependence of submunition lethal agent size (weight) vs. lethal pattern radius vs. laydown pattern areal density (and hence, kill probability vs. delivery error)
- target mix and cost to determine the emphasis to be placed on the soft vs. hard vs. moving targets for warhead characterization and sizing
- warhead and endgame adaptation against moving targets to include cured circular and shaped submunition laydown patterns, dispensed guided submunitions, and terminal phase homing
- submunition laydown pattern fidelity to ascertain risks of and cures for the peculiarities of the submunition dispensing and post-release behavior for exo-atmospheric and hypersonic endo-atmospheric conditions
- GPS guidance countermeasure susceptibility to measure the differential affect of jamming on impact point errors as a function of terminal approach speed, trajectory, and submunition release standoff distance
- alternative guidance in the absence of GPS satellites to illuminate cost or configuration penalties or trajectory shaping requirements to cope with this adversity and to explore low-cost map matching as an alternative

Figure 2-1

LOW-COST PRECISION ATTACK WEAPON DELIVERY OPTIONS

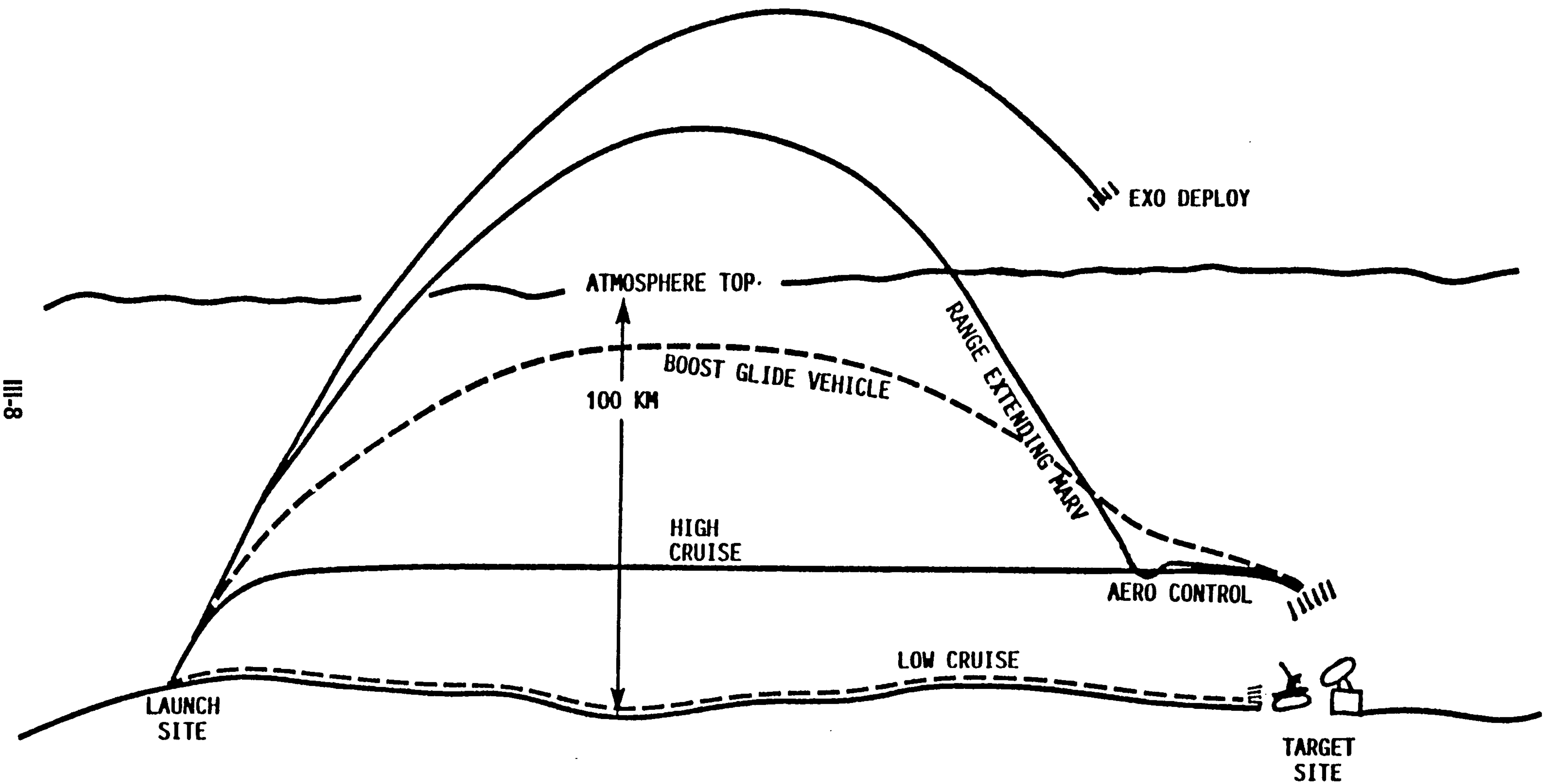


Figure 2-2
COMPETING DELIVERY SCHEMES (U)

Short Name	Launch	Midcourse	Terminal Phase
Exo-Release	Rocket	Exo-Ballistic	Exo-Bus (>M4 impact)
Rocket MaRV	Rocket	Exo-Ballistic	MaRV (>M4 impact)
HGV	Rocket	Hypersonic Glide	Lifting Body (>M4 impact)
Scramjet	Rocket Boost to M4	>M6, 35 km alt.	Powered Aero (>M4 impact)
Ramjet	Rocket Boost to M1.8	>M3, 25 km alt.	Powered Aero (>M4 impact)
Supersonic Turbine	Rocket Boost to MO.5*	>M1.5, 15 km alt.	Powered Aero (>M2 impact)
Subsonic Turbine	Rocket Boost to MO.5*	>M.75, 10-300 m alt.	Powered Aero (>M0.75 impact)
Subsonic Propeller	Rocket Boost to M0.2*	M0.5-0.7, 10-30 m alt.	Powered Aero (>M0.75 impact)
Hybrid Gun	Gun Launch Rocket	Exo-Ballistic	MaRV (>M4 impact)
Pure Gun	Gun Only	Exo-Ballistic	MaRV (>M4 impact)

*Air launch eliminates need for rocket booster

- weapon penetration survivability to show strengths and weaknesses due to enroute and terminal phase speed, altitude, observability, maneuverability, and submunition release standoff

- weapon time-responsiveness to quantify the benefits of rapid response (intell/command lag and transit speed) for such purposes as tactical surprise, timely SAM suppression in concert with air strikes, timely close support of ground combat forces, early debilitation of airfields, terminals, choke points, rail lines, etc., inventory-conserving shoot-look-shoot cycle, minimizing exposure of forward observing assets, and limiting target positional uncertainty of portable or mobile targets

- launcher compatibility to recognize ground, sea, and air backfit and loadout constraints

- low production and support costs to assure that large numbers of low value targets ($50K) can be attacked economically, using high rate, ordnance grade manufacturing techniques and weapon subsystem commonality

- treaty implications to assure compliance with launch source, range, and transit mode constraints

Several of these issues are treated qualitatively in Figure 2-3 to try to illustrate the pronounced performance difference among the various delivery schemes with respect to the operational variables of interest, namely, flyaway cost per kill, kill response time, survivability/CM resistance, tailorability of warhead, and launcher restrictions. By the reasoning displayed in the charts, the rocket/MaRV appears to be inherently superior to other means.

Figure 2-3
EVALUATION OF 500 KM PRECISION ATTACK WEAPON OPTIONS

	Payload Delivery Cost	Response Time (min)	Enroute and Terminal Survivability	Counter-measure Resistance	Warhead-Trajectory Tailorability	Launcher Restrictions
Exo- Ballistic						
Rocket/ MaRV						
Gun/ MaRV	o					
Boost Glide	o					
Scramjet (>M6)	o					
Ramjet (>M3)	o	10 o		o	o	
Supersonic Turb. (>M2)	o	14 o	o	o	o	
Subsonic Turb. (>M0.8)						
Recip. Prop (M0.6)						

Strong
o Marginal
Weak

2.2 PREFERRED DESIGN

Four conventional attack weapon variants, shown in Figure 2-4, have been configured to meet the performance requirements specified above, two theater and two regional, differing mainly in launch source and range:

Mission	Launch Source	Ballistic Range (km)	Porpoise Range (km)
Theater	ground air	500 990	- - -
Regional	ship air	1500 2081	1910 2750

All of the weapons carry a common 476 lb, 72" biconic throwbody containing 248 lbs of submunitions, mounted on a booster or combination of boosters depending upon the mission. The two theater variants are boosted by a single stage while the regional variants require two stages.

There are two basic booster units, differing only in the nozzle configurations. The solid rocket case itself is a cylinder 72.9" long and 21.4" in diameter for both booster configurations. The nozzle for a booster stage firing at sea-level (i.e., either the ground launched theater weapon booster or the first stage of the sea launched regional weapon) is designed to have an expansion ratio of 7 to 1, is 10.1" long and has an exit diameter of 13.5". This booster is estimated to achieve a delivered specific impulse of 253 sec. Alternatively, the nozzle for a booster firing at altitude (i.e., air launched variants and the second stage of the sea launched regional weapon) has an expansion ratio of 30 to 1, a length of 23.1" and an exit diameter of 21.4". This booster achieves a delivered specific impulse of 280 sec. All stages have nominal 27 second burn times.

The MaRV throwbody is displayed in Figure 2-5 with a representative ordnance load of 250 lbs (539 Mark 77 submunitions). GPS receive antennas are mounted on the upper two sides and rear.

Figure 2-6 shows the trajectories of the four variants, including the porpoise maneuver which converts the excess kinetic energy after reentry on the regional variants into additional range. All variants can pull high g turns in terminal phase to correct for trajectory error, to evade defenses and to tailor the target approach axis (e.g., hit the back side of mountains). Each also can deliver submunitions to a 3 km release altitude at M4.

Figure 2-4

CONVENTIONAL ATTACK WEAPON VARIANTS

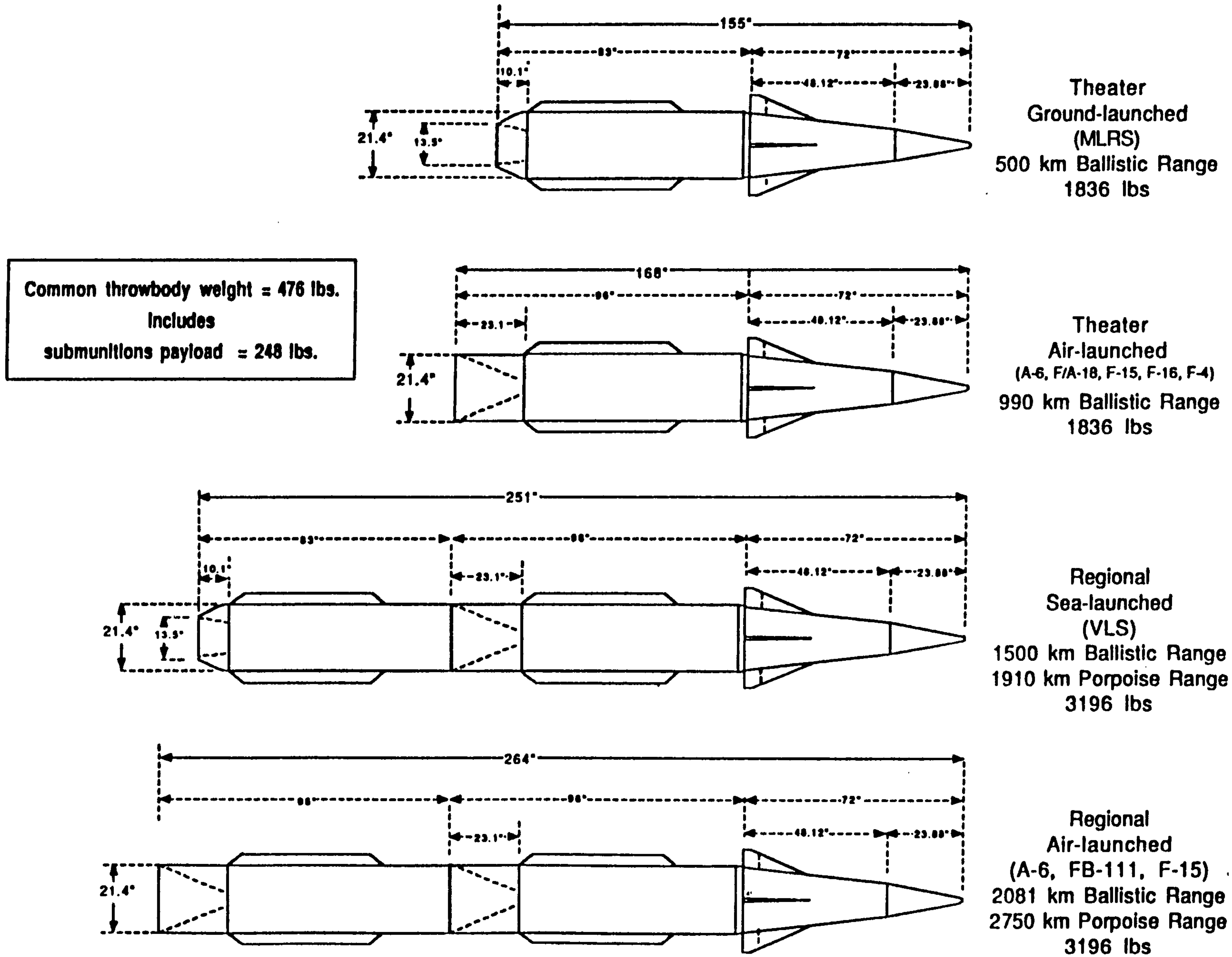


Figure 2-5

REPRESENTATIVE CONVENTIONAL MARV

CONVENTIONAL THEATER MARV WEIGHT BREAKDOWN

	lbs	lbs
Ordnance		250
Submunitions (539 Mk 77 grenades)	248	
Blow-off gas generator and skin cutter	2	
Airframe		152
Titanium nose tip	8	
Carbon phenolic skin/heat shield	80	
Munition mount & internal structure	38	
Stabilizer (4)	16	
Rudder (4)	10	
Guidance & Control		44
Battery	10	
Power conditioning & distribution	10	
Control surface actuators (4)	14	
Flight management (GPS/IMU/FCC, antennas)	10	
Margin		30
TOTAL		476

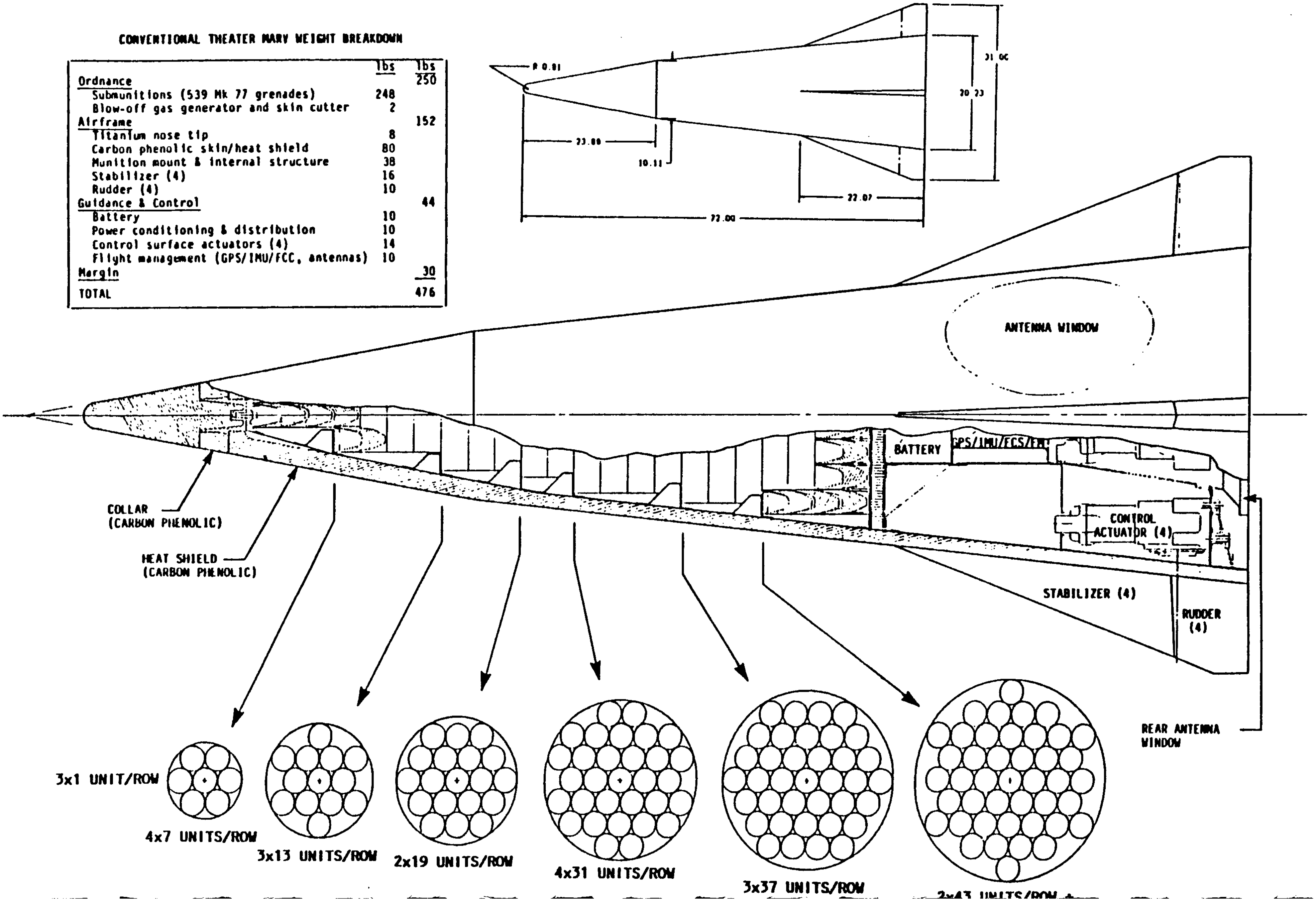
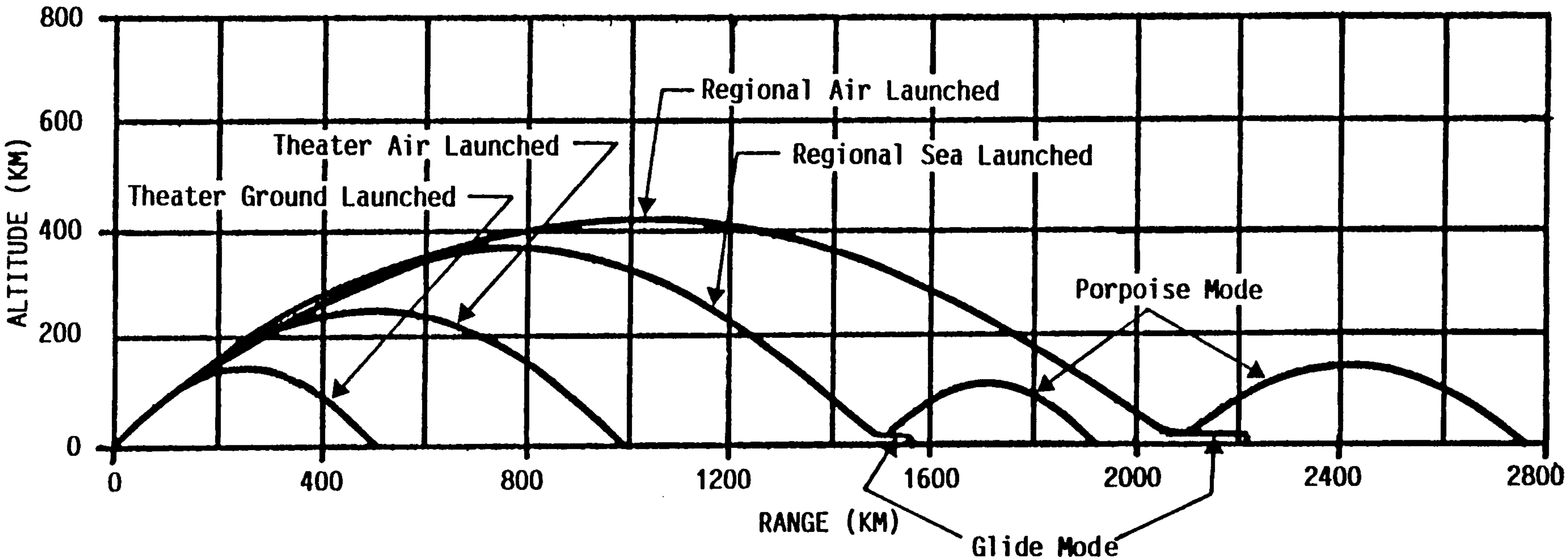


Figure 2-6

LOW-COST, PRECISION ATTACK WEAPON TRAJECTORIES



	Launch Source	Max Range (km)	Flight Time (min)
Theater	ground	500	6.3
	tactical air	990	8.3
Regional	sea	1910	15.9
	air	2750	18.7

2.3 ESTIMATED FLYAWAY COST

Cost of the precision attack weapon must be kept extremely low for two reasons:

- dollar exchange ratio - the U.S. cannot affort to attack large numbers of low value tactical targets with weapons which cost substantially more than the targets they destroy.

- budget affordability - To be pervasively applied, hence to fundamentally change warfare and to displace other force modes which currently fulfill the attack function, large numbers (>100,000 units) must be fielded.

Typical low-value targets of interest are individual parked trucks, with contained equipment, APCs, tactical command posts, SAM antennas, artillery pieces, etc. These soft and semi-soft equipments can cost as little as $50-$100K each and represent a significant fraction of the total target set. Hardened targets such as tanks, aircraft shelters, and C^3/ammo/weapon bunkers are generally much more expensive, hence are worthy of the expenditure of several low-cost attack weapons.

If the price of the attack weapon can be held down to $50-$100K, then life cycle cost of 100,000 units (flyaway, launchers, and support) can be held to $15-$30B (FY96), a tolerable amount for such a major force component.

The outlook for meeting the cost goals in large production runs is encouraging. Figure 2-7 displays cost goals for each of the major components, based on cost estimates from current programs. For example, DARPA GPS guidance package (GGP) program estimates a $15K price (15,000 units) for a 20 m CEP worst case jammed guidance subsystem. M77 submunitions for the Multiple Launch Rocket System (MLRS) were $6.75/lb in FY87, leading to a $10/lb 1996 allowance for a warhead which includes mounting structure, deployment mechanism, and submunitions. Baseline propellant was delivered in FY87 for <$2/lb and the propulsion section of the MLRS was $6.85/lb, while the flyaway MLRS missile in shipping container was approximately $10/lb. After inflation adjustment, an allowance of $15/lb is given to the propulsion module which benefits from economies of scale but suffers from all-carbon cases and thrust vector control.

A learning curve of .85 per production doubling is assumed for all subsystems except the ordnance load which would be drawn from current high-rate manufacturing sources.

Figure 2-7
LOW COST, PRECISION ATTACK WEAPON COST BREAKDOWN (1996 $)

	High Rate Reference Cost ($/lb)	Total Production Run Length: 5,000 units ($K)	10,000 units ($K)	20,000 units ($K)	40,000 units ($K)	80,000 units ($K)
MaRV Throwbody (476 lbs)	52	44.6	39.0	33.1	28.5	24.5
Warhead and Deployment (250 lbs)	10	2.5	2.5	2.5	2.5	2.5
Aeroshell and Structure	20	5.7	4.9	4.2	3.5	3.0
Control Actuators (4)	500 ea	3.8	3.8	2.8	2.4	2.0
Electrical & Power Conditioning	200	3.8	3.3	2.8	2.4	2.0
GPS Guidance Package	1,500	19.2	16.4	13.9	11.8	10.0
Integration & Test	10	9.6	8.1	6.9	5.9	5.0
Propulsion (1,360 lbs, 1-stage, Theater)	15	39.3	33.4	28.4	24.2	20.5
Propellant (1,224 lbs)	4	9.4	8.0	6.8	5.8	4.9
Case, Nozzle, TVC	115	29.9	25.4	21.6	18.4	15.6
Integration (1,836 lbs flyaway, Theater)	3	10.5	9.0	7.6	6.5	5.5
Shipping/Launch Container (Theater)	1	3.4	2.9	2.5	2.1	1.8
FOB (Theater Weapon)	28	97.8	84.3	71.6	61.3	52.3
Propulsion (2,720 lbs, 2-stage, Regional)	15	78.6	66.8	56.8	48.4	41.0
Integration (3,200 lbs flyaway, Regional)	3	18.4	15.6	13.3	11.3	9.6
Shipping/Launch Container (Regional)	1	6.1	5.2	4.4	3.8	3.2
FOB (Regional Weapon)	24	147.7	126.6	107.6	92.0	78.3

2.4 LAUNCHER COMPATIBILITY

Operational circumstance will no doubt continue to demand a multiplicity of launch sources, close-in survivable ones for time responsive shots against threatening, fleeting or moving targets, and more economical less logistically burdensome ones against less time sensitive targets (see Figure 2-8).

Careful consideration should be given to current launcher configurations such as the MLRS and the Vertical Launch System (VLS) as well as various air launch options. The MLRS launcher pod measures 32.9" high by 41.4" wide by 164" long, into which two 21.4 inch weapons can be packed by folding one of the four fins as shown in Figure 2-9. Alternatively, a two-fin bank-to-turn missile can be used to avoid fin folding entirely. Also shown is the MLRS launch apparatus (less the armored transporter) which holds two launcher pods and thus four missiles. Each pod is capable of holding 4,100 lbs, well in excess of the 3,600 lbs that two theater weapons weigh.

The VLS shown in Figure 2-10 can hold eight 21.4" diameter, 254.4" long missiles per launcher pod and eight pods per launcher, easily accommodating the 21.4" diameter, 251" long sea launched regional weapon.

Several aircraft are possible carriers for both the theater and regional air-launched weapons: A-6E, F-14A, F-15, F-16, B-1, B-2, and B-52 were considered. The A-6E is theoretically capable of carrying two theater missiles per wing pylon plus two on the belly mount with sufficient landing gear clearance for a total of ten theater missiles, shown in Figure 2-11. It is also able to carry one regional weapon per station for a total of five regional missiles, shown in Figure 2-12. But operational restrictions (due mostly to landing, will likely limit loadout to inner stations for both weapon variants.

Because these very long standoff weapon ranges provide launch sanctuary, less expensive commercially based launch platforms will likely be adopted eventually: trucks for land launch, cargo/replenishment ships for sea launch, and transport/cargo aircraft for air launch.

Figure 2-8
Compatibility with Full Spectrum of Launch Sources and Standoff Ranges

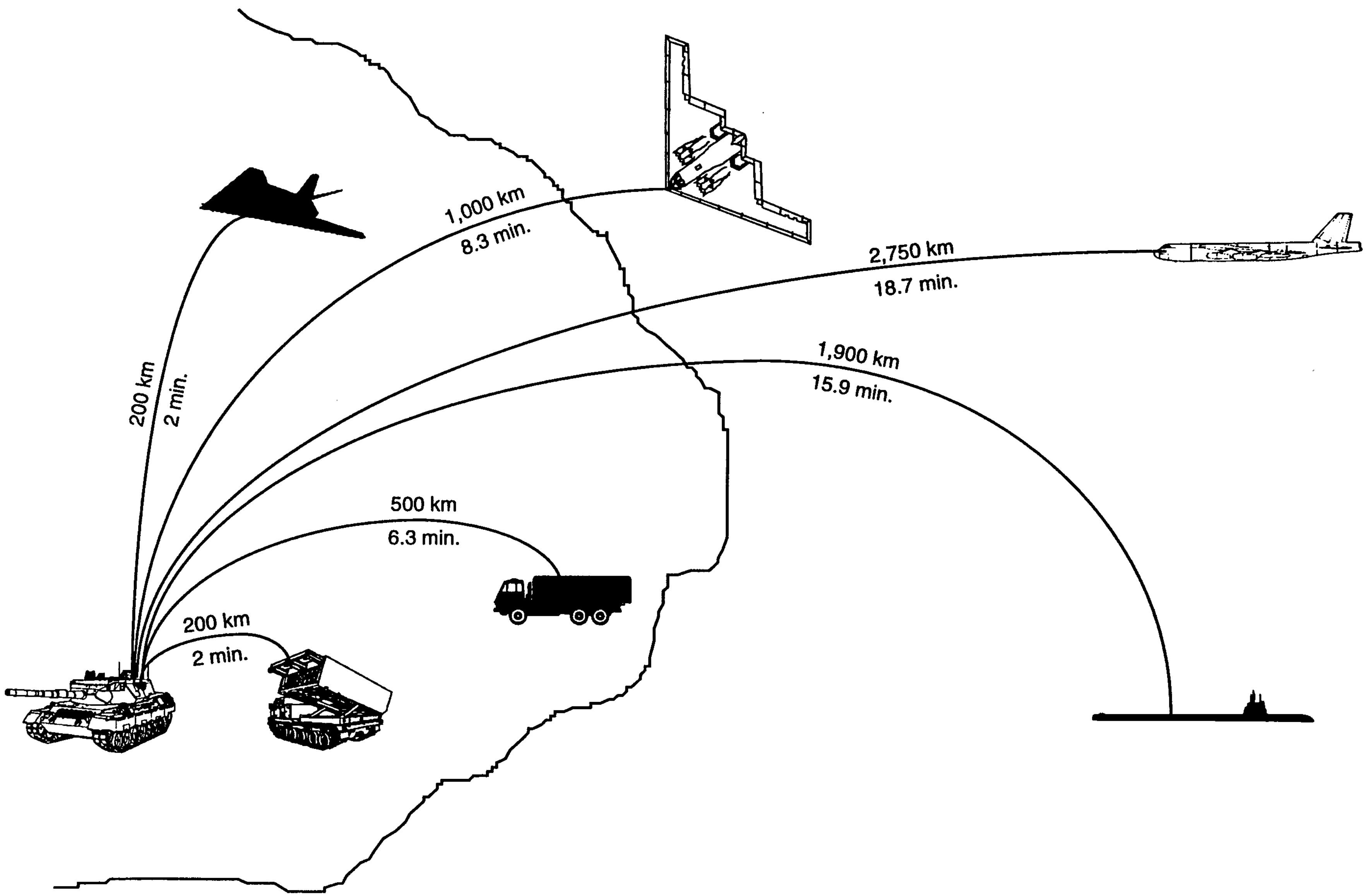


Figure 2-9
MLRS LAUNCHER AND MISSILE CONTAINER POD CONFIGURATIONS

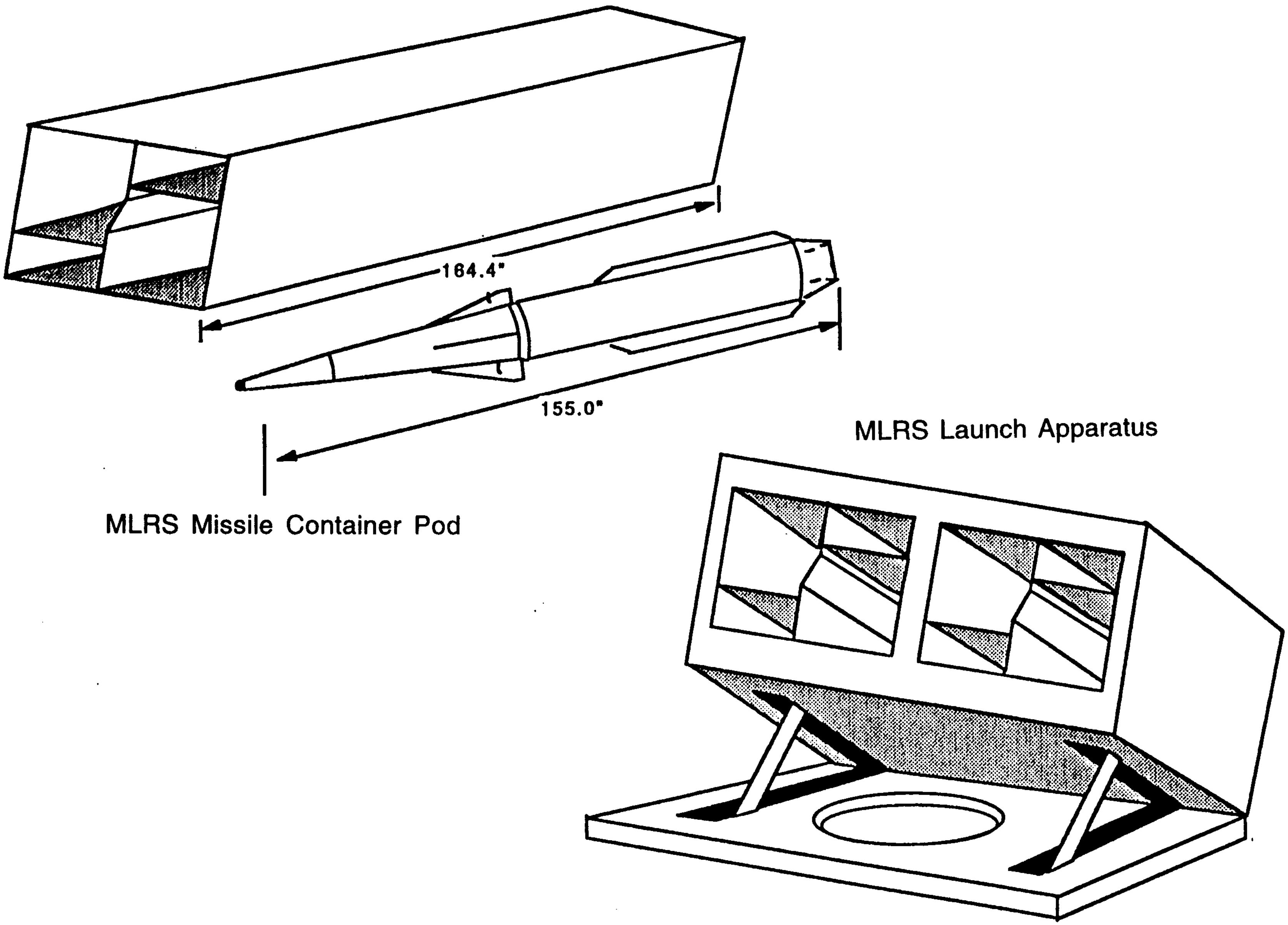
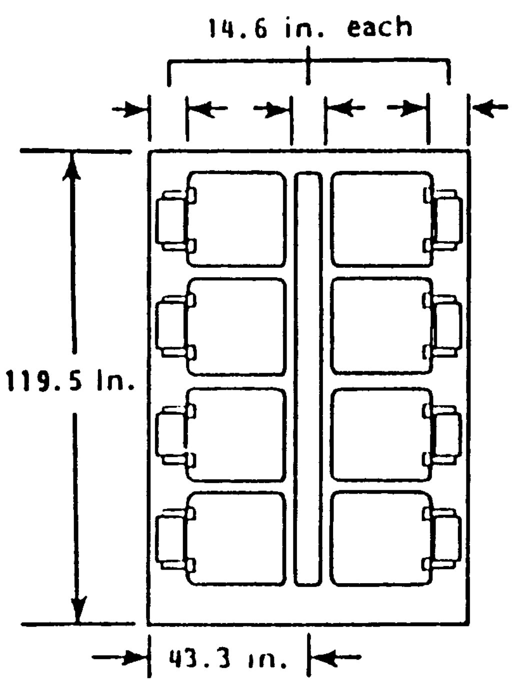
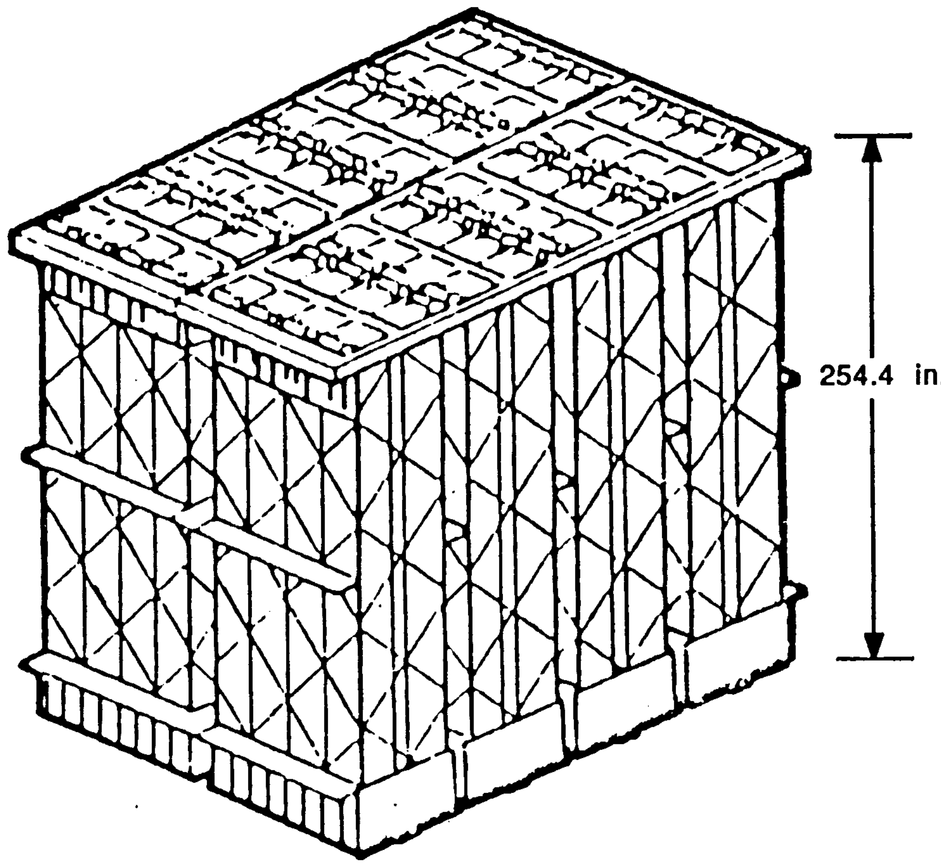


Figure 2-10

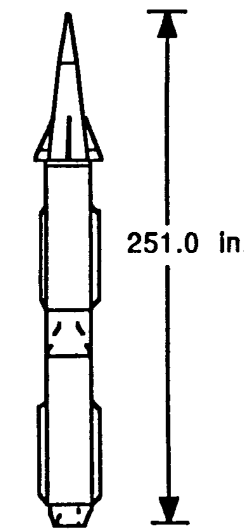
VERTICAL LAUNCH SYSTEM CONFIGURATION



Launcher Packing Dimensions



Launcher Apparatus



Sea-Launched Regional Strike Weapon

Figure 2-11
THEATER WEAPON ON A-6E

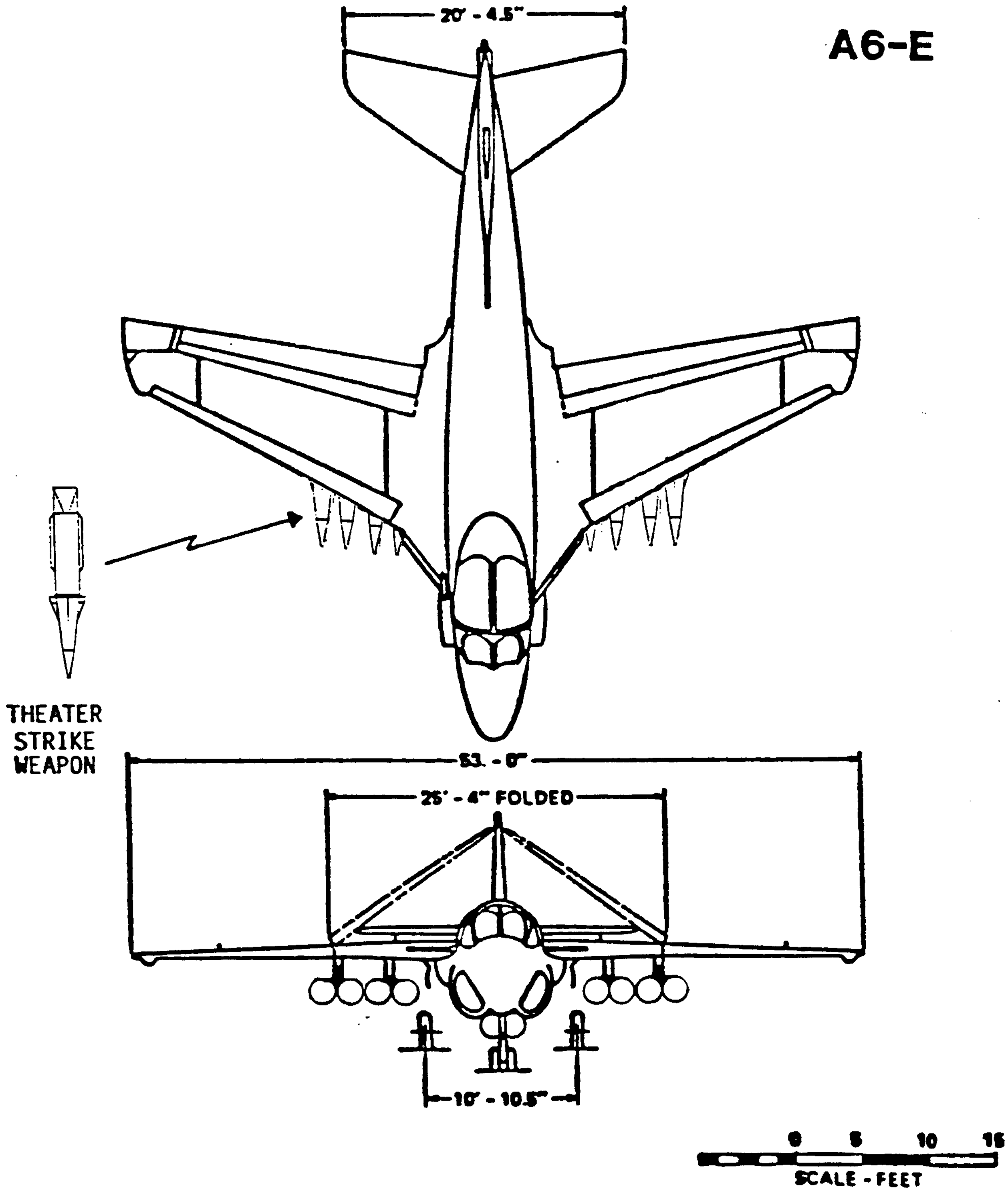
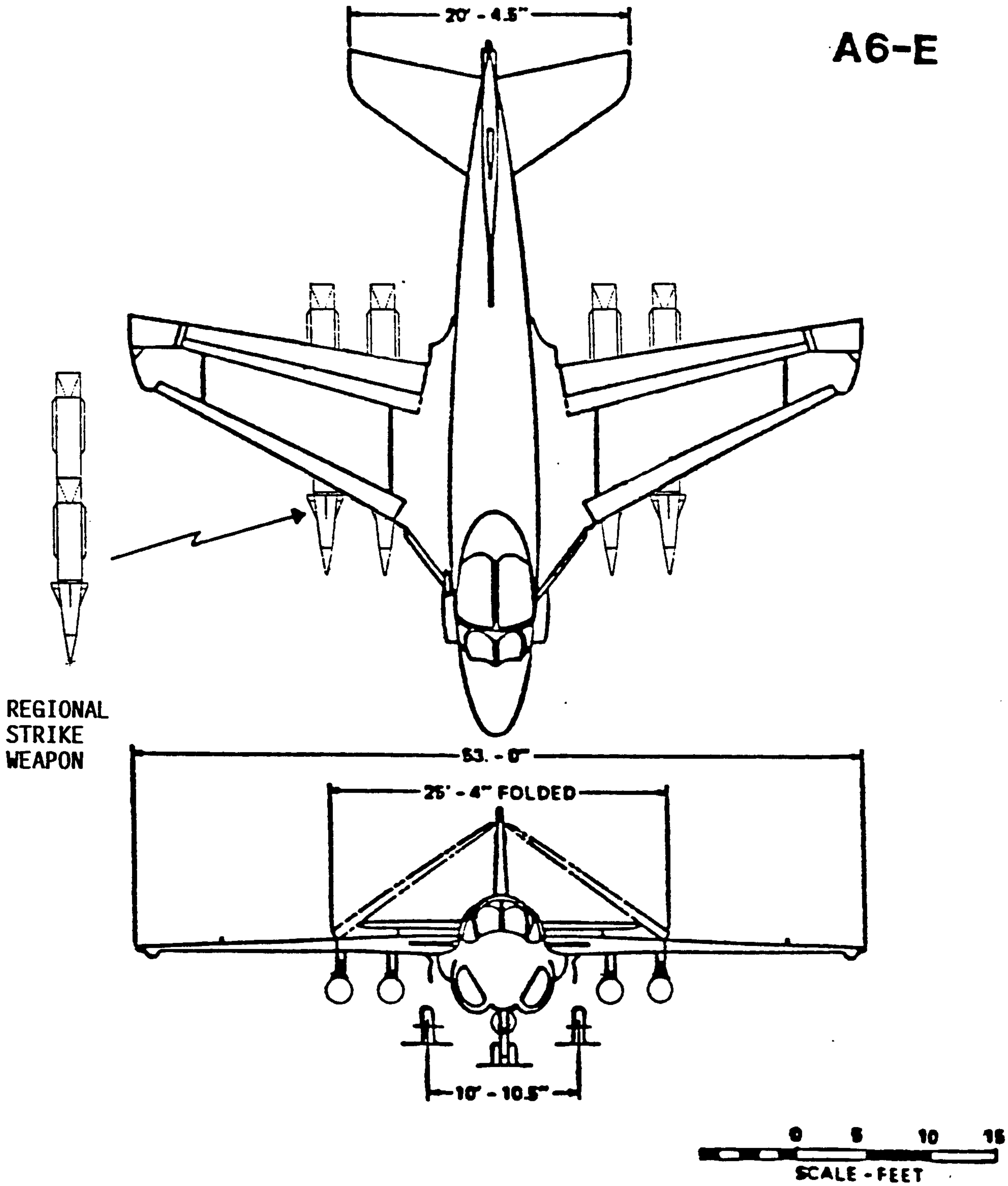


Figure 2-12

REGIONAL WEAPON ON A-6E



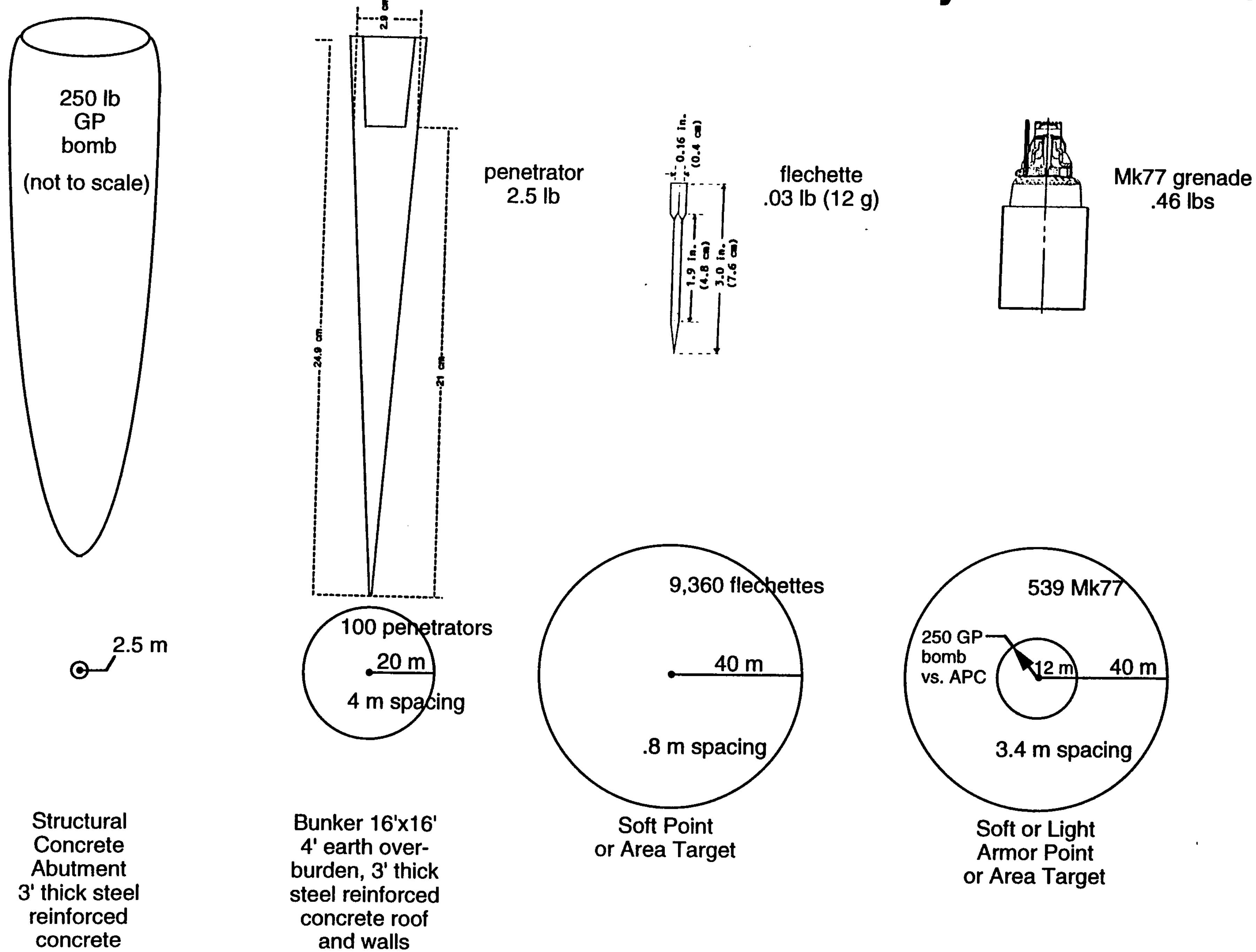
2.5 WARHEAD TAILORABILITY

If we assume a nominal 10 m CEP GPS-guided impact distribution in a clean environment with target mapping errors less than 5 m, as would be considered reasonable today, then a weapon with a 250 lb ordnance load would be adequate for most targets provided that a jammed environment did not deteriorate the impact distribution to more than 20 m CEP. Figure 2-13 displays a few of the nominal 250 lb ordnance loads which could be placed in the MaRV throwbody.

Note first that 539 Mk77 shaped charge grenades (100 mm armor piercing shaped charge and lateral anti-personnel shrapnel) with 3.4 m spacing or 9,360 flechettes (hypersonic anti-personnel) with 0.8 m spacing can be laid down in 80 m diameter patterns (i.e., football field size) to assure .95 probability (2 CEP) coverage of a severely jam-degraded 20 m CEP impact distribution. Alternatively, 100 hypersonic 2.5 lb bunker penetrators could cover with .95 probability a 20 m (2 CEP) unjammed impact distribution.

Only the very hard structural targets such as bridges and underground facility entrances would present a problem for current 10 m CEP unjammed impact distributions because a 250 lb GP bomb (for instance) needs <2.5 m standoff and preferably an orthogonal direct hit to take down even a 3' thick steel reinforced concrete abutment.

Figure 2-13. Alternative 250 lb Ordnance Laydown Patterns



3.0 FEASIBLE NEAR-TERM DEMONSTRATION PROGRAM

Because of the recent success of early ACTD low cost demonstration programs, it is instructive to estimate what a four-year schedule would cost. As seen in Figure 3-1, two years of development (including submunition dispensing, maneuvering warhead, and single stage rocket propulsion module) can, according to various experienced subcontractors, be accomplished for approximately $75M, followed by a 20 unit prototype development flight demonstration for $34M in the third year and a $26M 100-shot field trial in the fourth year, for a total of $135M.

Note that the development of DARPA's GPS/inertial Guidance Package (GGP) is assumed to be complete and available by late CY97.

Figure 3-1

Long Standoff, Low Cost Precision Attack Weapon Demonstration Rough Order of Magnitude Budget

	all figures in millions of FY 96 dollars				
	98	99	00	01	Total
Program Support	2	2	2	1	7[1]
Submunition Dispensing	5	7			12[2]
Maneuvering Warhead Vehicle	15	25			40[3]
Propulsion	5	10			15[4]
Prototype Production (20 units)			20		20
Flight Demo			10		10
System Integration	2	2	2		6[5]
Pilot Production (100 units)				15	15
Service Trials				10	10
TOTAL	29	46	34	26	135

Note: ARPA GPS Guidance Package is assumed completed by second year of this program.

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[1] 5% of program
[2] Estimate based on NSWC program
[3] WAG relative to AMBER development costs
[4] ARC estimate
[5] 5% of program

4.0 LEVERAGE TECHNOLOGIES FOR FUTURE APPLICATION

If the universe of potential standoff weapon improvements is listed as in Figure 4-1, then only five areas look worthy of pursuit for big gains, since all others are mostly a matter of design. These are the three factors affecting geodetic targeting impact accuracy (namely, GPS guidance accuracy, GPS countermeasure resistance, and target localization accuracy) and the two factors influenced by improvement in chemical energetics (namely, warhead explosive yield and propellant Isp).

Figure 4-2 illustrates three points about guidance accuracy improvements:

- impact accuracy is the single highest leverage area available for point targets - ordnance weight, hence throw weight, hence missile size, hence missile flyaway cost goes approximately as the square of the required lethal pattern radius for submunitions at a given areal density or the cube of the standoff radius for monolithic HE.

- programmed or expected improvements in GPS ephemeris and receiver accuracy will reduce CEP to less than 2 m in an unjammed environment without heroic development effort - WAGE 1, 2, and 3 improvements and normal receiver technology advances will bring about this 2-5 fold reduction.

- the fiber optic inertial unit in DARPA's GGP should hold jamout impact distribution deterioration to ≤3 m - GGP is expected to give .003/hr drift and not worse than 0.3 nm/hr in a high "g" terminal maneuver.

If, as expected, surveillance imagery from space and airborne sources and long baseline SIGINT from airborne sources can be registered to 1 m CEP accuracy in reasonably feature-rich, keystoned geographies, then overall target localization CEP can be held to ~2 m CEP.

Therefore, if high quality anti-jam antennas and clock can be incorporated with the GGP, such as to hold onto GPS lock until 20 seconds (40 km) prior to impact, then 3 m CEP impact distribution in a jammed environment are not beyond hope.

Figure 4-2 and Figure 2-13 combine to demonstrate that unlikely improvements in high explosive energy density (factors of 2-4) result in only small lethal radius improvements (factors of 1.26-1.59). These gains would still be markedly inferior to submunition lethality per weight against soft and armor, point and area targets. Further, these mild factors help only slightly against deep underground and structural targets. Accuracy remains the dominant lever.

The same unlikely factors of 2-4 in energy density if translated into mass Isp improvements in propellant (factors of 1.4-2) would give noticeable reduction in missile weight (33%-50%), but not nearly that offered by foreseeable guidance improvements (see Figure 4-3).

Figure 4-1
LEVERAGE AREAS FOR STRIKE WEAPON IMPROVEMENTS

Payload Size

- delivery precision
  - guidance accuracy
  - countermeasure resistance
  - target localization accuracy
- lethal area per ordnance weight
  - explosive energetics
  - dumb submunition areal density and kinetic energy
  - smart submunition capture area
- response time

Delivery Efficiency

- propulsion technique
- fuel energetics
- ordnance payload wrap factor

Terminal Phase Flexibility

- approach path diversity
- impact velocity

Transit Survivability

- observables
- transit velocity and trajectory profile
- evasive maneuverability

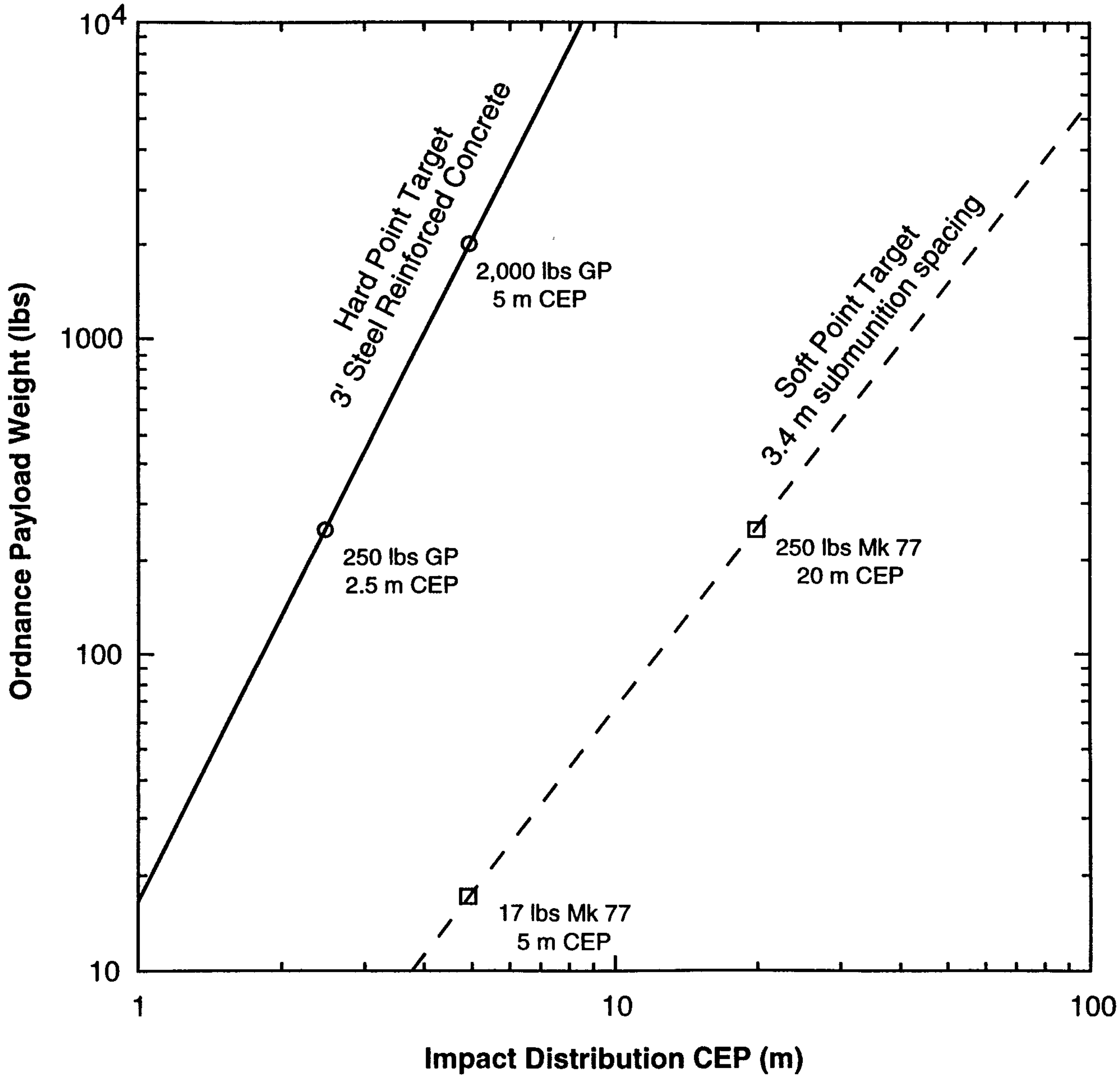
Launcher Survivability and Economic Burden

- compatibility with most air, land, sea platforms
- standoff range
- weapon weight and size

Flyaway Cost

- guidance
- propulsion
- production run length
- modularity/tailorability

Figure 4-2
WEAPON PAYLOAD VS. GUIDANCE PERFORMANCE

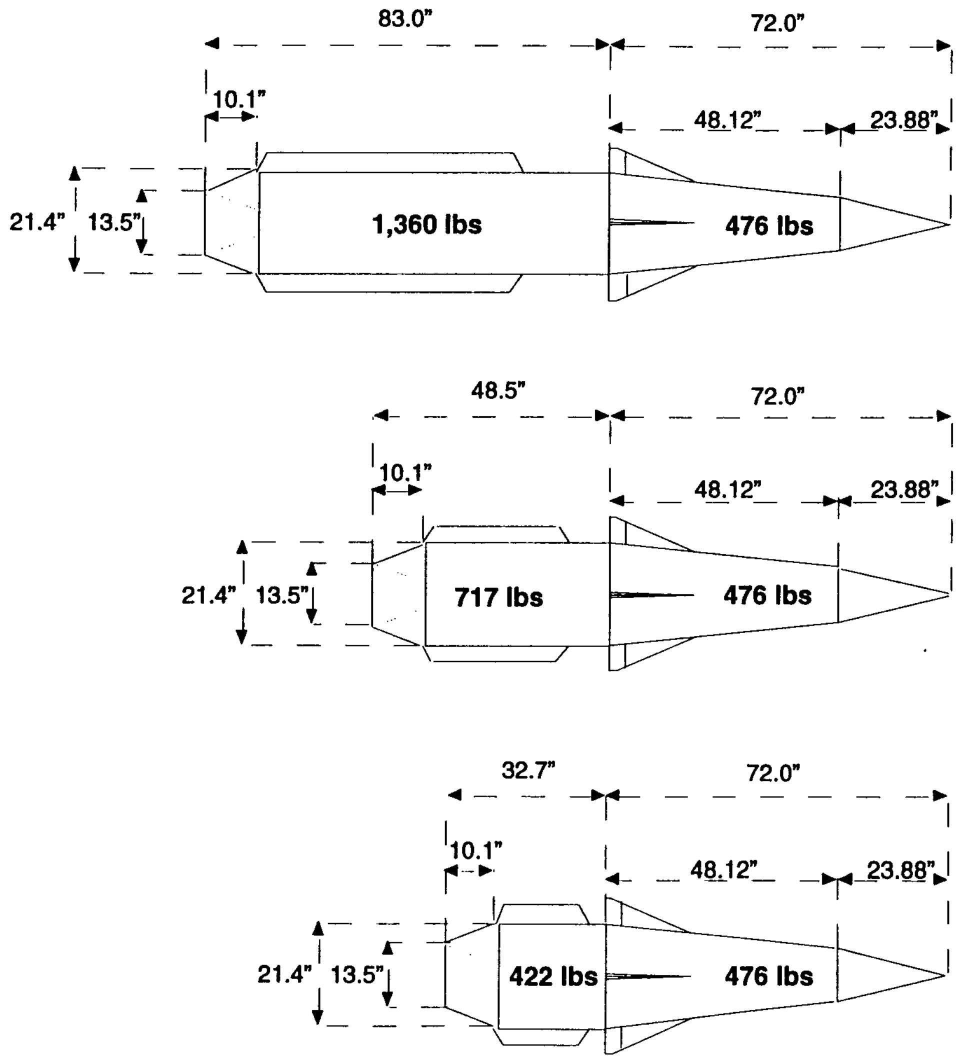


	Non-Differential GPS Unjammed	
	CEP (m)	SPE (m)
Advertised	10	16
Achieved	4.0	6.8
WAGE 1	3.2	5.6
WAGE 2	2.7	4.8
WAGE 3	2.4	4.3
Next Gen.	1.4	2.4

Impact Point Deterioration in Jammed Environment

Loss of GPS Signal		Inertial Drift	
Time to go (secs)	Distance to go (km)	1 nm/hr (m)	0.3 nm/hr (m)
20	40	10	3
40	80	20	6
60	120	30	9

Figure 4-3
Impact of Increasing Effective Propellant Isp on Weapon Size



Current Effective Propellant Isp (Sea-Level Launch)

Propellant Isp of 254 seconds
Launch weight of 1,836 lbs

1.4 Increase in Effective Propellant Isp

Propellant Isp of 359 seconds
Launch weight of 1,193 lbs

Doubled Effective Propellant Isp

Propellant Isp of 508 seconds
Launch weight of 898 lbs

Common throwbody weight = 476 lbs

Submunitions payload = 248 lbs

5.0 CONCLUSIONS ABOUT STANDOFF PRECISION STRIKE WEAPONS

5.1 AFFORDABILITY

Highly target-adaptive, extremely rapid response, maneuverable ballistic weapons, compatible with all current land, sea, and air launchers and treaty compliant, can be produced for less than $100K flyaway provided that long production runs of >5,000 units, modular configuration, and high grade inertial/GPS guidance (no homer) are adopted:

Missions Served	Launch Source	Standoff (km)	Flight Time (min.)
close support and suppression of enemy air defense	tactical air	200 1,000	<1.5 8.3
	ground	200 500	1.5 6.3
deep strike and interdiction	ship/sub	1,910	15.9
	strategic air	2,750	18.7

5.2 GUIDANCE IMPROVEMENT POTENTIAL

The largest leverage for further life cycle cost reduction for strike of point (not area) targets is provided by improved impact accuracy (and consequent ordnance throw-weight/missile size and weight reduction) with GPS WAGE 3 ephemeris improvements, receiver clock and antenna jam resistance, and high grade inertial (GGP):

	Unjammed CEP (m)	Jammed CEP (m)
Current GPS with 5 m map registration, 1.0 nm/hr inertial drift	10	20
WAGE 3, 1 m map registration, and 0.3 nm/hr inertial drift	<2	<3

Submunition ordnance load can be reduced to <10% (25 lbs) of nominal 250 lbs for a yet better areal density laydown pattern. All up missile flyaway cost could be <$30K and weight less than 320 lbs vs. 3,200 lbs for the 1,900-2,750 km surface and air launched two-stage variant.

5.3 ENERGETICS IMPROVEMENTS

Near term chemical improvements in propulsion Isp of solid propellants are focused on improved volume energetics, not mass energetics. This does little for missile weight/cost, hence is not viewed as a make a difference improvement. Similarly, the greater "lethality per mass" of submunitions vs. monolithic HE for all strike targets except deep underground and massive structures (e.g., bridges), prevents even 2-3 fold improvements in HE energetics from delivering across the board gains in all up missile affordability or performance.

5.4 DEEP UNDERGROUND AND STRUCTURALLY HARD TARGETS

Because of the unpromising future for brute force HE warhead improvement, the technology of penetrators, void fuzes, and residual lethality enhancers deserve special attention.

INFORMATION REQUIREMENTS FOR HARD TO DEFEAT TARGETS

White Paper

E. Sevin, Consultant

Information Requirements for Hard to Defeat Targets

The tactical targets considered in Scenario III, "Operations in Urban Settings", as well as in Ira Kuhn's proposed precision attack weapon, include a class of what can be termed "Hard to Defeat" targets. These are fixed facilities which are intended to survive the damaging effects of an attacking (non-nuclear) weapon either through structural hardening, burial, and/or other blast-mitigating construction (e.g., C2/Weapon Bunkers or tunnels), or through damage avoidance by limiting the attacker's options to control collateral damage (e.g., BW/CW production/storage facilities and other WMD targets, targets located in population centers) and/or through CCD techniques. For particularly high value targets, these passive defensive tactics may be combined and supplemented by active air defense. As a consequence, the military planner is forced to reconsider basic information requirements concerning target intelligence, damage criteria, and weapon attributes. This note elaborates on these requirements.

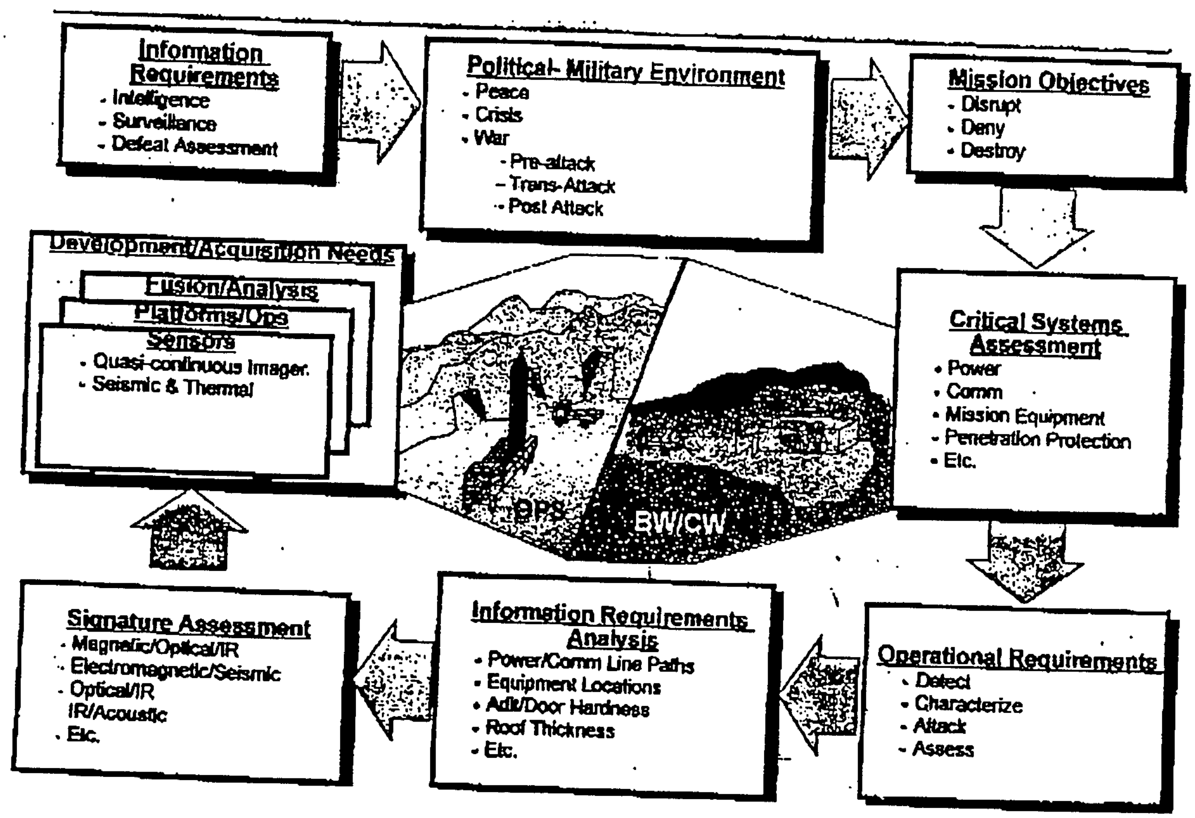
Typically, the military objective in attacking a target is to destroy it. From a targeting perspective, this is the equivalent of achieving a severe physical damage objective (i.e., the facility must be essentially rebuilt to perform its mission) with high probability ($SSP_k > 0.95$), and confirmation through unequivocal post-attack BDA. For non-nuclear weapons against buried, structurally hardened targets, this level of damage usually is associated with being able to detonate one or more warheads within the facility. If this cannot be achieved with confidence, then it becomes necessary to consider alternative damage objectives such as mission disruption or denial (e.g., hours-to-days down time). The probability of successful attack under these circumstances, as well as confident BDA, depends strongly on the quality of target intelligence information, pre-, trans-, and post-attack, including knowledge of mission functions and concept of operations, facility construction details, equipment layout and details, etc.). From an attack weapon perspective it means precision delivery, "smart" fuses, and (perhaps) "enhanced" payloads.

A series of target functional damage workshops conducted by DNA and the Services during the past year emphasize these points. Both exemplary and real targets—C3I Command Post, BW and CW storage bunkers, Missile Storage Tunnels, and a Nuclear Power Plant—were selected to cover an interesting range of resistance to weapon penetration, functional complexity, and collateral damage risk. On this basis it was concluded that

- Hardening is an effective passive defense measure against non-nuclear weapons
- Hard targets are proliferating; underground construction technologies are available worldwide and improving
- Functional damage may be scenario dependent, requiring detailed intelligence information
- Penetrating weapons can damage many, but not all, types of underground targets; they must detonate inside the facility to be effective; a smart fuse that can sense void areas is required
- R&D should be focused on improved penetrators, enhanced payloads, and means of defeating tunnels

Work currently is underway to more fully define intelligence, surveillance, and defeat assessment requirements for hard to defeat targets. This effort supports OSD's Milestone 0 Concept Exploration activity for Hard and Deeply Buried Target Defeat Capability, and is complemented by the CIA's activities to identify improved means for remotely detecting underground targets. The general approach is target-centered; that is, individual target types are analyzed from a mission/functional perspective in which target elements critical to mission performance are first identified, characterized as to exploitable vulnerabilities (i.e., Achilles' heels) and associated observables, and finally related to signature determination and applicable sensor/platforms. This process is depicted in the attached chart.

Intelligence, Surveillance & Defeat Assessment Requirements



The core of this activity concerns an information requirements analysis based on assessment of mission-critical systems comprising the target facility. The range of this analysis is indicated in the following chart.

Information Requirements Analysis

Information Requirements

- Location
- Size
- Hardness
- Spares
- Design, Performance
- CCD
- Connectivity
- CONOPS
- Signatures

Information Requirements Depend On:

- Target Function
  - WMD - C^3I - Missile
  - Production - Storage - Operations
- Nature of Assessment
  - Detect - Characterize - Attack - Assess
- Attack
  - Disrupt - Deny - Destroy
- Type of Attack
  - Penetrate - Non-penetrate
  - Internal - External
- Type of Weapon
  - EG: Large HE - Small HE
  - EG: EMP - Contaminants
- Weapon Accuracy

The critical systems assessment serves to identify individual elements associated with each system which might provide an exploitable vulnerability, especially as it may constitute a single mode of failure. An example of this is shown in the table below for a representative communications system.

Critical Systems Assessment

Critical Systems

- Penetration Protection
- Structure
- Power
- Communication
- Mission Equipment
- Environment Control
- Environs

Critical Element Examples (for Communications):

- Transmitters
- Switch Rooms
- Cables / Vaults / Pull Boxes
- Antennas
- Computers
- Modems
- UPS
- EMP Filters
- Entry Points
- Tech Control Center

Criticality Depends On Facility Function

Penetration/non-penetration is the key to target information requirements. Penetration is possible for many bermed bunker and shallow buried facilities. For penetrating munitions with warheads not exceeding 50 or so pounds of explosive, severe blast damage probably will be confined to the rooms immediately adjoining the detonation room. Information requirements, therefore, concern the exterior protection design (e.g., berm geometry and material, burster slab description, walls and doors, etc.), interior room layout, roof and floors, equipment fragility, etc.). Information of this nature is summarized in the attached table (To be completed).

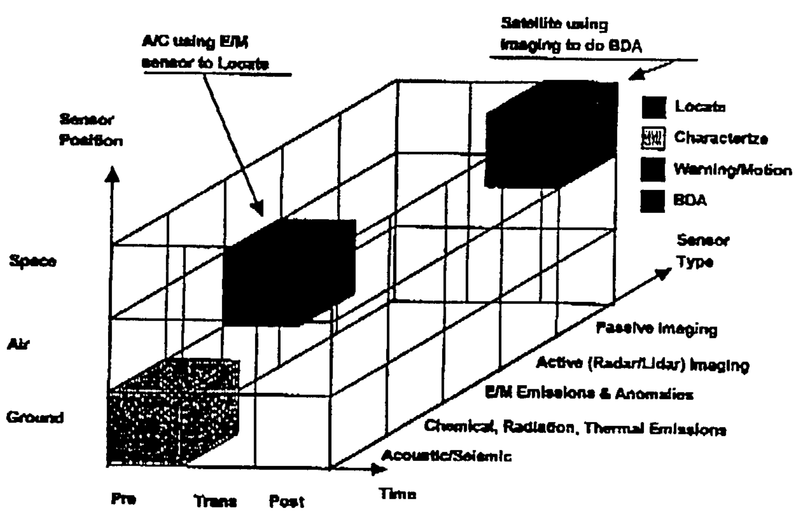
Information Requirements Summary

Exterior	System/Element	Interior
	Protection	
	Structure	
	Mission Equipment	
	Operations	
	Communications	
	Power	
	Environmental Control	
	Environs	

Note, that unless the aimpoint was known to house mission-critical equipment, multiple weapon attacks must be presumed against multiple compartmented targets. Where penetration is not possible or practical, other types of critical elements must be identified and attacked as suggested in the above table.

The signature assessment phase depends on exploitable observables identified earlier in the analysis, and relates to military objectives (disrupt, deny, destroy) and operational requirements (peacetime/crisis: detect, characterize), trans-attack (warning/motion, weapon performance), and post-attack (BDA). This leads to a discrete 3-dimensional "sensor/platform" space whose axes are Time (pre-trans-post attack), Sensor Position (space, air, ground), and Sensor Type (acoustic/seismic; chemical/radiation/thermal emissions; E/M emissions & anomalies; active (radar/lidar) imaging; passive imaging). A graphical depiction of this is shown in the attached chart (courtesy of Harold Rosenbaum).

World of Surveyor



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GPS CAPABILITY PROJECTIONS

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29 March 1996

GPS Capability Projections

Introduction

The Global Positioning System (GPS) has emerged as a low-cost, highly accurate location and navigation system for a wide variety of military applications. Since GPS relies on relatively low-power signals transmitted from high altitude satellites, missions which require user equipment to operate close to high-power jammers, or in forested areas where foliage attenuation reduces the L-Band GPS signal level, are at risk. Advanced GPS receivers with adaptive nulling antennas and highly integrated inertial measurement units are beginning to address the jamming issue; other location/navigation approaches which do not depend on GPS, such as low cost, high-precision, highly stable inertial systems may be required to address the signal attenuation concern. This paper summarizes the current GPS capabilities, discusses potential enhancements, and outlines operational approaches which could alleviate some problems in the field. It is a complement to a paper on accurate, inexpensive guidance systems which could serve as alternatives during GPS outages whether they be due to jamming or reduced signal levels.

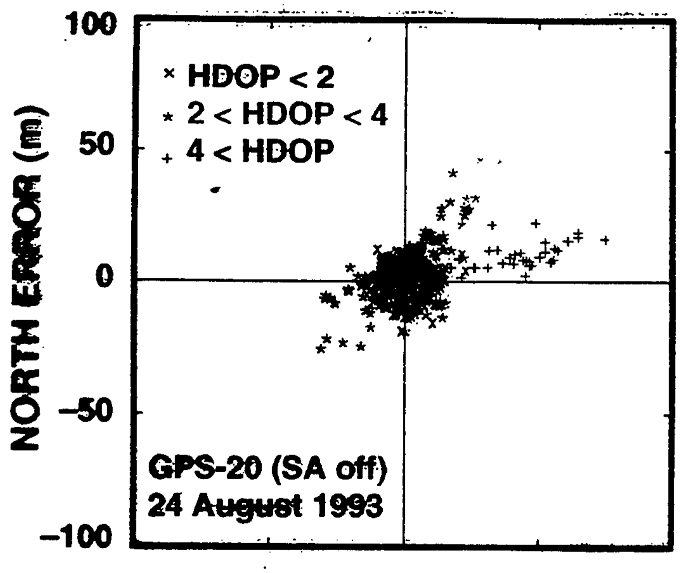
Current GPS Capabilities

GPS is a space-based navigation and location system using a constellation of 24 satellites in 12-hour, 20,000 km orbits. The orbits themselves are precisely known: at any instant each satellite position is known to 3 m accuracy. Each satellite transmits low power, L-Band, spread spectrum signals. Especially designed user equipment can receive these signals even though they are below receiver noise, lock up to them and track code and carrier phase. Signals at two frequencies (L-1 at 1575 MHz, L-2 at 1227 MHz) are transmitted simultaneously to permit ionospheric corrections by the user equipment processor.

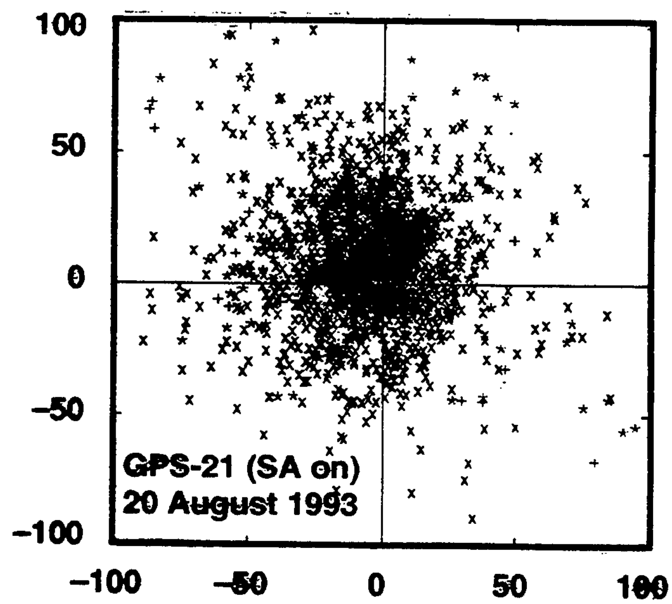
Two types of signals are transmitted at L-1, an encrypted 10 Mbit/s (P(Y)) signal for military use, and a 1 Mbit/s clear/acquisition (C/A) signal for unrestricted tracking and for use by decryption-equipped users in acquiring the military signal. At L-2, P(Y) is the only signal transmitted. With these signals, the military user can track ten times more accurately than can the civilian user who is limited to the C/A signal; further, the military user can track signals at both frequencies and obtain ionospheric corrections to enhance his precision.

Tracks of four satellites allows use equipment to estimate the corresponding four pseudoranges (each containing a common bias due to clock error) from which position and clock error can be computed by multilateration methods. With this approach, a user could ideally estimate his position to about 10 meters CEP using the C/A code on L-1 alone. But as this capability became widely accessible, even to an enemy GPS user, an intentional distortion (selective availability (SA)) was added to the C/A signal increasing the achievable CEP to 30 meters. At present, SA is included on the L-1 signals, although the U.S. has announced its intention to remove SA in 10 years time. Figure 1 shows a scatter plot generated by civilian GPS receivers using C/A signals with and without SA.

As indicated above, the GPS signals are very weak, ~ 10^{-16} Watts reaching a receiver at the earth's surface. Contrast this to the noise level in a 1 MHz bandwidth receiver with a 3 dB noise figure, ~ 10^{-13}. The only way such weak signals can be tracked is though their spread



(A) SA off



(B) SA on

Figure 1. Position Estimates From GPS and Glonass (1-Minute Samples Over a Day)

spectrum coding and a coherent integration process which collects all energy from the signal over the entire coherent integration interval. Processing gain can be obtained when the signal structure, including carrier phase, is precisely known. As a result, users with decryption equipment can benefit from processing gain on the more precise, but encoded, P(Y) signal while others cannot.

The low level of the GPS signals makes them susceptible to jamming. When the user equipment approaches a jammer, the receiver has difficulty acquiring and tracking the GPS signals. Of course, the range at which this occurs depends on the power transmitted by the jammer and on the user equipment function in question. This range also depends on the user equipment design details and can vary significantly. Some receivers designed for use on maneuvering aircraft must compensate for platform motion by coupling the GPS receiver to the aircraft inertial measurement unit (IMU); with such a receiver, the jamming range depends on the quality of the IMU. Some user equipment is intended to operate close to high power jammers; in that case, aggressive antenna systems may be included in the user equipment suite to assure continued GPS operation. Figure 2 shows the jammer-to-signal power ratio as a function of the range to a jammer with the specified transmitted powers. The range at which various user equipment functions are lost due to jamming can be approximated by entering this graph at the J/S level associated with loss of each specific function. Some representative J/S thresholds are listed in Table 1.

Table 1 J/S Levels for Representative GPS Receiver Functions

Function	J/S (dB)
C/A Code Acquisition	27
P(Y) Code Acquisition	35
C/A Code Lost Lock - Conventional Receiver	47
P(Y) Code Lost Lock - Conventional Receiver	54
P(Y) Code Lost Lock - Advanced Receiver	65
Conventional Receiver with Nulling Antenna	79
Advanced Receiver with Nulling Antenna	95

One can see, for example, that a 100 Watt jammer can deny C/A code acquisition out to 100 km. Such jamming effects have motivated strong interest in GPS user equipment anti-jamming enhancements. Some of these will be discussed in the next section.

Advanced Receiver Projections

Many improvements to the currently available military (encryption equipped) GPS receivers have been suggested; some have been demonstrated. The key GPS user equipment shortcomings addressed have been:

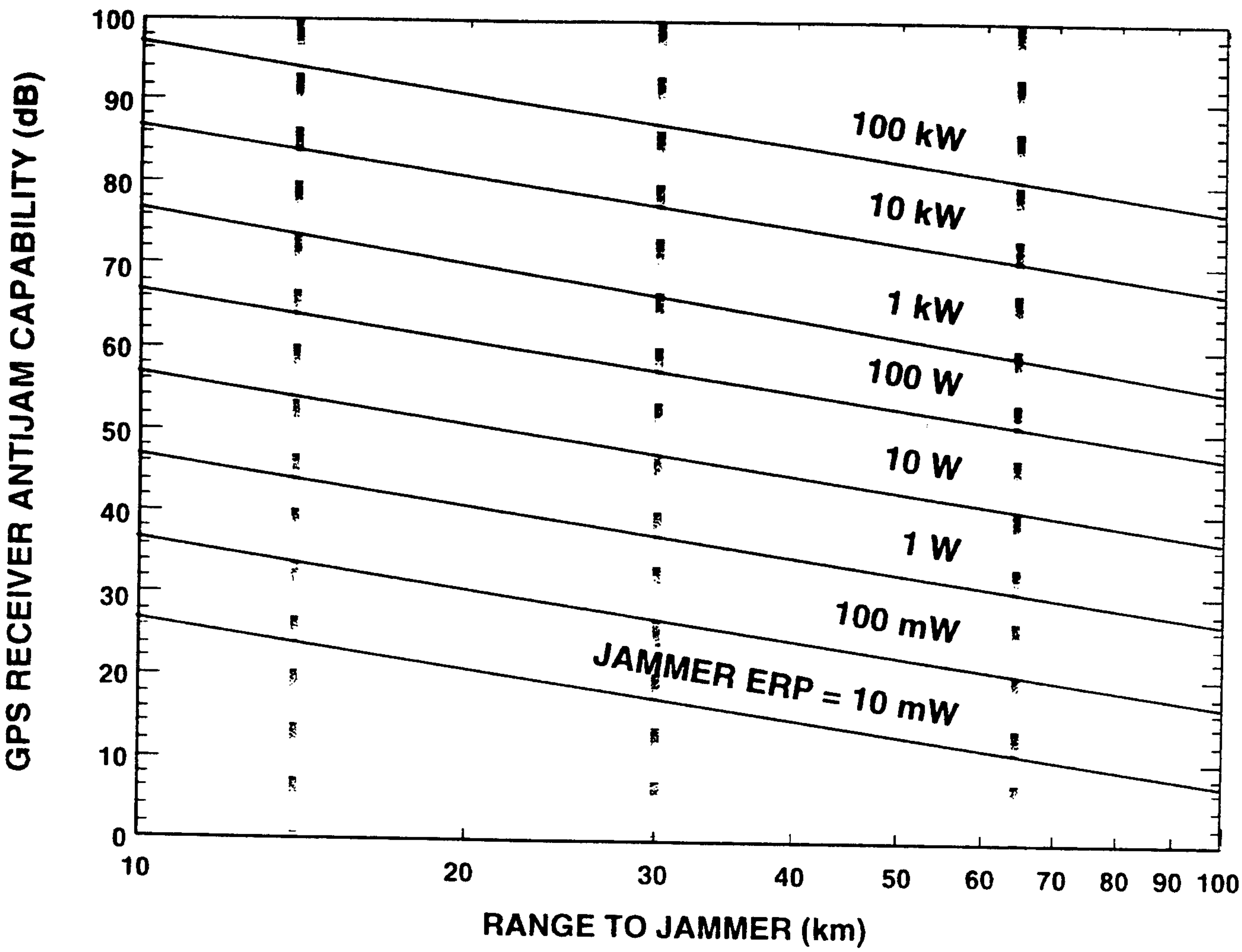


Figure 2. GPS Jamming Calculations

Increased Integration Time. As indicated above, the user receiver must coherently integrate the GPS signals to obtain processing gain. Doing so requires knowledge of the signal phase. As the integrating receiver is tied more closely with the aircraft IMU, and that IMU's quality improves, the phase is more accurately included in the integration process; integration time and coherent integration gain increases, and jamming resistance is enhanced. A more advanced GPS receiver is expected to be 11 - 16 better than a conventional one as a result of this closer receiver-IMU coupling.

Multiple Correlators. As indicated in Table 1, signal acquisition is one of the weaker receiver functions. Furthermore, under many operational circumstances, even most decryption-equipped military receivers must acquire the C/A signal first. This problem motivates a receiver which can directly acquire the P(Y) signal. But doing so requires that many P(Y) code epochs must be tested for correctness as part of the acquisition process. A receiver with a large number of correlators can test many code epochs in parallel, allowing the receiver to rapidly examine all possible code epochs within its time uncertainty. Integrated circuits with thousands of parallel correlators have been fabricated; these should find their way into operational receivers in the next 5-7 years.

High Accuracy, Miniature Clocks. Direct P(Y) acquisition can be accomplished quickly if there is little initial time uncertainty. Cesium standard clocks, packaged in a few cubic inches, are being developed for tactical use and should also become common components of GPS receivers in 5-7 years.

The enhancements associated with increased integration time will also contribute to more jam resistant acquisition as the ability to search for correct P(Y) code phase improves. Longer integration time, and less initial doppler uncertainty, will increase the acquisition threshold above the 35 dB level listed in Table 1. Still, there are limits to integration gain since the 50 bit per second data included in the GPS signal format creates phase uncertainty. Methods such a "data-aiding" or equivalently "data-wiping" may provide a few more dB of acquisition immunity once high accuracy IMUs and precision clocks are included in a receiver design.

Antenna-based Enhancements

All GPS receiver functions will benefit from antennas which provide some gain in the direction of a satellite, and simultaneously place nulls on jammers. Several approaches to this form of increased jamming resistance are being developed; some early versions are already in use.

Adaptive Nulling Antenna. These antennas can place deep nulls in the directions of several strong jamming sources. As a result, jamming power reaching the receiver is attenuated sharply. The adaptive nulling antenna relies on differences in the direction of arrival between the desired GPS signal and the undesired interference. With these methods, interference can be rejected by 20 to 50 dB or more; as long as there is sufficient angular displacement between the GPS signal direction and that of the interferer, there is little degradation to the GPS signal power. Fortunately, such conditions are typical of the geometries relevant to most GPS jamming scenarios.

The Controlled Radiation Pattern Antenna (CRPA) with its antenna electronics unit (AE-1) uses a seven-element array (see Figure 3) and adaptive nulling processing to provide AJ protection in a hostile environment, while maintaining good GPS performance in a benign environment. This nulling system is used on the F-15, F-16, and other Air Force platforms today. Based on extensive testing, it is appropriate to assume that the CRPA can contribute, on average, 25 dB to the jamming resistance of airborne GPS user equipment when a small number of jammers generate the interference.

Performance enhancements to this system are being investigated. These focus on 1) providing gain in the direction of a specific GPS satellite, 2) more effective nulling patterns in the presence of multiple interference sources, and 3) enhanced gain in the direction of low-elevation satellites even when nearby jammers are nulled. These enhancements should provide a more robust 25 dB jamming rejection when multiple jammers are present, and 40 dB nulling when a small number are threatening.

Low-elevation Antenna Patterns. Antennas can be designed to operate in two modes: in the normal mode, with no anti-jamming (AJ) capability, the antenna pattern is designed to optimize horizon-to-horizon coverage for maximum satellite acquisition capability when no jammers are present; in the AJ mode, the low-elevation coverage is sacrificed to attenuate the ground-based jamming signals relative to the (generally) overhead satellite signals. It is expected that these two modes will be switch selectable.

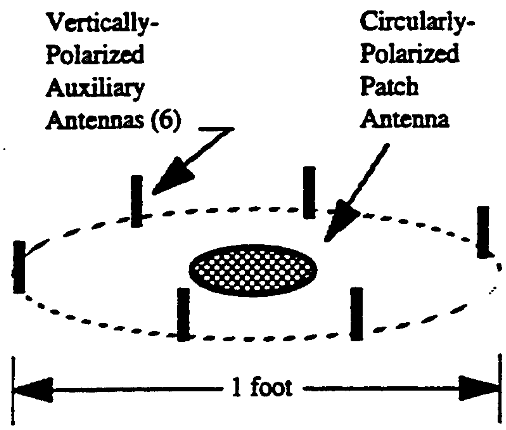
Figure 4 conceptually illustrates this approach to antenna design. A jammer at the horizon or below will be attenuated at least 20 dB compared to a satellite above 20° elevation.

Airframe Body Shielding. Typical aircraft GPS installations place the antenna on the upper surface of the airframe where there is usually a clear line-of-sight to the GPS satellite constellation. When the aircraft is in level flight, any ground-based jammers will be at the horizon or below, implying that the airframe will often lie between the aircraft GPS antenna and the ground-based jammer; this geometry should significantly shield GPS from the jamming interference.

Surprisingly, this shielding has not been accurately quantified with careful measurements of GPS antennas installed on full-size airframes. Most antenna measurements appear to have been made with full-size antennas mounted on relatively small sections of a simulated fuselage. These measurements were planned to provide accurate estimates of the GPS antenna gain and mainlobe shape, but not the shielding provided by the entire airframe. Unfortunately, it is difficult to model the airframe and antenna accurately at GPS operating frequencies; thus reliable computer model estimates of airframe shielding are not available either. Figure 5 gives an example of how much body shielding is obtained on a test Falcon-20 aircraft; 15-20 dB average rejection is representative.

GPS Receiver Startup Issues

Before a GPS receiver can provide navigation and location information, it must lock up to at least four GPS satellite signals and estimate their pseudoranges. This synchronization process is normally carried out by locking to the periodic C/A signal, a relatively easy task in a benign environment. When the jamming levels preclude acquisition of the C/A signal, the user



(Unclassified)

Figure 3. Controlled Radiation Pattern Antenna

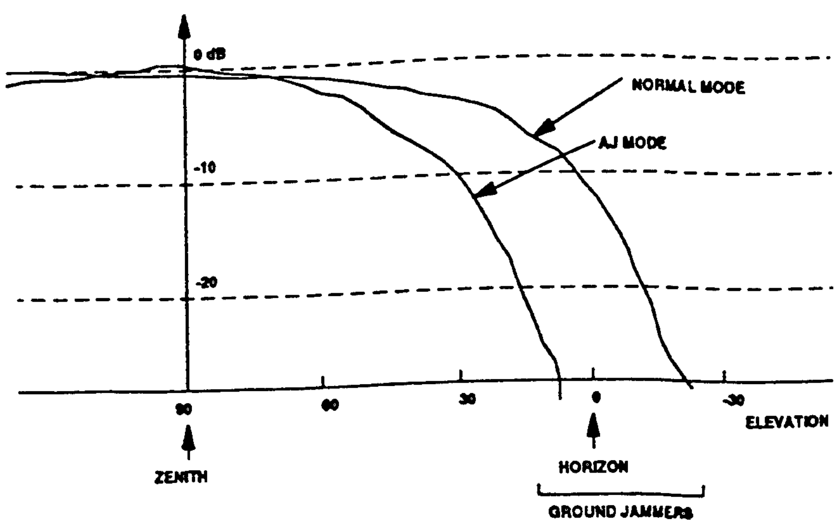


Figure 4. Sketch of GPS Dual Mode Antenna Patterns

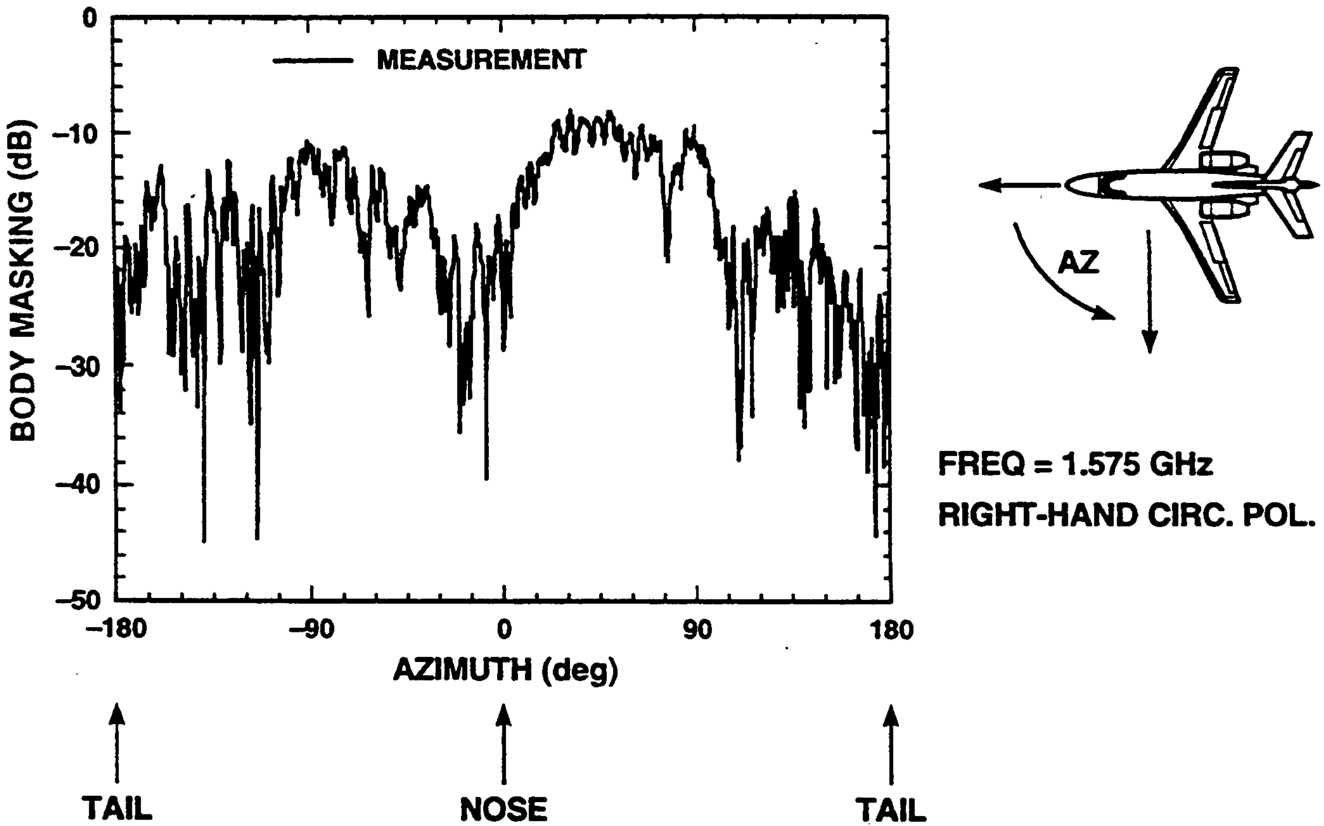


Figure 5. Fixed Radiation Pattern Antenna (FRPA) on Falcon 20 (Elevation = -20 deg)

equipment can begin a direct P(Y) code acquisition process. But without a large number of multiple correlators to test many code epochs simultaneously, this is a slow process. Alternatively, the user can synchronize by locking to a GPS receiver which is already tracking the GPS signals.

In many applications, this approach is sufficient. However, it is not adequate under many circumstances such as when 1) the GPS receiver is without a continuously-available power source (e.g., on a wing-mounted munition), 2) the receiver has lost track due to jamming, foliage attenuation, etc., or 3) the GPS receiver must operate in a remote area where access to another operating GPS receiver is impractical. Then, when C/A is jammed, the direct P(Y) acquisition approach must be used.

Enhanced Accuracy - Differential GPS

There are many potential applications of GPS which require accuracies much better than the 100 meters (95%) afforded by the C/A code with SA active, or even the 20 meters with SA off. Examples are ship navigation in narrow channels, aircraft landing guidance in instrument meteorological conditions, or precise position determination for offshore drilling. The requisite accuracy for such applications can be achieved by so-called Differential GPS (DGPS). The basic approach is to measure the errors in the signals received from each GPS satellite in view at a precisely known location, and then to broadcast these errors to the user receiver. The user receiver then applies these errors to its measurements from the satellites, achieving a positioning accuracy of 10 meters, down to fractions of a meter, depending on the specific technique and equipment used. Most DGPS systems also provide a message indicating whenever a satellite is transmitting erroneous data and should not be used; this is called an "integrity message."

Both the U.S. Coast Guard and the Federal Aviation Administration are implementing DGPS systems to serve the navigation and guidance needs of their respective communities. The USCG is implementing a local area DGPS system to cover the coastal areas ind principal inland waterways of the U.S. Full operation of 61 sites has just begun.

The FAA is developing the Wide Area Augmentation System (WAAS) to meet the navigation and landing guidance needs of the national airspace system for Category I instrument approach minimums. Local Area Augmentation Systems (LAAS) are also being planned for Category II and III operations.

Numerous privately operated DGPS systems have been developed; some are operating today and many more are expected to operate in the future. All these systems utilize the C/A code. It is also theoretically possible to operate a differential system which uses rebroadcast Y-code without the benefit of a cryptographic key. Such a system has the potential to provide enhanced accuracy as well as enhanced jamming resistance.

End of Selective Availability

As indicated above, the U.S. has committed itself to eliminating selective availability within ten years. This means that C/A users will have the 20 meter accuracy associate with this code (Figure 1). The wide availability of this accuracy, or even better, in areas where DGPS has been deployed will improve enemy navigation capabilities; these potential improvements should be considered in small unit operation planning.

Operational GPS Use Considerations - SUO Scenarios

In some small force operations, it may be necessary to cold start a GPS receiver without access to another operating unit. As long as C/A signals are unjammed, this is not an issue. If GPS jammers are present, another signal acquisition strategy will be required. Direct P(Y) acquisition has already been discussed above.

Hand-held GPS (PLGR) units capable of operating with P(Y) code will no doubt be important players in these operations. Such units have certain problems:

1. Antenna-based, anti-jamming enhancements will be difficult to implement,

2. They will be required to operate in urban areas where reflected signals from buildings generate multipath signals, sources of signal tracking error,

3. Buildings will limit the areas where there are direct views of at least four GPS satellites, and

4. PLGRs will be required to operate under tree canopies and other foliage which attenuate the GPS signals.

On the positive side,. the urban and foliated areas will make GPS jamming of PLGRS difficult.

Summary

GPS is already an important system and it is expected to become more important with time. More and more missions will rely on its accuracy and wide availability. On the other hand, GPS has limited jamming resistance. This will be enhanced over the next 10-15 years, but there are limits to these enhancements. Operational strategies to circumvent this jamming limitation are expected to be developed and used widely in the future. These will include new technologies such as the higher accuracy IMUs discussed in a companion paper, low-cost terminal seekers, and miniature, high accuracy clocks. Certainly GPS will have an important role in small unit operations, but this role will be supported by these other technologies.

Inertial System Technology and GPS Aiding

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1. Introduction

Many military vehicle inertial navigation systems could be replaced with less accurate inertial systems if GPS were continuously available to update the inertial system to limit its error growth. A less accurate inertial system usually means a less costly system. However, given the uncertainty in the continuous availability of GPS in most military scenarios, an alternate way to reduce the avionics system cost would be to attack the cost issue directly by developing lower cost inertial sensors while maintaining their current accuracy and low-noise levels. This paper reviews the benefits and issues in using inertial navigation systems augmented with GPS updates, surveys the current state-of-the-art in inertial sensor technology, and makes projections for future lower-cost inertial sensors and systems.

2. Benefits and Issues of Inertial Systems Aided by GPS

As will be explained in this section, low-noise, accurate inertial sensors are important for the following reasons:

(1.) Aiding the receiver's carrier and code tracking loops with inertial sensor information allows the effective bandwidth of these loops to be reduced, even in the presence of severe vehicle maneuvers, thereby improving the ability to track signals in a noisy environment such as caused by a jammer. The more accurate the inertial information, the narrower the loops can be designed. In a jamming environment, this allows the vehicle to more closely approach a jammer-protected target before losing GPS tracking. A factor of 3 to 4 improvement in approach distance is typical. Even outside a jamming environment, INS data provides a "smooth" and accurate navigation solution in situations where GPS receiver navigation solutions alone would be subject to short-term outages caused by geometry, signal-strength variations, and antenna shading.

(2.) The inertial system provides the only navigation information when the GPS signal is not available. Then inertial position and velocity information can reduce the search time required to reacquire the GPS signals after an outage and to enable direct P(Y) code reacquisition in a jamming environment.

(3.) Low-noise inertial sensors can have their bias errors calibrated during the mission by using GPS measurements in a "tightly-coupled" navigation filter that combines inertial system and GPS measurements to further improve the benefits listed under (1) and (2).

The synergistic benefits of combining inertial data with GPS data as described in the previous paragraph are notionally shown in Figure 1.

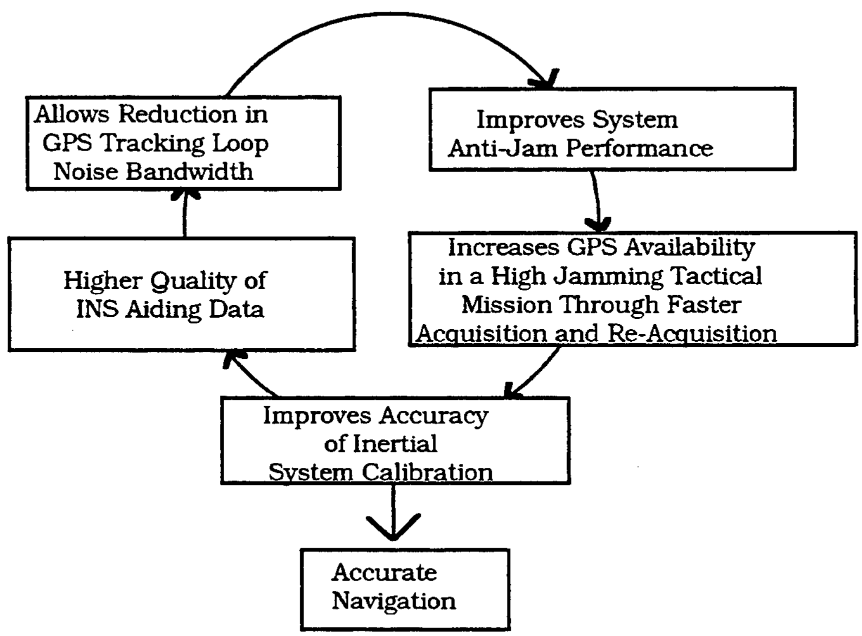

Figure 1. The Synergy of GPS/INS Integration

In order to further illustrate and explain, in detail, inertial system/GPS integration, a conceptual example will be developed to show how navigation system CEP might vary with time for three system architectures and three inertial instrument qualities. The three architectures to be illustrated are: (1) unaided receiver loops/cascaded filters, (2) aided-loops/cascaded filters, and (3) aided loops/tightly-coupled filter. The three inertial system qualities (cases 1 to 3) are described in Table 1 by their gyro and accelerometer bias stability characteristics.

	Case 1 INS Flight Controls, Smart Munitions	Case 2 INS Tactical Missiles	Case 3 INS Cruise Missiles, Aircraft INS
Accelerometer Bias Stability (micro g's) - 1σ	1000	200	50
Gyro Bias Stability (deg/hr)- 1σ	10	1	0.01

Table 1. INS Error Budgets (1s)

In the conceptual example, it is assumed that the GPS receiver is on a vehicle flying into an area of jamming. The jamming begins at t=0 with the GPS receiver loops locked and tracking as shown in the lower left hand corner of Figure 2. Each of the curves in the figure will be described next.

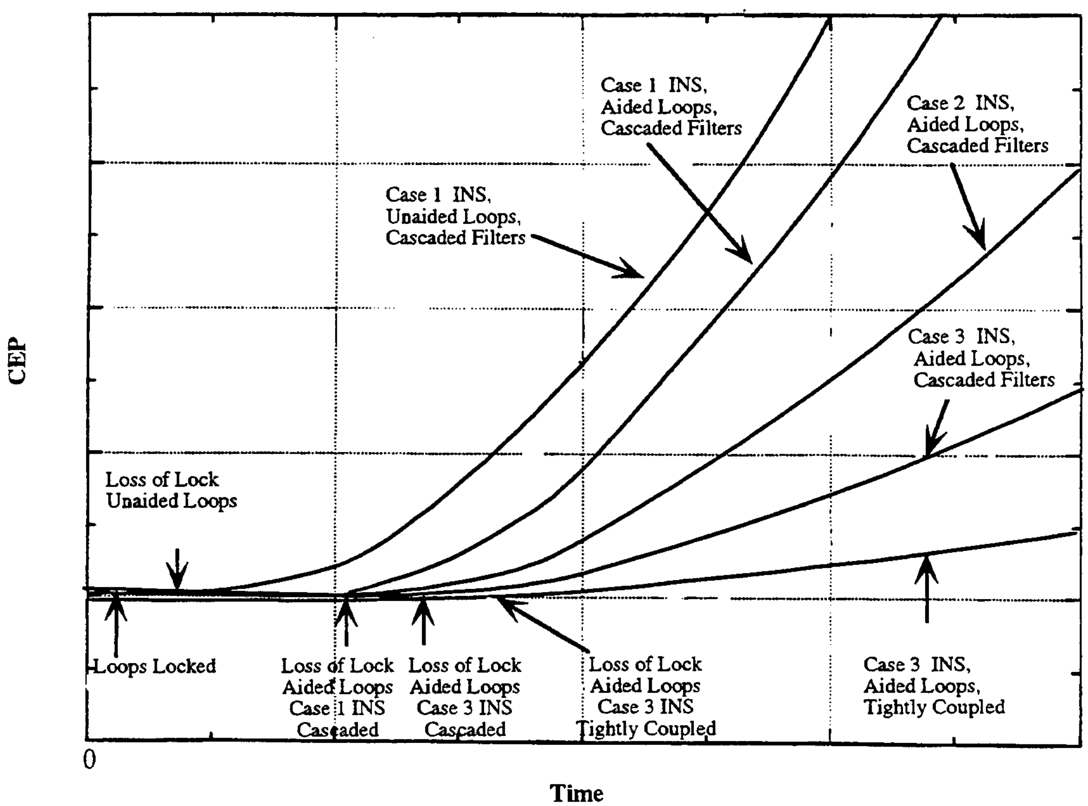

Figure 2. Benefits of Inertial Equipment in Face of GPS Jamming

The benefit due to aiding the receiver tracking loops can be seen by noting the difference in the loss of lock time between the unaided-loops curve and the aided-loops curve. The growth in CEP for the unaided loops begins sooner but follows the same form as the CEP for the aided loop architecture. Anti-jam performance improvement due to tracking loop aiding is typically 10 to 15 db. This corresponds to a factor of 3.2 to 3.9 improvement in penetration distance to the target (e.g., if the jammer were powerful enough to jam the unaided loops at 80 nmi., then the loops could maintain lock with inertial aiding until a distance of about 25 nmi. to the jammer.) In Figure 2, it was assumed that the vehicle was traveling at constant velocity, so the 3.2 factor of improvement in distance directly converts into a 3.2 factor in increased tracking time.

The effects of improvements in INS quality are shown in the three curves, INS Cases 1 to 3, aided loops, cascaded filters. There are several factors that contribute to the improvement in CEP with increasing INS quality. First the performance of a higher quality INS yields more accurate navigation during GPS outages. Second, a lower noise instrument is "more calibratible" via GPS updates. This further improves performance after GPS loss. Third, a higher quality, better calibrated INS can have yet narrower tracking loop bandwidths and yet better anti-jam performance. Although not shown in the figure, better navigation is also consistent with reduced search time for reacquisition.

However, the ability to adequately calibrate the biases in low-noise inertial system components depends on the avionics system architecture. There are two fundamentally different system architectures that have been commonly implemented to combine the GPS receiver outputs and the inertial navigation system information and thus obtain inertial sensor calibration and estimate the vehicle state. They are referred to here as the "cascaded filter" and the "tightly-coupled" approaches. As indicated in the lower right corner of Figure 2, it is generally expected that a tightly-coupled filter implementation would result in better inertial system calibration and better CEPs. The reasons for that expectation will now be explained.

In the typical cascaded filter approach, as shown in Figure 3, there are two separate Kalman filters in the GPS/INS system. The first is within the GPS receiver. The GPS receiver loops are aided with information from the inertial system, and the receiver outputs position and velocity data from its own Kalman filter. The receiver's Kalman filter is usually not optimized for the vehicle dynamics or for the errors in the inertial system aiding it. Furthermore, its position and velocity errors are highly correlated in time with the inertial errors. The second Kalman filter that compares the receiver position and velocity outputs with those of the inertial system is usually run at a much lower rate (typically 5 to 10 seconds update interval) than the receiver filter (10 to 1 Hz). This is to avoid filter instability because the second filter is designed as if the errors in its input measurements were uncorrelated.

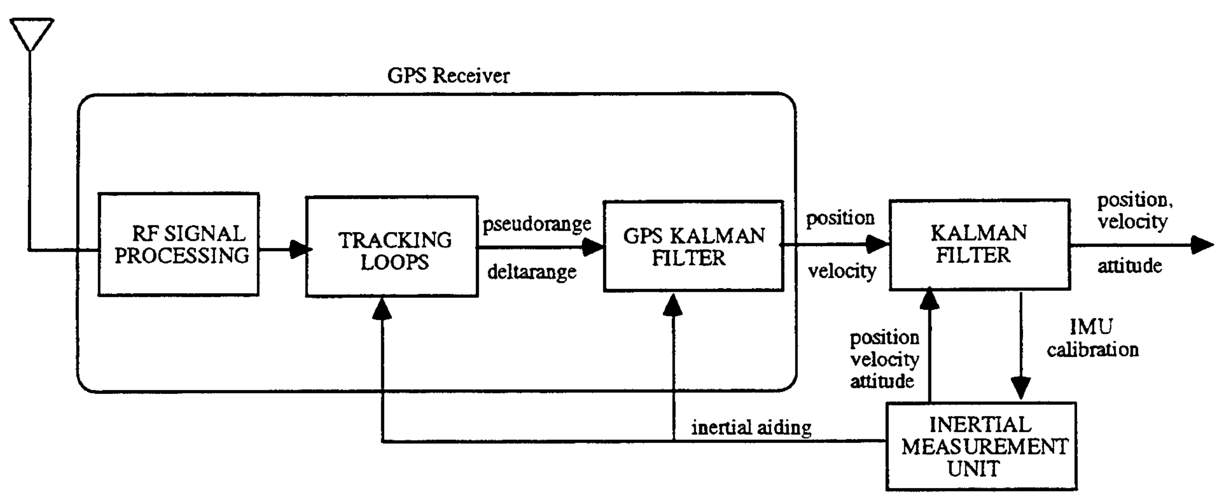

Figure 3. Cascaded Filter Approach

In the tightly coupled approach, shown in Figure 4, there is only one Kalman filter. The GPS measurements of pseudorange and deltarange as derived from the code and carrier tracking loops are treated as measurement inputs in a single Kalman filter that also includes the INS error states. The measurements are typically processed at a 1 Hz rate. One single, overall optimal filter in the tightly-coupled approach will provide more accurate estimates than two cascaded filters operating at a lower update rate. Incorporating measurements much more frequently will contribute to faster calibration of the inertial sensors.

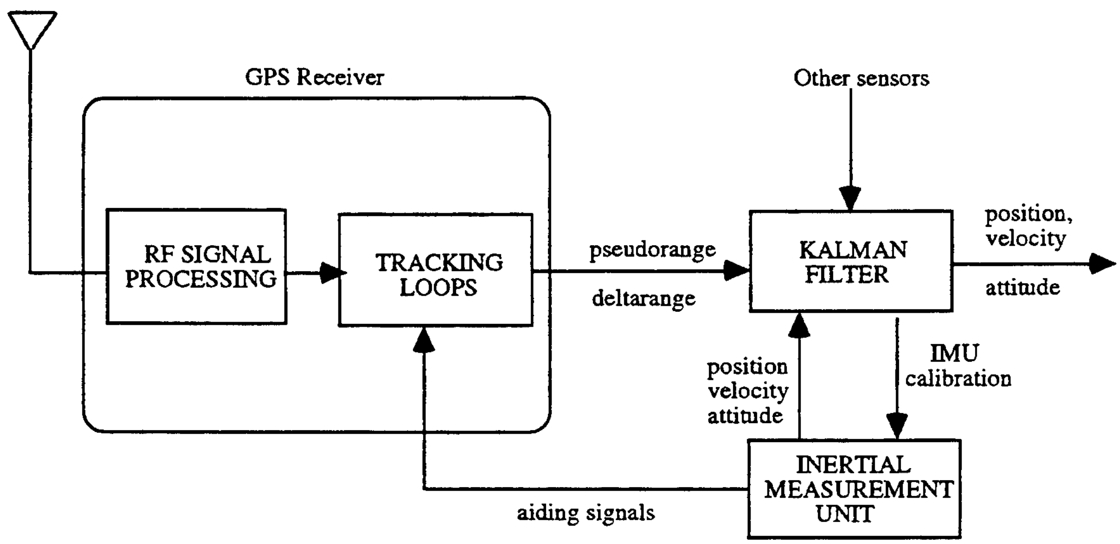

Figure 4. Tightly Coupled Approach

Tightly coupled implementations are also more robust against jamming in that the cascaded filter usually cannot provide a GPS update to the inertial system if fewer than four satellites are being tracked by the receiver. The receiver navigation solution degrades and begins to track the inertial system errors. The tightly-coupled system, however, can make use of measurements of pseudo-range from three, two, or just one satellite. This could be extremely beneficial in a jamming scenario especially if large areas of the sky are blanked out by a nulling antenna and only a few satellites are available for tracking.

The trend during the last several decades in the design of multisensor navigation systems has been to use one centralized Kalman filter that accepts raw measurement information from all available sensors (e.g., Doppler radar, synthetic aperture radar, GPS receiver, and other sources). Implementation of the tightly-coupled architecture allows for the straightforward inclusion of additional sensors or upgrades of existing sensors. Tightly-coupled systems should be implemented in many applications even in the presence of contemplated, improved receiver security features, such as GRAM/SAASM* , which may limit the availability of pseudorange and deltarange measurements outside the security boundary of the receiver. In this case, the security boundaries will have to be appropriately defined.

Having now reviewed some of the main issues in GPS aiding of inertial systems, the next section will summarize current inertial sensor military applications.

3. Current Inertial Sensor Military Applications

Tables 2 and 3 depict, respectively, a perspective of current gyroscopes and accelerometers and their military applications. The instruments are grouped according to their performance quality as measured by their bias stabilities, in degrees/hour (_/h) for the gyroscope and micro g's (mg's) for the accelerometer. The gyro costs vary from over $100 K per instrument for very high performance to $500 at low performance levels. The accelerometers indicated in Table 3, range from high-cost, mechanical floated instruments to less expensive force-rebalance, pendulous accelerometers. Again costs vary from $100K per instrument down to $500. While these performance factors are not the only ones that influence sensor selection, they are useful for comparison purposes.

Current Navigation Application	**Gyro Stability Requirement (°/h) 1s**	**Typical Gyro Types Used**
ICBM Strategic Guidance	0.0001	Floated, Single Degree of Freedom
Stellar-Aided Strategic Missile	0.001	Dry-tuned, Two Degree of Freedom

* GPS Receiver Applications Module/Selective Availability Anti-Spoofing Module (GRAM/SAASM)

Cruise Missiles and Aircraft Navigation	0.01	Dry-tuned, Two Degree of Freedom, or Ring-laser Gyro
Tactical Missiles	0.1 - 10	Dry-tuned, Two Degree of Freedom, or Ring-laser Gyro
Flight Controls, Smart Munitions	Greater than 10	Rate and integrating gyros

Table 2. Current Gyro Requirements vs. Applications - No GPS Aiding

Current Navigation Application	Accelerometer Stability Requirement (mg)1s	Typical Accelerometer Types Used
Strategic Missiles	Smaller than 1	Mechanical, floated accelerometer
Cruise Missiles and Aircraft Navigation	10 - 100	Pendulous Force-rebalance Accelerometer
Tactical Missiles	100 - 1000	Pendulous Force-rebalance Accelerometer
Flight Controls, Smart Munitions	Greater than 1000	Pendulous Force-rebalance Accelerometer

Table 3. Current Accelerometer Requirements vs. Applications - No GPS Aiding

Referring to Tables 2 and 3, it is immediately apparent that electromechanical instruments dominate today's high performance applications. These are mature, proven technologies with inertial instrument performance able to satisfy mission requirements but at high cost. For lower performance applications, less accurate electromechanical or ring-laser gyros and pendulous accelerometers are typically implemented. In the last several years, new technologies have been applied to inertial sensors and the next section will discuss emerging lower cost sensor technologies that may meet instrument accuracy requirements for many applications.

4. Emerging Lower Cost Sensor Technologies

Major changes are currently underway in technologies associated with inertial sensors.

These changes are allowing proliferation of inertial sensors into a wide variety of new military and commercial applications. Inertial sensor manufacturers have begun to adopt many of the fabrication techniques that have been developed by the solid-state electronics industry over the last decade. Inertial sensors are being fabricated in silicon, quartz, and with electro-optic materials, such as lithium niobate, by employing low-labor-intensive batch processing techniques. The utilization of these techniques will result in low cost, high reliability, small size, and light weight for inertial sensors and for the systems into which they are integrated. Some inertial sensors have already been fabricated with dimensions so small that they are barely visible to the naked eye. Some of the more interesting emerging sensor technologies are described next. They are fiber-optic gyros, micromechanical gyros, resonating beam accelerometers, and micromechanical accelerometers.

4.1. Fiber-Optic Gyros (FOG)

Sagnac effect rotation rate sensors result from the counter propagation of light beams in a waveguide which exhibits optical reciprocity between its clockwise and counterclockwise paths. Rotation normal to the waveguide plane upsets this symmetry, which is then photoelectronically detected and processed to provide an indication of rotation rate. The FOG is implemented using an integrated optics chip constructed in lithium niobate, and fiber-optic sensing coil (a few meters to a kilometer long), diode light source, and photodetectors. This configuration is expected to be supplanted eventually by quantum well technology, such as gallium arsenide, which will then allow integration of most of the above components into a single substrate attached to the fiber-optic coil thus increasing reliability and reducing costs. FOG sensors have no gas or mirrors and do not exhibit lock-in at low rate, which are disadvantages associated with some ring laser gyros. They therefore should be an economical replacement for the RLG providing the same level of gyro bias performance.

4.2. Micromechanical Gyros

Micromechanical gyros are usually designed as an electronically-driven resonator, often fabricated out of a single piece of quartz or silicon. Such gyros operate in accordance with the dynamic theory that when an angle rate is applied to a translating body, a Coriolis force is generated. When this angle rate is applied to the axis of a resonating tuning fork, its prongs receive a Coriolis force, which then produces torsional forces about the sensor's axis. These forces are proportional to the applied angle rate, which then can be measured capacitively (silicon) or piezoelectrically (quartz). The output is then demodulated, amplified, and digitized to form the device output. As an example, Systron Donner's QRS (Quartz Rate Sensor) uses this technology and has been incorporated into a tactical missile guidance set. Silicon micromechanical instruments can be made by bulk micromachining (chemical etching) single crystal silicon or by surface micro-machining layers of polysilicon. Many manufacturers are developing gyros and accelerometers using this technology. Their extremely small size combined with the strength of silicon makes them ideal for very high "g" applications.

Draper Laboratory has demonstrated a 30 deg/hr open-loop silicon tuning fork gyroscope with folded beam suspension in which the flexured masses are electrostatically driven into resonance with a comb-like structure. Rotation is sensed capacitively along the axis normal to the plane of vibration. The Draper gyroscope is aimed at the automobile market and is being marketed through an alliance with Rockwell International. Between 3,000 and 10,000 devices can be produced on a single five-inch silicon wafer. Devices with lower drift rates are being developed for more demanding applications, such as autopilot control and smart munitions.

4.3. Resonating Beam Accelerometers

Resonant accelerometers (sometimes referred to as vibrating beam accelerometers, VBAs) have a principle of operation that is similar to that of a violin. When the violin string is tightened, its frequency of operation goes up. Similarly when the accelerometer proof mass is loaded, one tine is put into tension and the other into compression. These tines are continually electrostatically excited at frequencies in the hundreds of kilohertz range when unloaded. As a result, when "g" loaded, one tine frequency increases while the other tine frequency decreases. This difference in frequency is a measure of the device's acceleration. This form of accelerometer is essentially an open loop device, in that, the proof mass is not rebalanced to its center position during the application of a force. For accuracy, it relies on the scale-factor stability inherent in the material properties of the proof mass supports. These accelerometers can be constructed using several different fabrication techniques. One method is to etch the entire device (proof mass, resonating tine, and support structure) from a single piece of quartz. Using such techniques can result in low-cost, highly reliable accelerometers with a measurement accuracy of better than 100 μg. Constructing this accelerometer from a single piece of quartz results in high thermal stability, along with dynamic ranges approaching those obtainable in the timekeeping industry.

Kearfott and Sundstrand have developed laboratory prototypes aimed at strategic missile guidance in the belief that these solid-state devices hold potential for good lifetimes and reliability. Sundstrand, Systron Donner, Draper Lab, and others have produced navigation- and tactical-grade quartz resonant accelerometers.

4.4. Micromechanical Accelerometers

Micromechanical accelerometers are either the force rebalance type that use closed-loop capacitive sensing and electrostatic forcing, or the resonator type as described above. Draper's force rebalance micromechanical accelerometer is a typical example, in which the accelerometer is a monolithic silicon structure (i.e., no assembly of component parts) consisting of a torsional pendulum with capacitive readout and electrostatic torquer. This device is about 300 x 600 μm in size. The pendulum is supported by a pair of flexure pivots, and the readout and torquing electrodes are built into the device beneath the tilt plate. The output of the angle sensor is integrated and then used to drive the torquer to maintain the tilt plate in a fixed nulled position. The torque required to maintain this balance is proportional to the input acceleration. Performance around 250 μg bias and 250 parts per million (ppm) of scale factor error have been achieved.

Micromechanical accelerometers can also be fabricated using wafer bonding sandwich construction techniques, as in Litton's silicon accelerometer. Kearfott and Sundstrand are also developing silicon micromechanical resonator accelerometers. Analog Devices has a polysilicon capacitive accelerometer fabricated with an on-chip BiMOS process to include a precision voltage reference, local oscillators, amplifiers, demodulators, force rebalance loop and self-test functions. Complete integration of sensor and electronics will likely become common in all future micromechanical instruments.

5. Future Technology Applications

Solid-state inertial sensors like those described previously have potentially significant cost, size, and weight advantages over conventional instruments, which will result in a rethinking of the options for which such devices can be used in systems. While there are many conventional military applications, there are also many newer applications that will emerge with the low cost and very small size inherent in such sensors, particularly at the lower performance end of the spectrum. In nearly every case, when these newer solid-state inertial technologies have been evaluated against today's technology, given comparable technical requirements, this new class of solid state inertial sensors becomes the winner because the basis of selection is almost always cost.

A vision of how the inertial instrument field for military applications might be expected to change over the next twenty years is shown in Tables 4 and 5 for the gyro and accelerometer, respectively. It is apparent that electromechanical instruments will be rapidly displaced, except at the high-performance levels involving fielded strategic missile applications. No new design efforts on these instruments are expected, and future activity will be devoted to increasing their reliability and life-times.

Future Navigation Application	Gyro Stability Requirement (°/h) 1s	Typical Gyro Types Used
ICBM Strategic Guidance	0.0001	Floated, Single Degree of Freedom Gyro
Stellar-Aided Strategic Missile	0.001	Dry-tuned, Two Degree of Freedom Gyro
Cruise Missiles and Aircraft Navigation Systems	0.01	Fiber Optic Gyro Ring Laser Gyro
Tactical Missiles	0.1 - 10	Fiber Optic or Silicon Micromechanical Gyro
Flight Controls, Smart Munitions	Greater than 10	Silicon Micromechanical Gyro

Table 4. Future Gyro Requirements vs Applications - No GPS Aiding

Future Navigation Application	Accelerometer Stability Requirement (mg) 1s	Typical Accelerometer Types Used
Strategic Missiles	Smaller than 1	Mechanical, floated accelerometer
Cruise Missiles and Aircraft Navigation Systems	10 - 100	Quartz resonant or Silicon Micromechanical Accel.
Tactical Missiles	100 - 1000	Quartz resonant or Silicon Micromechanical Accel.
Flight Controls, Smart Munitions	Greater than 1000	Silicon Micromechanical Accel.

Table 5. Future Accelerometer Requirements vs. Applications - No GPS Aiding

The middle-performance application region of about 0.01°/h for gyros is expected to shift from RLG's to fiber optic gyros, which will detect their rate-induced Sagnac frequency shifts using lithium niobate or gallium arsenide technologies. The ring laser gyro is an excellent instrument, but its manufacturing is heavily dominated by precision machining processes and alignment requirements, which force its costs to remain relatively high. However, one particular area where the ring laser gyro is expected to retain its superiority is in the area of scale factor. The laser gyro has its optical path maintained in a rigid structure, whereas the fiber-optic gyro has its path in glass, making the FOG fundamentally much more susceptible to environmental effects such as temperature changes. For comparable performance applications, the selection between the FOG and the RLG will very likely depend on the scale factor requirements (i.e., the accuracy in measuring an applied rotation rate).

The tactical low-performance end of the application spectrum will be dominated by micromechanical inertial sensors. These could be, for example, gyros and accelerometers photolithographically constructed in silicon or quartz and subsequently etched in very large numbers as a single batch. The military market will likely push the development of these sensors for applications such as "competent" and "smart" munitions, aircraft and missile autopilots, short time-of-flight tactical missile guidance, fire control systems, radar antenna motion compensation, "smart skins" utilizing embedded inertial sensors, multiple intelligent small projectiles such as flechettes or even "bullets," and wafer-scale GPS/inertial integrated systems.

The potential commercial market for micromechanical inertial sensors is orders of magnitude larger than any contemplated military market. The application of micromechanical gyro technology to the automobile industry is one case where, for example, a true skid detector requires a measure of inertial rate in order to operate successfully. Products designed for this industry must be inexpensive and reliable, both characteristics of solid-state technology. Many other micromechanical inertial sensor applications exist for automobiles such as airbags, braking, leveling, and GPS augmented navigation systems. Additional commercial applications can be found in products such as camcorders, factory automation, general aviation, and medical electronics. The performance of the micromechanical instruments will likely continue to improve as more commercial applications are found for this technology.

Since the end of the "Cold War", the actual number of military inertial systems that will be procured in the future has been uncertain. However, the general trend is clearly away from large strategic systems towards smaller tactical systems and towards military applications of commercial products. Table 6 gives some projections of cost for quantity production of future inertial systems. The systems are made up of gyros and accelerometers whose performance match the mission requirements. Current research and development activity for inertial sensors spans the spectrum of the four performance ranges shown. ARPA is pursuing the FOG based 0.01 °/hr INS in its GPS Guidance Package (GGP), while many commercial firms are pursuing the mid to very low performance ranges in Table 6.

	Flight Controls, Smart Munitions	**Tactical Missiles**	**Tactical Missiles**	**Cruise Missiles, Aircraft INS**
Accelerometer Technology	Silicon micromechanical	Quartz Resonant or Silicon micromechanical	Quartz Resonant or Silicon micromechanica l	Quartz Resonant or Silicon micromechanica l
Accelerometer Bias Stability (mg)	1000	200	100	50
Type of Gyro Technology	Silicon micromechanical	Silicon micromechanical or Fiber Optic Gyro	Fiber Optic Gyro	Fiber Optic Gyro
Gyro Bias Stability (deg/hr)	10	1	0.1	0.01
Future INS Production Cost	$500	$2K	$10K	$15K

Table 6. Future INS Error Budgets (1s) and costs

6. General References

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IMPACTS OF 1-METER GPS NAVIGATION ON WARFIGHTING

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IMPACTS OF 1-METER GPS NAVIGATION ON WARFIGHTING

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BIOGRAPHY

Dennis Holeman received a BS in Engineering from Harvey Mudd College in 1968 and a Master of Engineering in Mechanical Engineering from UC Berkeley in 1970. He has been involved in analysis and development of avionics systems since joining SRI International in 1978. He has worked in the area of advanced applications of satellite-based navigation systems since 1982 and is currently a Principal Engineer in the Systems Development Division.

ABSTRACT

The inaccuracy of weapons employed from standoff ranges has historically had a great influence on tactics and strategies, because of the need to employ large numbers of weapons to neutralize a target. Advanced satellite-based geocoordinate positioning systems capable of navigation accuracies of 1 meter or better, such as wide-area differential GPS (WADGPS), will cause fundamental changes in military tactics and strategies. Weapons employing this capability are about to emerge, as demonstrated by a recent set of trials supported by SRI under the Air Force's EDGE High Gear program. The determining factor for weapon miss then becomes the accuracy with which the desired aimpoint can be specified in geocoordinates. Improved techniques under development will use the same differential GPS technology to register their image data into absolute geocoordinates to accurately determine the locations of target aimpoints for use by the new classes of weapons. This paper examines the end-to-end sequence of operations for attack using air-launched precision-guided weapons employing WADGPS to determine each of the elements that will be affected by the new capabilities. Other warfighting applications of improved GPS Precise Positioning Service accuracy are also described.

1.0 INTRODUCTION

Historically, the typical air-to-surface or surface-to-surface tactical weapon missed its aimpoint by a substantial distance due to statistical inaccuracies in the guidance process of the overall weapon delivery system. For example, the average bomb miss in World War II was hundreds of meters. The delivery inaccuracy was increased for greater standoff distances. Tactics and strategies took into account the need to employ many weapons to neutralize a target because only a small fraction of those launched would impact within their lethal radius. Alternately, the weapons were designed for large lethal radii (the epitome being, of course, nuclear weapons).

Beginning at the end of World War II, electronic advances enabled sensor-guided weapons (such as infrared-homing missiles and television-guided bombs) to achieve extremely precise impact accuracies (a handful of meters or better). Seeker-guided weapons, however, have a number of constraints that have limited their use. For example, the target must have suitable characteristics for the seeker guidance, and the weather conditions must allow the sensor to acquire the target at sufficient range to permit guidance. Many of the highest-performance weapons require continued involvement of the launching platform until the weapon impacts, thus increasing the vulnerability of the platform. Furthermore, sensor-guided weapons can have particularly high per-round costs.

Advanced satellite-based geocoordinate positioning systems capable of navigation accuracies of 1 meter or better--e.g., wide-area militarized differential GPS as proposed by SRI--will cause fundamental changes in military tactics and strategies. They will enable relatively low-cost, all-weather, launch-and-leave standoff weapons suitable for all types of fixed and relocatable targets to achieve extremely high impact accuracies and, thus, greatly increased kill probabilities. Weapons employing such guidance techniques are about to emerge.

For such geocoordinate-guided weapons, a primary determining factor for weapon miss then becomes the accuracy with which the geolocation of the desired aimpoint can be specified. A variety of overhead sensing systems with extremely high resolution is under development (particularly all-weather sensors such as interferometric synthetic aperture radars on a variety of platforms); the same wide-area differential GPS technology also provides means to help register their image data into absolute geocoordinates to allow accurate mensuration of the geolocations of target aimpoints for use by these new weapons.

The availability of very accurate weapons guidance will dramatically change the conduct of warfighting operations. High impact accuracies will allow much smaller warheads to achieve the desired target neutralization effects for most types of targets. The combination of small radius of lethal effects and the minimization of misses will greatly reduce the problem of collateral damage, which is assuming an ever-increasing importance in contemporary military operations. Smaller weapons will allow the payload capabilities of a given platform to be used to neutralize more targets per sortie; alternately, smaller platforms can achieve the same effects per sortie. Smaller weapons enable increased use of reusable unmanned systems such as unmanned tactical aircraft (UTAs). Also, the increased effectiveness of each sortie will decrease the exposure of manned platforms and their crews to attrition. The increased combat effectiveness of each weapons delivery sortie will greatly increase the operational tempo of combat. It will also greatly reduce the size of the logistics support pyramid that must be provided (both in-theater and out-of-theater) to enable the campaign to achieve a planned level of effect on the enemy. Further applications of very high navigation accuracies will have additional important warfighting impacts.

2.0 PRECISION GEOCOORDINATE NAVIGATION FOR WEAPONS GUIDANCE

2.1 Origin of the Wide-Area Militarized DGPS Concept

SRI initially proposed the use of wide-area militarized differential GPS (DGPS) for Precision-Guided Munition (PGM) navigation in 1993 as a means for achieving a 3-m circular error probable (CEP) impact accuracy capability for the Joint Direct Attack Munition Product Improvement Program (JDAM PIP). Seeker-based concepts were the primary focus for the nine-month JDAM PIP Concept Exploration (CE) study performed by four independent contractor teams. In our CE study, however, we determined that the JDAM PIP goals of low cost, all-weather day/night operation, launch-and-leave capability, target independence, countermeasures resistance, reliability, and suitability for in-flight retargeting strongly favored a non-seeker solution based on geolocation coordinate homing [Reference 1]. A major consideration influencing our conclusion was the fact that the baseline JDAM weapon concept, designed to achieve a 13-m CEP accuracy against horizontal soft targets, already involved use of an onboard P(Y) code GPS receiver integrated with a low-cost Inertial Navigation System (INS) guidance package. The baseline JDAM GPS-INS guidance package was to be packaged in the form of a strap-on tailkit for either Mk 84 or BLU-109 2,000-lb bombs, and was intended to also be suitable for the Joint Standoff Weapon (JSOW). We realized that innovative use of differential correction information for the JDAM's P(Y) code GPS receiver could substantially improve the JDAM PIP guidance accuracy performance without adding a terminal seeker system, ideally to meet the JDAM PIP's 3-m CEP goal.

2.2 Comparison with Civil DGPS Architectures

Prior to our JDAM CE study, the use of differential corrections for military GPS-based systems had received relatively little attention in the tactical systems community because of the lack of clear requirements for such a capability. DGPS has been emphasized in the civilian community as a way of achieving high levels of accuracy for civilian C/A code receiver systems, particularly through its ability to overcome the accuracy degradation imposed by the DoD's selective availability (SA) dithering of the satellite clock signal. Because authorized military GPS users could remove the SA effects to obtain the full accuracy of the Precise Positioning Service (PPS), this was not seen as a driver for military users. In addition, DGPS was perceived by military users as having severe operational limitations that would constrain its tactical utility.

Civilian DGPS systems use pseudorange corrections generated by a surveyed GPS reference receiver (RR) station to compensate for ionospheric delays, satellite clock and ephemeris errors, and SA clock dither. These schemes require that the RR be no more than about 300 nmi from the user receiver to preserve commonality of the lines of sight to each satellite in order to compensate for the ionospheric signal delay. Also, to offset the effects of the SA clock dither (which generates errors at a rate of about 30 cm per second), the user GPS receiver needs to receive correction signals from the RR at a rate of up to 1 Hz for each satellite over a continuous datalink. Such datalink and separation limitations were perceived as posing severe constraints for any military tactical use of DGPS.

2.3 Postulated Militarized DGPS Architectures

SRI realized that a militarized DGPS that took full advantage of military GPS receiver characteristics and capabilities could overcome the most severe limitations for military users while still achieving greatly enhanced position location accuracy. In the case of authorized (keyed) dual-frequency GPS receivers that are capable of using ionosphere-free L_1/L_2 pseudorange measurements, the user is not constrained to maintaining common ionospheric lines of sight between the user receiver and the RR. This allows the separation between the RR and the user receiver to be limited only by satellite visibility and (to a lesser extent) satellite orbital error projection differences induced by different satellite-receiver geometry. Also, because SA is not a factor for an authorized (keyed) receiver, the correction update rates can be drastically reduced over civilian DGPS systems. In effect, such a military DGPS correction need only compensate for a satellite's clock and ephemeris drift. The drift rates for these factors are very slow.

A single RR is not sufficient to generate accurate DGPS corrections over a wide area without significant loss of accuracy because of problems with satellite visibility, as well as to variations in atmospheric delays. The answer to this problem is to provide a network of widely dispersed RRs that surround the operating area. Our analysis concluded that the separations between the user receiver and any of the RRs could be over 1,000 nmi with minimal loss of accuracy, so a very sparse network of RR stations will be sufficient to provide corrections over a theater-sized area.

2.4 Communicating Corrections to the User

The low correction data rate enabled a further innovation for the militarized DGPS concept to be developed. We recognized that the correction information could be transmitted to the user through the GPS satellites' own navigation message, using available space in subframe 4 of the GPS 50-bps downlink message. This has the advantage that the user's navigation system needs no additional datalink, since the correction information is obtained using the integral capabilities of the receiver itself. Use of this mechanism, of course, requires the involvement of the NAVSTAR operating authorities to modify the control segment uplink data to the satellites. These techniques can be looked at as being functionally equivalent to providing a more accurate PPS GPS signal in space (SIS) to the theater GPS user. For the near term, correction datalink schemes that do not involve alterations to the GPS Control Segment procedures should also be considered. A variety of datalink schemes that link theater-area RR networks with user receiver systems can be used, depending on the specific capabilities of the user receiver system platform. Options for optimizing the effective SIS accuracy are described in Reference 2.

2.5 Implementation of Militarized DGPS for Submeter Position Accuracy

Reference 3 describes techniques established by SRI to allow a militarized RR network for DGPS corrections to optimize the accuracy achieved by independently accounting for clock bias, atmospheric delay, multipath effects, and errors in the monitor station surveyed location. The reference also describes techniques to minimize the GPS user receiver-related error sources, including multipath effect mitigation, tropospheric delay model optimization, satellite selection algorithms, and use of additional receiver channels.

3.0 DEMONSTRATION OF MILITARIZED WADGPS CAPABILITIES: THE EDGE HIGH GEAR PROGRAM

3.1 Background

Many of the elements of the wide area militarized DGPS concept were demonstrated by the Exploitation of DGPS for Guidance Enhancement (EDGE) High Gear program in mid-1995. Sponsored by the USAF Joint Direct Attack Munition System Program Office (JDAM SPO) at Eglin AFB, the EDGE program demonstrated the feasibility of dramatic SIS error reductions using militarized differential corrections. SRI developed a wide area DGPS (WADGPS) reference receiver network for EDGE with four RRs, each located greater than 1,000 nmi from the test range at the Eglin Test Range, Florida. Corrections from the network were uplinked to an F-16 trials aircraft carrying a modified GBU-15 glide bomb equipped with a GPS/INS package for guidance navigation. Details of the EDGE program results and the techniques developed to maximize the accuracy of the corrections sent to the user receiver are provided in Reference 4.

3.2 EDGE Program Results

Figure 1 indicates the general quality of the DGPS corrections obtained in the EDGE trials. This histogram shows the distribution in errors for the DGPS-corrected two-dimensional position over a period of approximately 6.5 hours. The 50% CEP for this representative sample against the DMA-surveyed benchmark is 30 cm. The 50% CEP for this sample against its mean solution is only 17 cm.

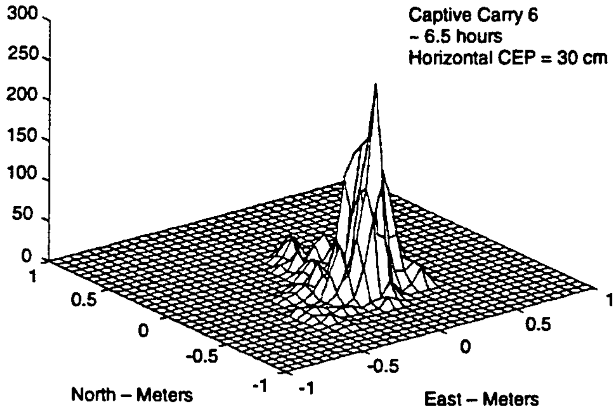


Figure 1 Histogram of 2-dimensional position errors in DGPS-corrected data (as determined by EDGE correction quality monitor)

Figure 2 illustrates the result of one of the vertical-target test drops. This shows an unpowered 2,000-lb glide bomb, dropped from a range of 14 miles at an altitude of 25,000 feet above a cloud layer, impacting within 2 meters of the aimpoint on a vertical target at the correct impact angle for hard target penetration using only GPS-aided inertial navigation. The EDGE trials are the first known demonstration of such a precision attack capability with a non-seeker equipped weapon.

4.0 SPECIFICATION OF AIMPOINT LOCATION

As geocoordinate-guided weapons use high-precision differential corrections to reduce navigation errors to a very low level, and as guidance loops are optimized for minimum guidance error, the controlling factor for the weapon CEP becomes the accuracy of specifying the target aimpoint location in three-dimensional absolute coordinates (target location error [TLE]). Because the weapon guidance error is independent of the target location error, the two error sources can be root sum squared (RSS'd) to predict the weapon impact error. Figure 3 illustrates the growth of projected weapon impact error for an assumed level of weapon navigation/guidance error as a function of TLE. The optimum solution for overall

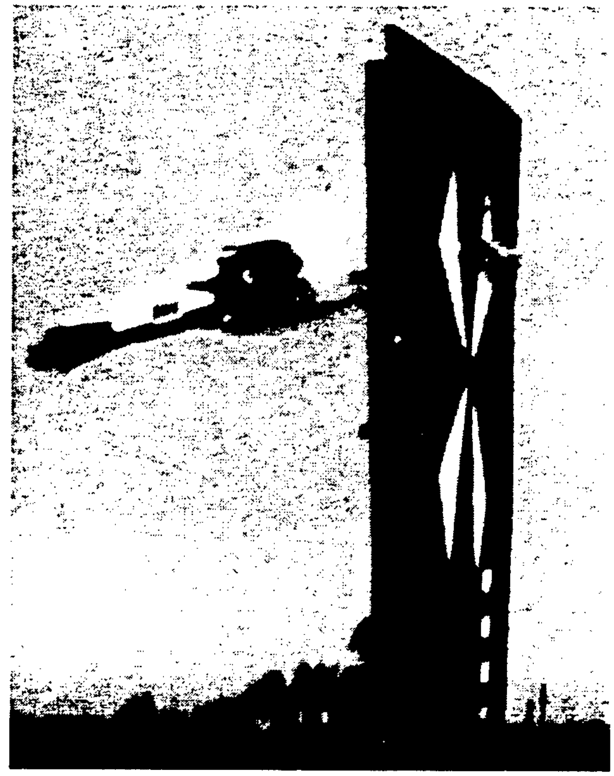
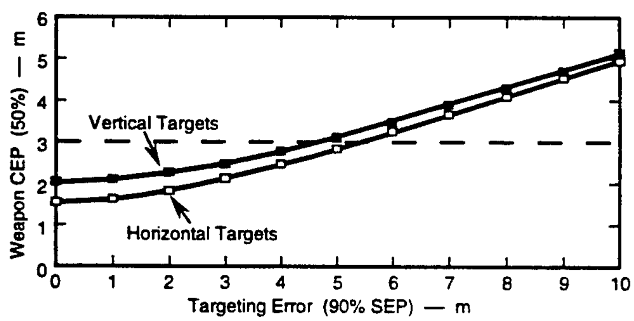


Figure 2 Typical EDGE trial against simulated hardened vertical target (2 m vertical miss with no target location survey error)

weapon system impact error minimization balances the burden between target surveillance and weapon guidance functions.



Assumptions for weapon navigation:
1.2 m horizontal GPS positioning error (HDOP = 1.5)
2 m vertical GPS positioning error (VDOP = 2.5)
0.3 m weapon guidance loop error

Figure 3 DGPS weapon CEP vs targeting error

Prior to the advent of geocoordinate-homing weapons systems, the motivation for achieving extremely accurate target geolocation data using overhead surveillance and reconnaissance systems was limited. New weapons such as JDAM and JSOW are changing these requirements rapidly. Although it is beyond the scope of this paper, much work is currently under way to achieve reconnaissance/surveillance system TLE performance compatible with the capabilities of the weapons we describe. A key component will be very high-resolution and accurate topographic data referenced to absolute geocoordinates.

While the primary use of geocoordinate-guided weapons is against stationary targets, moving targets can also be attacked if the projected aimpoint is provided in real time to the weapon by a sensing platform that tracks the target in georeferenced coordinates.

5.0 BENEFITS OF WEAPON GUIDANCE ACCURACY

As a part of our JDAM CE study, we performed a parametric analysis of the influence of weapon accuracy on the cost per kill for fixed, point-type targets. Figure 4 illustrates a typical result we obtained. In keeping with the scope and tone of this paper, the costs are expressed in relative terms and the specifics of the case are not described. The case illustrated by the figure assumes precision-guided JDAM-type weapons are dropped from a bomber flying a medium-altitude level delivery profile. The baseline weapon in our comparison is a standard JDAM-type 2,000-lb weapon with a nominal impact accuracy of 13-m CEP. The alternatives examined are DGPS-aided JDAM-type weapons with three levels of increased accuracy: 5-m, 4-m, and 3-m CEP. Ten representative target conditions were studied for this particular case. The targets in the set were relatively challenging for neutralization by a guided weapon: they included both vertical and horizontal targets and targets with high levels of hardness. The overall cost per kill was computed considering such directly allocable factors as aircraft attrition.

For all of the parametric analyses we conducted, the benefits of improved accuracy to cost per kill were apparent. A steep decrease in cost per kill is apparent for most of the targets in the set as the weapon CEP goes from the nominal 13 m to 5 m. The improvement in cost per kill generally flattens out as 3 m CEP is reached, indicating the declining marginal utility of greater impact accuracy still.

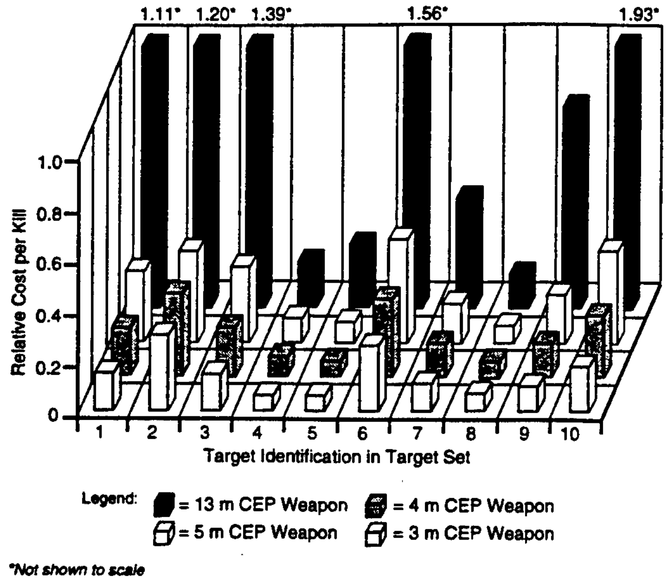


Figure 4 Cost per kill for typical precision target subset

6.0 END-TO-END SEQUENCE OF OPERATIONS

To make full use of the capabilities for improved military effectiveness using geocoordinate-guided weapons based on wide area militarized DGPS, it is necessary to consider the end-to-end sequence of operations for attack. We wish to consider each of the elements that will be affected by the new capabilities. For this discussion, we will assume that the weapon is an air-launched system and that a theater-area DGPS network determines the corrections and datalinks them to the aircraft to provide to the weapon.

6.1 Pre-Conflict Area 3-D Mapping

Pre-existing, photo-identifiable image control points surveyed into GPS absolute coordinates will help register overhead imagery data collection by satellites during routine peacetime mapping operations using different look angles. Differential corrections can maximize the accuracy of the image control point surveying function. The data will be collected into multi-attribute, georeferenced databases with shared access by a wide range of military users.

6.2 Pre-Attack Reconnaissance/Surveillance

When a specific geographic area becomes tactically significant as a result of imminently expected combat operations in the area, reconnaissance/surveillance missions will be mounted to obtain specific situation assessment and targeting information in the area. This will supplement the pre-existing map data with higher-resolution data tailored for subsequent mission operations. These missions may be performed by satellites, UAVs, manned aircraft, or other types of platforms. The goal will be to rapidly generate digital terrain elevation and feature data to the required accuracy and then perform automatic or semi-automated mapping functions to indicate significant features of interest in the data (such as buildings, roads, etc.). Differential GPS corrections will be important to accurately navigate the reconnaissance platforms, to point sensors at pre-established target locations, and to improve the resolution and registration performance of sensors such as synthetic aperture radar systems through the use of precise GPS position and velocity data. The pre-attack phase can also emplace unattended ground sensors of various types that can be precisely located using WADGPS techniques. Accurate data registration will facilitate data fusion of all sources of sensor data.

6.3 Reconnaissance/Surveillance Data Analysis

The data obtained from the reconnaissance/surveillance missions in the operating area then need to be analyzed. Accurate georegistration of images will allow multiple data sources (e.g., from different vantage points and using different sensing phenomenology) to be combined into three-dimensional databases. Data fusion will be used to compare imagery databases to current sensor imagery for change detection. Semi-automated processes will be used to determine the presence, identity, and characteristics of targets based on multiple attribute analysis. Aspects to be considered include defenses, pre-existing damage, and potentials for collateral damage.

6.4 Attack Planning

The data obtained in the previous step will be used for target prioritization, delivery platform and weapon selection, attack profile planning, and selection of specific aimpoints. As smaller weapons with reduced lethal radius are used and collateral damage avoidance becomes more important, the specification of the exact aimpoint to achieve the desired damage escalates in criticality. All available data must be used to determine the best estimate of the absolute geolocation coordinates of the target aimpoint. In some cases, the weapon trajectory, impact angle, and detonation point must be specified accurately as well as the desired weapon impact point. Mission data preparation for geocoordinate-guided weapons is particularly straightforward because it consists primarily of coordinate data, rather than sensor-oriented alternatives such as reference images. The data may be assembled prior to initiating the mission, or it may be developed while the platform is enroute to take advantage of the latest information obtained by various sensing systems.

6.5 Attack

The platform will transit to the preplanned weapon launch point while obtaining optimum data for inertial system initialization. Any target update data (including specification of an alternate target or aimpoint) will be transferred to the weapon prior to launch. The GPS initialization just prior to weapon release will include the latest version of differential corrections, obtained via the datalink system in use by the platform.

6.6 Weapon Flyout

The weapon will fly out over its optimum trajectory based on its launch conditions and its preplanned aimpoint coordinates and endgame conditions, using GPS-aided inertial navigation. In some cases, the trajectory will be specified in time coordinates as well as spatial coordinates, so that weapon arrival times can be synchronized. The inertial system will be calibrated by the differentially corrected GPS data to minimize the inertial errors and calibrate the inertial drift model in the weapon's navigation filter. If jamming near the target causes the GPS receiver to lose lock, the weapon will navigate using the calibrated inertial system data alone. The inertial system quality establishes the maximum range from the target that jamming may occur without significantly degrading the weapon miss distance.

6.7 Weapon Endgame

The weapon will perform endgame maneuver guidance using the best navigation data to minimize the final miss and align the weapon for correct impact angle. The weapon will fuze per appropriate sensor data according to preprogrammed conditions (e.g., deceleration profile to detonate inside a hardened shelter). In some cases, the weapon effects may be a non-lethal mechanism instead of an explosive (for example, the carbon filament warheads used in the Persian Gulf War against electrical power stations).

6.8 Attack Effectiveness Assessment Data Collection

Attack effectiveness ("bomb damage") assessment will increase in importance as well as difficulty with the greater use of small precision-guided munitions with reduced lethal effects radii. For example, a building might appear virtually undamaged because the attack used a small penetrating bomb to neutralize a communications center in the basement. Innovative sensing techniques are being pursued to determine the effectiveness of attacks, both in near-real time and in post-attack reconnaissance. (Details of these techniques are beyond the scope of this paper). These sensing techniques will typically make use of differentially corrected GPS positioning data to resolve the sensed information into geospatially registered coordinates. This may be either in real time or in a post-processing environment.

6.9 Post-Attack Reconnaissance Data Analysis

Post-attack reconnaissance data analysis is basically similar to pre-attack reconnaissance data collection, the difference being that most resources are focused on identifying unstruck or undamaged targets, adjusting aimpoint coordinates to remove errors, and selecting alternate aimpoints to achieve effective target neutralization.

6.10 Reattack Planning

Reattack planning is similar to the initial attack planning, using data gathered in the first attack to ensure the success of the second attack. The reattack must take into account probable enemy reactions to the first attack, which might include strengthened defenses, relocation of vital target centers under cover from reconnaissance imaging, and preparation of point and area GPS jamming capabilities to reduce weapon delivery accuracy.

6.11 Reattack

Reattack will principally repeat the functions of the initial attack; the steps will be performed recursively until the objectives are achieved or alternate tactics are determined to be necessary.

7.0 OTHER WARFIGHTING APPLICATIONS BENEFITING FROM IMPROVED PPS ACCURACY

This discussion has focused primarily on air-launched bombs and missiles as the military applications benefiting from improved PPS accuracy derived from WADGPS techniques. In fact, a wide range of other warfighting activities that currently take advantage of the existing level of PPS accuracy will benefit from the improvements possible from the techniques described in this paper. Some examples are given in the following paragraphs.

7.1 Mine Warfare

GPS PPS accuracy at the 1-meter level will significantly aid mine warfare through improving the knowledge of the location of friendly mines as they are emplaced and enemy mines as they are located. Accurate mine location will greatly aid the safety of negotiating through surveyed minefields without requiring neutralization of the mines.

7.2 Precision Airdrop

One-meter GPS PPS accuracy will facilitate the use of new tactics for precision airdrop of supplies and personnel to extremely restricted landing sites using high control authority parafoils.

7.3 Aiding for Overhead Imaging Sensors

A wide range of enhancements to overhead imaging sensor systems is facilitated by providing meter-level accuracy for the GPS PPS. Although SRI's concepts were primarily developed with terrestrial systems in mind, satellites in low-to-medium altitude orbits can also take advantage of the wide area differential corrections to improve the accuracy of their position location at the time they image a target, using sensors such as infrared or visible light cameras or synthetic aperture radars of various types. In addition to improving the platform positioning knowledge, highly accurate differential corrections can be used directly by the sensor systems themselves. Highly accurate velocity data from a differentially corrected GPS receiver can be used to improve the resolution of synthetic aperture radars. Furthermore, for real-beam sensor systems that use frame stacking to improve the contrast of the image, extremely accurate position and velocity data are necessary to minimize the smearing of the image, particularly for target features in the image that are moving.

7.4 Improved Landing/Terminal Area Guidance

Reliable provision of GPS PPS accuracy at the level of 1 meter or better with WADGPS will facilitate improved landing and terminal area guidance for both manned and unmanned aircraft. This is important both for autolanding capabilities for unmanned systems at multiple recovery bases and precision, adverse-weather approaches for manned systems at forward sites that may have no instrumentation (requiring only an accurate survey of the coordinates of the landing zone).

7.5 Improved Forward Observer Targeting

WADGPS will facilitate the provision of geolocation targeting information for rear-area indirect fire through forward observers using remote sensing systems (e.g., laser rangefinders) to image moving and relocated targets. The ability of the forward observer to locate himself to meter-level accuracy in absolute coordinates will register his targeting data into a coordinate grid usable by all other battlefield systems.

8.0 SUMMARY

A militarized WADGPS can provide the navigation accuracies necessary to support relatively low-cost, all-weather, launch-and-leave standoff weapons suitable for all types of fixed and relocatable targets. Such geocoordinate-homing weapons can have extremely high impact accuracies and thus achieve greatly increased kill probabilities per sortie (compared with alternative low-cost weapons such as unguided bombs). SRI has demonstrated the accuracies achievable by a militarized WADGPS concept in the EDGE program. SRI has also provided concepts for distributing differential correction information using the GPS system's integral datalink capability. With the availability of advanced techniques to provide highly accurate target location information in absolute coordinates, these weapons will dramatically alter military operations by providing high probability of kill per attack while substantially reducing the logistics support pyramid for a campaign. Other significant applications include mine warfare, precision airdrop, aiding for overhead imaging sensors, improved landing/terminal area guidance, and improved forward observer targeting.

ACKNOWLEDGMENTS

The author would like to acknowledge John Gagliano, Lt. Col Greg Teman, Capt. John Dargan, and Capt. Vince Jolley at the JDAM SPO, who provided the opportunity to do the work underlying the wide area DGPS concepts and gave their continued support to make it a reality. Much credit goes to numerous colleagues at SRI involved in the advanced GPS program, particularly Earl Blackwell, Mark Moeglein, and David Nakayama, whose creativity and hard work continues to make our effort in enhanced PPS accuracy a success. A special acknowledgment is also due the late Joe Murray and others at ARMCON, Inc., for key work on the JDAM CE study, including the mission benefits of increased weapon accuracy. Members of the EDGE demonstration team included Honeywell, Interstate Electronics Corp., and Sverdrup Technologies.

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White Paper
GPS Aided Inertial Guidance
for
Long Range Precision Strike Systems

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Introduction

The delivery of conventional, low yield nuclear or other special purpose payloads with long range ballistic missiles may demand a higher level of accuracy than is currently provided by the guidance systems of those missiles. Although the survivability of the Global Positioning System (GPS) in some strategic scenarios may be questionable, it will likely be some time before all but a very few potential adversaries can threaten that system. It should therefore be considered as a viable candidate for navigation for a guided reentry body (RB) intended for delivery of payloads that require enhanced accuracy. The use of a GPS aided inertial navigation system offers this enhanced accuracy with the added advantages of smaller size and lower cost, both of which will be important in the applications proposed above.

Although there are unlikely to be serious threats to the GPS constellation in the near future the potential for jamming of the signals in the vicinity of a high value, well defended target must be considered. Furthermore, the tracking of the GPS signals in the dynamic and RF attenuation environments associated with the reentry potions of a long range ballistic missile flight may prove to be a formidable (but not necessarily insurmountable) problem.

The navigation accuracy of a GPS aided inertial navigation system in applications where GPS measurements are assumed to be unavailable during some terminal phase of the trajectory will depend on the quality of the inertial system and point at which GPS measurements are lost. The limits of this trade off will range from the very high quality ballistic missile guidance system with no GPS measurements to the case where GPS is assumed to be available over the entire trajectory to the target. A viable design for such a system will trade high cost and larger volume against increased vulnerability to jamming of the GPS signals as it nears the target.

An inertial navigation system, whether gimballed, strapdown, or hybrid must maintain an attitude reference so that the orientation of its accelerometers with respect to some navigation coordinate system is known. The attitude reference can be initialized though various preflight procedures or can be initialized in flight. The design of a guided reentry body for delivery by a long range ballistic missile is likely to use an in-flight initialization procedure utilizing data from the booster guidance system. The estimation of the attitude of the accelerometers requires that the platform be accelerating to make this attitude observable. The boost phase of ballistic missile flight is ideal for this process. In a system design where the reentry body inertial system must navigate to the target without further aiding, the attitude reference must be maintained so that the acceleration associated with reentry can be resolved with the required accuracy. Typically the reentry bodies are spin stabilized after deployment from the booster system. In this case, gyro scale factor errors for a strapdown system where the gyros must measure the total angle resulting from spinning for a significant length of time result in significant attitude errors. A single gimbal system isolates the inertial instruments from the spin but at a cost of increased size and complexity.

The inclusion of GPS measurements offers the opportunity to update the attitude reference if the measurements are available when aerodynamic drag induced acceleration makes the attitude error observable in the same manner as boost acceleration does. If GPS measurements are available during coast but are lost before reentry then the requirements on attitude accuracy are the same as stated above. On the other hand if GPS measurements are available for the entire flight then accuracy is determined by GPS performance and the quality of the inertial system becomes moot.

Analysis

In this white paper the tradeoffs between quality of the inertial system and the availability of GPS measurements is quantified using the inertial navigation system covariance analysis code, NAVCOV. In covariance analysis the inertial sensors are represented by a model that describes error associated with the sensors or the associated electronics. The models used generally reflect the compensation routines that are used in an INS but include other error sources that may not be modeled in the INS instrument compensation algorithms. An initial variance and optionally a process noise parameter that causes this variance to grow with time are input for each parameter modeled by the covariance code. These values generally reflect the expected quality and performance of the INS. The covariance matrix associated with the basic navigation errors, the IMU instrument errors and parameters associated with GPS are propagated over a trajectory. In the figures shown the 2 by 2 submatrix associated with latitude and longitude errors is used to draw an error ellipse. This ellipse is the one-sigma contour for the bivariant normal distribution for horizontal error.

In the analysis two representative inertial systems were considered, relative high quality system and a smaller, low cost system. IMU-1 is assumed to have relatively high quality gyros with 0.01 degree per hour bias stability and 1.0 part per million scale factory performance. Typically such an IMU would occupy 200-400 cubic inches and costs between $100,000 and $300,000. IMU-2 is assumed to have smaller lower cost gyros with 1.0 degree per hour bias stability and 150 part per million scale factor stability. This IMU would occupy 50-100 cubic inches and costs between $30,000 and $60,000. In all cases the INS is assumed to be perfectly initialized at reentry body deployment and errors are propagated from that point. This approximation is made for convenience as the errors at the target are dominated by the GPS measurements and the errors that accumulate during the coast and are largely independent of initial state.

Figure 1 shows the error ellipse under these assumptions for the IMU-1 assuming that the last GPS measurement is available at an altitude of 300,000 feet. In this case GPS is lost before any significant drag acceleration is sensed and therefore no improvement in attitude errors results. The corresponding plots for IMU-2 are not shown as the errors at the target are too large (> 30,000 feet) to be of any interest.

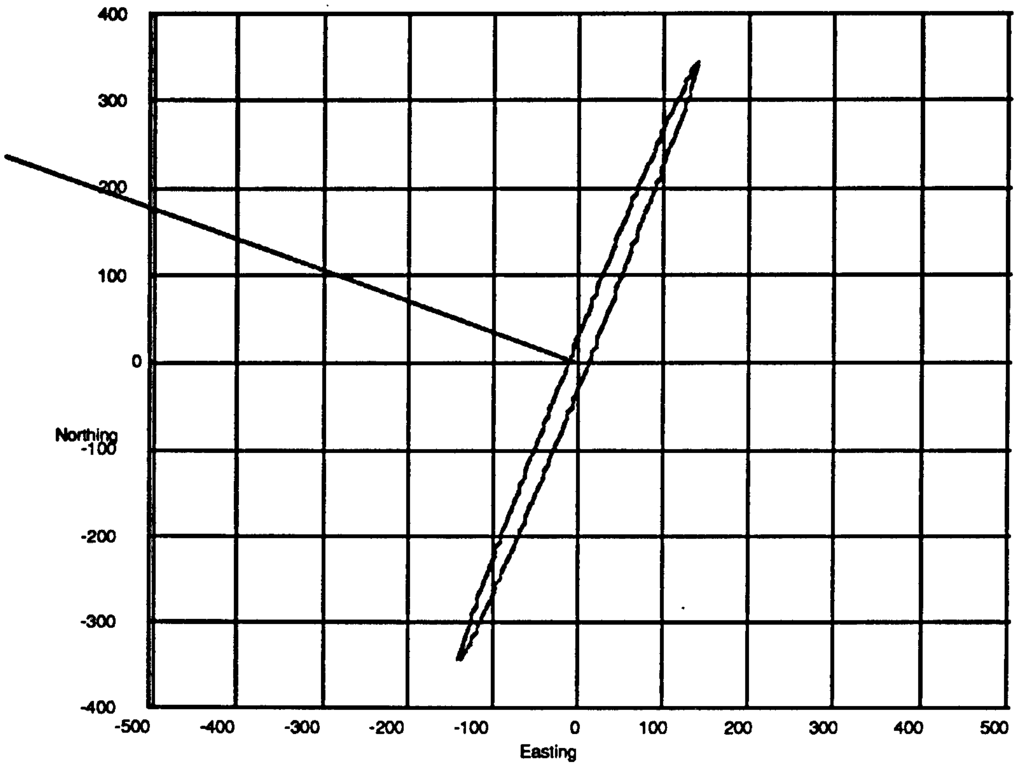


Figure 1. *One sigma error ellipse for IMU-1 assuming that the last GPS measurement is made at an altitude of 300,000 feet and the reference trajectory ground track.*

In Figure 2 it is assumed that GPS measurements are available to an altitude of 200,000 feet. And even though the drag acceleration has reached only approximately 0.2 Gs, significant improvement in performance results. In Figure 3 GPS measurements are assumed available to an altitude of 120,000 feet. At this point drag acceleration has reached approximately 1.8 Gs. It can be noted that the performance of IMU-2 is only slightly worse and the difference is mostly in the down range direction. The CEPs of the two systems in this case would be quite similar. In Figure 4 GPS measurements are assumed available to an altitude of 60,000 feet where drag acceleration has risen to approximately 25 Gs. The performance of IMU-1 remains somewhat better in the down range direction. In Figure 5 GPS measurements are assumed available to an altitude of 20,000 feet. In this case accuracy is dominated by GPS and the performance is nearly identical for both IMUs.

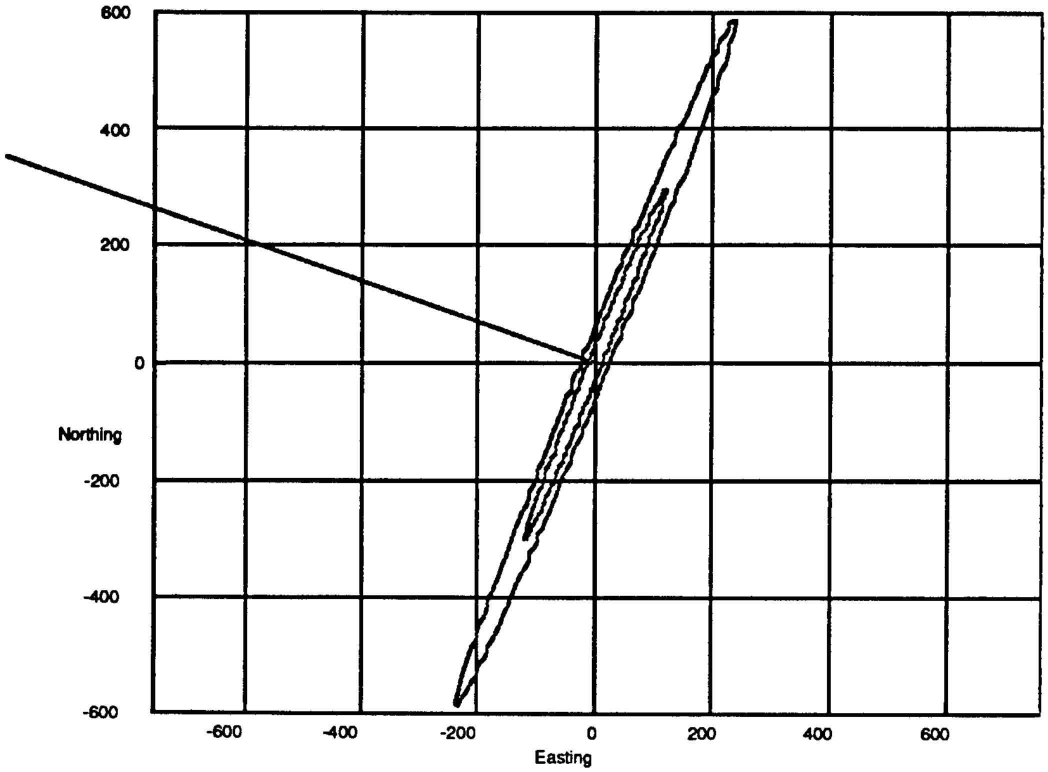


Figure 2. *One sigma error ellipses for IMU-2 (larger) and IMU-1 assuming that the last GPS measurement is made at an altitude of 200,000 feet.*

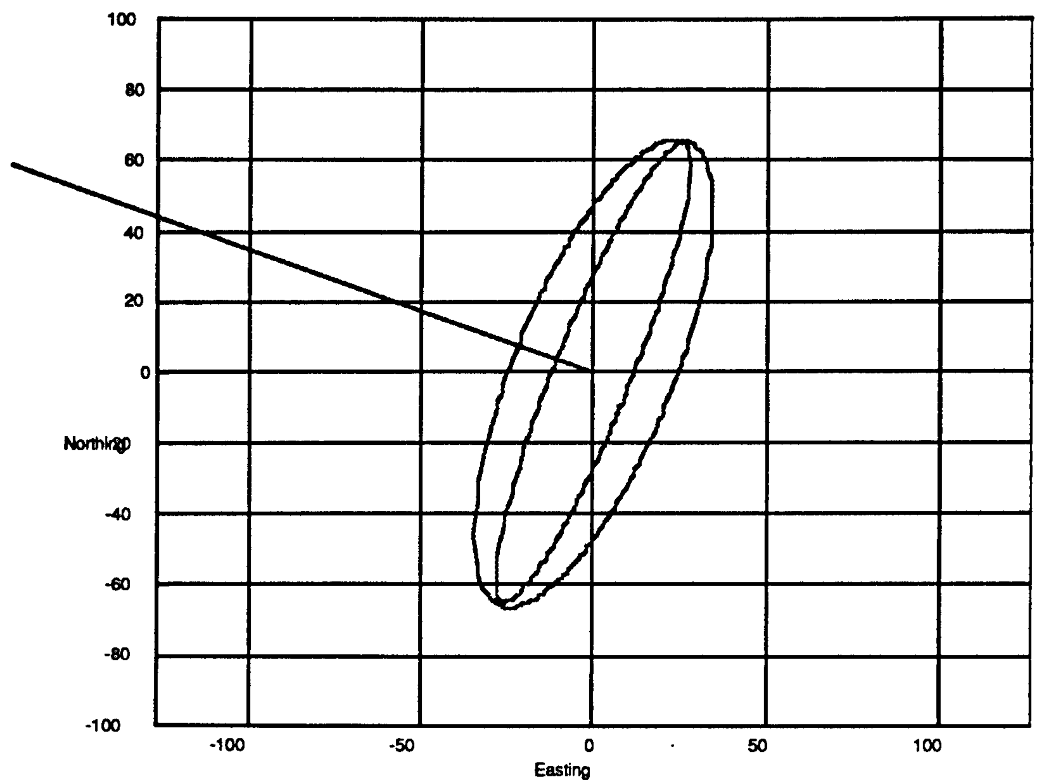


Figure 3. *One sigma error ellipses for IMU-2 (larger) and IMU-1 assuming that the last GPS measurement is made at an altitude of 120,000 feet.*

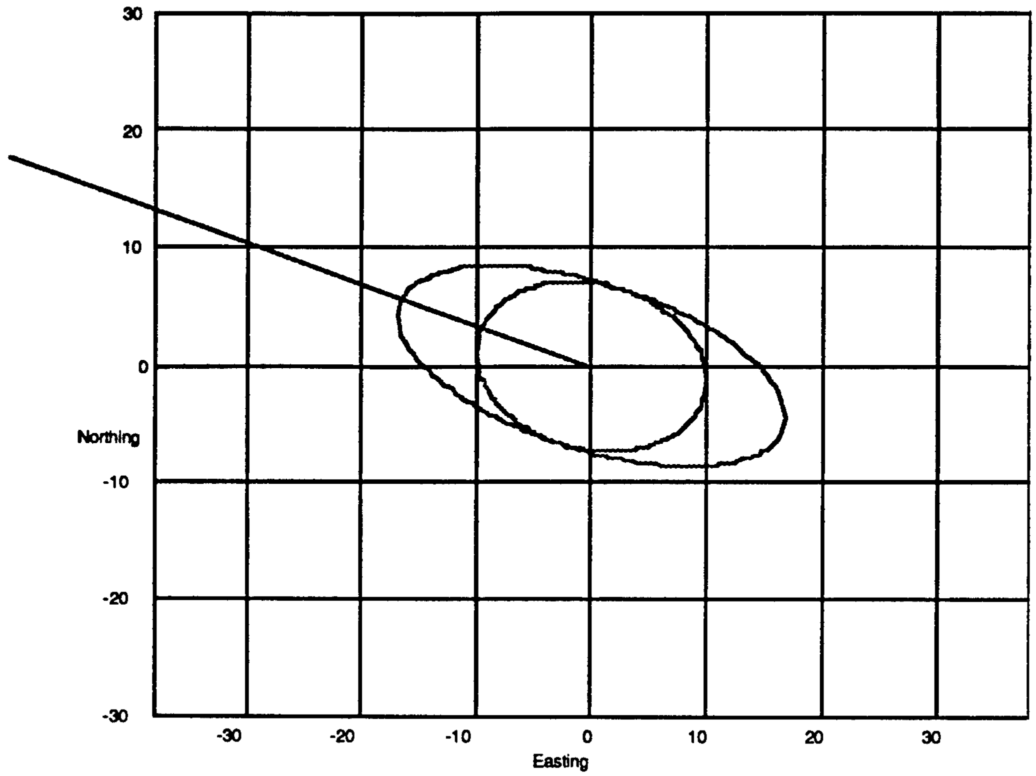


Figure 4. *One sigma error ellipses for IMU-2 (larger) and IMU-1 assuming that the last GPS measurement is made at an altitude of 60,000 feet.*

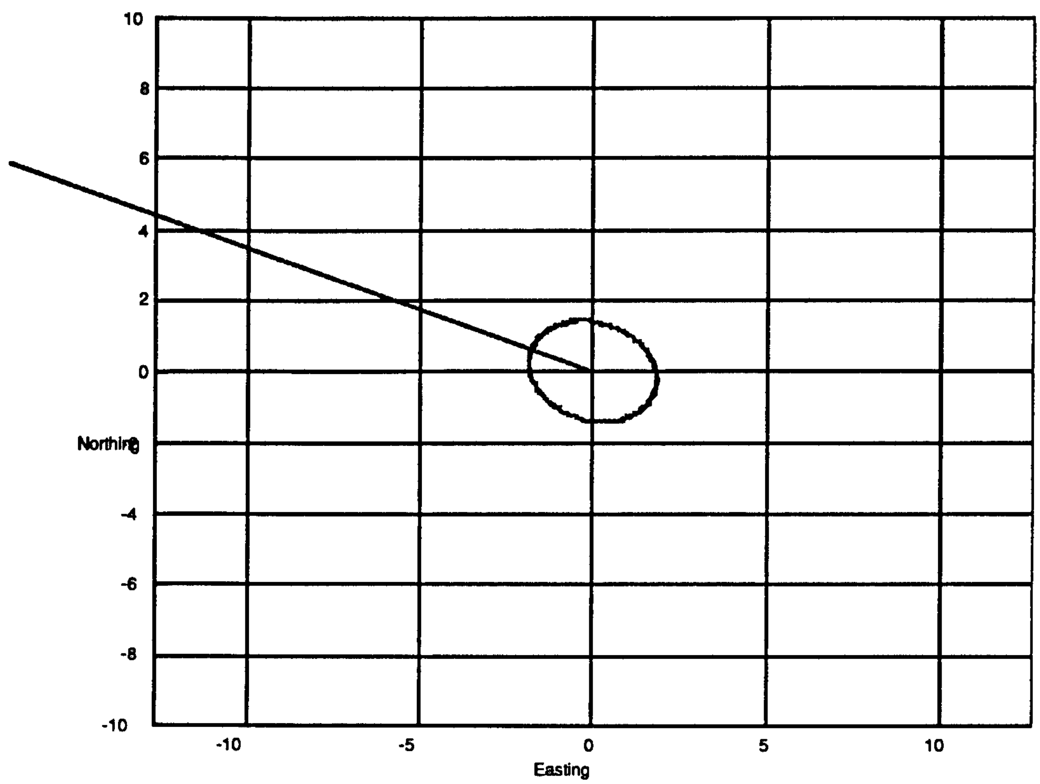


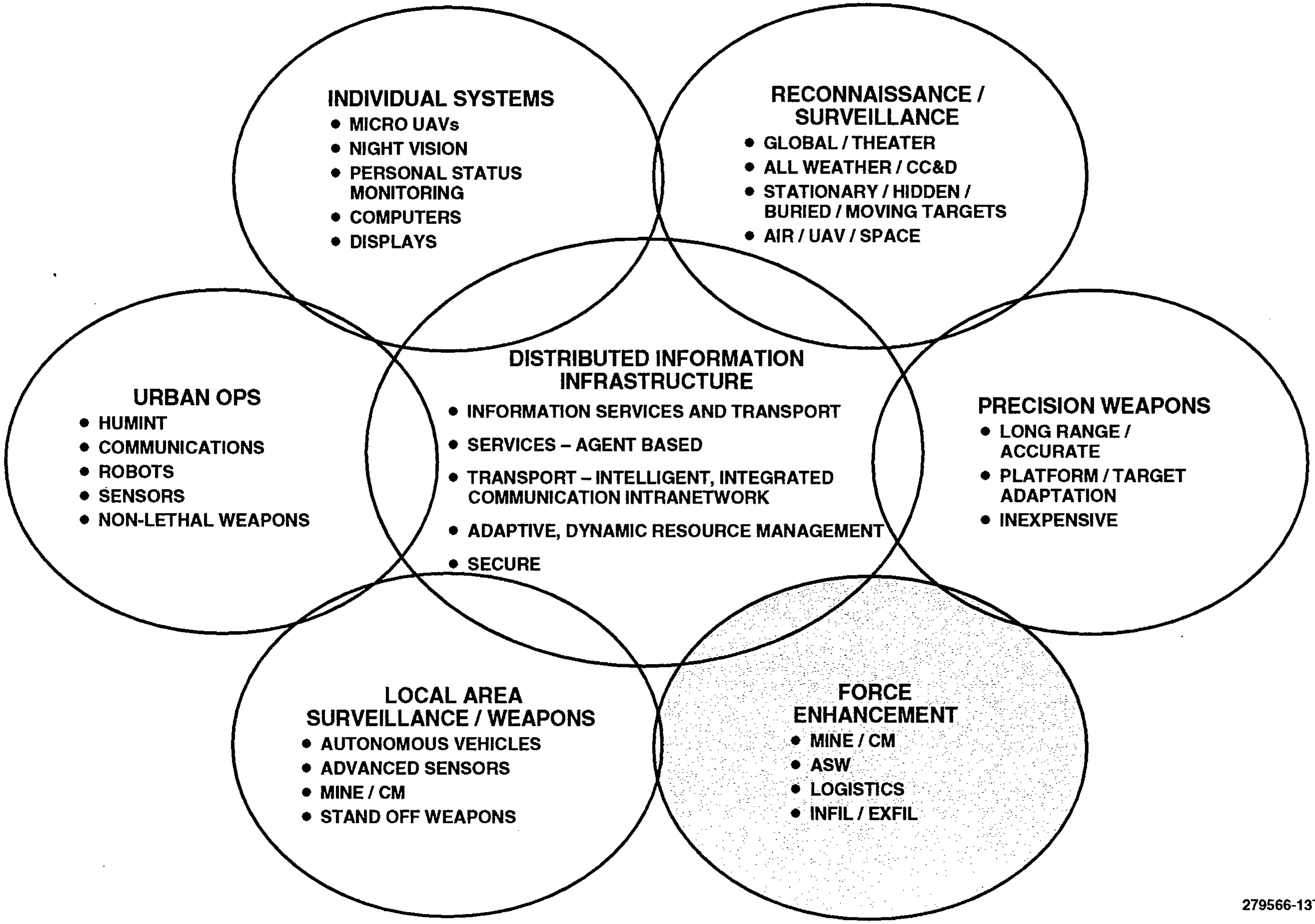
Figure 5. *One sigma error ellipses for IMU-2 and IMU-1 assuming that the last GPS measurement is made at an altitude of 20,000 feet.*

Conclusions -

If GPS measurements are available to altitudes where any significant drag acceleration is sensed, the benefits gained from the higher quality IMU is not great. Only in cases where GPS is lost early is a higher quality IMU required for achieving useful accuracies. Currently available GPS receivers will operate without inertial aiding to acceleration levels that will result in significant improvements in accuracy on target. Available receivers that can be aided will extend this range and it is likely that with additional development that could be done at modest cost the entire range of accelerations associated with reentry could be covered. Inertially aided systems also offer significant advantages in jamming rejection and can operate at lower signal levels and therefore are less susceptible to RF attenuation form plasma effects during reentry. Existing GPS receivers and a relatively small low cost IMU would provide useful system accuracy if jamming or plasma induced blackout does not result in the loss of GPS measurements well above 120,000 feet. The performance of such systems could be improved at modest cost with little impact in required volume by further development of integrated GPS/INS systems. Such a system using a low cost IMU with 1.0 degree per hour laser gyros would be suitable for applications where plasma blackout or long range GPS jamming can be avoided.

TACTICS AND TECHNOLOGY FOR 21st CENTURY MILITARY SUPERIORITY

TECHNOLOGY CONCEPTS PANEL



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UNDERSEA WARFARE
CURRENT ISSUES AND FUTURE CONFLICTS

White Paper

Paul Kolodzy

UNDERSEA WARFARE
CURRENT ISSUES AND FUTURE CONFLICTS

The dominant technical and system issues germane to the current and future *undersea warfare* (USW) missions are described in this paper. The scope of undersea warfare will dramatically change as the geopolitical climate changes. The change from a "blue ocean" problem of detecting former Soviet nuclear submarines of the 1950-1990 era to one that includes the 1990s littoral or "brown water" problem of detecting rest-of-world diesel-electric submarines is underway. However, as conflicts become more localized and the available offensive weaponry becomes more sophisticated, additional changes will be required of the USW community.

CURRENT ISSUES

In the 1990s, the ability of US naval forces to detect submarines and mines is critical for both peacekeeping and power projection roles. The 1990s USW mission has shifted emphasis from a predominance of detecting *former-Soviet nuclear submarines* in the open ocean to the broader mission of detecting *quieted nuclear submarines*, *rest-of-world (ROW) diesel-electric submarines*, and *mines* especially in the littoral environment.

Three fundamental problems exist: the detection and classification of quieted former-Soviet submarines, the detection and classification of diesel-electric and *limited-crew* submarines in littoral environments, and general surveillance of underwater *anti-ship, anti-submarine mining operations*. Each of these problems is pushing technology in a different direction due to the associated tactical environment (blue ocean versus littoral) and the readily exploitable signal features.

1. The quieted nuclear submarine poses a difficult problem in both wide-area surveillance and tactical settings. In either case, it is fundamentally SNR-limited and thus range limited. Detection improvements, for both surveillance and tactical systems, will rely on the capacity to narrow beamwidths or employ innovative background filtering. The traditional approach to narrowing beamwidths is via long hydrophone arrays. However, tactical systems have had difficulty using towed arrays during maneuvering periods. This potential deficiency will become increasingly more important as detection ranges decrease due to signature reduction. Also, as the detection ranges decrease, more signal features will play a role in detection and classification and thus the operator loading will quickly become unmanageable.

2. The littoral anti-submarine warfare (ASW) problem has become increasingly important over the past few years. This is due to Third-World procurement and the willingness of major powers to sell non-nuclear submarine assets. The littoral environment leads to significantly more complicated clutter environments due to both confusable manmade signatures and more complex acoustic propagation that then become the performance limiting factor. The use of smaller diesel-electric submarines leads to reduced and potentially more complex acoustic signatures
3. Potentially the most severe problem, politically and militarily, is mine warfare. With the end of the Cold War, Navy operations have focused increasingly on shallow-water regions and support of littoral warfare. Operations in the Persian Gulf are characteristic of this new emphasis. More than half of the casualties to naval vessels in terms of damage and sinking over the past several decades have been due to encounters with mines. The emphasis of current mitigation techniques is on the removal and detonation via mine-sweeping. Currently there are no mine surveillance techniques readily available. The accessibility and low cost of potentially stealthy mines can provide any adversary with the means to inflict damage. Current mine sweeping techniques are either slow (removal) or incomplete (detonation).

CURRENT ACTIVITIES

These problems have motivated the development of new technologies for both passive and active acoustic systems. For passive systems, there are currently programs in improving towed arrays by both increasing the length and the number of arrays, programs in exploiting the full range of acoustic signatures, programs in clutter mitigation techniques, and programs in information processing to improve the ability of the operator to sort through the plethora of acoustic data and large search space (space and signatures).

Attempts to improve the capabilities of the current active acoustic systems programs are also currently underway in active classification, leave-behind sources, multistatic sonar, low probability of intercept (LPI) sonar, and underwater communications. All of these programs are attempts to transition the active sonar from just a targeting sensor into a surveillance sensor.

FUTURE CONFLICTS

Although this shift in scope produced changes in both the type of systems developed for the USW mission during the past five years, the next twenty years will see a possibly greater change. Third World countries continue to procure advance weapon systems at an increasing rate. Future adversaries may wage war based on economic hardship by holding hostage the world's commercial shipping, a neighbor country, or even on an adversary's own population. The lessons from the Gulf War will have taught our future adversaries to focus on denying our access to the region and to inflict political over military damage.

Naval forces will be called upon to support military operations for regional conflicts. The surface forces including carriers, missile ships, cargo vessels, amphibious landing ships, and troop carriers will be required to either operate close-to-shore or perform shore landings. This would put those assets in direct contact with opposing USW forces. Low intensity conflicts would present a fixed and relatively small operational area in which surface naval forces would be required to operate. This might nominally be a 200 nm shore region by 50 nm out to sea. Sophisticated bottom and bottom-moored mines would be used to deny Allied access to coastal regions, protect the adversary's limited submarine forces, and deny combatants and commercial shipping access to valuable sea-lanes. Submarines would be used to provide a serious challenge to those Allied forces that attempt to access coastal regions despite the mine threat.

In particular, to prevent Allied operations, the opposition would use both bottom and bottom-moored mines to limit access and to provide safe havens for their less sophisticated submarine forces. Their submarine forces would not be classically deployed as individual attack platforms using the sensors indigenous to the submarines. The submarines would maintain stealth by their low speed and small size. Acoustic listening posts, such as sonobuoys and fixed arrays, would be positioned as trip-wires to provide location information instead of the submarines own sensor systems. Then an attack would be launched via modern wake-homing or fiber-linked torpedoes at a range in excess of current passive detection capabilities. This would allow the defender to expend their limited monetary resources on advanced weapons instead of sophisticated launch platforms.

The opposition will deny access to coastal regions using the stealthy, inexpensive mine warfare; use the advantage of local territory to position acoustic trip wires to local potential targets and to prevent exposing limited and less sophisticated submarine force; and stealthy, via low speed and small size, launch platforms with sophisticated weaponry will be used to inflict damage on vessels determined to access coastal regions. The Allied forces have the advantage of speed, air superiority, communication infrastructure, sensors, and processing technology. These advantages can be used to counter the future threats outlined here.

TECHNOLOGY OBJECTIVES

The goal is to develop the technology for two scenarios: to clear threats for an approaching military formation; and to clear a region of open water for naval coastal operations. This requires the ability to detect both the small, low speed submarines as well as the deployed mine fields. Current passive-centric systems will be unable to complete this mission due to the lack of signals from the mine fields; the limited source levels from the low speed, smaller submarines; and the high ambient noise fields of coastal regions. Active sonar can play a dominant role is completing this mission.

This active acoustic USW mission is extremely difficult from monostatic measurements due to the low target scattering cross-section and the lack of discernible features between the targets and background clutter including sea mounts, biologics, and reverberation. Multi-static measurements provide additional features for exploitation. Two potential characteristics to distinguish mine fields and small (diesel-electric and limited crew) submarines from the background are symmetry and spatial scales. An active acoustic system that exploits these scattering characteristics directly is one viable approach for this USW mission.

- Mines are symmetric about the vertical axis. Therefore, ensonification from multiple aspects will produce identical scattering less the effects of aspect variable acoustic propagation medium. Scattering from the sea floor, sea mount and marine life all have a high degree of ensonification aspect dependency.

- Submarines also have a high degree of ensonification aspect dependency. Submarines, however, differ from clutter in the number of spatial scales that are present in the structure's geometry. Therefore, the fusion of multi-static measurements from the target being ensonified by single or multiple aspects will provide for a high level of discrimination.

Multi-static measurements in both ensonification and reception are key to the littoral USW mission. They provide robust signatures, reduced signature variability, and for clutter discrimination. The multi-static measurements require tight coordination between sensors, communication systems, and processing architectures.

USW CONCEPT FOR SMALL, REGIONAL CONFLICTS

As stated earlier, Allied forces have the advantage of speed, air superiority, communication infrastructure, sensors, and processing technology. This USW mission concept would exploit these advantages via multistatic sensor networks and underwater communication networks while maintaining the stealth characteristics of tactical USW assets. The concept is to encircle the regions of interest with acoustic undersea surveillance assets and exploit the specific acoustic scattering phenomenology the can be obtained by multiple aspect measurements. The two scenarios discussed above require different sensor configurations.

- *Remove threats for an approaching military formation*: Underwater, unmanned vehicles as "pilot fish" in advance of transiting ships or submarines. These "pilot fish" would be placed in front of the vessels. Groups of "pilot fish" could be netted via communication links to create a large multi-static active acoustic array. They would become indigenous to individual ships as the Seahawk helicopter is currently used for destroyer squadrons.
- *Remove threats from a region of open water for naval coastal operations:* Acoustic surveillance assets would be placed concentrically around a 50 nm coastal region. Submarine and surface assets would be placed in positions furthest away from the coast. Fixed deployable acoustic arrays, such as a smaller version of ADS (Advanced Deployable Surveillance), would be placed near shore for a 30 to 90 day period.

Sensors

Two source technology efforts would be exploited to provide both stealth for the surveillance assets and high source power: the development of an LPI (low probability of intercept) sonar and the development of leave-behind sources. The LPI sonar using spread spectrum and chaotic waveforms maintains the stealthy characteristics of both the attack submarines and the stealth ships under development. Both rely on stealth for survival and would not employ active acoustics unless assured of maintaining stealth. The leave-behind source provides a means for multi-static measurements as well as desirable source-target-receiver geometry. Any source that would be used would be programmable to allow skip frequency waveforms to allow the signal processing algorithms to exploit the spatial scale variations between submarines and the underwater topology.

Communication Networks

In order to exploit the multiple aspect geometry of the measurements, data links between each of the sensor systems (pilot fish, surface ship, submarine) is required. A communication network would be needed to provide links between the surface, submarine, and fixed assets. This provides the means to incoherently combine the multistatic signals. An underwater cellular network is one method of providing both covert and reasonably high bandwidth between submarines, fixed arrays, and surface ships.

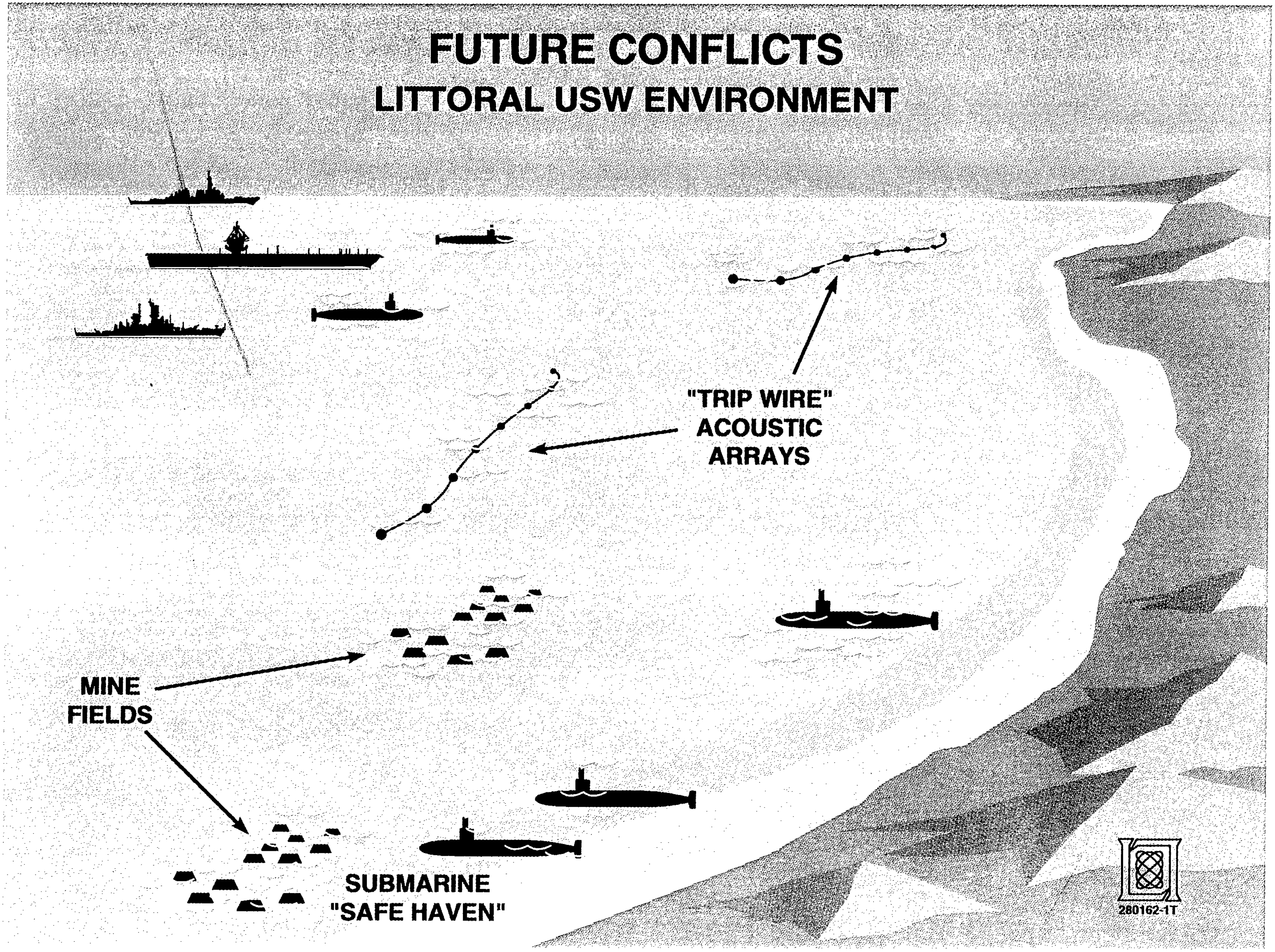
A series of vertically mounted arrays concentrically spaced around the operating area would act cell sites. The cell sites would communicate using combinations of bottom-layed fiber optic links and buoys with RF links. A submarine wishing to communicate would require the location of the cells to within the order of a hundred yards. A submarine would communicate with these cell sites by first measuring the transmission loss characteristics and then use the minimum channel power to insure low loss communications. The data rate would be high from submarine to cell site and low from cell site to submarine. The transmission loss characteristics would be measured in-situ since the cell site would emit a "LPI" signal intermittently.

Processing Architectures

Once the beamformed information from all the platforms is available at one site, preferably a surface ship, then processing techniques would be applied to exploit the multi-aspect information. A plethora of new processing architectures would be developed to exploit the specific features of these measurements. A partial list would include: adaptive aspect correlation, underwater active tomography, wavefront projections, topographic processing, skip frequency scattering, and matched field beamforming. Target information (submarines and mine fields) would then be placed back on the RF and underwater cellular network.

OTHER TECHNOLOGY ISSUES

Although not part of the surveillance problem, ship and submarine self defense should be another focus area for future conflicts. Offensive reaction to an adversary's sonar or torpedo is within the reach of technology. The technology to link the transmitter, receiver array, and signal processor can both be used to deceive an adversaries own acoustic system as well as enhance the active and passive signatures that are collected. The two technologies that could be developed spawn from the concept that both the transmitter and receiver should be adaptive. The sophisticated torpedoes in the future may still be susceptible to acoustic jamming and/or spoofing.


FUTURE CONFLICTS
LITTORAL USW ENVIRONMENT
"TRIP WIRE"
ACOUSTIC
ARRAYS
MINE
FIELDS
SUBMARINE
"SAFE HAVEN"
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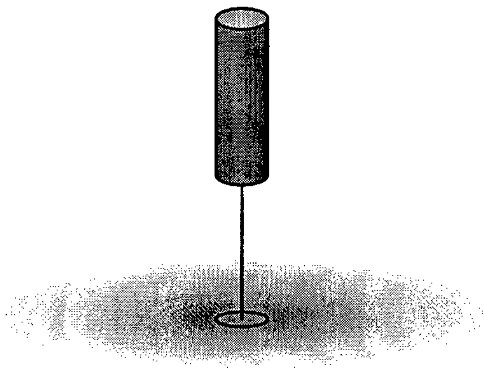
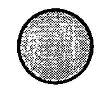
SYMMETRICAL TARGETS

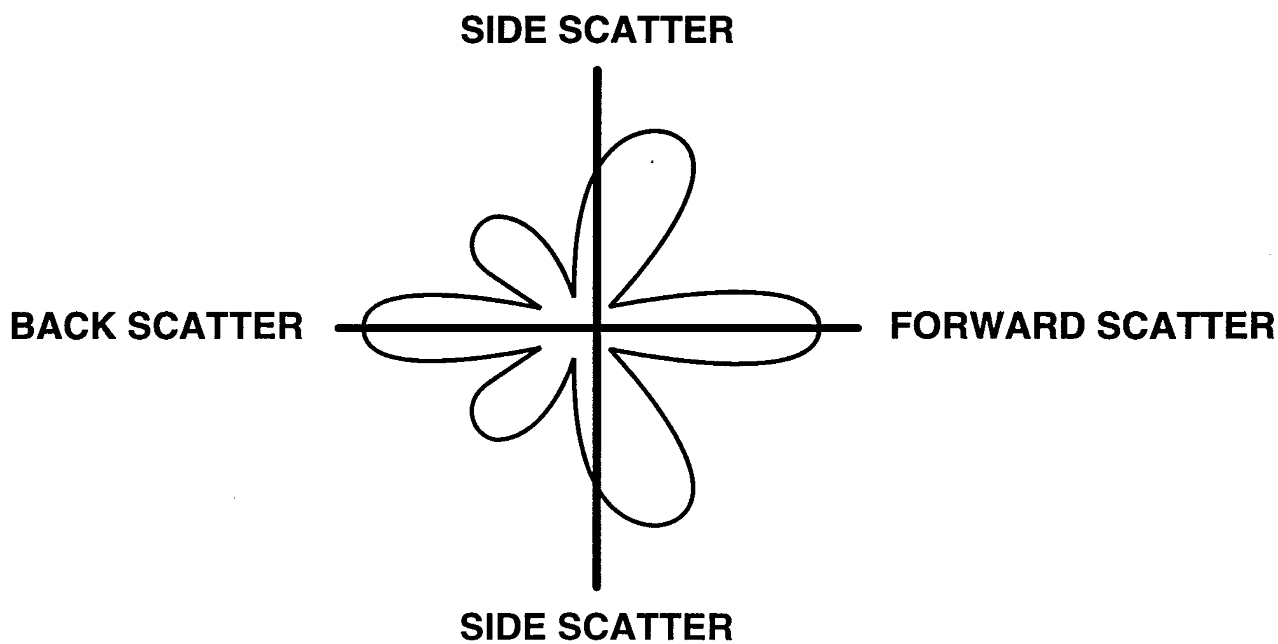
(Independent of Illumination Direction — *Notional*)



SIDE VIEW



TOP VIEW



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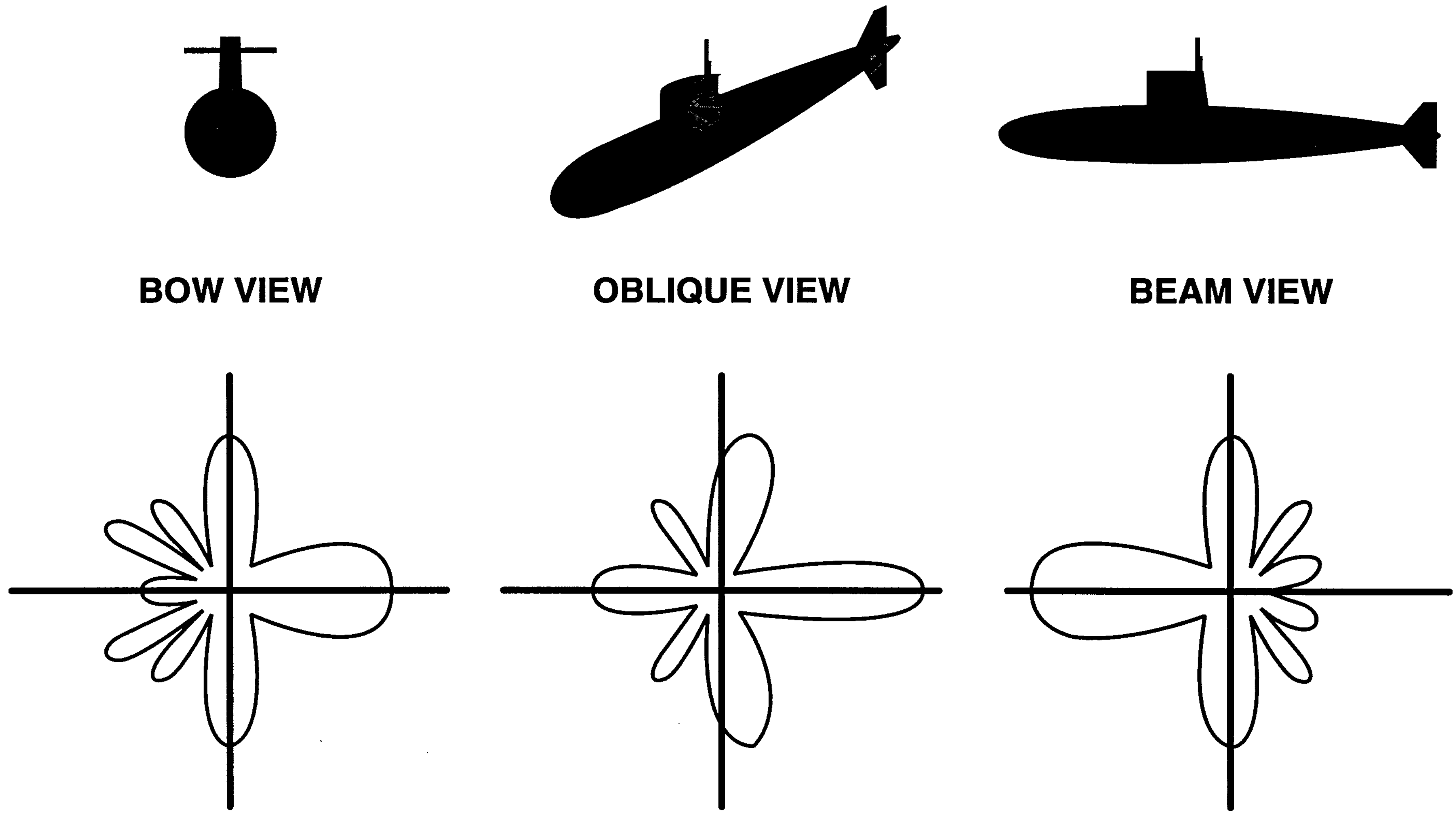
ASYMMETRICAL TARGETS

(Aspect Graphs — *Notional*)



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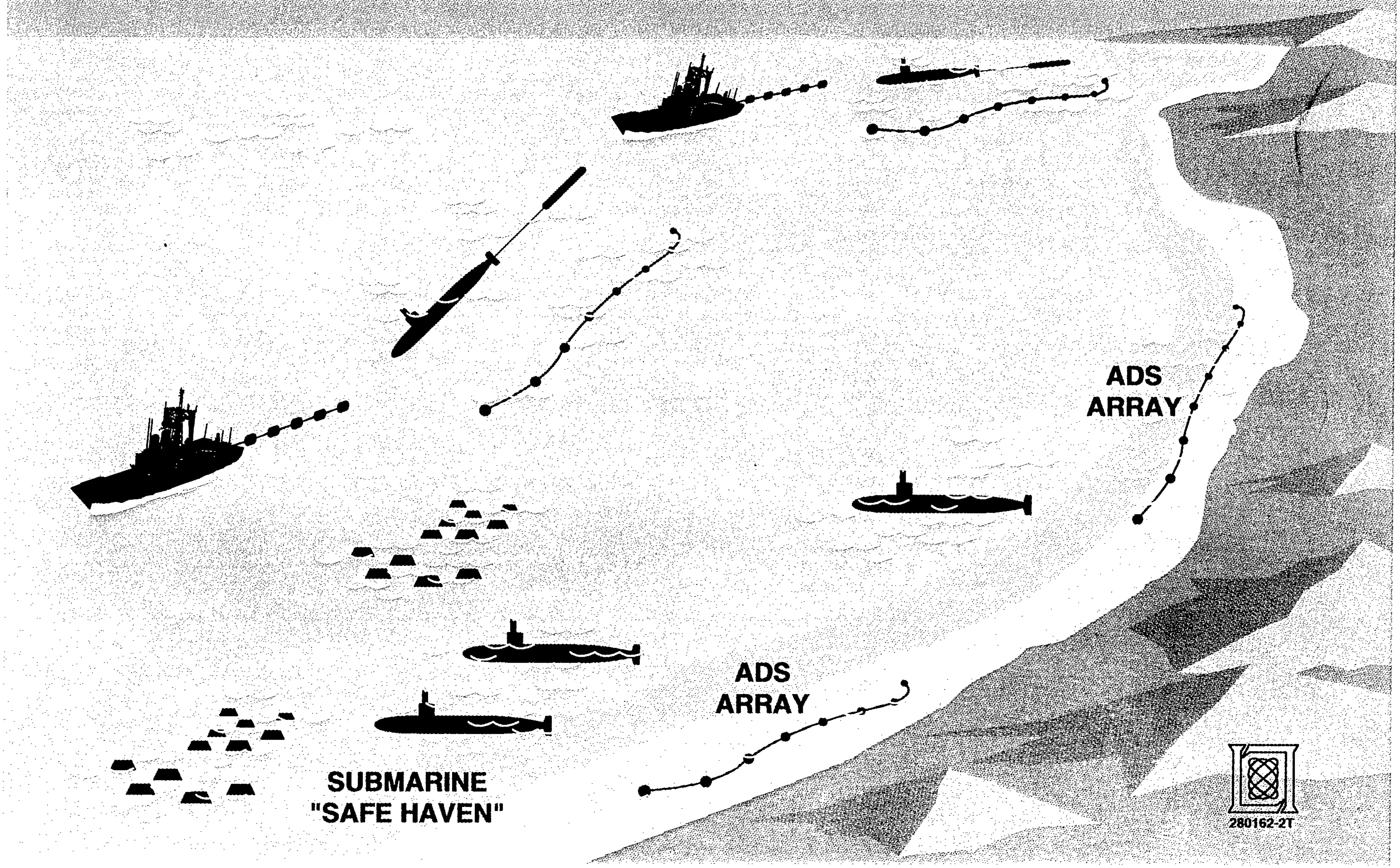
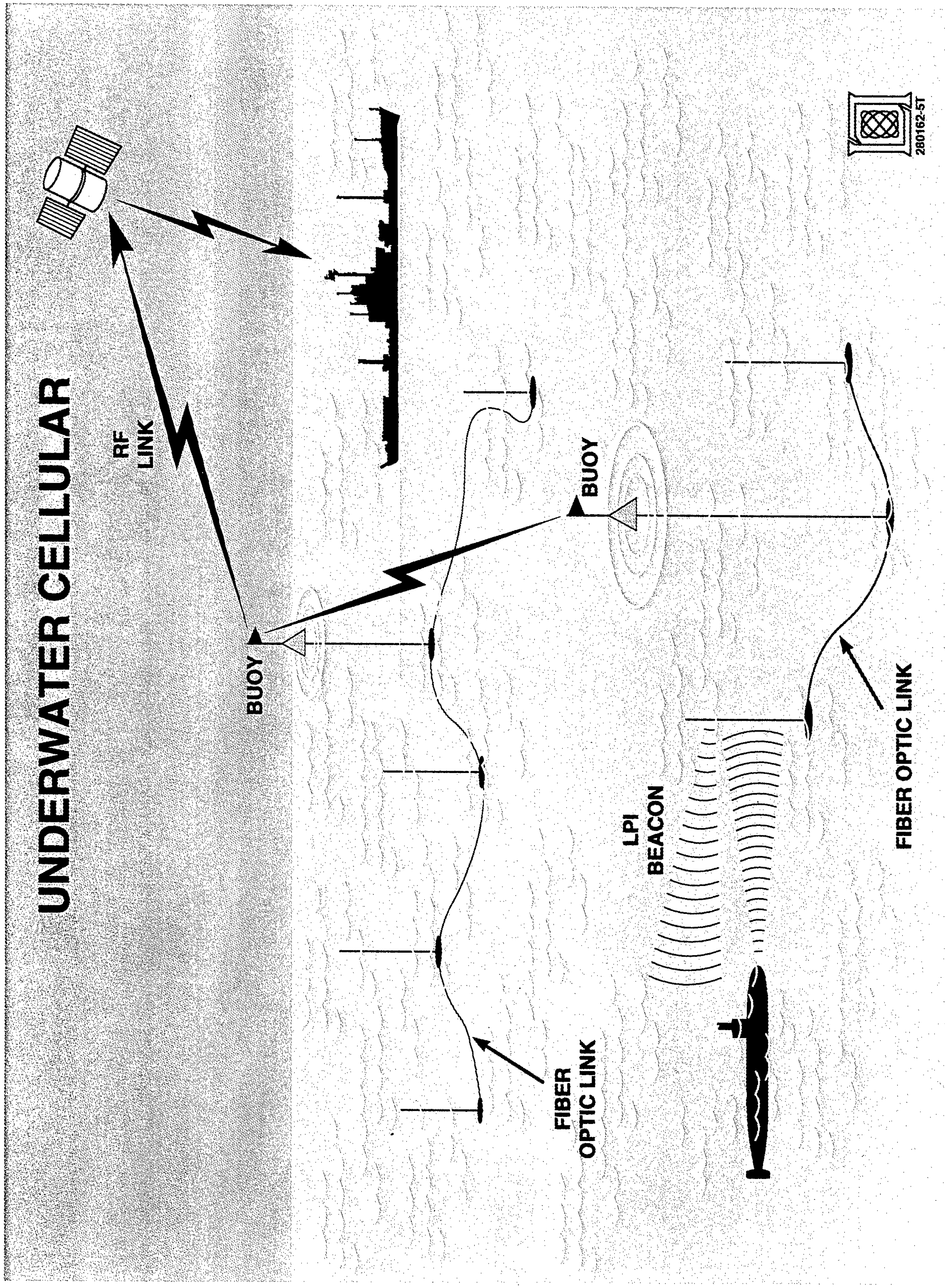
MULTISTATIC SURVEILLANCE
LITTORAL USW ENVIRONMENT





UNDERWATER CELLULAR
RF LINK
BUOY
BUOY
LPI BEACON
FIBER OPTIC LINK
FIBER OPTIC LINK
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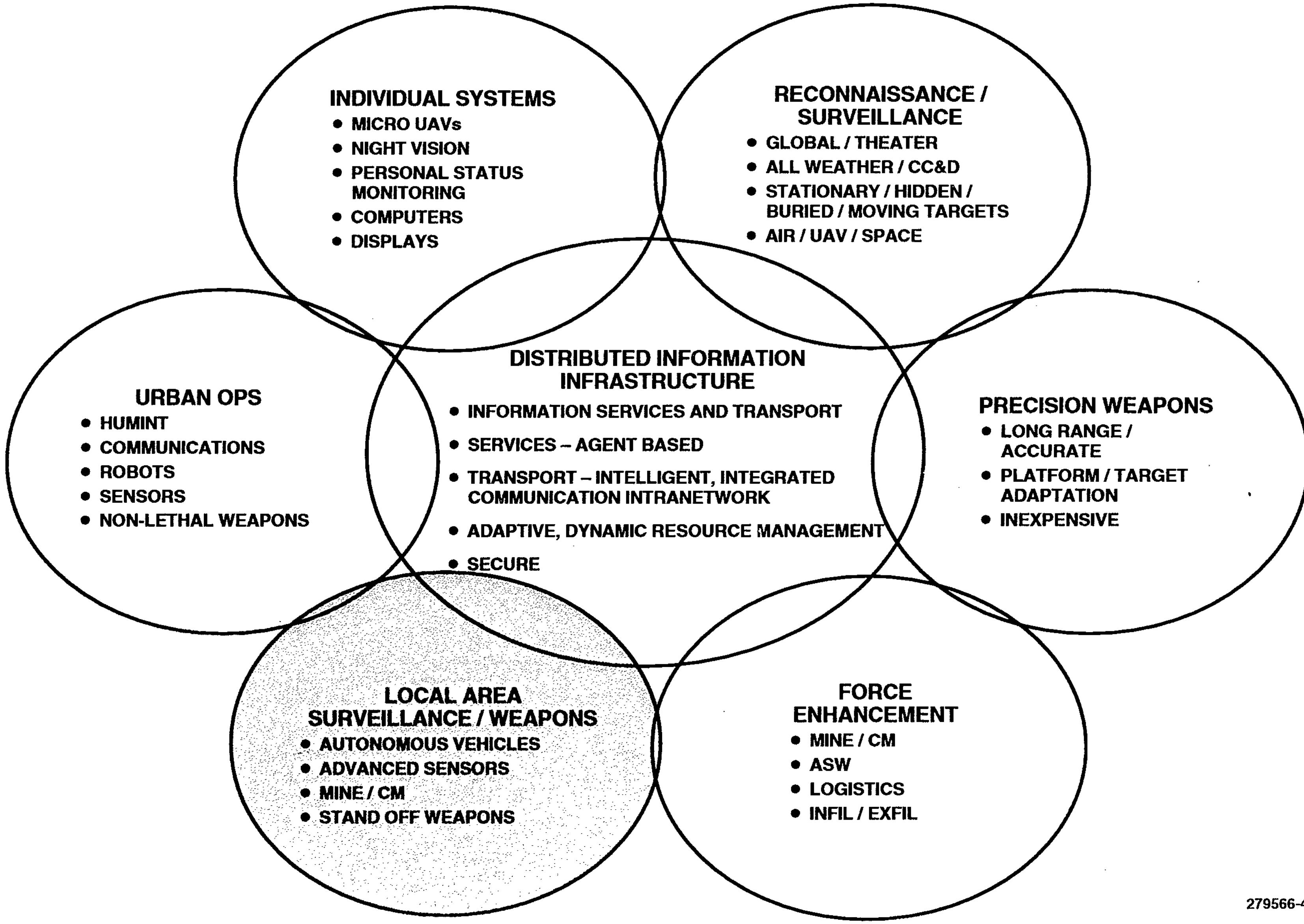
TACTICS AND TECHNOLOGY FOR 21st CENTURY MILITARY SUPERIORITY

TECHNOLOGY CONCEPTS PANEL



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Tactics and Technology for 21st Century Military Superiority: Systems Concepts for Relatively Small, Rapidly Deployable Forces

A White Paper
prepared by
Sandia National Laboratories

Joe Polito
Dan Rondeau

May 1996

INTRODUCTION AND BACKGROUND

The purpose of this white paper is to discuss systems concepts that impact mission success for the use of relatively small (5000 or less personnel), rapidly deployable forces to perform tasks heretofore only possible with much larger and massed forces. In particular, the context for this paper is five example tasks:

- Halting an armored invasion
- Controlling territory against widely distributed light infantry/militia type forces
- Accomplishing large scale special operations
- Conducting a series of widely dispersed offensive operations deep in hostile territory
- Extracting a force that has been inserted

To accomplish these tasks, the friendly forces will need to be extremely mobile, exquisitely aware of the enemy situation, stealthy, and pack a good punch - all without traditional heavy armament and long logistics tails characteristic of today's conventional forces. This is because their mission responsibility requires that they not only strike and run, but sometimes stand and fight against forces that are, in a conventional sense, much superior. A major shift in capability and tactics will be required to allow this new warfighting unit to succeed in battle.

CRITICAL SUCCESS FACTORS

If the example tasks were accomplished by a 5000 member force behind enemy lines with today's assets and supply concepts, there would be several likely shortfalls that would affect unit survivability and mission effectiveness:

Sustained operations:

Shortfall: Inherent logistics limits (e.g. no/constrained resupply line) would inhibit operations beyond a few days and thus reduce the scope of missions these forces could successfully undertake and the period of time they could remain viable in the field.

Combat operations in hostile territory by lightly armed, relatively small units will require a significant support commitment of air, ground, and/or sea resources, as well as an unprecedented intensity of C4I activity. Also, normal logistics functions such as resupply will be very difficult and will be dangerous to both the supplying and the supplied forces. As a result, it will not be possible to sustain such operations indefinitely. Therefore, the remote forces will be given very specific tasks and will be under severe pressure to perform those activities and no others. They will then be extracted as quickly as possible.

To the extent possible, the forces and their equipment will be tailored to the mission at hand in order to reduce logistics requirements and to reduce the amount of support manpower required. Multi-purpose equipment and weapons which impose a mobility or other cost to the unit for lower priority functions will not be effective. Similarly, the amount of support effort needed to operate equipment and perform other needed logistics functions must be minimized. A likely characteristic of such units will be equipment that is as specific to the mission as possible and personnel that are as broadly trained to perform multiple functions as possible.

New concepts for force multipliers will be essential. In the case of software, the C4ISR functions must be very intelligent. Multi-function consoles requiring few operators will be the norm. Systems will have intelligent displays that filter out unimportant detail and automate all procedural activities. Only high value, cognitive tasks will be presented to the operator/commander for human interaction. Communications systems will self configure and will automatically adjust to changing situations. Direct communication with each individual in the unit will be available. For mechanical systems, automation and robotics will reduce the workload and increase the reliability for many combat and non-combat functions.

New technology, in areas such as robotics, intelligent information processing, energetic materials, caseless ammunition, light weight armor, directed energy, microelectronics and sensors, and real time, high bandwidth, low signature communications, will be required to dramatically increase the unit's "effectiveness per pound of asset".

Firepower:

Shortfall: The mobility characteristics of current heavy weapon assets would limit indigenous direct fire support. Furthermore, the dispersed operating environment suggests that the units will not always be within the range of MLRS type support. This would significantly limit the size and type of force the unit could successfully engage.

Force application will often be required for mission accomplishment. In addition, lethal force will be needed to deter the enemy and deny opportunities to engage the friendly forces in unfavorable circumstances.

When the unit has specific, high value targets as its objectives, precision, quick response attack will often be required. These targets may be in urban environments where collateral damage is to be limited. They may also be deeply buried targets or critical mobile targets. In these cases, very high accuracy weapons capable of striking from a great distance will be needed. These weapons will be expensive but affordable because of the value of the targets.

In other cases, area defense weapons will be needed. If the friendly forces must defend themselves against superior forces or stop a large armored attack, expensive, point-attack weapons may not be affordable. Broad area fires comparable to MLRS/BAT, close air support, or carpet bombing will be required. Operational concepts and planning must include ready access to large scale fire support for contingencies and for accomplishing the unit's primary missions. The ability to support and defend these units will often depend critically on whether air superiority has been achieved.

New technology is required in the areas of lower cost, standoff, precision strike weapons (ground, air, and sea launched), warheads and fusing for precision strike weapons that are tailored for different target types, lighter weight and greater lethality anti-armor weapons, directed energy weapons, autonomous light-weight portable area defense weapons such as WAM, rapid tasking and targeting for remote fire support, and non-line-of-sight damage assessment.

<u>Situation awareness:</u>

Shortfall: No indigenous wide area recce/surveillance resources exist today at the division level. Therefore, unless a command and control link can be maintained with corps and higher level resources, the unit is essentially blind beyond its immediate area of operation. This will certainly create unacceptable risk for the unit.

The greatest need these forces will have is for exquisite situation awareness. Their only hope for survival and success is to sense and understand the enemy's activity soon enough to select the time and place for engagement and to control the tempo of hostilities. Without situation awareness, these forces will be very vulnerable. Furthermore, they will be ineffective. Mission success will require that they utilize their unique combination of awareness, precision strike, and maneuver. Absent these capabilities, they are just conventional, small forces operating in a very unfavorable environment.

Nothing will differentiate the operating environment of these forces from today's capabilities so much as the intensity of the sensing and communications systems that will link the force with itself, with other similar forces participating in the same operation, and with remote C4I centers. A mix of local and remote sensors must create an envelope of awareness around the force. These sensors will include coordinated space-based assets, airborne sensing platforms (both UAV and manned), and local ground based sensors (both unattended and manned). The information gathered by the sensors must be automatically fused into a single, knowledge-rich presentation that is available in real time to the on-site commanders and at the remote command centers. ISR assets will be moved and re-tasked in real time to minimize at all times the position uncertainty of friendly and enemy forces. Imaging systems and automated recognition and identification capability will be essential as will a robust communications architecture that is able to manage the increased traffic from disparate sources.

Unattended sensors must take on new intelligence and may need the ability to move autonomously to position themselves optimally, respond to changing situations, and keep up with the force when it moves. These unattended ground sensors may be mobile themselves or they may be deployed and picked up by tracked or flight capable "mother" platforms. Similarly, airborne and space assets must redeploy to address changing situations. In fact, tasking of these assets will need to be optimized more or less automatically from statements of commanders' intent. In other words, asset deployments will be optimized for all units operating in the theater based on knowledge of the current situation, knowledge of enemy movements, and knowledge of commanders' intended operations. From this information, intelligent systems will anticipate the need for information and will schedule air and space asset movements and taskings accordingly.

This exquisite situation awareness is needed because keys to success for these forces will be to dominate maneuver and apply precise, overwhelming force at just the right time and place. Since sustained combat ability will not be an attribute of these forces, they will need the capability to know where the enemy is and how he is configured, so they can plan and execute precise, very effective combat operations while minimizing the risk of being themselves caught in an unfavorable situation.

Finally, the remote C4I centers that support these operations must be able to handle a very high level of complexity in real time. Most likely, multiple units will be deployed simultaneously to cooperate in performing a mission. Logistics and command support for the mission will involve shared resources for ISR, fire support, supply, insertion and exit transport, and real time planning. Contingencies will raise the intensity of these operations to a fever pitch. Mission planning and command systems capable of continuously coordinating all aspects of the operation will be a crucial element of the robustness of this concept.

New technology is needed in communications architectures, sensors, signal, and image processing (SAR, multi and hyperspectral, video, acoustic, seismic, chem/bio, etc.), automated identification and recognition, autonomous systems and intelligent robotic vehicles, sensor fusion, and human factors with decision support systems.

Mobility:

Shortfall: Today's unit would require excessive assets to quickly move from one location to another. Airlift or ground transportation systems sufficient for the task would require logistics tails of their own to maintain and would likely have high signatures.

No aspect of these units' operating concept will require more careful consideration or operational planning than their ability to move to and from their forward locations and their subsequent ability to maneuver to accomplish their missions and to escape undesired contact with enemy forces. In most cases, mobility will probably delimit the envelope of acceptable missions available to these units.

This issue has two main elements: 1) deployment and recovery of the force (in other words, deep insertion and recovery), and 2) local maneuver while deployed. Then there are two operational considerations: a) is the airspace secure, and b) how important is it that the unit's activities be surreptitious, especially on insertion?

In most cases for operations 100km or more from friendly forces, airlift is the preferred transportation method for deep insertion and recovery. Ground insertion and recovery would themselves be significant military operations that would be incidental to the main mission. Furthermore, the longer response time for ground tranport might seriously jeopardize the force.

Small forces of a few hundred or less can probably be inserted surreptitiously by helicopter, can carry sufficient supplies for several days of operations, and can keep the helicopters with them for local transportation. Certain types of high value missions can be performed by a force this small. With sufficient C4ISR support, it can avoid unplanned enemy contact, accomplish its mission, and extract itself with reasonable safety.

Significantly larger forces become problematic, however. The airlift resources needed now become more difficult to hide and certainly too great to leave in the field to provide local maneuver. New technology and systems will be similar to that listed below:

- Fast, heavy lift helicopters or hovercraft with relatively low signatures.
- Lightweight, fuel efficient, low signature ground vehicles to provide a degree of mobility while deployed.
- Precision delivery of supplies to forward deployed units without high signature operations (e.g. stealthy, precision guided parachutes).

<u>**Survivability:**</u>

Shortfall: Some elements of survivability have been discussed above. Two additional factor are the ability to avoid detection and to be invulnerable to offensive information warfare (IW). While today's forces are striving to lower critical signatures, the detection problem is heightened when behind or near enemy lines. IW technology will be widely available in 15-20 years, and today's systems will be vulnerable to this type of attack.

These forces must have low signatures. They must be able to hide and to deceive the enemy. Both offensive and defensive operations will require these capabilities. In particular, communications systems will need the ability to operate in low observable modes and perhaps go completely dark. Vehicles, personnel, and sensors will also need reduced signatures.

The ability to deceive with spurious radio traffic and other decoy methods to spoof the enemy will be valuable in many situations. The enemy will attempt to infer the position of these units from sensible information emanating from the forces themselves and their transportation systems, from the configuration of friendly ISR assets, and from friendly shooters. Therefore, the entire friendly force structure must participate in deception when a unit needs it position to be uncertain.

In addition to protection against conventional jamming technology, the C4ISR systems must be hardened against offensive information warfare (IW) weapons. Systems composed of commercially available components will be very vulnerable to this type of attack. New emphasis must be placed on the design of hardened battlefield systems across the board, but this will be nowhere more important than for these small forces that will be very vulnerable without communications, sensors, and the ability to call in remote fires.

Robotic Concepts for Small Rapidly Deployable Forces

May 30, 1996

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I. Abstract

In this paper several robotic and related technologies are highlighted that will enhance small unit operations for 21st century military personnel. Aspects of these suggested technologies will have impact in urban environments, in more rural mission settings, or in both. Technologies to aid humans in mission planning, surveillance, reconnaissance, fabrication, logistics and execution are described, as well as additions such as intelligent mobile vehicles to supplement the smaller, more distributed forces envisioned for 21st century missions.

II. Introduction

As part of the Defense Science Board (DSB) 1996 Study of Tactics and Technology for 21st Century Military Superiority, this report provides an overview of several technology areas where robotics and related technologies can have an impact. This paper presents a view which is very optimistic about the future of robotic systems in military operations ranging from the forward edge of the battle area to the ships offloading supplies on the littoral. This view is in contrast to the recent pessimism in the U.S. about robotic systems both by the military and the larger civilian user and supplier community. The reasons for this optimism are enumerated in the paper.

The DSB study is focusing on several mission scenarios where small unit operations in the 21st century can replace larger forces needed for the same type of mission today. The mission scenarios for the study include urban environments, settings such as Desert Storm where a combined arms attack must be halted, securing territory, extended offensive operations, and extracting forces. We describe technologies that apply over a broad range of these scenarios; only a few will be described relative to specific missions. Our discussion focuses on local unit operations, which are operations within a range of 30-50km, and small unit operations in urban environments performing surveillance and reconnaissance.

Since the DSB study is focused on operations in approximately 2016, the technologies that we considered are those that will be ready for use in the field at that time; this means that they can be in R&D today, or could realistically be started in R&D in the next 5 years. This gives the technologies from the late 1990's to the late 200X time frame to become mature and fieldable. The last five years are reserved for taking the technologies into the field, implementing training environments, and incorporating them into the policies and procedures of the armed forces; this is a more cultural and administrative phase of technology development and implementation.

This paper conceptualizes "robot" in several different ways. At the most narrow, a robot is a mechanical device - either a mobile vehicle, or a manipulator, or a combination of both. At the most expansive, a robot is an integrated system which contains a multiplicity of components which could be related to carrying out a mission, such as a mine-sniffing device, or to making the robot itself intelligent. An example of the latter component would be sensors and algorithms which allow a mobile robot to autonomously navigate around obstacles in its path. [1]

The technology areas which are described in this report will be grouped into the following areas: Mobile Intelligent Vehicles; Human-Assisted Platforms, both teleoperation in the battlefield, and logistical and other aids for tracking, loading, and unloading of cargo and equipment; Field Maintenance and Repair Aids; Extremely Rapid Programming and Deployment Environments; and Advanced Training and Simulation. Each section defines the technology area, assesses its current state of technology, identifies the emerging capabilities in that area, and predicts the impact of this technology area on small unit operations.

The Enablers

Advances in a host of key areas have been made in recent years - far too many to discuss in this paper. However, here are some which are at the top of the enabler pile:

- The architecture and the technology have been developed which permit the rapid, reliable integration of complex intelligent systems. Integration had been one of the most difficult aspects of all intelligent robots whether industrial or military.
- The intelligent machines technology community has made strides in the construction of architectures and technologies for systems which contain a mixture of autonomy and human-in-the-loop. These advances, coupled with those in communication technology, will provide radically new opportunities to remove troops from harm's way, and to gather information about the battlefield.
- Technology has been developed which permits rapid, reliable mission reconfiguration of a system *in the field*. In this paper, we go so far as to postulate that all-new, smart robots, including both hardware and software components, will be constructed in the field depending on the needs of the operation.
- Developments in the micro-world will permit the use of intelligent machines in wholly new ways. Macro-, mini- and microrobots will be in use -- perhaps even in collaboration. In an urban sniper situation, for example, a mobile robotic "mother ship" camouflaged as a brick will enter a building, climb the stairs and offload smaller robots, disguised as waste, which will roam the hallways searching out snipers. These robots will "chain communicate" with each other and, via the mother ship, with the operation commander.

III. Intelligent Mobile Vehicles

Definition:

This section discusses mobile intelligent sensing platforms for applications such as surveillance and inspection; searching, following and tagging; and/or locating and identifying targets. These platforms can be land-based but are not limited to that domain. They can be large, such as unmanned fighter aircraft, or small, such as an "invisible" surveillance device. However, in each instance these systems will have on-board intelligence, have some form of autonomous capability, and be able to cooperate with other systems in achieving a desired outcome.

Current State of Technology

The "intelligence" of mobile vehicles still limits such systems to operate only in the domain of known environments. For example, navigation down a known hallway is certainly available.[2] Recently there have been demonstrations of vehicles driving themselves on roads at highway speeds.[3] Mobility and transport have been demonstrated by projects such as Dante's crater exploration in Antarctica.[4] All of these systems are large in size. Miniaturization of these systems is still an area of evolving capabilities. Such miniaturized systems have been developed but they are mostly only operated in laboratory environments, are tethered or have a very limited operating duration (e.g., 30 minutes), have limited mobility (e.g., typically "wheeled" systems) and have very limited onboard intelligence systems.[5-7]

Emerging Capabilities

Miniaturization -- Moving to the Small and the Inexpensive: Miniaturization in the electronic world has revolutionized our daily lives. Are the emerging miniaturization capabilities in the mechanical world, such as micromachining and LIGA parts, going to generate the same effect?[8] In the next decade, motors of $80mm^3$, fuel cells with densities of 50 joules/mm^3 and actuators of 8 mm^3 will all be available. These are technologies which are going to revolutionize the battlefield as is described in the Impact section below.

Systems That Learn on the Job: Intelligence for mobile systems will no longer be limited to our ability to capture human-knowledge in algorithms and expert systems. Natural learning approaches, genetic algorithms, and Linked Learning Classifier systems will be coupled with systems, both individual platforms and "swarms" of platforms, to form an adaptable, reliable and optimal system deployment capability.[9]

Distributed Intelligence and Sensor Systems: Most of the recent benefits of information technology are going, not into more powerful computers, but into more widely distributed, networked intelligence. This truism of commercial life can be applied to the battlefield with even greater force. Several factors suggest that such distribution is not only possible but optimal. It may be a more cost-effective solution to deploy less sophisticated products manufactured in the millions rather than a handful of very sophisticated products costing tens of millions. In the military realm, thousands of sensors could be networked and their information fused together to form a more complete description of the changing military situations.[10] Dispersion is also beneficial for locating an object. A hundred low-power noses can detect, and more important, track a scent better than a single high-power nose stuck in one place.[11] Distributed systems are also more robust against accidental failure than large ones. The greater the desired reliability, the greater the advantage of distributing capacity into smaller units.

Major Technical Challenges: The major technical challenges for miniature systems are production of low cost platforms, energy consumption, communications, on-board sensor systems including data interpretation, transport mechanisms (e.g., moving from "wheels" to devices that can swim, hop and/or fly), guidance and navigation systems and behavior modes including cooperating behaviors.

Impact

Urban Operations -- Find the Sniper: Urban operations provide unique challenges in the areas of surveillance, intelligence gathering, and targeting: how many people are in the building, what's the layout of the structure, are there civilians and/or hostages present, if so, where are they located, and how can I neutralize the target without causing damage to surrounding areas? All of these questions can be answered in the future with the use of intelligent mobile vehicles. In the scenario of a sniper being located in an urban area the first element is to deploy a larger type vehicle capable of surviving small-caliber gunfire. The primary purpose of this vehicle is transport and deploy smaller devices which will ultimately perform the desired mission. This larger vehicle could be deployed behind safe lines (such as is depicted in Figure 1) or it could be a vehicle which is intentionally left throughout the urban area but "hidden" from view such as the "brick" shown in Figure 2. This vehicle, which would be capable of self navigation, would attempt to enter the sniper's building. This could mean breaking through a barrier or more likely deploying the smaller mobile devices which would be capable of penetrating barriers through means other than force. Such an example is depicted in Figure 3 where these smaller devices, disguised as bottle-caps, would be capable of jumping up steps and sliding under doors, or in Figure 4 where the devices float along the outside of the structure. These smaller devices would cooperate with each other as they disperse throughout the building, acquire the desired knowledge, and perhaps even assist in the neutralizing of the sniper by being a homing device for a precision weapons system or being the weapon system itself. Having acquired the desired information they could transmit this data directly back to the home base or return to the transport vehicle which then in turn would deliver the information back to the original deployment location.

<u>In the Field -- The Small and the Many:</u> Large numbers of miniature intelligent machines will alter battlefield and peacekeeping operations in several areas. These systems will employ stealth, remote operations, remote transmission and multi-agent cooperation to enhance the operations of a small, rapidly deployable troop force. Systems composed of millions of miniature intelligent machines, carrying sensors, emitters, and mini projectiles, will, in concert, be able to detect, track, target, and land a weapon on any military object. These systems may work in small groups to identify a facility's activities, generate a map of the structure and provide targeting (Figures 4 and 5); may be dispersed across the entire battlefield region to locate and track vehicles (Figure 6); or may be used in an urban setting to identify and neutralize targets with minimum collateral damage (Figure 2).

<u>The Secret and the Patient</u>: Pop-up warfare describes the battlefield or urban environment in which the means of war/peacekeeping are quiet and hidden until they rise and engage. [12] Mobile miniature intelligent systems which can hide until needed, be inert until activated, and be forever disabled when the mission is completed, will impact not only the deployment of operations but also the withdrawal after the mission is completed.

<u>The Powerful and Agile:</u> Small numbers of larger intelligent machines will enable new capabilities in weapons and troop deployment. Precise and high performing remotely operated aerial platforms will redefine stealth, surveillance and targeting operations. This will be realized by the enabling capabilities described in the next section.

IV. Human-Assisted Platforms: Battlefield and Peacekeeping Operations

Definition:

Human-assisted platforms are systems which are designed such that the operator(s) and the computing system(s) share control of the device(s). In this approach there are two modes of operation. In the first mode the operator defines high level tasks (e.g., fly to this location) while the computing system performs the lower level operations required to complete the task (e.g., generate the appropriate path to take, and couple the flight controls to this trajectory to reach the desired location). In the second mode, the operator has complete control of the platform with the computing system running in the background to verify the correctness of the operator's inputs.

Current State of Technology

<u>Teleoperation versus Telerobotic:</u> In a purely teleoperated environment the operator is required to control all aspects of the device at all times. Because of the limitations inherent

in dealing with remote systems (e.g., lack of sensory input to the operator) this results in significant operator fatigue and reduced performance.[13] Using a hybrid *telerobotic* approach, where the operator can enter tasks and then allow the system to perform the lower-level operations (e.g., operator states "go to the other side of the building" and the system then determines an appropriate path to take using sensors and geometric information to achieve the task), reduces the demands on the operator and results in overall improved system performance.

Emerging Capabilities

Stability Guaranteed: One of the challenges of sharing control between human and computer inputs is to ensure the stability of the resulting control system. Since each operator is unique, the resulting transfer functions between the computing systems and the operator are going to be non-deterministic. This unknown time delay can cause instabilities in the system. The answer to this problem is two fold. First, decouple the operator's inputs from the computer's low level inputs to ensure that timing is no longer an issue. For example, have the operator input tasks for the system to perform (e.g., "go to next location") and then have the system "autonomously" perform this operation. This will be the optimum solution in many instances. However, for remote systems it does not allow the use of real-time "human-in-the-loop" control capabilities such as force reflection. To enable the latter, the use of passive control with modeling information versus classical feedback control becomes the solution. This is currently available in the control of robotic systems and could be extended to the control of other forms of mechatronic platforms. [14,15]

Computer Co-pilot: At times the operator may want to take over direct command of the platform and return to a teleoperated mode of operation. In this environment the computer systems would continually be checking to ensure the operator's inputs are valid. For example, if the operator is telling the vehicle to move forward but an obstacle is present, the computing system would override the operator's commands thus preventing damage to the vehicle. Improvements in sensors, modeling, database architectures, and information retrieval are making such real-time validation a near term capability.[15]

Lose the Keyboard: New capabilities in operator interfaces are rapidly emerging. Heads-up displays, stereo sound, audio inputs, natural language interpretation, 6-D+ input devices and textured force reflection are all examples of emerging technologies which will enable new capabilities in human-assisted platforms.[16]

Impact

No Seatbelts to Fasten: This technology will enable semi-autonomous remote operation of high performance platforms which will result in smaller troop force size, dispersed assets, with overall improved performance. Unmanned fighter aircraft, reduced personnel onboard ships, unattended surveillance platforms, materials that transport themselves, and peacekeeping platforms that are operated remotely are all examples of the types of systems which can be developed using this "Human-Assisted" approach. The degree of autonomy of these systems will increase as the technology evolves. Currently the operator is involved in controlling most of the platform's motions; in the future the operator will be able to input increasing higher levels of commands -- "investigate region", "determine enemy troops movements."

As further examples, battlefield and peacekeeping operations suggest many uses of human-assisted platforms. For example, securing territory is a typical mission objective in such operations. This mission, like any other, requires the basic elements of intelligent behavior: sensing (e.g., information gathering), planning (e.g., deciding what to do), and responding (e.g., implementing the plan through action). Human-assisted platforms will be valuable in providing the sensing and responding capabilities needed for securing territory, plus an intelligent mission planning assistant could be used to plan a securing strategy (most likely this would be a computer system, not a robotic platform). Such a plan would be based on prior knowledge of the territory, the local unit's resources, "securing territory" criteria, and real time information provided by the sensor and communication systems.

Sensing operations, used to improve situation awareness, could be conducted by human-assisted platforms such as UAVs or mobile ground sensors. A UAV could be deployed to scout portions of the target territory "over the next hill" or "beyond a designated wooded area". Flight paths could be preset by the human, generated autonomously by the UAV according to high level search objectives, or modified on-the-fly if the operator, because of incoming data, wanted to further investigate an area of interest. Search areas could be defined by the human, or flagged by intelligence on-board the UAV, or resident in a smart ground station. Information about threats (e.g., personnel, equipment, other potential targets) and local weather, road and terrain conditions would be used to determine strategic locations to control and preferred routes and resources needed to secure them. Paths for moving resources could be further refined by ground-based robotic "scouts" with suitable sensors that are sent out on patrol to detect and communicate the presence of mines. Prospective paths could be defined by an operator and the scout would confirm that the paths are free of mines (or other hazards).

Other human-assisted platforms could be employed for "responding" operations. Once paths toward strategic locations are identified, autonomous all-terrain "mules" could provide the brawn to carry gear, relieving soldiers' individual loads. When required, the motion of the mules could be assisted by a human operator; for example in crossing a stream. Once in control of the desired locations, the local unit could deploy robotic "sentries" (with fins, wheels, wings, tracks, or legs, depending on the local terrain) to monitor the surrounding area for new threats. The sentries might even be armed to defend against identifiable enemy intruders. Multiple sentries could coordinate themselves with higher level commands being given by an operator.

V. Human-Assisted Platforms: Logistical, Loading Docks, Littoral

Definition

Again, human-assisted platforms help the operator complete tasks that s/he assigns at a high level, while the computing system performs the lower level operations required to complete the task. Here human-assisted platforms are implemented in the planning of loading of ships or planes, performing this loading, the subsequent unloading, and helping to track cargo and equipment both on port side and on the theater side.

Current State of Technology

In deploying forces rapidly, getting equipment, supplies and troops to the theater are all important. Using past approaches, mistakes unfortunately have been made in getting the right supplies to the troops in a battle area, and deployment has been slowed because of the time it takes to load the supplies on the port side and unload them in the battle area -- especially when rough seas or other inclement weather prevents the final steps to delivery.

Impact

Rain or Shine -- We Deliver: The goal of force projection is to deliver troops and supplies to the battlefield anywhere in the world at any time. At present, the Navy will not or cannot deliver troops and supplies to areas that are at Sea State 3 or higher.[17] The use of stability augmentation systems (SAS) that are common among high-performance aircraft has the potential to overcome the problems associated with high sea states. SAS systems are used to eliminate the unstable behavior of cranes on cargo ships (e.g., excessive pitching and rolling caused by the waves) in the high sea states by employing feedback control. The feedback control compensates for the motion of the ship and produces an environment for the crane operator that is similar to low sea state operations. To further increase the speed of logistics operations, swing-free technology can be added to the crane once the SAS is in operation.[18]

Faster and Better: Swing-free cranes could be used both on port side and near the battle area to speed the loading and unloading of supplies. Swing-free crane technology reduces the time of movement of the crane by eliminating the swing at the end of the movement. (See Figure 7). [30] Without the need to keep swinging minimized, faster moves can be done and thus faster loading with fewer people. Swing-free cranes are available for port-side operations today. However, extensions to compensate for rough sea environments on the battlefield end of the trip have not yet been developed. This is an area which could be addressed in the very near term.[19]

What, Where, When and How: Logistical planning aids have been identified as a military need.[20] One aspect of this is maximizing the amount of cargo that can be transported in one trip through better planning of loading of ships and planes. This would speed delivery of equipment and supplies to the field. It is expected that operations like UPS and Federal Express will continue to develop the state of the art in this area. With smaller crew size and more dispersed operations, AGVs (automated guided vehicles) or automated stacker/retriever systems (AS/RS) could replace people for greater automation of loading and unloading operations. This will be more important on the battlefield side of operations. AGVs and AS/RS systems are available today, and smarter versions integrated with planning algorithms should appear in the marketplace for 21st century operations in military and industrial environments.[21]

Finding "Lost" supplies: Getting the correct product to the field location that needs it can also be a problem. A "smart card" for tracking of supplies could be attached to the supplies for location purposes. The card would record what is inside the container it is attached to, and send a signal out periodically to aid the troops in finding the supplies that have been delivered for them. The concept here is not beyond technical capabilities, but the communication method selected for this card's signal will need the same sorts of security/stealth that is envisioned for other distributed force communication capabilities (e.g., soldier 911).[11]

All these human-assisted platforms result in faster deployment of troops and their supplies, plus reduction of personnel and time through improved efficiency of logistical operations.

VI. Field Maintenance and Repair Aids

Definition

Quicker deployment of troops and their equipment and having smaller units in the field can also be aided by making quicker and easier equipment repairs or maintenance in the field. The technologies described here are similar to world-model building and simulation being done today for robotic environments.

Current State of Technology

Repairs and maintenance in the field today in general requires people, tools, and paper copies of manuals. Conversion to electronic manuals is beginning, and may be implemented in some cases; like your local mechanic's shop, computerized diagnostic equipment is likely in use today. However, specialized training is necessary for these advanced diagnostic systems, and spare parts are whatever you choose to take to the field, or are only as close as the next transport to the field.

Emerging Capabilities

Smart, Hands-free Manuals: Electronic manuals may begin to enter the field in the next few years to replace paper manuals.[10,22] For later versions, we envision integration of smart agents, hypertext and searching aids, and/or heads-up displays to make diagnosis of repairs, and finding the right repair or maintenance instructions easier and quicker. Video clips or animated CAD models of parts would also show assembly or disassembly sequences to the repair person. Voice-activated search could also be included.

X-ray vision repair diagnosis: An "x-ray vision" heads-up display shows a 3D CAD image of an assembly (e.g., an airplane fuselage) in the viewer. For aid in diagnosing a problem beneath the surface (e.g., wiring or hydraulic lines, a pump), the CAD model also shows the repair technician what parts should lie behind the surface s/he is looking at.[20,22] Full 3D assembly models may not typically be created today. However, the effort to do so should drop significantly well within the time frame being studied here, so it is reasonable to expect that such models will be available for integration into such a system. Calibration of the position of the viewer/display to the assembly is an extension of the types of world-model to actual equipment calibration being done today in R&D for unstructured robotic and simulation environments.

In the next steps of repair diagnosis, the technician moves a sensor, which we called the "super stud finder", over the surface of the assembly. Another view would be overlaid on the screen showing parts actually detected. This concept is similar to through-the-wall surveillance, which is an R&D topic today.[11]

Part "Replicator" in the field: Another field repair and maintenance aid is a part "replicator" with a field manufacturing cell. Metal deposition technology in the lab, and entering industry today, should become available for many applications in military environments; research is being done today for creating parts on submarines out at sea.[22-24] Such equipment with metal powder would be used in the field as a "replicator" to create single spare parts, or the many parts for an assembly, for repairs of equipment in the field. A Field Manufacturing Cell (FMC) could also be used to rapidly assemble the replicated piece parts. The FMC, consisting of robotic manufacturing cells with automated programming features, would be capable of rapidly assembling the replicated piece parts.[25-26] Flexible manufacturing cells like this are entering industry today, but smart part assembly algorithms are still in R&D. One could picture these FMC systems in the back of a typical large military transport truck; auto-alignment characteristics will need to be integrated into these systems to initialize them after moving from one site to another, with its jostling of the equipment which will no doubt occur after the vibration or bumpiness in the road. This auto alignment type of feature is in the lab today, but could be ruggedized for the field environment. (See Figure 8).

Impact

These repair/maintenance aids are expected to make field repair operations easier, quicker and more able to adjust to various mission environments. They can be used to support more distributed small unit operations with fewer people.

VII. Extremely Rapid Mission Design and Deployment Environments

Definition

This section discusses systems, which can be composed of numerous subsystems (e.g., tanks, ships, and planes are subsets of the entire battlefield deployment), which are capable of programming themselves to perform the specific tasks required for the military operations.

Current State of Technology

Software languages and architectures enabling rapid and reliable reprogramming of systems are now available. Object oriented languages, such as C++, coupled with communications tools, such as CORBA, have enabled the design of systems which have modifiable components. Languages such as Java are further extending this capability by enabling independent sections of code to be easily transmitted and executed via networks.[27]

Emerging Capabilities

Never Far from Home: Networking, especially wireless, technologies are rapidly evolving which will enable platforms to be "electronically" linked any where at any time. Reliability, security and data integrity are all technology challenges which are being addressed. With the emergence of these new types of networks, this will enable new capabilities, as is described in the following section, in battlefield and peacekeeping deployment operations.[28]

Impact

Physician -- Heal Yourself: Each given mission has specific attributes which need to be entered into weapons systems. Two examples of this are the geometry of the target (e.g., what does the enemy tank look like) and the geography of the region. Using wireless networks, future weapons systems will automatically know they need this information, locate and download this information from databases, and then use this data to program execution plans (e.g., flight paths or image recognition algorithms). The same is true for other platforms such as a mobile vehicle, an airborne surveillance system, or a deployed sensor package. This will reduce the time required for deploying systems and improve the ability to respond to changing military situations.

Mission Impossible?: Using this approach, entire missions can be rapidly planned, simulated, and modified as situations dictate. High level tasks (e.g., "destroy bunker") are distributed to lower levels of systems until ultimately each task for each system is defined, automatically programmed, coordinated, monitored, and modified. The key is that the platforms, such as the missiles or the aircraft, program themselves so they can immediately respond to changing scenarios.

VIII. Advanced Training and Simulation

Definition

As the number of troops decreases, and the technology content of deployed systems increases, there will be an increased need to train personnel on the maintenance and operation of these numerous systems. These training systems must be flexible to handle multiple systems and scenarios, must be cost effective to produce and operate, and most important must be accurate. What we're proposing: Training and simulation environments which have multiple inputs, multiple players in dispersed locations, rapid reconfigurability, inherent accuracy, which cover complete systems, and have interchangeable real and virtual components.

Current State of Technology

The capabilities of simulation and training environments have advanced tremendously over the past few years. The amount of activity occurring in this area is much larger than can be covered in this paper (see reference 29 for more information). Some key aspects are that the performance of computing platforms has rapidly increased while the costs have decreased. This has enabled higher fidelity models to be generated and, when coupled with the emerging networking technologies, has enabled multiple participants to share in the training and simulation environments. In practicality, today's technology still forces assumptions and simplifications to be made in the training and simulation environments (e.g., homogeneous properties, predefined coefficients of restitution and friction, ...).

Emerging Capabilities

Is it Real, or is it a Simulation?: Simulation environments are moving beyond "animations" of what a system or mission scenario will look like, to become the actual system itself. This somewhat surprising statement is reflected in many of today's remote systems. What the operator sees is simply the interfaces, not the physical platform. By replacing the physical device with an unseen model of the device, the operator can still drive the system. The technology that is enabling this capability are increased processor speeds which will in the next decade enable real-time analysis of physics such as flexures of parts, flowing of liquids, or the movement of dirt. This "fractal" approach to simulations will enable the high accuracy of complete systems from a micro to a macro scale.[15]

Impact

Where's the Reins?: Highly accurate real-time modeling of systems will enable new capabilities not only in the training of operators but in the design of the platforms themselves. Just as the automobile of the 1920's caused the steering wheel to replace the reins as the input device to steer a carriage, new interfaces will be created to replace those which we are currently using. Heads-up displays are an example of a technology which has already been implemented. What will the future cockpit look like when, if the previously discussed remote capabilities are implemented, that cockpit is not part of the plane but rather a room connected to the aircraft via a satellite system? The partial answer is that the training and simulation environment becomes the actual interface environment for the physical platform. The issue of "is the simulation environment accurate" disappears because it is the actual system the operators will be using during operations.

The 100% Solution: Design of systems using today's virtual platforms always involves compromise. Assumptions are made such as coefficients of restitution, friction properties, and homogenous materials. In the future, increased processing capabilities will enable modeling at the atomic level to be meshed with the macro scale to derive highly accurate, and complete (e.g., sensors, power supplies and gear train friction will all be included) solutions to be derived.

IX. Conclusions

The applications of robotics and related technologies in 21st century military operations are broad. Intelligent mobile vehicles of many sizes will supplement manpower, and micro-robots will enable mission surveillance and reconnaissance not previously possible. Other technologies incorporating telerobotic environments, rapidly reprogrammable platforms, and intelligent planning assistants will provide more flexible and faster operations for small unit troops. Advanced simulations, training aids, and maintenance and repair aids will also further optimize the use of the personnel in the smaller, rapidly deployable units envisioned in the 21st century battlefield. All of the technologies presented in this paper will work together, not simply cooperating, but synergizing their individual capabilities to produce new overall capabilities in the operation of future military missions. Enabling technologies are within reach now. With an appropriate amount of additional investment in these areas, the capabilities described here will be in use in the field in the second decade of the 21st century.

X. Figures

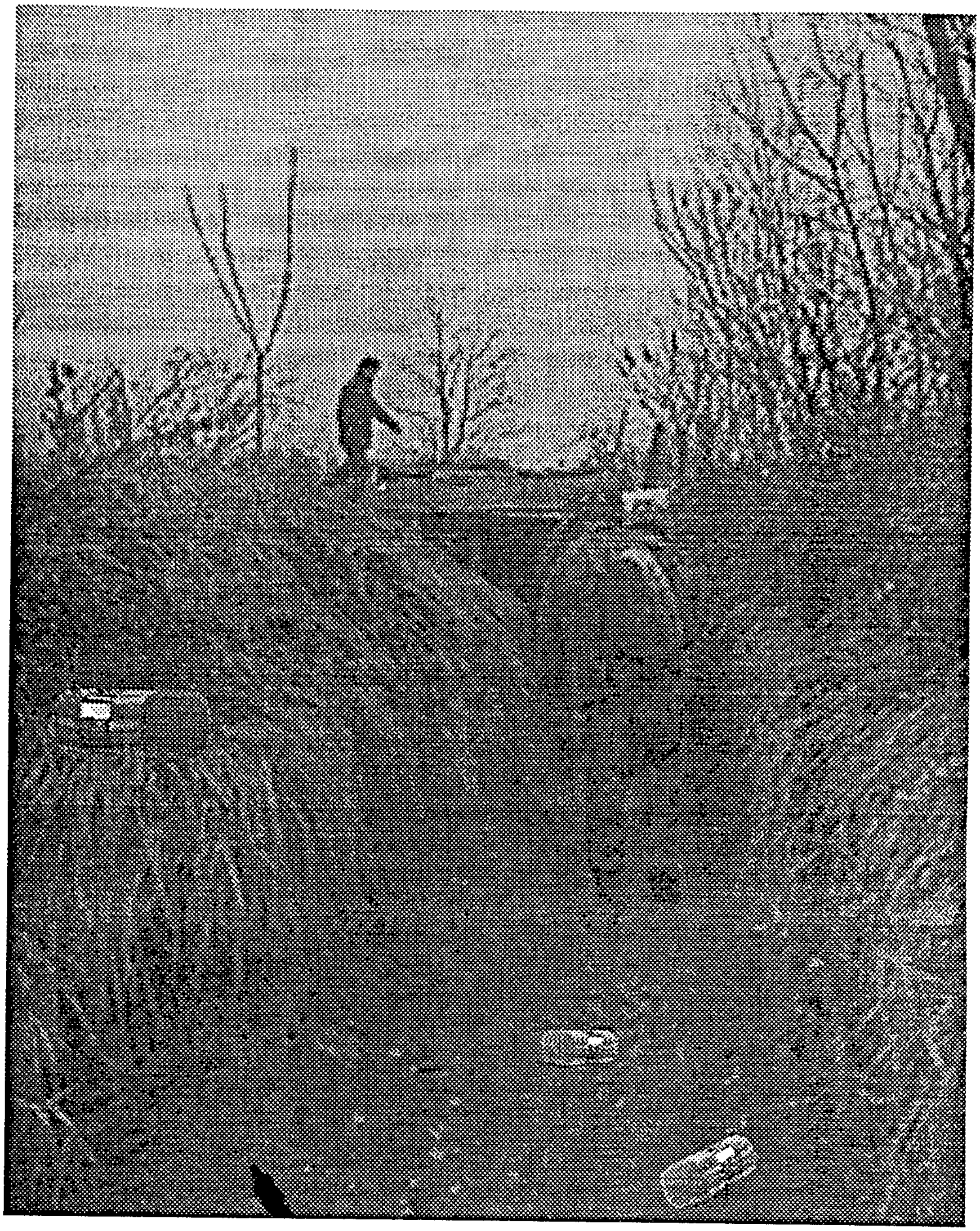


Figure 1: Deployment of Miniature Intelligent Mobile Vehicles

Miniature intelligent mobile vehicles will be used to perform surveillance, intelligence gathering, and targeting missions. These roles will be performed in both urban and field environments. In this particular scenario the mobile devices are being deployed at the front-lines. As they gets closer to their target the larger transport devices will deploy smaller devices which will work together to complete the mission and transmit the information back to the deployment location.

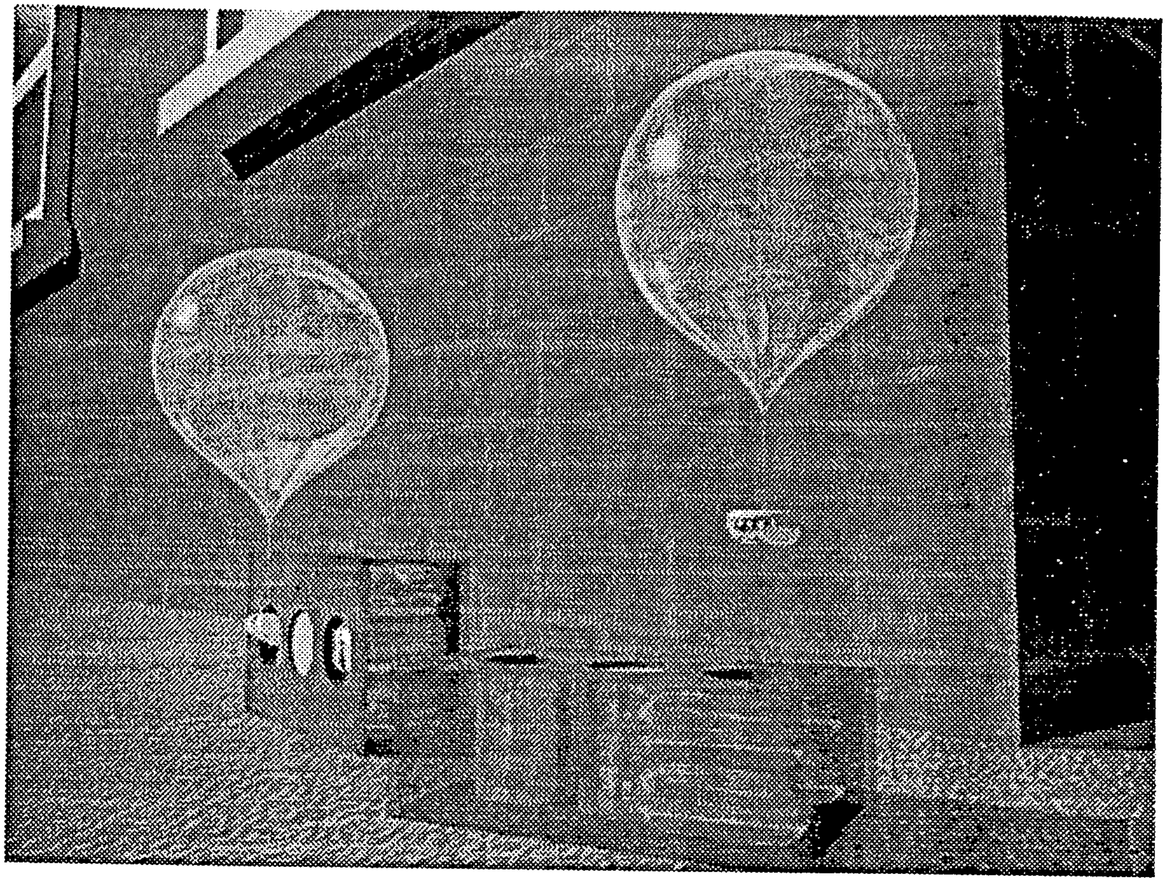


Figure 2: Miniature Intelligent Mobile Vehicles in Urban Operations

In an urban environment, visual stealth can become an important element. Here the transport device is disguised as a brick. These devices, in varying disguises, can be dispersed throughout the urban setting and then deploy their smaller devices to perform mission specific tasks, such as determining who is in a building or generating a facility's layout, when commanded by a remote link.

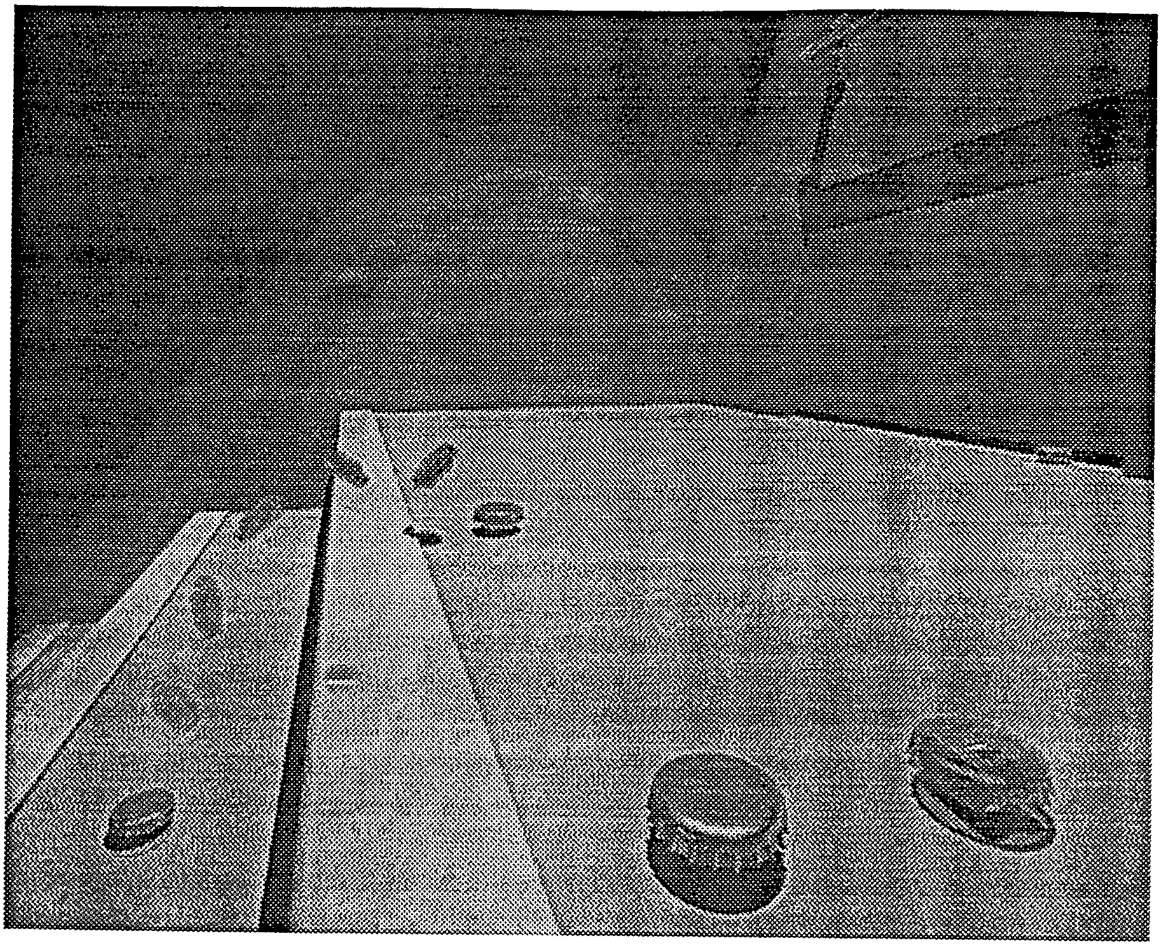


Figure 3: Surveillance, Intelligence Gathering and Targeting in Urban Environments.

Entering a building will at times be required in order to successfully complete missions. In this scenario devices disguised as bottlecaps have been deployed by a transport device (such as in Figures 1 and 2) and are capable of jumping up stairs and sliding under doors as they disperse throughout the building to perform their designated tasks.

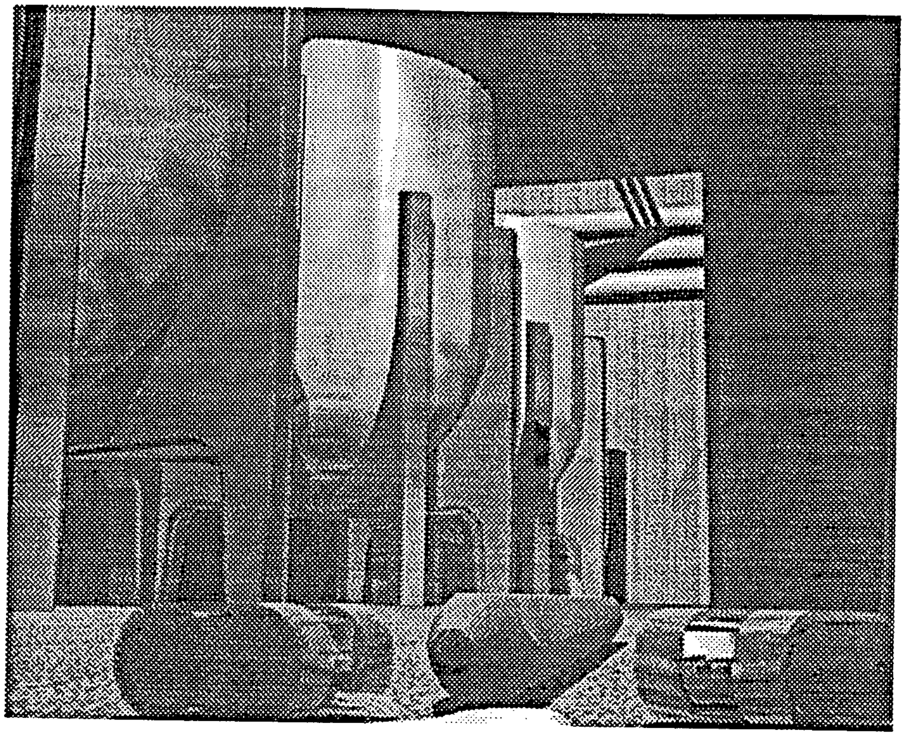


Figure 4: ID Facility Purpose and Layout

Miniature intelligent mobile vehicles will be used to determine a facility's activities, provide weapon guidance, and a post-attack assessment. Another element depicted in this vugraph is that the mobile vehicles will have different capabilities and work together in achieving the given mission. In this particular case, the one vehicle is equipped with sensors to detect the facility's activities while the other is equipped with long-range communications capabilities to relay this information back to the operators.

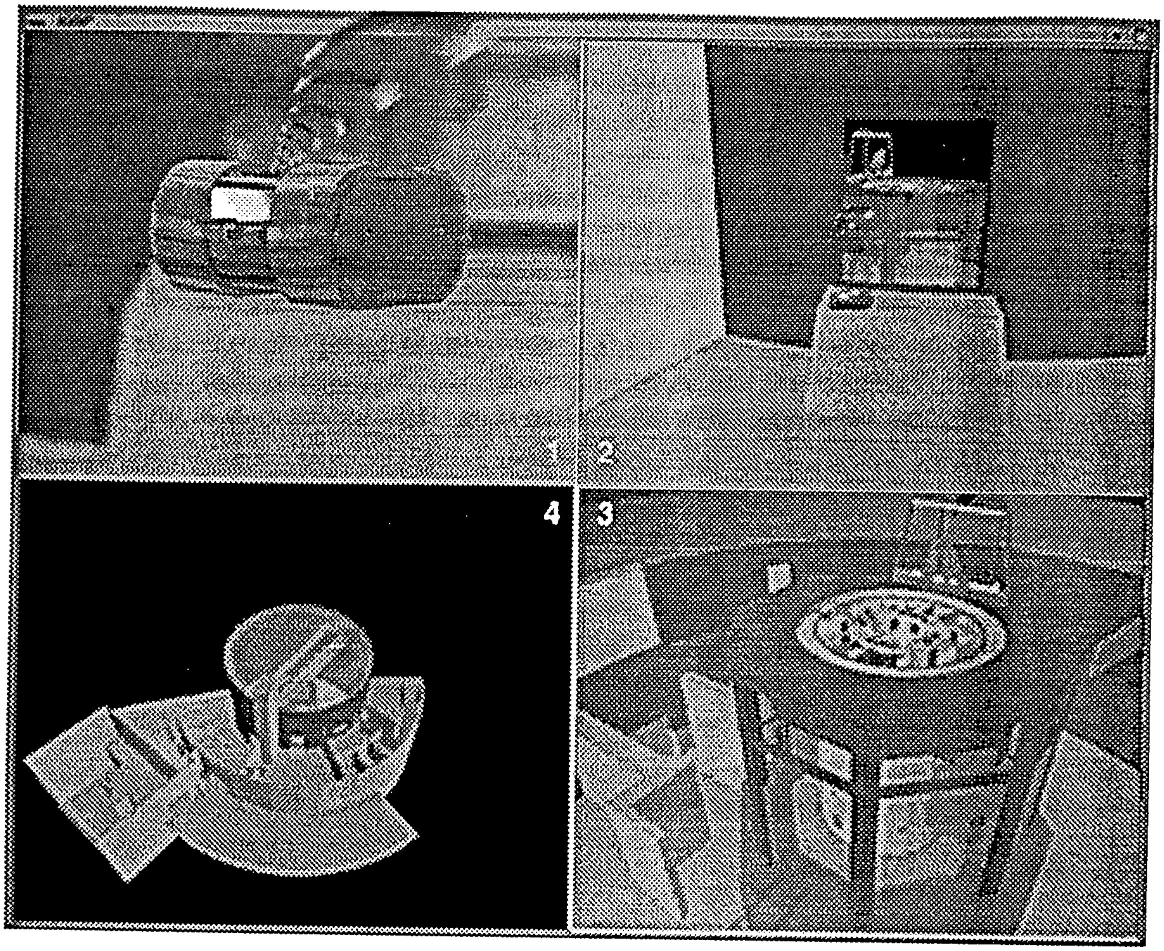


Figure 5: Facility Mapping

The ability to covertly identify the purpose of a facility (e.g., a bunker) and generate a map of its layout will alter both peacekeeping and battlefield operations. This vugraph depicts a small vehicle entering such a facility, generating a geometric map, and identifying a particular piece of equipment -- in this case detecting the radiation being emitted by the reactor's core.

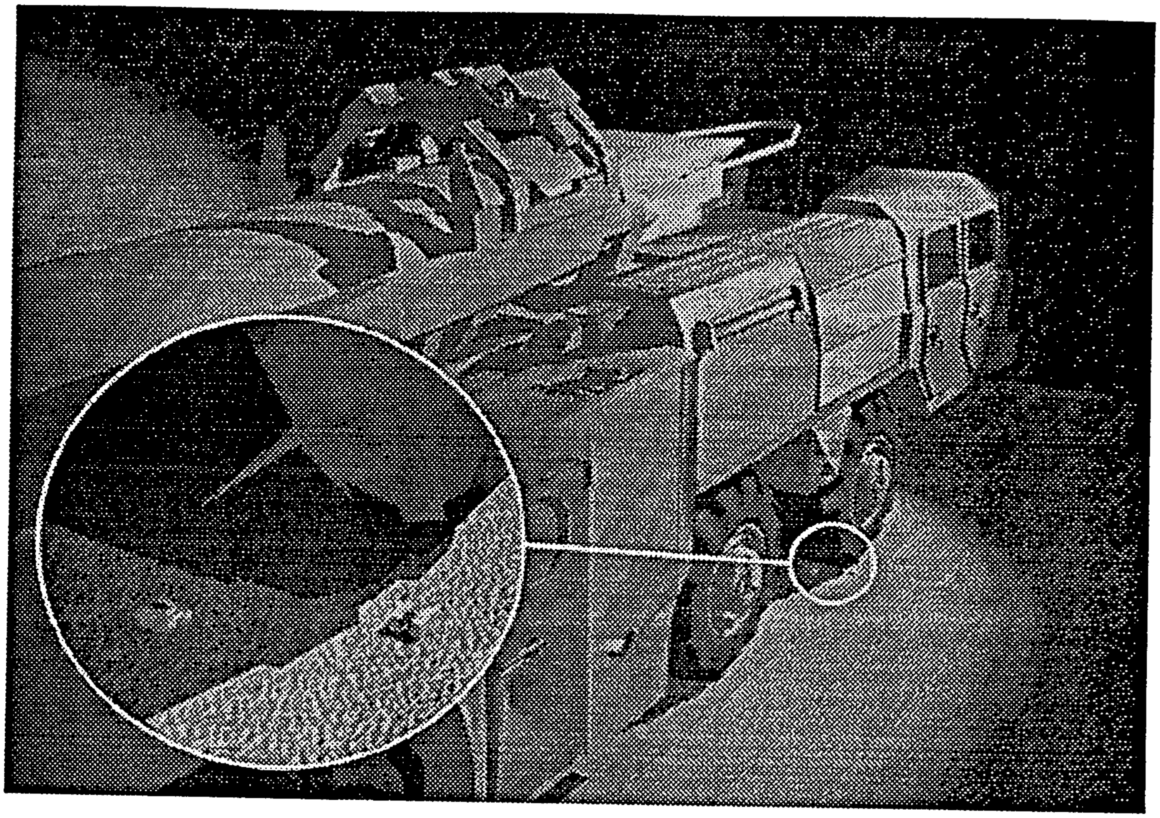
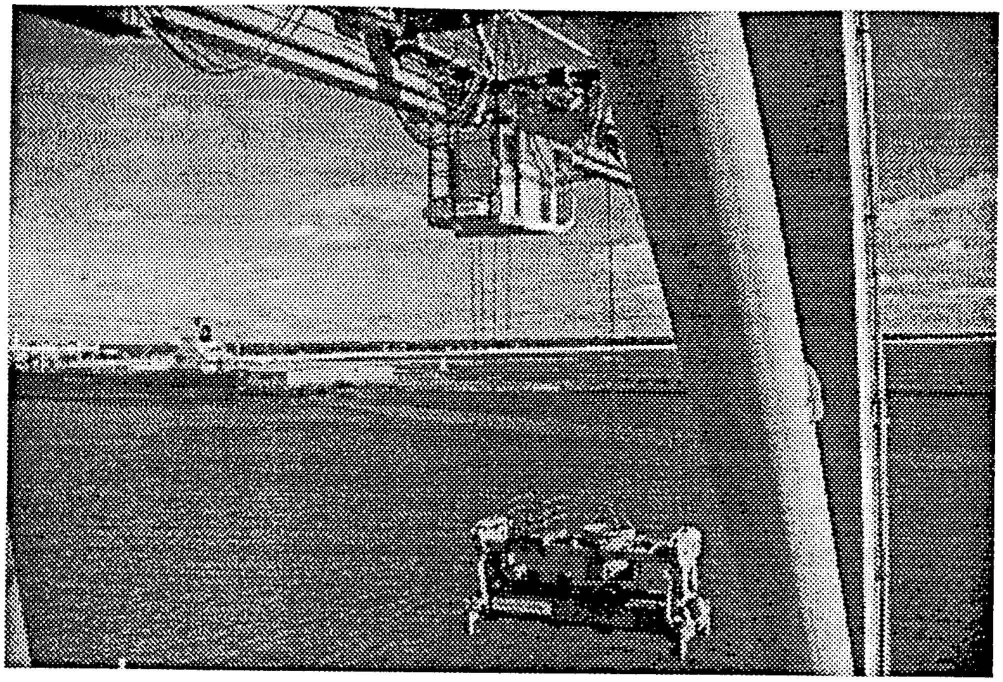


Figure 6: Vehicle ID and Tracking

Tracking the location of vehicles will also provide information on the location of facilities such as missile bunkers or artillery placements. In this scenario we know the enemy is launching missiles from a general area (say 40 square kilometers), but after launch the platform is returned to the bunker before we can act. We could populate this area with devices which would attach to the launcher and provide a tracking capability from which we could determine the location and neutralize the bunker.



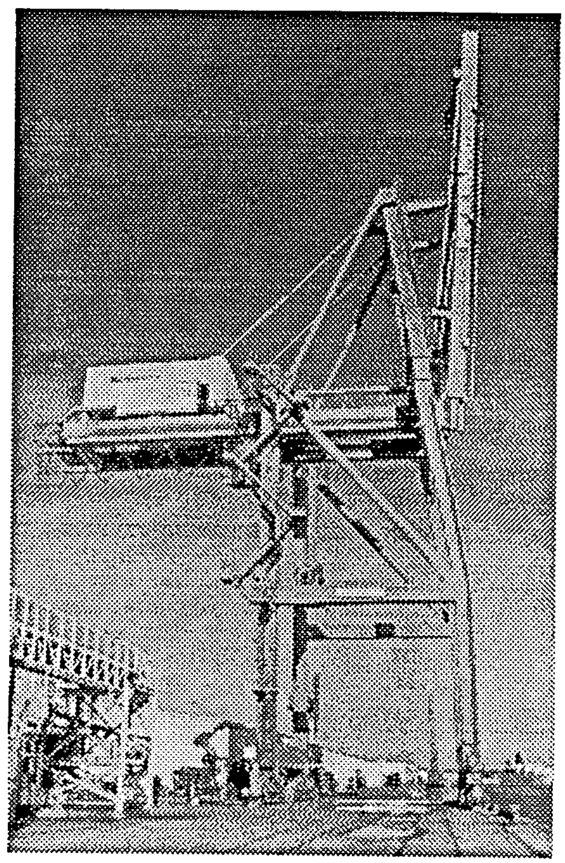


Figure 7: Swing Free Cranes in a shipyard

Swing free cranes have been implemented for port-side operations today. Extensions of this technology for swing-free unloading from ships in rough seas is being investigated.

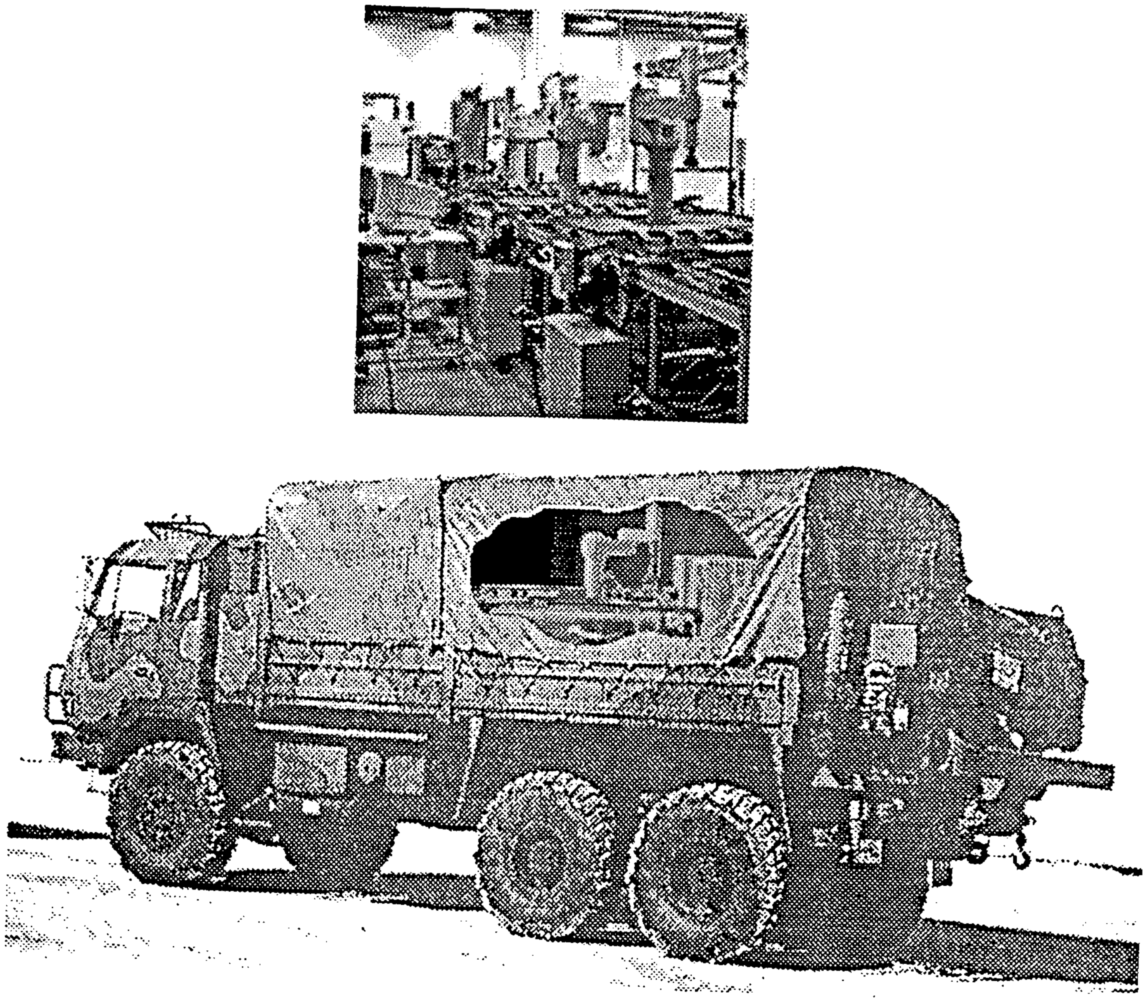


Figure 8: Field Manufacturing Cell in a truck

A system like the Agile Manufacturing Prototype System pictured here, both in a laboratory environment and in a military transport vehicle, could be sent to the field with metal deposition equipment for spare parts "replication" and assembly.

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A White Paper on the Potential for Distributed Ground Sensors in Support of Small Unit Operations

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May 9, 1996

Introduction

Information will be a key weapon in the US arsenal of the future, critically essential to the principle of dominant battlefield knowledge, the desire for short decision cycles and most other precepts of modern warfare. This information will come from a variety of sensor systems and platforms, of which Distributed Ground Sensors (DGS) could play a significant role.

DGS offer several advantages, including geographic range and broad phenomenological coverage. As individual sensor units, DGS may have a short range of effectiveness, but operating as a distributed system with relatively unconstrained emplacement, they have the potential to provide in-depth coverage for the battlefield. DGS can also monitor "friendly" territory for physical intrusion or other threatening actions such as electronic surveillance. An enemy cannot easily hide from DGS systems in most tactical scenarios.

A primary advantage of DGS in support of small unit operations is the reduced risk to personnel when sensors can be used to perform tasks normally undertaken by operators. Surveillance, long-range reconnaissance, and activity tracking are missions typically envisioned as being performed by DGS which can complement small unit actions without exposing a human to detection. In fact, small physical size, continuous monitoring and the use of stealthy communications techniques make DGS ideal for long-term, deep interdiction missions.

Current Capabilities of Distributed Sensor Systems

Numerous DGS exist in the services, in the law enforcement agencies and the commercial security market. Generally, these systems rely on fixed, hand-emplaced units to define an event when a large enough signal is received in the sensor's field of regard. More recently, sensors have been developed with sufficient onboard processing to allow identification of particular targets or behavior patterns.

Data processing has reached a high level of sophistication in current DGS. Some fielded systems have the capability to perform transducer-level signature analysis and sensor-level data fusion, all on-board an individual unit. Modular architectures allow plug-and-play transducer selection and field reprogram ability. These capabilities provide tremendous flexibility to adapt to the target environment and expand the mission space.

As with the sensor suites, current communication techniques range from simple, hard-wired links to encrypted RF relays to aircraft or satellites. Systems are now fielded which provide sensor-to-sensor communications to help eliminate false alarms and provide additional signature information for target discrimination.

Emplacement of most existing systems is done by hand. Most of the expected requirements for DGS involve some level of stand-off or remote emplacement, which has been done operationally in the past, but is not a current capability. Sensors will need to be hardened and reconfigured to be accommodated by a range of possible delivery systems for tactical situations requiring fast response and covert deployment.

Developmental Efforts

Three major military development programs are underway with government sponsorship, with numerous other governmental agencies and commercial enterprises carrying on product development activities. DARPA, DIA and DNA are currently sponsoring DGS development program in support of military users. The DARPA and DIA efforts are focused on detection and identification of vehicles. The DNA effort is primarily concerned with the characterization, localization and damage assessment of fixed, high-value facility targets, with Indications and Warning (vehicular and pedestrian traffic) as a secondary concern.

Much of the focus of current DGS efforts is on understanding the physical processes associated with signature generation and developing appropriate sensor packages that provide robust methods of target characterization. The growing capabilities for on-board data processing and sensor fusion are providing platforms for employing new techniques and transducers.

A second area of interest has been in the development of stand-off sensor emplacement. The current hand-emplaced technologies are extremely limited in terms of operational utility if they must be put in place by operators. In order to deploy DGS deep in hostile territory, it is necessary to use some type of aircraft or missile as a delivery platform. This has been recognized by the community and some efforts are underway to develop concepts for remote emplacement. Two approaches appear to have dominated the thinking in this area: precision DGS, with autonomous or semi-autonomous guidance systems that allow stand-off from the delivery platforms and bomblet approaches that may require integration with existing payloads, i.e. JSOW. Each approach has advantages and both may play a part in future DGS deployments.

A third area of increasing operations and technology focus is the development of communications architectures. Some sensor systems that have been designed for small unit operations have addressed the problem of information transfer and utilization by sending essentially all transducer output to a single site where the data is analyzed and decisions are made. Other systems have been developed to test each unit for signature uniqueness or threshold values and only transmit certain parts of the data collected. The communication problems for DGS needing sensor-sensor links is quite different locally, but may require a similar global architecture. All of the developmental programs must contend with the problem of how to get DGS data fused with data from other sources and input into the general battlefield intelligence network as well as be utilized for operations support and planning.

A Forecast: DGS for Small Unit Operations in the Future

Current trends point toward the development of two classes of DGS and we are beginning to see the distinction today. One group of DGS will be part of the general battlefield intelligence and mission planning network. These sensors will be used in battlefield monitoring, target tracking, performing BDA and collecting a variety of signatures from all locations on the battlefield. They may be emplaced far in advance of the start of hostilities or co-deployed with weapon systems. These DGS will likely be air-deliverable, modular, field reprogramable and possess significant on-board intelligence. They may also be designed to be mobile to enhance detection, survivability and communications. These sensors will be integrated with mission planning tools, such as the future versions of RAAP and MEA. It is to be expected that the trend toward use of commercial components will continue and the cost of DGS in the future could be measures in hundreds instead of thousands of dollars.

The second class of DGS would be more specialized systems with the emphasis on small size, reliability and ease of use. The communications requirements may center around the need to internet numbers of DGS units for effective local communications. These systems are likely to evolve from the current requirements for small unit support missions and will greatly enhance the effectiveness of the operators, acting as force multipliers in the areas of surveillance and site security.

<u>Summary</u>

The case for the utility of DGS in the battlefield is being increasingly strengthened by the development of small, long-lifetime. intelligent systems that have the potential to be integrated into military operations. Intelligence gathering, operations planning, mission support and BDA can all be facilitated with the type of timely information provided by current and developmental DGS. Technology trends point toward even more dramatic improvements in capabilities and cost performance over the next twenty years. As the focus of our military shifts to small, regional conflicts and peacekeeping activities, it is likely that DGS will become an indispensable part in meeting the challenge of providing critical information to the war fighter.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

MINIATURE REMOTE SENSING

White Paper

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MINIATURE REMOTE SENSING
MIT LINCOLN LABORATORY WHITE PAPER

1.0 GENERAL CONCEPT

The general concept is to provide continuous monitoring of ground activity using networks of easily deployable small, inexpensive, sensors. Representative sensors include but are not limited to visible imagers, IR imagers, and acoustic/seismic sensors. Outputs can range from generic activity reports, to detailed target recognition reports. Outputs may include selected sensor data for human analysis as well as decisions resulting from automatic in-sensor processing. Sensors may report autonomously or be interrogated. Sensors may be hand emplaced by dismounted personnel or be deployed from moving ground vehicles and/or aircraft. Sensors must be small and light to allow for easy use in relatively large numbers to compensate for sensor operational range limitations. Sensors and sensor networks must be smart to limit communication requirements, avoid data overload for users, and minimize the need for expert in-the-field human interpretation skills.

2.0 WHY MINIATURE REMOTE SENSING?

Following is a summary list of general operational motivations for utilizing miniature remote sensors.

1. Some environments are difficult for standoff sensors

    a. Rough areas with severe terrain masking
    b. Urban areas
    c. Heavily foliated areas
    d. Bad weather conditions (Less of a problem for Radar than EO)

2. Cost effective time-continuous surveillance of limited areas

3. Replace human observer/surveillance teams with sensor teams

    a. Reduce personnel requirements and exposure to harm
    b. Operate in otherwise impossible situations
    c. Provide many more observers than otherwise possible
    e. Tireless observers that always perform at peak level
    f. Minimal logistical support compared to observers

4. Flexible resource for local on-the-ground needs

    a. Useable in urban, suburban, rural, and remote areas
    b. Useable in desert, forest, mountain, jungle, etc. environments

3.0 REPRESENTATIVE MONITORING/SURVEILLANCE APPLICATIONS

Following is a list of more specific applications for mineature remote sensors.

1. Vehicular/personnel activity on/near roads or pinch points
    a. Secure areas / neutral areas / own areas
    b. Unsecured areas / hostile areas

2. Surveillance of other high interest local areas
    a. Suspected missile or other mobile weapon hiding areas
    b. Movement in/out of special or high interest facilities/structures
    c. Airfield activity

3. Perimeter/border defense

4. Detect and locate firing weapons: small arms and artillery

5. Electronic monitoring of tagged vehicles and sealed facilities

6. Sensors for "safe" mine fields with removable stand-off weapons

Items 1-4 are the most obvious and probably the most important applications of miniature remote sensors in tactical warfare. In all cases a significant point is that, once emplaced, the sensors provide time-continuous coverage at very low cost. The primary distinction between items 1.a and 1.b is that emplacement, replacement, and survivability will be more important issues for the 1.b case. Case 2.a applies to any weapon systems, including TELs and associated vehicles, that might be kept in hiding but must come out to be redeployed or used. Airfield monitoring applications might be coordinated with airborne surveillance resources to eliminate or minimize the need for continuous airborne coverage. Case 3 relates to self-defense applications and controlling infiltration. Case 4 ranges from the problem of the localization of small arms fire and artillery in a difficult urban environment to the easier problem of operation in other venues.

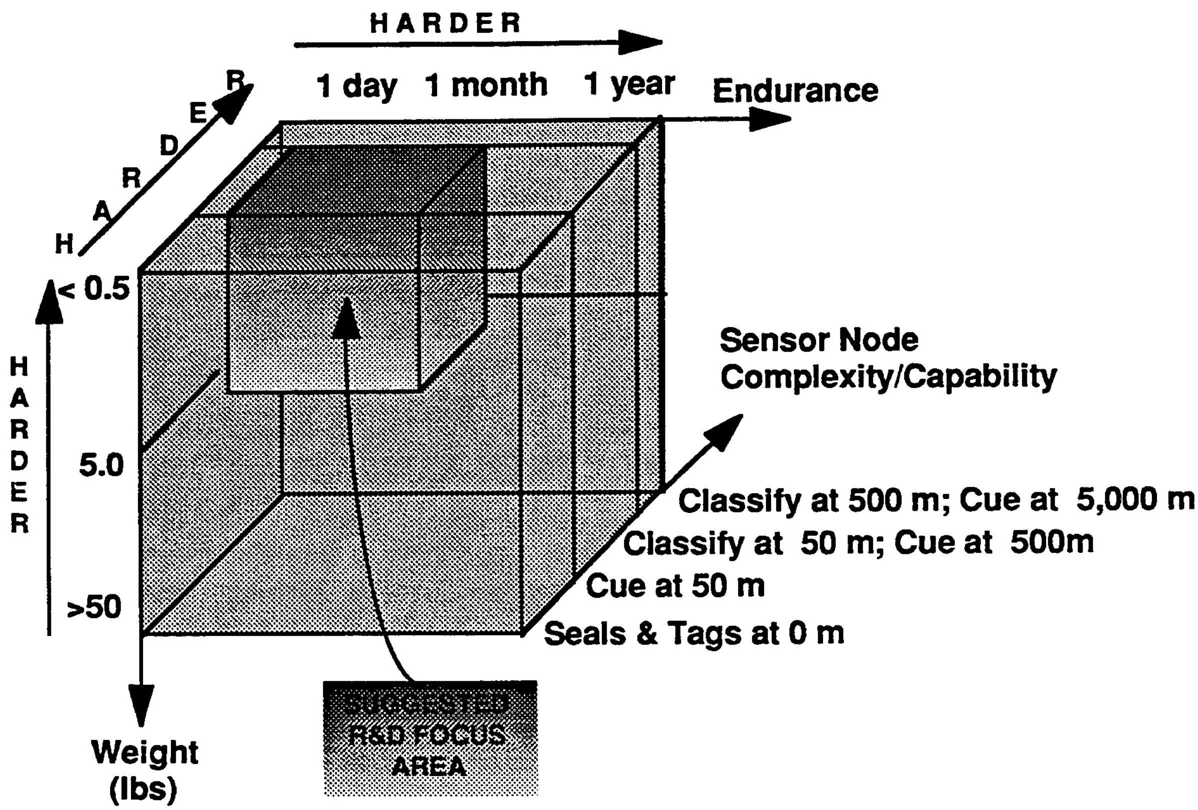
Items 5 and 6 are require more clarification. Small locator/communicator packages could be attached to vehicles (vehicle tagging) to monitor movements. This is feasible, and potentially valuable, for own-forces tracking but, because of emplacement difficulty and covertness requirements, seems an unlikely option for monitoring enemy vehicles. In either case, the "sensor" would not include a sensor other than whatever is needed for position determination.

Sealed facility sensors would be straightforward to develop but would have very specialized utility at best. They could be attached to buildings to monitor the opening, closing, or breaking of doors and windows, much like standard security systems.

The "safe" mine concept is to use a network of expendable sensors to locate and target vehicles or personnel in an area where one wishes to deny access. Some form of stand off weapon would be needed to complete the system. This could become important if the U.S. were ever to forgo the use of traditional mine fields for humanitarian reasons. Without the standoff weapon, which would be easy to retrieve and provide use controls for, the deployed sensors would have no lethal capability.

4.0 WEIGHT, ENDURANCE, CAPABILITY, DIFFICULTY TRADE-OFFS

An ideal remote sensor would have no weight or volume, would operate unattended without external power for unlimited time periods, and would detect, locate and classify activities or targets with certainty and no false alarms. In reality there are trade-offs between weight/size, endurance, sensor capability, and engineering difficulty. The following figure illustrates this. (The sensor package includes sensor, processing, radio system, etc.) The figure also shows where we believe miniature remote sensor R&D effors should concentrate for the greatest payoff.



Excessive endurance requirements can make system development overly difficult, with energy storage being the limiting factor for small light sensor packages. In many situations sensors can be replenished, and many (most?) fast-changing warfighting needs can be met without replenishment using sensors with only modest endurance. The figure indicates our belief that sensor endurance in the range of a month to a day, depending upon the application, should be emphasized. It is hard to envision many significant applications for sensors with less than one day endurance, and all but a few of the longest term applications should be served by a sensor with a month of endurance. Efforts to achieve a much longer duration are not likely to have a high payoff in utility, and may be impossible to achieve without compromising capability or size.

Sensor useability will be limited by deployability, which is significantly influenced by size and weight. Large heavy packages cannot be used in large numbers and large individual packages may be easy to locate and neutralize. How big is too big clearly depends on the scenario, sensor capabilities, deployment mechanisms, etc. We have indicated in the figure the weights that we believe make sense for many applications; less than about five pounds, and the smaller the better. The goal should be sensor packages that weigh much less than five pounds and less than one pound if possible. Weight reduction without compromising performance should be a major goal.

The third axis represents the complexity and surveillance capabilities of the sensor package, with the assumption that enhanced performance will usually require more sophisticated and complex systems. In many cases enhanced performance may be very difficult to achieve without increasing size and weight. For example optical sensors will require larger optics to operate at long range and acoustic sensors may require larger arrays to suppress noise and localize direction.

Our view is that sensors with operating ranges less than several tens of meters will not be of much value because they will be useable in only very specialized situations. Small sensors with very long ranges (e.g. a kilometer or more) would be of great value but may not be achievable within an acceptable size, weight, and endurance envelope. As the figure implies emphasis should be put upon reducing size and weight and increasing endurance (up to a month or so) rather than on extending sensor ranges beyond a few hundred meters. This certainly applies to most optical and mechanical wave sensor applications. An exception is the detection and localization of large firing weapons. Acoustic sensors can easily achieve much longer (many kilometers) operational ranges. Other exceptions might be chemical, biological, nuclear, or magnetic sensors that may have such limited range capabilities that even achieving several tens of meters will be difficult.

The emphasis of this white paper is on miniature sensors having realistic expectation of being developed into useful military systems in the foreseeable future. The goal would be significant improvements in size, weight, and capability compared to systems such as the old IREMBASS system and other more current systems [1,2] that are available or under development.

Micro sensor packages with advanced capabilities and autonomous mobility are interesting in concept[3], but would involve high technological risk and would require a long term research and development commitment. Micro sensor technology development should be pursued, but not on a critical path to the demonstration of an effective miniature remote sensor capability.

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[1] System Innovations, Inc. of Fredericksburg, VA produces and markets one interesting system with several sensor, communication, and power source options. A single field processing unit and power supply unit weighing several tens of pounds can service many attached sensors. The individual sensors weight from about a pound for seismic and acoustic sensors to much more for imaging sensors. See World Wide Web home page at http://www.ahoynet.com/business/si/si.html.

[2] An Air Mobile Ground Security and Surveillance System (AMGSSS) is under development at NRaD. Sensor pods for this system will be deployed using an air-mobile platform based on the Sikorsky Cypher ducted-fan unmanned air vehicle. See the World Wide Web site: http://www.nosc.mil:80/robots/air/amgsss/amgsss.html for more information.

[3] These are addressed in some detail in a recent RAND Documented report "Future Technology-Driven Revolutions in Military Operations: Results of a Workshop", DB-110-ARPA by Richard O. Hundley and Eugene C. Gritton. The thrust was technology to revolutionize military operations over the next 20 years. The workshop took place in the last part of 1992.

5.0 TECHNOLOGY DEVELOPMENT AREAS

1. Small, low power, rugged (short range) surveillance sensors

There are many sensor options: acoustic, seismic, visible imaging, IR imaging, IR non-imaging, laser ranging, electromagnetic emission, magnetic, pressure, chemical, biological, etc. Even a brief discussion of all the options is beyond the scope of this White Paper. The discussion here is limited to visible and IR imaging sensors and to acoustic sensors organized into small direction finding arrays. The reason is that we believe these options have the greatest scope of application and are technologically mature enough to be the basis of an initial demonstration system.

It is now possible to obtain visible images under conditions ranging from bright sunlight to overcast starlight conditions using a small CCD imaging chip. The technology to do this has been under development at MIT Lincoln Laboratory over a period of decades for various applications. One current application focus is low-light CCD images to replace and improve upon the performance of image intensifier tubes for night vision applications.

A 128x128 CCD demonstration chip has been built. It requires modest cooling and temperature stabilization to operate under very dark conditions (much less than moonlight) but can operate without cooling under most conditions. Even when cooled it requires only one watt of energy and it may be possible to reduce that somewhat. Even if cooling is required, the system stabilizes quickly, perhaps a few tens of seconds or less, and so can be cued by other sensors to operate only during critical short time periods when there is something to see. This technology appears to have a potentially significant use in miniature remote sensor applications. Limiting factors in size reduction will be optical components but if the sensor is designed to image and recognize vehicles and personnel at only modest ranges this should not be too much of a problem.

The other important advance in imaging sensors is the development of LWIR sensors using Bolometer arrays. This technology supports the development of low cost and low power LWIR imaging systems. Like the low light visible CCD imager, the new IR systems require modest cooling and temperature stabilization. Current systems require about two watts of power but it may be possible to reduce this by using the same approach that was used for the Lincoln CCD chip; cool only the chip and other absolutely essential parts and no more.

Both the low-light CCD imager and Bolometer-based IR imager are discussed in a separate EO sensing White Paper.

Microphones have a long history of use in remote sensor applications, usually in the form of a single omnidirectional microphone or in some cases as a more complex microphone with limited ability to determine source direction. More recently small arrays of microphones have begun to be used in experimental systems and in developmental systems such as the Wide Area Mines (WAM) and Brilliant Anti-Tank (BAT) systems. The advantages of arrays are their direction finding capability, the ability to null or reduce interfering sources, and the ability to distinguish false alarms from signals by tracking signal directions in time. The result is a surveillance capability that is far superior to single microphone systems. Advances in processor technology are the primary technological factors that have made arrays practical for use as miniature remote sensors. Small arrays might contain from as few as three to as many as ten sensors. The upper bound is probably set by the power required to perform necessary array processing, not by the power required by the sensor.

The most useful frequency band for acoustic sensors is from several Hertz to perhaps a few Kilohertz. The low end utility is limited by wind noise. The upper end is limited by excess attenuation in the atmosphere. Applications requiring target detection at long ranges, perhaps several kilometers, are limited to only a few hundred Hertz at the high end. At ranges of a hundred meters there is less attenuation of high frequencies and the useful frequency band can be extended. Target signatures include: harmonic sets associated with engines, drive system components, and auxiliary equipment; tire and tread noise; and turbine noise.

Acoustic array apertures of a meter or less should be sufficient. A one meter array can determine directions to within several degrees for frequencies on the order of 100 Hz. Operating at close range may make it possible to reduce the aperture to well below one meter.

The challenge for microphone technology is not sensor sensitivity. Performance is limited by background noise and wind noise. Small inexpensive microphones have sufficient sensitivity. Also, microphones do not require much power to operate, perhaps 0.1 Watts for a complete array. Further reduction in sensor power requirements are also possible and desirable but not essential in the near term. For miniature sensor applications it appears that the most pressing need is for good packaging and a collapsible array structure that is easily deployed in the field and is not overly obvious when deployed. Wind noise reduction is another problem but this is more of a problem for long range detection applications where signal levels from targets are low. This is less of an issue for close range applications (10s to a few hundred meters) which are more typical of those envisioned in this White Paper.

A longer term microphone development effort could be undertaken with the goal of reducing power required not only by the basic sensor, but by the associated processing. This would be particularly appealing if sensors are to placed close (no more than several tens of meters) to potential sound sources, resulting in large signal levels and more severe requirements for small size and covertness. One approach would be to fabricate microphones, analog processing, a/d conversion and some digital processing on a single chip. The analog processing and microphone could operate at very low power levels, monitor sound levels, and invoke additional processing, and associated power drain only when there was sufficient signal present to justify further processing.

Other sensor options also should probably be investigated but acoustic and small imaging sensors should be considered as the primary baseline general purpose sensors.

2. Algorithms

Sensor data processing, interpretation, and compression algorithms will be required. They are essential to eliminate or minimize the need for sensor data interpretation experts in the field and to eliminate the need for people to review all the remote sensor data. Algorithms must be developed to detect events of interest and eliminate uninteresting data. Communication limitations also make it impractical to transmit all sensor data. The algorithms must at the least identify the important subsets of data to transmit. If sensor data is transmitted for human review or additional computer processing then compression algorithms will be required. In some cases it may be possible for sensor-based algorithms to reduce the data to brief intelligence reports without actual sensor data, with the option for a remote user to request more detailed supporting sensor data.

There are two distinct algorithm types: one which processes the data from a sensor or sensors located at a single geographic location, and another which jointly interprets the date from sensors that are geographically distributed. The former are essential for reducing communication requirements. The latter will emphasize the interpretation of patterns of activity based upon highly condensed reports from the individual sensors. The processing of data from geographically distributed sites cannot require extensive communication of raw data. Single site processing will typically involved the largest data rates and processing loads and is constrained by available power. The interpretation of data from several sites may be less compute intensive and can be less power constrained since it may take place at a vehicle or more centralized manned site.

Algorithms are sensor and application specific. Small acoustic arrays and passive imaging sensors should have broad utility for the detection and classification of moving ground vehicles and personnel. Such sensors may be used separately or together at a single observation site. These applications present a considerable challenge for algorithm developers if false alarms are to be minimized without missing some of the targets. The goal should be to at least approach the detection, false alarm elimination, and target classification performance that might be achieved by a well trained observer using the same sensor data. This goal may be approachable for detection and false alarm elimination but the automatic classification goal may be more difficult to approach, requiring more human intervention for difficult situations.

Algorithms will be needed for all sensor types but the acoustic (perhaps including seismic) and imaging sensors may be the most difficult as well as among the most useful. The algorithms for many other sensors such as magnetic, chemical, biological, or nuclear sensors can be based upon directed physical measurements and should be much simpler. The recognition of sound and images is more of a perceptual problem, which is far less understood.

The issue of low power implementation of algorithms is a separate issue covered in the next section.

3. Low power algorithm implementations (analog or digital)

There are three approaches to reducing power requirements for algorithms: Power-reduction algorithm re-engineering, exploitation of trends in the commercial COTS parts, and development of ultralow-power custom devices.

Power-reduction algorithm re-engineering is the redesign and restructuring of algorithms for the purpose of achieving a power-efficient implementation. Algorithm re-engineering is now routine for real-time signal processing applications, but the goal is not low power, it is to achieve real-time performance. The initial form of the algorithm may meet functional requirements but with little attention given to ultimate real-time operations. The re-engineering is not just good coding, but may involve significant restructuring of algorithms to better match target hardware. Re-engineering for power reduction is not yet as widely practiced, but will be required for the development of miniature remote sensors. It will involve knowledge of the algorithms and implementation hardware options, including analog devices, digital devices, and digital systems.

COTS digital parts and systems are becoming more and more capable every day as device critical dimensions are reduced[4]. What is less commonly noted is that there is a corresponding decrease in power needed per unit of computation. The development of miniature remote sensors will benefit from this trend and should anticipate gains that will be made over the next several years. A system based upon current technology might be significantly reduced in power and size in five to ten years simply by adapting the best available digital technology at that time. All proposed research and development efforts targeted at hardware oriented power reduction should be evaluated with respect to commercial trends and expectations. All miniature remote sensor development efforts should try to anticipate likely technology advances.

The third approach is custom device development. The miniature remote sensor niche market, although potentially substantial, will not be large enough to influence the mainstream commercial market. It may, however, be large enough to justify targeted low-power device research and development. Miniature remote sensors may be distributed widely on future "battlefields". Large numbers will be acquired by DoD and their cost must be low. This contrasts with typical high-performance military systems in which only small quantities are purchased. That typical case has led to high cost if custom components are used, hence the present strong emphasis on use of commercial, off-the-shelf (COTS) components. COTS components have several other significant advantages too, so their use in military systems is likely to become much more widespread. There is a disadvantage, however, in that they often have much greater capabilities than are needed for a particular application, and those extra capabilities result in a component which is substantially larger and dissipates substantially more power than one which was designed for the specific purpose.

The unusual characteristics of distributed microsensors make dedicated design more appropriate than for many military semiconductor devices. First, the requirements for low power and small size are orders of magnitude more extreme than in the high volume commercial markets such as portable communicators, placing a premium on implementing only the needed capabilities and no more. Second, the substantial volume of components required allows amortization of tooling cost over many parts, the very mechanism which makes commercial integrated circuits so cost effective. Of course manufacturing volume will still be low compared with a mainstream microprocessor, but if these sensors are successful the volume will be much larger than for a typical specialized military chip.

4. High density energy sources for low power applications

Energy storage is a critical issue for achieving low weight long endurance remote sensors. A representative modern high energy battery provides about 200 kwhr/m^3 and 175 whr/kg. A sensor package using 1 watt of average power for 30 days will consume 720 whr of energy. The battery to provide this energy would weigh about 4.1 kg, or about 9 pounds. It is clear that 30 endurance can be achieved either by requiring a much smaller average power or by significantly increasing the energy density in the power source. Achieving this should be a high priority research effort.

One innovative approach is the use of micro-machined electromechanical electrical energy

4 "Semiconductor Lithography for the next millennium", Linda Geppert, IEEE Spectrum, April, 1996.

generation devices. For example, one research effort[5] is working on the development of a turbine-generator demonstration system in the 10 to 100 watt range. The predicted energy densities for the demonstration system are 3000 kwhr/m^3 and 3500 whr/kg, an energy density increase of more than an order of magnitude. The turbine technology is less efficient for lower power levels, but it may be possible to develop other micro-mechanical systems incorporating reciprocating internal combustion engines in place of the turbines.

Micro-electromechanical power sources should be pursued and other approaches should be sought. Another option, although there are some obvious drawbacks, is solar power. The power in sunlight is about 100 mW/cm^2 so that only a small area would be sufficient to provide power for a sensor with average power drain of a watt or less. Drawbacks include collector sizing and energy storage problems to allow night operation and compensate for periods of bad weather. The need to position the collector for exposure to the sun for long periods of the day compromise sensor covertness. Fuel cells offer increased energy density but small size may be a problem. Nuclear sources are a technical option that is not politically or environmentally viable.

Excellent miniature remote sensor systems can be developed using current battery technology by putting emphasis on low power sensors, processing, and communication, but ultra small sensors will also require significant advances in energy sources as well.

5. Appropriate low-power communication

Communication from sensors to users/interpretation sites is a key technology requirement. Smart sensors will reduce the communication requirements but communication will still remain an important issue. A broad range of communication issues need investigation: choice of system architecture, transmission frequency bands, bandwidth, modulation scheme, network structure and protocols, etc.

Antennas need to be small, inconspicuous, and easy-to-deploy and power requirements must be small. The most practical overall option appears to use UAVs (or possibly low altitude satellites if there is a large enough constellation of them) as airborne communicators for the deployed sensors, and this should be investigated. This should include a consideration of jamming issues since the UAVs will be required to receive information from small low-power ground sites.

The number of sensors in a area serviced by a single UAV could be hundreds or even thousands. However, the average data rate per sensor would be very low and traffic would be intermittent. Traffic from the sensors would include intelligence reports without supporting sensor data and, occasionally, some sensor data, for example a small compressed image of a vehicle or a segment of audio data. Traffic to the sensor would be limited to short command sequences.

Small poorly-sited antennas and limited power will make ground-to-ground communication difficult. An exception is when distances are very small, say one hundred meters or less. This

[5] First Semi-Annual Interim Technical Progress Report on Grant #DAAH04-95-1-0093 entitled Micro Gas Turbine Generators, Alan H. Epstein, MIT Department of Aeronautics and Astronautics, May 1, 1995 - December 31, 1995.

might be the case if a small number of sensors are locally deployed and operate as a team. For example, acoustic sensors might alert nearby imaging sensors to power up and collect data. Another option is that several ground sensors in a small area communicate with one nearby elevated miniature communication node for longer range communication. Ground-to-ground communications options and limitations need further investigation.

The large number of sensor sites, their low power, and their intermittent use would provide some inherent protection against their being detected, located, jammed or destroyed. Some additional LPI or AJ capability might be included but it will be important to keep it simple and no more than is essential because complexity will add size, weight, power, and cost.

6. Sensor location/orientation technology

Knowledge of sensor location is needed for all applications and sensor orientation is important for many. In the case of hand emplaced sensors this should be fairly straightforward. Location could be obtained using a GPS system carried by the deploying personnel. Orientation information could be based on a compass or orientation with respect to roads and landmarks. Sensors deployed from moving ground vehicles, manned aircraft, or unmanned aircraft might require additional equipment as part of the sensor. In addition to GPS options, airborne platforms interacting with the sensor communication system to measure time difference or arrival and directions could be used to locate deployed sensors. One goal would be to minimize the sensor-based part of the location determination system. Modifications to the standard communication link might be superior to GPS in this regard. In the case of GPS only essential receiver and front end processing might be in the sensor with the rest remotely located.

Except in the case of hand emplaced sensors, mechanisms would be required to orient sensors as well as to measure the orientation, for example an imaging sensor should point towards the road that it is monitoring. This is trivial for hand emplaced sensors but not for other modes of deployment.

6.0 SUGGESTED EVOLUTIONARY CAPABILITY DEVELOPMENT PLAN

It is tempting to set very aggressive goals with respect to system capability, size, and endurance. We believe, however, that it will be better to define a sequence of increasingly difficult goals with the intention that the less ambitious initial goals will produce demonstrable useful capabilities for timely transition to the services. For example an initial system might use existing technology to demonstrate an easily deployable (hand emplaced in less than a few minutes) 5 pound smart acoustic/imaging sensor package with UAV as well as short range ground-to-ground communications and having a few weeks of endurance. Such a system would have many applications and would serve as an effective concept demonstration without an overly aggressive, long term, and risky push towards miniaturization. The initial demonstration system would require practical solutions to the communication problem and the sensor data interpretation which is to minimize the need for human analysts while maintaining a high level of system performance.

More technologically advanced systems, for example a system with more endurance and weighing a pound or less would require more time to develop and have higher technical risk. Having only aggressive long term goals could result in having no system while less ambitious plans could result in a very effective if not ideal capability.

Nuclear, Biological, and Chemical Detection Technologies

A White Paper
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May 1996

NBC Detection Technologies

To be prepared in twenty years to face an adversary who possesses and is willing to use NBC (nuclear/biological/chemical) weapons, our forces will require advanced sensor systems to warn when these weapons are about to be used, to indicate when and where CW/BW (chemical warfare/biological warfare) weapons have been used, and to identify what type of agents are present. These sensing tasks are likely to be performed by a suite of sensors: radiation detectors to detect the neutron and gamma emissions from nuclear materials; point chemical and biochemical sensors with ultra-high sensitivity and specificity for detecting selected target molecules in the midst of a large and complicated background; and laser remote sensing techniques for chemical and aerosol measurements at large standoff distances. The anticipated state of field deployed technology some 20 years hence in each of these detection areas is summarized below.

Nuclear Detection Technology

Nuclear materials emit three types of radiation that can be detected at a distance: neutrons, charged particles and photons. The technologies in use today to detect all three of these radiation types are limited and great improvements are possible in the range and sensitivity of future detectors and detection systems. In the following paragraphs we will present our vision of the improvements that are possible with detectors for each type of radiation, and comment on the impact of system design to improve radiation detectability.

Many weapons of mass destruction (all plutonium containing devices) emit neutrons. These energetic neutrons are very difficult to shield and have a substantial range in many materials. Furthermore, the natural background of neutrons is very low compared to other radiation sources, thus neutrons are potentially an excellent signature of special nuclear materials and identifiable at a large distance. Neutron detection is probably the most primitive nuclear detection technology at present and the technology likely to undergo the largest improvement in the near future. Present day neutron detectors consist of gas tubes containing ^{3}He or BF_3, or scintillators coupled to photomultiplier tubes. These detector systems are not rugged, and because of the low density of neutron absorbing species, they have low sensitivity.

Future neutron detectors will consist of all solid state devices. Semiconductor neutron detectors consisting of wide band-gap semiconductor materials that contain a neutron absorbing isotope will offer the possibility of highly efficient, rugged neutron detectors in a small package. A limited amount of research has already been done on materials such as BP and $LiInSe_2$, and they appear very promising for use in future neutron detectors. Another future neutron detection scheme would employ improved scintillators coupled to solid state light detectors. In particular, improved hydrogenous scintillators (plastics) attached to low noise light detectors (few photons of noise at room temperature) would have the possibility of reconstructing the direction of an incident neutron as well as its energy. Simultaneous energy and direction information would be obtained by reconstructing the track of the proton produced when a neutron scatters off of a hydrogen nucleus. For this scheme to work effectively very uniform plastic scintillators must be produced as well as improved solid state light detectors such as avalanche photodiodes or drift photodiodes. However, the payoff would be great; by adding directionality and spectral information, the sensitivity to localized neutron sources at large distances would be significantly enhanced.

Charged particles are also emitted from special nuclear materials, but they are much less attractive than other radiation types for detection at a distance, and we mention them here only for completeness. Charged particles from nuclear materials consist of either alpha particles (helium nuclei with energies in the few MeV range) or betas (electrons of energy usually less than 2 MeV). Both of these charged particle types have very short ranges in most materials; even in air alpha particles have a range of less than 10 cm and betas a range of less than 1 m. In addition, charged particles are very easy to shield, and thin layers of metals (< 1mm thick) will completely stop all charged particles from a weapon. Thus, direct detection of these particles at great distances is not possible, and we are confident that charged particle radiation detection will not play a major role in future search techniques.

Energetic photons (X-rays and Gamma-rays) are also characteristic emissions of special nuclear materials, and they are detectable at some distance. Gamma-rays can be difficult to shield (close to 1 in. of lead would be required to shield the gamma-rays emitted by plutonium). Furthermore, the gamma emissions from special nuclear materials have a very specific radiological signature - their energy spectrum. However, the natural background of gamma rays in the environment is significant (from natural sources), and this background limits the delectability of specific gamma ray emitters in a detection or search environment. Existing gamma-ray detection technology is more advanced than neutron detection. For example, while present day neutron detectors can merely count neutrons, gamma ray sensors are widely available that measure the energy of individual gamma rays as well as count them with high sensitivity. The present state-of-the-art detectors for gamma ray detection are high purity germanium detectors (HPGe). HPGe devices have good energy resolution (< 1 keV FWHM) and are available in volumes up to about 400 cm^3. The biggest deficiency of present day HPGe detectors is that they must be cryogenically cooled to operate. The use of a cryogen (liquid N2) makes the deployment of these detectors very awkward: several hours are required to cool the detector down to operational temperature, and the cryogen must be refilled periodically (every several hours) making unattended operation impossible.

Future gamma ray detectors should have the following characteristics: detector volumes up to 2000 cm^3, improved energy resolution (~100 eV FWHM for up to 10 MeV photons), the ability to operate at room temperature, and the ability to sense the direction of an incoming gamma ray. Achievement of these goals in a twenty year time frame will require the development of room temperature gamma ray detector materials based on high atomic number semiconductors, such as CdZnTe or HgI_2, or the development of compact, low power cooling units for germanium based detector systems. In addition, advances in readout electronics will have to be made to produce gamma ray detector systems capable of determining the direction of an incoming gamma ray. One attractive solution for future gamma detectors would be large arrays of small room temperature semiconductor detectors, with each individual detector element having an active volume of about 10 cm^3. Such an array could be configured to emulate a single large detector element, or could be configured as two planes of two dimensional detector arrays. This latter configuration would be ideal for implementing a "Compton telescope", a device recently employed by gamma-ray astronomers to precisely locate the direction of incident gamma-rays.

In the next two decades we can expect great changes in the *systems* used to detect radiation (as opposed to the individual detectors). For instance, the development of inexpensive and rugged detector modules with local readout and module identification would permit large numbers of small detector modules to be deployed over large areas. A detector module could be designed to "wake up" and broadcast its position if and when it detects a certain amount of radiation. A network of such modules could be used to insure that certain regions are free of significant quantities of nuclear materials, or- conversely- to monitor the presence and motion of special nuclear materials through an area.

Through a combination of research into new semiconductor materials and the development of new readout electronics and systems, we can expect very large improvements in the performance of radiation detector systems in the next twenty years. Neutron detector systems should evolve into highly efficient solid state units and gain the ability to determine the energy and position of neutron emission. Gamma ray detectors should improve in energy resolution, efficiency, and ease of use (room temperature operation) and also become capable of accurately sensing the direction of incident gamma rays. Together, these improvements should greatly improve the ability of radiation detection systems to locate nuclear materials and weapons, even in difficult environments.

Chemical and Biological Weapon (CW/BW) Point Sensors

Over the next 10-20 years, dramatic advancements in chemical analysis systems will be achieved in terms of miniaturization, integration, sensitivity, selectivity, remote operation, automated data analysis, and interfacing to centralized command and control systems. These advancements will enable a variety of new operations related to the detection of chemical and biological weapons (CW/BW) including location of production and storage facilities, detection on the battlefield, rapid diagnosis of exposure, and monitoring during decontamination activities. Currently available technologies tend to be relatively large (0.5 to several cubic feet) and heavy, require significant power, and typically require human intervention and data interpretation. Typical analysis times are on the order of minutes. Detection levels are generally in the parts per billion range with some exceptions, such as ion mobility spectroscopy (IMS), which can detect selected compounds of interest in the parts per trillion range. In addition, all current instrumentation is limited in the types of analytes that can be measured.

The technical advancements expected to occur over the next 10-20 years should enable real-time (few second) detection and identification of CW/BW agents at the very low concentrations of interest (parts per trillion or less). This will be possible using miniaturized , low-power systems that can be utilized in a variety of operational modes ranging from person carried (pager size) to miniature unmanned aerial vehicle (UAV) mounted to ruggedized systems that can be "dropped" at key locations (for example, designed in a package that acts like a maple seed that helicopters down). These capabilities will be achieved through miniaturization and integration of a variety of key functions including: sample collection, preconcentration (to lower detection levels), chemical modification/reaction, separation (for improved selectivity), selective and sensitive (pico gm or less) detection, data acquisition and system control, data analysis and interpretation (chemometrics/pattern recognition), and communication/telemetry capabilities. Thus, these systems will have the functionality of what are currently large and heavy instruments but in a small, integrated package. In addition, this integration will result in advantages over current systems such as faster (few seconds) analysis (e.g., heating in msec rather than minutes due to low thermal mass) and improved system-to-system reproducibility based on batch processing.

There are a variety of critical technologies to enable these miniaturized analytical systems. These technologies will be important for the analysis of chemical compounds and identification of biological agents (e.g., miniaturized DNA diagnostics). First, miniaturized, integrated systems for sample capture, concentration, reaction, and transport are needed. Micromachined pumps and valves are being developed and should be available during the next 10 years. Alternative approaches to liquid manipulation include the use of electroosmotic and capillary forces. Advances will also be needed on integrated systems for sample concentration (e.g., adsorbent preconcentrators to enhance chemical concentrations 100-1000 fold) and, in some cases, chemical reaction to convert the analyte to a species that can be more selectively and sensitively detected (e.g., react with a fluorescent dye to enable use of very sensitive fluorescence detection).

Second, materials that provide highly-selective uptake or reaction with specific chemical or biological agents are needed. In some cases, these materials may be sufficiently selective to enable simple sensors that can selectively detect one or more agents of interest without additional sample conditioning. Biomaterials have already demonstrated their utility for selective sensing (e.g., immunoassays and biosensors) and nano-engineered materials are being developed that can provide tailored physical and chemical properties for specific needs.

Third, separation capabilities are one of the keys to providing improved chemical discrimination in complex chemical environments that contain thousands of chemical compounds. The most powerful analytical techniques currently available make use of high efficiency separations coupled to information rich detector methods. These systems need to be miniaturized and integrated to provide rapid and reproducible separations and, for some applications, to provide highly parallel separations to enhance sample analysis capabilities.

Fourth, small, very sensitive detectors are critical. A variety of detector subsystems are already available, including ion detectors (e.g., photoionization detectors, detectors used in ion mobility and mass spectrometers), optic detection systems (e.g., for absorption or fluorescence), electrochemical detectors, acoustic wave sensors, and field effect transistors (FETs). Advances will be made with these and new technologies to improve sensitivity, reduce size, increase versatility, and simplify integration with other system components. In addition, replacing single-output detectors such as photoionization detectors with miniaturized and integrated chemically-discriminating detectors, including spectrometers and arrays of detectors, will enhance performance.

Fifth, automated data acquisition and analysis capabilities will be needed to operate the system, take the data, use chemometrics/pattern recognition to identify and quantify the species that are present, and interface/communicate with centralized operations. Current systems often use specialized cards and computer systems to perform these functions; however, the advancements in miniaturized yet powerful microcontrollers and microelectronics will enable these functions to be performed with very small and low power modules (or integrated on the chemical analysis chip). In addition, the miniaturization of telemetry and global positioning system capabilities will allow these systems to identify their position and easily communicate information to remote sites.

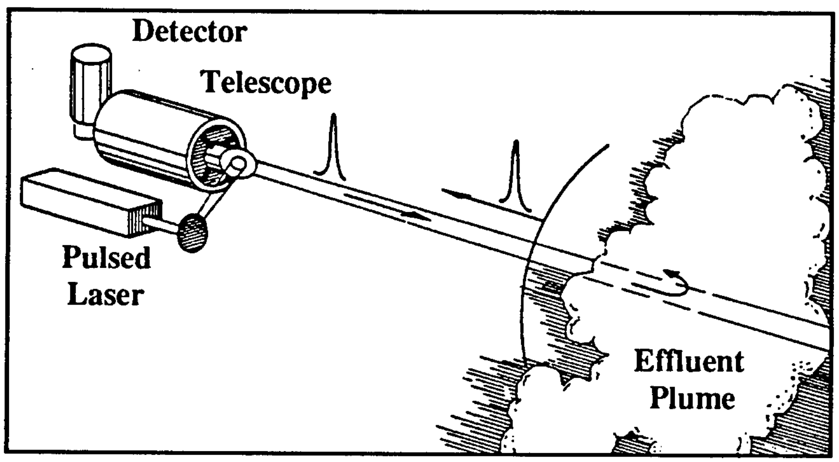
In summary, the ongoing refinement of currently existing technologies will allow us to address many of the needs of BW/CW detection, if that refinement incorporates the revolutionary advances that are being made in micro-electromechanical systems (MEMS) and integrated optics and electronics, in nanoengineered and biomimetic materials, and in information and data analysis. Undoubtedly, new analytical techniques will emerge, but they too will depend on these rapidly advancing technologies to enhance their usefulness for chemical sensing applications. These advances, continuing over the next 10-20 years, will enable many of the visions described above and provide a capability to batch-produce large numbers of miniaturized, high performance microanalytical systems to meet CW/BW sensing requirements.

Laser Remote Sensing (lidar)

Introduction

To be prepared in twenty years to face an adversary who possesses and is willing to use NBC (nuclear/biological/chemical) weapons, our forces will require advanced sensor systems to indicate when and where CW/BW (chemical warfare/biological warfare) weapons have been used, and to identify what type of agents are present. Laser remote sensing can make a strong contribution in these areas, providing the warfighter with crucial information from a safe distance. Typically, sensing the presence of chemical or biological agents involves sample collection and analysis which exposes vehicles and/or personnel to contamination; laser remote sensing techniques may allow such analysis to be conducted remotely. In addition, laser probing techniques potentially may be employed for battle damage assessment, investigation of underground facilities, measurement of wind velocity, land mine detection, observation of shallow underwater objects, and detection of vehicle activity. Such information could contribute useful intelligence to be considered in conjunction with other techniques such as satellite imaging.

After a brief overview of laser remote sensing techniques and configurations, the applications listed above will be described in more detail in the context of the future battlefield. Critical technologies for the implementation of these applications and their current status and development needs will then be reviewed.



Laser Remote Sensing Overview

Lidar (light detection and ranging illustrated above), the most appropriate form of laser remote sensing for these applications, probes a target of interest with a laser and measures the optical response to learn information about the target. Lidar may be employed to examine gaseous (including aerosols), liquid or solid substances to determine such characteristics as chemical composition, density, spatial extent and movement. In measurements of gases or aerosols, lidar returns information about the target along the line of sight of the laser beam, giving a response which is a function of depth into the target. A lidar system may additionally return imaging information in the transverse dimensions using either laser scanning techniques or a large beam diameter and a detector array, thus providing a three-dimensional image of the target material. A lidar system may be designed for remote use – on an airborne platform such as a UAV (unmanned aerial vehicle) or on a ground-based robotic system – or for direct use in a hand-held or vehicle-mounted form. Many of the applications to be discussed will require significant advances in laser design, detection technologies, and information processing.

Lidar System Configurations

Compact, high-efficiency, robust tunable lasers combined with high-performance detectors and advanced analysis algorithms can be deployed in multiple configurations. For example, information may be gathered remotely from a satellite or high altitude aircraft-mounted laser remote sensing system. Such an airborne monostatic system, in which the laser source and detector packages both are mounted in the same platform, would provide a flexible and responsive configuration. Alternately, satellite or high-altitude aircraft-mounted tunable lasers could be combined with UAV-mounted or ground-based detectors in a bistatic scheme. Bistatic configurations involve more complex coordination issues between source and detector, but allow for passive, and thus more stealthy, detector platforms, and may reduce the laser requirements. As a third option, a small or miniaturized lidar mounted on a vehicle, in a hand-held suitcase-sized package, or on a remote-controlled device, could allow for shorter range ground-based operations. In any case, the lidar system would be designed to operate under as wide a range of scenarios as possible, including different weather and lighting conditions.

For dispersed ground forces on the future battlefield, a UAV equipped with a chemical-detection lidar system could be shared among several small dispersed units in circumstances where continuous real-time monitoring by each individual unit is not required. This would alleviate the need for each unit to possess it's own chemical detection infrastructure. Additionally, for short-range chemical detection, each unit could be equipped with a small vehicle-mounted or hand-held lidar system. The particular application for which the system is designed will determine which configuration is most appropriate.

Applications and Impacts

The central promise of lidar technology stems from its ability to detect and characterize materials from a remote location. Several potential wartime applications of lidar which may be achievable in the next 20 years are listed below.

Sensing the release of CW/BW agents

Laser remote sensing technologies may actively sense the release of CW/BW agents during a mission, giving our forces warning of a nearby release without the need for sample gathering and analysis. A vehicle-mounted or hand-held lidar unit could use multispectral, spatial and temporal information to sense the presence of a gas or aerosol cloud within a few hundred meters, and possibly determine its spatial extent and movement. For CW agents, it may be possible to characterize the chemical species present in the cloud. This would prepare troops for protection against these agents by relaying useful processed information in seconds, allowing time for the troops to respond as required.

Scouting for NBC agents from past releases

A similar system could scout for NBC agents still present from past releases in an area which had not been actively monitored. Due to rapid degradation of CW/BW agents in the environment, this would only be an issue soon after a release. During or after warfare, lidar could detect whether and which agents had been spread, and to what extent, by detecting surface contamination consisting of either chemical solids or liquid films. An airborne system or a unit mounted on a lead vehicle could search for such NBC agents in advance of maneuvering units, possibly with enough range to avoid exposing the scout vehicle itself to contamination. Systems could also be deployed on unmanned robotic vehicles to increase the range and sensitivity of lidar measurements. These systems would aim to rapidly determine the safety of entering an unmonitored zone, and relay sufficient information to the following units to allow them to either avoid or prepare to enter a contaminated area.

Detecting land mines

To increase further the safety of advancing troops, an airborne lidar system could be designed to detect land mines well in advance of troop movement. Land mines, even when exposed on the surface, are typically well camouflaged and very difficult to find by visual inspection. A lidar system potentially could detect an exposed surface of a mine or leaking explosive material, which may exhibit a fluorescence signature. An equipped UAV or robotic vehicle could proceed ahead of maneuvering units and relay back information regarding the locations of detected surface land mines to allow the units to avoid, neutralize, or breach the mine field without significant slow down.

Assessing battle damage

Laser remote sensing could provide useful data for battle damage assessment. Such assessment often proves difficult, especially when the target is an underground facility. Lidar could be employed, for example, to detect smoke from burning insulation or other debris. Smoldering building materials like insulation typically produce carbon monoxide and formaldehyde, which are both detectable by lidar techniques; the presence of these gases would indicate a high probability that a building had been hit. In cases where it is simply desirable to determine where a bomb had exploded, detection of nitrates such as sodium nitrate could provide a useful indicator.

Confirming the presence of NBC agents at bombed facilities

Lidar information could be used not only to determine whether a bombed target had been damaged, but also to confirm the type of facility. If a suspected NBC facility is bombed, then characterization of the resulting emissions may allow confirmation that NBC agents were indeed present.

Inspecting an inaccessible facility

To inspect an inaccessible location such as an underground facility, a miniaturized remote device such as a robug could be designed to carry a small lidar system and penetrate a building, for example, through the ventilation system. It may be possible to task such a device to evaluate the contents of work rooms within a facility. Such a small lidar system would imply very restrictive power, size and weight limits, which would require small, efficient solid-state laser and detector development.

Detecting underwater objects

It may be possible to detect shallow underwater objects using laser bathymetry. This lidar technique employs blue-green lasers, which propagate well through water. Pulses of laser light are reflected from the bottom or from any submerged object. Imaging is achieved by measuring the time delay between the surface and bottom reflections, inferring the depth of the reflector, and scanning the laser beam. Imaging in this straightforward manner may not be possible in turbid water, where much of the laser light would be scattered, confusing the return signal. Intense ultrashort pulse (< 1 picosecond) lasers may allow for imaging under somewhat turbid conditions. Such imaging technology could provide valuable information to look for underwater mines in rivers or littoral areas, to expose frogmen, and to detect hidden objects such as NBC packages placed off-shore of populated areas.

Sensing wind velocity

Several lidar techniques which are sensitive to the motion of particles in the air could be exploited for remote wind sensing. A lidar wind sensor could be employed to improve munition trajectory calculations and guidance, and for better accuracy in precision cargo drops.

Providing information regarding vehicle activity

Lidar may be employed to examine an area of suspected activity for the presence of vehicles. For example, a system could be designed to detect the presence of exhaust plumes, or signs of vehicle refueling. A multispectral lidar system could characterize the ambient atmospheric conditions in an area, including species, densities and particle size distributions, and then look in a specific location for additional exhaust or evaporated fuel. Aromatic hydrocarbons, which would typically be released during refueling, have specific spectroscopic signatures which can be detected and distinguished. A lidar system of this type could allow confirmation of intelligence data regarding the presence of vehicles at a specific location inaccessible to direct visual inspection.

Combinations of the above

The development of compact, robust, and efficient laser and detector technologies would allow multiple tasks to be performed by the same lidar package. A low-flying UAV, for example, could be equipped to both search for CW/BW agents and to assess bomb damage.

Critical Technologies

Advances in laser remote sensing capabilities will depend on progress in three key areas: laser technology, receiver/detector technology, and information processing. Lidar field applications in general, and hand-held and miniature systems in particular, will require compact, high efficiency, robust, rapidly tunable lasers throughout the optical spectrum. It may be possible to miniaturize a lidar system to the size of a coffee mug for short range operations by incorporating small devices such as diode lasers. Lidar systems intended to operate over several kilometers will require larger systems in order to meet the increased laser power requirements. In any case, laser cooling needs and damage thresholds of laser media and optics limit the minimum attainable system size, and laser efficiency strongly impacts these limits; thus, improvements in laser efficiency are crucial for development of smaller devices. Lasers with wall-plug efficiencies of 5-10% will likely be available at the watt level over a wide range of wavelengths in the next 20 years. The ability to tune the source laser among the desired wavelengths limits the number and type of materials which can be simultaneously detected, so rapid tunability is also critical. Laser systems used for lidar are more reliable than they were 20 years ago, and new technologies such as diode lasers have further improved the potential usefulness of lidar systems in the field. However, certain wavelength regimes are still awkward to achieve and involve complex and sensitive laser designs which are difficult to tune. Simplified, more robust systems will be required in real-world applications.

The receivers and detectors which gather the returning optical signal from the target must also be technologically advanced in order to improve system sensitivity, species discrimination, and stand-off distance. High efficiency receivers and high quantum efficiency detectors are needed for detection of small signals over long distances (tens of kilometers), and lower noise detectors are needed in the IR region. In addition, efficient techniques to detect multispectral and temporal information would aid in efforts to improve species specificity. Time-resolved multichannel detectors, which would be a tremendous asset for almost all lidar systems, are under development based on multichannel avalanche photodiode technology. Finally, sensor fusion of multiple lidar systems in a single package would access a broader range of target materials. This could involve simultaneous application of lidars in multiple wavelength regimes, or of multiple techniques in the same wavelength regime.

Improved laser and detection technologies alone will not lead to a useful lidar system in the field. Providing prompt and understandable information to the user will require fast and adaptable analysis algorithms, capable of distinguishing multiple species and interferences in mixtures, and capable of controlling lidar functions by adapting to scenarios. Knowledge-based recognition algorithms must be developed to extract the required information from spectral, temporal, and spatial data. Databases must be developed which include not only characteristic spectra of the chemicals of interest, but the influence of environmental factors on these spectra. In remote applications, preprocessing data on the sensor platform would enable reduction of bandwidth requirements to transmit the information to the user. Maximum system flexibility would be achieved by adaptable lidar configurations which allow smart data processing algorithms not only to supply useful information products, but also to simultaneously influence measurements. Intelligent algorithms could be designed to analyze measured data real-time and then request further measurements to clarify and refine the interpretation of these data.

Current status/needs

Field tests have demonstrated the utility of laser remote sensing techniques for discrimination between some specific chemical species, and it should be possible to distinguish between chemical and biological agents. In addition, preliminary tests have shown that lidar may have some ability to distinguish between biological materials, although this is more difficult. Gas-phase, aerosol, and solid-phase chemicals have been measured with active laser probing techniques, taking advantage of characteristic absorption and/or fluorescence spectra. Some chemical species exhibit recognizable signatures in multiple wavelength regimes, but other materials of interest have signatures only in limited spectral regions. In either case, and especially when sorting out mixtures, operation in multiple wavelength regimes is optimal, since this provides the most information. Therefore, rapidly tunable lasers are under development in all optical regimes to allow improved material discrimination.

For a practical system which could be employed in the field, robust rapidly-tunable all-solid-state lasers which are more compact and more efficient than those presently available are needed. Lasers over the full range of wavelengths must be developed in order to access as many types of materials as possible. For very short range probing, lasers in the EUV may further expand the list of accessible species. Lasers ten times more powerful than current models would enable very-long-range field demonstrations. Extended demonstrations of long-range stable lidar operation are needed in realistic environments and with real-world chemical targets. Further research and development is required to explore the full range of chemicals accessible to laser probing, to learn to discriminate biological versus chemical agents, to identify specific biological species, and to study environmental influences on all of these. Finally, advanced algorithms are needed for data analysis, lidar control, and data fusion among multiple sensors.

Stand-Off Detection of Biological Warfare Agents

A White Paper Prepared for

The Defense Science Board Summer Study

on

Tactics and Technology

for

21st Century Military Superiority

Submitted By

Los Alamos National Laboratory

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Stand-Off Detection of Biological Warfare Agents

Los Alamos National Laboratory

It has recently been recognized that biological warfare (BW) poses a major threat to U. S. military forces. With easily available technology, any country or group can cultivate the bacteria that causes violent infectious diseases such as anthrax, cholera, botulism, and pneumonia, that can be dispersed in the form of an aerosol cloud endangering deployed military forces or large population areas. Western intelligence analysts believe that at present more than 10 countries possess, or could easily develop offensive biological weapons.

To counter this threat to U. S. military forces, the Army, under the management of the Chemical and Biological Defense Command (CBDCOM), is pursuing the development and demonstration of biological-warfare-agent detectors. A very important component of this program is long-range, stand-off detection systems that can be deployed on airborne platforms to provide early detection and warning of aerosol clouds that are characteristic of biological-agent releases. Having identified the cloud, forward-deployed point-detection systems mounted on ground vehicles (Biological Integrated Detector System (BIDS)) would be utilized to identify the specific agent and thus the nature and possible hazard associated with the cloud. These advanced indicators of a biological attack will provide commanders with the increased decision time required to mitigate the potentially disastrous effects of such an attack.

To advance its remote detection capabilities, the U. S. Amy CBDCOM funded Los Alamos National Laboratory (LANL) in FY 1993 to design, build, test, and maintain a mobile system for remote detection of aerosols in the atmosphere. This system, designated as the XM-94 by the Army, is based on the lidar (light detection and ranging) technique. This request was a follow-on to the successful program undertaken by Los Alamos during Operation Desert Shield, to design, build, and demonstrate an effective long-range biological standoff detection system (BSDS) for use in a C-130 military aircraft. The purpose of the latter system, which was called ODS (Operation Desert Shield) C-130, was to detect any airborne aerosol that might represent any BW threat before the cloud could reach friendly forces. The ODS C-130 program exploited LANL experience and expertise in lidar technology, that had been previously developed and successfully deployed on similar Army programs, in addition to programs to characterize atmospheric pollution, laser weapon emission energies and agriculturally important evapotranspiration.

The XM-94, LANL built lidar, is based on the elastic-backscattering technique, where the light being backscattered is unchanged in color or wavelength from that which is originally emitted by the illuminating laser. This XM-94 lidar was designed and constructed to be installed on an Army UH-60 Blackhawk helicopter, operate on the onboard power and be capable of rapid mounting and dismounting. The device was designed for detection, tracking, and ranging of biological-agent clouds at ranges up to 30 km and has been demonstrated to be effective at a range as long as 53 km.

The XM-94 lidar system has been used extensively at Dugway Proving Ground (DPG) over the last three years to detect, map and track clouds of biological warfare simulants. This system is operated in a Blackhawk helicopter by privates who, in war time, could radio back a warning when they observe a cloud that exhibits the dispersal characteristics of biological agents. They can measure the location, velocity, altitude, and ground contact location so as to enable the ground-based point sensors to contact and sample the cloud for type classification of the pathogen. This lidar system can characterize the cloud to make estimates of particle size and can differentiate threat clouds from other obscurants such as diffuse and invisible (to the human eye) aerosol clouds; explosions, from mortar and artillery fire, white phosphorous rounds, chaff, road dust, or smoke from fires.

A lidar system operates much like radar but uses laser light rather than radio waves to scan distant objects. When the beam of light generated by a laser strikes airborne particles, some of the light is scattered back toward the source. If the scattered light is unchanged in wavelength or color, the phenomenon is called elastic backscattering. The returned light is collected by an optical telescope and focused onto a sensitive detector. Specialized data-processing electronics then process the light generated signal from the detector and produce a two dimensional display of the data on a computer monitor. Variations in signal intensity, indicating variations in aerosol density, are displayed in false color for ease in discrimination. When graphically displayed, the light signal can easily indicate location, altitude, distribution, eddy dispersal, and atmospheric movement of airborne particles.

The method of discrimination between threat clouds and others of more benign origin, either natural or man made, is predominantly by shape and aerodynamic characteristics. Probably the most effective means of dispersing biological materials is from a crop duster airplane along a military front, but this is also the most easily identified threat cloud. A long cylindrical cloud represents an unmistakable signature that is easily identified. Other dispersal methods may present greater challenges but all biological warfare materials have a distinctive aerodynamic signature. To be a threat to humans, these materials must be capable of penetrating our natural defenses and getting into the lungs. This requires the cells or spores to be 10 microns in size or smaller. Such materials can remain suspended in the atmosphere for hours. In contrast, dust kicked up by explosions or moving vehicles is often an order of magnitude larger is size and therefore three orders of magnitude greater in weight and would settle out of the air much faster. Any cloud or plume or collection of such that drifts and disperses but does not fall should be considered with suspicion and more thoroughly analyzed.

Threat identification is enhanced by the limited conditions under which biological agents can be effectively used. Typically such biological agents would be dispersed on the battlefield during a temperature inversion, in long clouds, upwind of the forward edge of the battle area. The cloud altitude ideally would be about 100 m but must be below the atmospheric mixing layer, and the minimum agent concentration would range from 100 to 1000 live cells or spores per liter. The agents must be dispersed in the early morning hours before dawn when the inversion layers are very low, the wind is light and there is very little turbulence or mixing in the boundary layer. Sunlight heats the earth's surface, generating thermals with consequent atmospheric mixing and rapidly disperses the aerosols, making them effectively harmless. Fortunately for the defense of our forces, the best atmospheric conditions for biological agent deployment are also excellent for lidar detection of the event.

The accumulation of experience with the XM-94 since 1993 has demonstrated that this technology is very effective for detection, tracking, and ranging of biological-agent clouds. Simulant clouds have been tracked for more than a half hour all the while measuring its size, shape, position, density and signal to noise characteristics of the return signal. Drift velocities have been measured. The dispersion coefficient has been determined and found to correlate well with what would be expected for the atmospheric conditions. The sensitivity of the lidar to the backscatter coefficient of the aerosols has been measured and the effective scattering cross-section of the agent simulant measured. The clouds have been tracked at 20 km ranges until the aerosol density has fallen to a density of 100 to 1000 particles per liter, clearly demonstrating that this lidar is an effective tool for early warning, remote detection of airborne threats.

With the continuing rapid evolution of electronics, optics, and lasers it is possible to reduce the size of the lidar sytem such that a biological detection payload could be built which would easily fit into existing UAVs.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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BIOLOGICAL AGENT MONITORING FOR GROUND FORCE SUPPORT

White Paper

C. A. Primmerman and R. R. Parenti

BIOLOGICAL AGENT MONITORING FOR GROUND FORCE SUPPORT

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1.0 INTRODUCTION

Biological and toxin weapons are, in many ways, a more serious threat than nuclear or chemical weapons because they are much more lethal by weight and require a significantly lower level of production technology. The requisite raw materials and industrial hardware are accessible to even the least sophisticated organizations, and the initial monetary investment is relatively small. In addition, the facilities required for the production of biological agents are essentially identical to those used for agricultural insecticides, and essentially no agent-specific effluents are generated that can be externally monitored. Thus, the clandestine production and stockpiling of weapon-quality pathogens is possible for even the smallest military organization or terrorist unit.

2.0 OVERVIEW OF THE STUDY SCENARIOS

The five engagement scenarios selected for the Defense Science Board Summer Study describe a fairly diverse set of tactical situations, each of which presents the enemy with a unique opportunity to exploit biological agents as a means of obtaining a near-term military advantage. In order to provide a basis for the system analyses developed in the later sections, a brief assessment of the issues specific to each of the three cases is appropriate.

Case I: High End Conflict -- This case, which assumes the civilian populations to be well separated, is probably the most common scenario for chemical or biological agents deployment. Material delivery can be accomplished through a variety of means including tactical missiles, short-range aircraft, and ground troops. The object of the attack might be a command center, airbase, or a concentration of field solders. In addition, the use or threat of use of biological agents against a civilian population could be effective in reducing a country's will to fight. Because of the physical distance between the two forces, the aggressor's risk of self-infection is small, if reasonable precautions are taken.

In order to protect both the military assets and civilian population of Country B from biological agents, the U.S. troops would need to supply instrumentation capable of an early detection of the first wave of deployment, and a rapid identification of the specific agent. Once the enemy's use of an agent has been verified, it will then become necessary to conduct a continuous wide-area surveillance to determine agent distribution patterns so as to establish appropriate procedures for protection and/or evacuation. The risk of false alarms is serious, since they can lead to unnecessary procedures (such as the use of protective clothing) that severely impede troop movement.

Case II: The Distributed Force -- For tactical situations in which the enemy is in a defensive position, the use of biological weapons would have limited benefit, since the risk of self-infection would be significant. The threat of terrorist action aimed at neighboring civilian populations may offer some military advantage, in which case a reliable means for monitoring the presences of agents in the air and water supplies would be of great importance. The detection requirements for this scenario would be adequately addressed by a distributed network of point detectors.

Case III: Operations in an Urban Area -- The primary goal of this mission is the neutralization of a chemical/biological stockpile. Such an operation could be performed by a variety of means, including a bombing mission aimed at destroying the entrance to the stockpile or the capture of the the area by friendly ground forces. In either case it would be desirable to perform a remote surveillance of the area for material release due to an unintentional penetration of the containment area. Once the area has been secured, monitors would be useful to assess the potential danger to personnel involved in the removal of the material for eventual disposal. The initial phase of the disposal process might involve physical contact with the biological material to identify the active agents.

The option of stand-off neutralization, i.e. surgical bombing missions, would probably only be a consideration if some reliable means were available to assess the post-mission integrity of the stockpile. Even a small release of material could result in significant casualties in neighboring civilian populations, and the blame for those deaths would be directed at the U.S. forces. Given the difficulty of performing long-range remote detection (discussed in a later section) an assessment of the area surrounding the stockpile might best be performed by a UAV. Alternatively, a network of autonomous point detectors could be dropped into the area prior to any assault on the facility.

Case IV: Extended Offensive Operations -- An enemy intent on retaining control of occupied territory may have an incentive to deploy or threaten to deploy biological weapons against the occupied population when faced with a strong offensive operation by US forces. Stand-off detection would be an important factor in maintaining the security of recaptured air bases and command posts, and a network of point monitors throughout the secured region would provide an immediate indication of any release of toxic agents. Such information could be important in convincing the resident civilian population that the US forces are capable of providing adequate protection for the occupants of the region.

Case V: Force Extraction -- The probability that a biological agent might be used in a force extraction situation is probably low, since it would occur in a region surrounded by enemy forces attempting to regain immediate control of the territory. Non-specific point monitors carried by individual soldiers of the extraction force would probably be adequate as a precautionary measure.

A brief summary of the principal features of the five engagement scenarios described above and the requirements of the agent detection system is given in Table 2-1. The high end conflict (Case I) and the extended offensive operation (Case IV) are believed to represent the most likely scenarios for biological agent deployment.

TABLE 2-1

ENGAGEMENT SCENARIO SUMMARY

Case Description	Likelihood of Agent Deployment	System Required	Response Requirements
I High End Conflict	High	Layered Network	Real Time
II The Distributed Force	Low	Point Sensor Network	Hourly Updates
III Operations in an Urban Area	Moderate	Stand-Off Monitors	Real Time
IV Extended Offensive Operations	Moderate	Layered Network	Hourly Updates
V Force Extraction	Low	Personal Monitors	Hourly Updates

3.0 THE BIOLOGICAL THREAT

The characterization of biological agents is an inherently difficult process because biological material is ubiquitous in nature, biological substances can take a wide variety of forms, and the lethal dose of a toxic biological agent can be exceedingly small. The agents that have been developed specifically for warfare include bacteria, viruses, and toxins, all of which can be delivered to a remote point by a suitably designed missile. A brief overview of the biological substances that might be encountered in a military engagement is provided in Table 3-1.

In addition to the diversity of biological weapon material, the problem of agent detection is further compounded by their extremely high level of toxicity, which in some cases results in a lethal dose as small as 10^{-8} mg/person. Detection of such low concentrations, particularly by remote means, is extremely difficult even with highly sophisticated monitoring equipment. In some situations it may be impossible to verify the presence of an agent until the first casualties are encountered.

TABLE 3-1
BIOLOGICAL WARFARE AGENTS

Agent	Description	Examples
Bacteria	A single-cell organisms that often have the ability to form spores under adverse conditions.	anthrax, brucellosis, tularemia, and plague
Rickettsiae	An intracellular parasite that can only reproduce inside animal cells.	typhus, Rocky Mountain Spotted fever, and Q fever
Viruses	A strand of genetic material surrounded by a protective coat, which can only reproduce inside living cells.	equine encephalitis, Lassa fever, Ebola fever
Fungi	a plant containing no chlorophyll that grows on organic material. Used primarily to destroy crops.	rice blast, cereal rust, potato blight
Toxins	A poisonous substance made by a living organism or a synthetic analog.	botulism, diphtheria, scarlet fever, cholera

4.0 A LAYERED PROTECTION APPROACH

The most effective approach to the biological weapon problem is likely to be a multi-layered sensor suite designed for wide-area cueing, moderate stand-off detection, and contact identification. The cueing function might involve a careful monitoring of missile explosions and the release of suspicious material from airborne platforms. Wide area surveillance of such activities can be performed by a variety of optical and radar systems, and LIDAR techniques can be employed to locate and map high concentrations of agents in the initial release phase.

The remote detection of a potential agent, even at relatively short stand-off ranges, is an extremely challenging problem, because it is difficult to identify a dependable signature that is common to all toxic agents but absent from natural benign airborne organisms. Ultraviolet fluorescence is a potential mechanism for recognizing the presence of amino acids, although the cross-section for this effect is extremely small.

Once a determination has been made that a biological agent is present in a well-defined area, direct samples of the material can be made by a properly instrumented UAV, pre-positioned point sensors, sensors dropped into the region, or samples taken by troops wearing protective clothing. Although immediate identification is always desirable, a delay of several hours between collection and analysis may be acceptable assuming the general precautions appropriate for positive detection have been implemented. The procedures for identification include the more traditional culture-growth techniques, which may require several days to complete, and more rapid approaches, such as immunoassays. Some of the more effective analysis techniques are summarized in Table 4-1.

TABLE 4-1
BIOLOGICAL AGENT ANALYSIS TECHNIQUES

Mission	Technology	Description
Cueing	Visible/IR Imagery	Wide-area surveillance of substance deployment from airborne or orbital platform.
	LIDAR	Wide-area search for concentrated clouds of newly-released material.
Remote Detection	UAV Sampling	Sampling of clouds by unmaned vehicles for immediate or subsequent analysis.
	UV Fluorescence	Interrogation of suspicious clouds by UV laser and detection of characteristic spectral return.
Direct-Contact Identification	Cell Culture	Culture of cells in growth medium and subsequent investigation of macroscopic morphology.
	Microscopy	Application of a variety of techniques including phase contrast imaging and fluorescence to investigate microscopic cell structure.
	Endotoxin Assay	Test for endotoxin found in the outer membrane of the cell wall of Gram-negative bacteria.
	Immunoassay	Test for the binding of a specific antibody to a targeted antigen. Test does not require extensive sample preparation
	Gene Probes	Test for specific DNA segments. Variations include polymerase chain reaction and restriction fragment length polymorphic analysis.
	UV Fluorescence	Spectral and temporal analysis of fluorescence signature obtained from a strong ultraviolet source. Individual cells can be analyzed.

Although a number of important advances have recently been made in detection methods such as immunoassays and gene probes, these techniques require physical contact with the biological agent and careful sample preparation. Optical approaches, such as LIDAR and ultraviolet fluorescent offer the advantages of stand-off analysis and real-time data processing. A brief overview of these two interrogation schemes is provided in the next section.

5.0 REMOTE OPTICAL SENSING

Stand-off sensing by an optical system may exploit a number of physical phenomena, including elastic backscatter, differential absorption, Raman-shifted radiation, and fluorescence. In all cases, a narrow-pulse laser used in conjunction with a gated receiver effects an interrogation of a small region of the atmosphere that is isolated in three dimensions. The sampling geometry for a laser of wavelength λ_ℓ and backscatter wavelength λ_b is indicated in Figure 5-1. The timing of the receiver gate is adjusted such that the range segment between R and $R+\Delta R$ is recorded by the system.

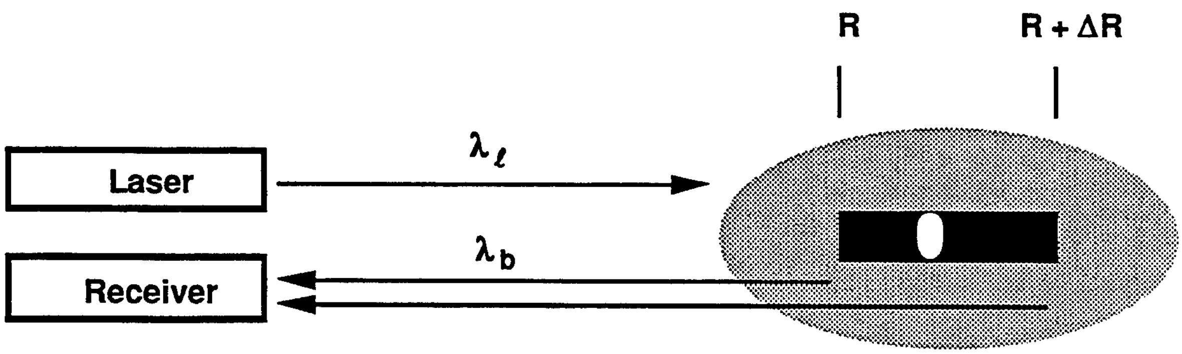

Figure 5-1. Remote sensing of fluorescence radiation is accomplished by projecting a pulsed laser beam into the region of interest and timing the gate of the receiver so that a narrow range segment is interrogated. The return radiation may have the same wavelength as the laser (elastic backscatter) or a slightly different wavelength (Raman and fluorescence).

Elastic backscattering techniques have a relatively large cross-section, but do not provide information that can be used to differentiate organic material from the normal dust and smoke that may occur on the battlefield. As such, this interrogation approach may be useful for cueing purposes, but not for the detection of biological agents.

Fluorescence backscatter provides more useful information, because it takes advantage of the fact that organic material contains amino acids that fluoresce when optically pumped by an ultraviolet source. The most optically active of the amino acids is tryptophan, which strongly absorbs radiation at 275 nm and subsequently emits light 300-450 nm band. The absorption and fluorescence spectra of this substance are compared in Figure 5-2.

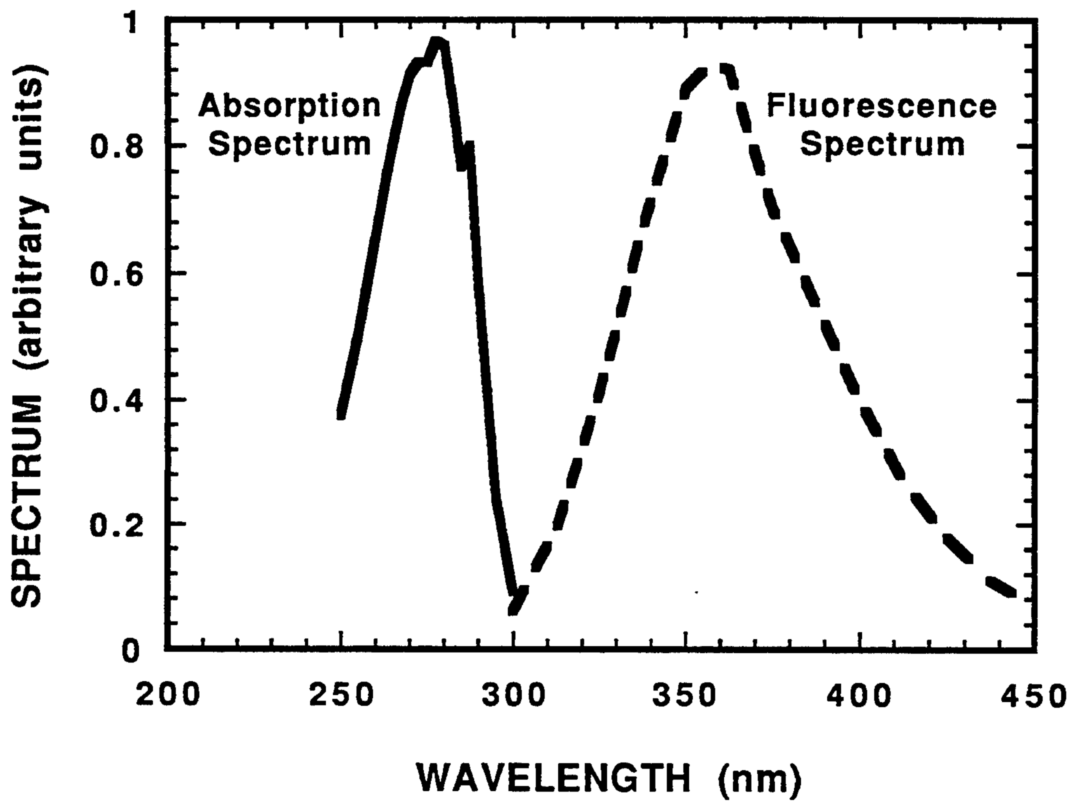

Figure 5-2. Comparison of the absorption and fluorescence spectra for the amino acid tryptophan. The characteristic spectral shift caused by this material provides a method for discriminating between organic and non-organic material suspended in the atmosphere.

Although fluorescence provides a power tool for discriminating between organic and non-organic substances, the extremely small cross-section for this effect precludes its use for long-range or wide-area interrogation. A comprehensive monitoring system might incorporate a LIDAR system to locate suspicious particulate clouds and a fluorescence sensor to test for the presence of amino acids. A qualitative comparison of the range capabilities of these two optical devices is provided in Figure 5-3. The design parameters assumed for these calculations are appropriate for a relatively small, field portable system; both constructs incorporate a 200-mJ laser transmitter and a 50-cm receiver aperture. The lower concentrations shown on this chart (10^2 particles/liter) are characteristic of clouds that may have dispersed for a period of several hours, whereas the highest concentrations (10^6 particles/liter) are likely to be encountered immediately after release.

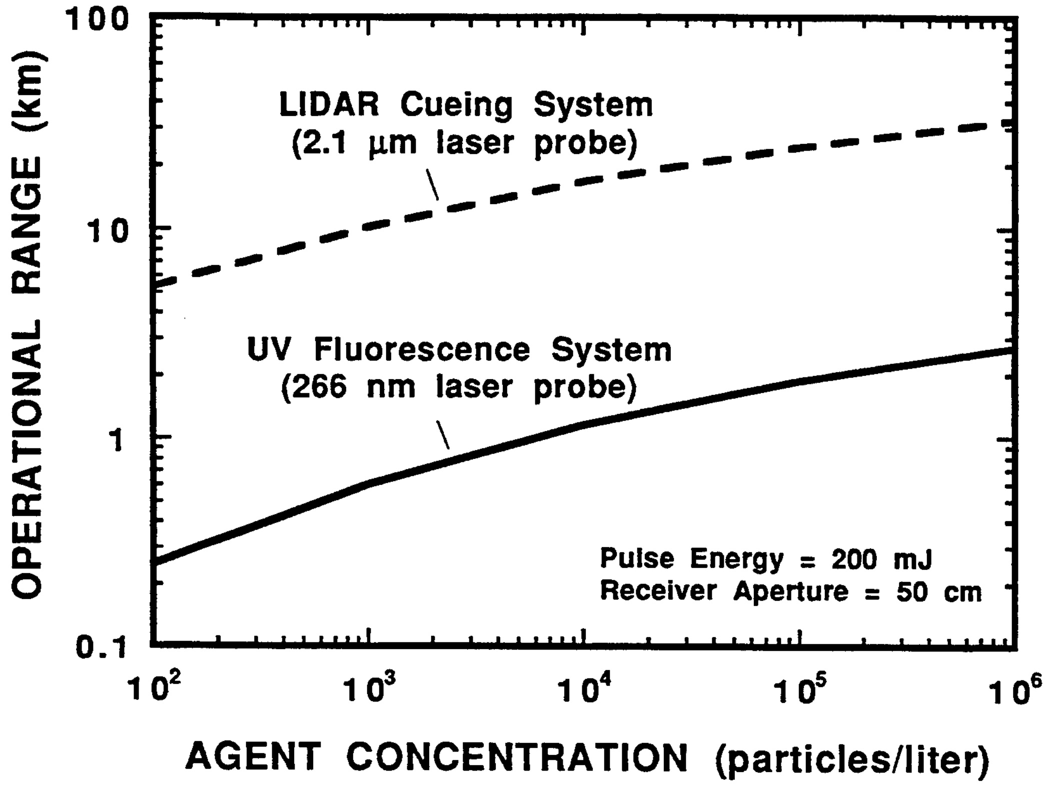

Figure 5-3. Comparison of the estimated range performance of a LIDAR system sensitive to elastic backscatter from a biological agent cloud and a UV fluorescence sensor as a function of substance concentration.

6.0 SUMMARY

Each phase of the biological-agent surveillance problem presents a unique set of challenges that are, at best, only incompletely addressed by current technology. Although laboratory approaches for agent identification are relatively mature, none of these schemes is suitable for real-time or stand-off applications. Remote sensing for pollution characterization is also a relatively well-developed field, but its application to biological agent detection is recent and few direct measurements have been made. The key to a comprehensive monitoring system will undoubtedly lie in the networking of an array of cueing, detection, and identification sensors, thereby providing data that can be quickly analyzed and widely distributed to the members of a small military force operation.

SRI International

White Paper • May 1996

UNMANNED AIR VEHICLE - BIOLOGICAL AGENT SENSOR

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INTRODUCTION

The capability to detect biological warfare (BW) agents over extended remote areas is a clear and urgent defense need as more countries view BW agents as an inexpensive and readily available mass destruction weapon. BW agents will most likely be disseminated as aerosols into the atmosphere at low altitudes, 25 to 100 km upwind of the intended target area. Therefore, early detection of a BW attack will provide valuable time for taking protective measures or initiating a treatment program. To date the most promising method of remote detection of BW aerosols is laser-induced fluorescence (LIF). However, this method is typically limited to distances of only a few km because of the poor ultraviolet (UV) transmission characteristics of the atmosphere. An approach to achieving longer range remote detection is to use a real-time BW agent sensor aboard an unmanned air vehicle (UAV) with a data link to friendly forces.

This paper describes a biofluorescence aerosol sensor (BAS) developed and demonstrated by SRI International (SRI) during the early phase of Desert Storm that has great potential for meeting the UAV-BW sensor requirements. The BAS system is a relatively simple biofluorescence sensor that transmits pulses of UV energy into the atmosphere and detects fluorescence energy emitted by biological aerosols that have absorbed the UV source energy. An array of wavelength filtered photomultiplier tube (PMT) detectors is used to detect backscattered fluorescence energy. In the demonstration unit multiple filtered PMTs were used to provide fluorescence spectral information for aerosol discrimination. The BAS system was shown to have high sensitivity to tryptophan aerosols while having almost no sensitivity (e.g., low false alarm rates) to dust, water, and various other aerosols used in the demonstration.

BACKGROUND

Virtually all biological organisms contain the aromatic amino acids tryptophan, phenylalanine, and tyrosine in their bacterial cell walls. If these amino acids are illuminated with UV radiation with a wavelength in the 200- to 300-nm range, they will produce characteristic fluorescence signatures at wavelengths between 300 and 400 nm. Figure 1 presents the relative shapes and strengths of UV signatures of the amino acids when excited with a UV laser source operating at a wavelength of 265 nm.

a. **Excitation spectrum of tryptophan fluorescence in water**

b. **Fluorescence spectra of the aromatic amino acids in water**

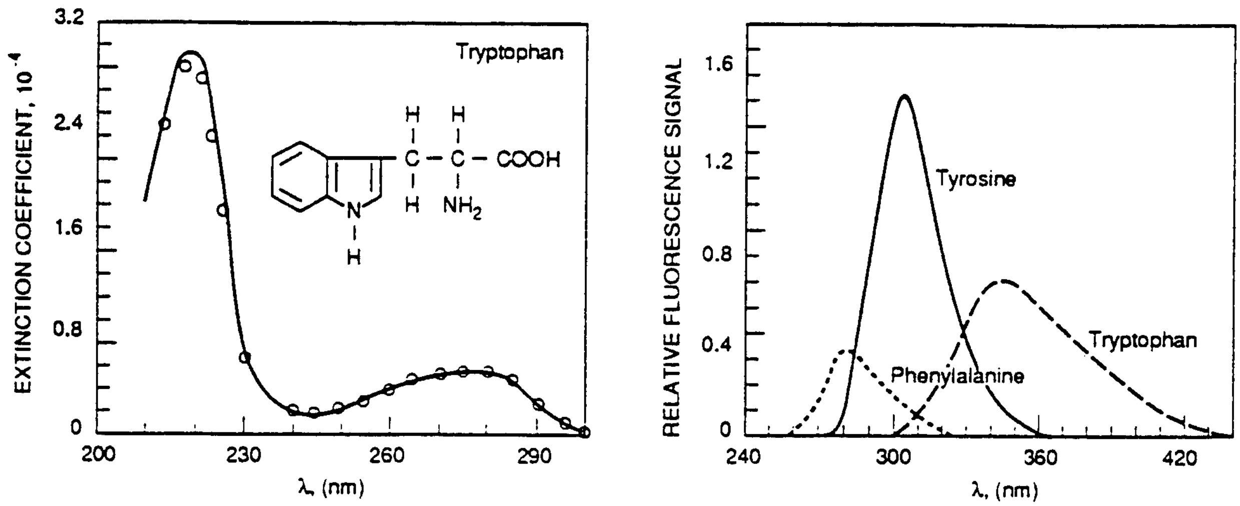

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Figure 1 UV ABSORPTION AND FLUORESCENCE SPECTRA OF AROMATIC AMINO ACIDS

Since all aerosols of biological origin contain varying admixtures of these fluorescent amino acids, the characteristic fluorescence signature may be used for the detection, identification, and quantification of BW agents in aerosol form. Therefore, the UV-induced fluorescence technique appears to be a promising and viable approach for the detection and identification of BW aerosols, and was the basis for SRI's development of portable biofluorescence sensors (PBS) during the early stages of the Persian Gulf war. During a very intense six-week effort SRI developed two types of BW sensors called the PBS Air Sampler and the PBS Outward Looking system. The Air Sampler uses an internal sample chamber that illuminates preconcentrated air samples, while the Outward Looking system illuminates an air volume external to the sensor. Both sensors use a narrow band (10 nm) filtered UV source (xenon arc lamp) to illuminate the aerosol with energy at 280 nm wavelength. The BW alarm is based on detection of specific fluorescence signal levels in four narrow bands (10 nm) in the 300-400 nm spectral region. A high detection sensitivity to tryptophan aerosols was demonstrated with both systems as well as an ability to discriminate tryptophan aerosols from dust, water, and various chemical aerosols. The program was terminated shortly after Desert Storm commenced as it became apparent that production systems could not be fielded in time to support the war effort.

The focus of this paper is to present a solution for the problem of BW early warning that utilizes the real-time detection capabilities of the UV-induced fluorescence techniques developed during Desert Storm. A PBS type sensor flown on a UAV has the potential to detect BW aerosols many tens of kilometers upwind of troops, thereby providing early warning. LIF LIDAR cannot provide this type of early warning from remote sites because of poor atmospheric propagation at UV wavelengths. Use of LIF LIDAR in airborne configuration has potential, but will require a complex system, and its applications will be limited because of operational requirements. The proposed UAV BW sensor does not preclude development of airborne LIF LIDAR but offers a very inexpensive and low-risk alternative approach to long-range BW detection.

The PBS Outward Looking system (now referred to as the Biofluorescence Aerosol Sensor or BAS) is well suited for operation on airborne UAV platforms. The BAS system is inherently technically straightforward, lightweight, modest in its power requirements, and relatively insensitive to contamination. Because the BAS system is projected to be very low cost in production, it can be considered an expendable unit. This of course implies that the UAV itself is expendable, which is only likely for miniature UAVs used for short range (a few kilometers) applications. In the case of larger UAVs required for longer range operations, decontamination procedures will have to be used for the UAV as well as the sensor. Finally, BAS detection is instantaneous; sampling speed is critical in airborne applications, where the sensor may be in a BW aerosol cloud for only a few seconds. For the above reasons, we believe the BAS operated on a UAV will provide the military inventory with a needed long-range BW detection capability.

Detection sensitivity calculations of the Desert Storm BAS indicate that bacillus subtilus

(BG) spores[1] detection can be achieved within two orders of magnitude of the 1000 particle/liter requirement of a point sensor established by ERDEC. A higher-powered source, more efficient bandpass filters, and optimization of the source/receiver beam geometry can easily increase the effective sample volume of the BAS system, thereby increasing its sensitivity by perhaps an order of magnitude. However, the ERDEC point sensor sensitivity requirement noted above is not necessary for the long-range UAV application envisioned. The UAV BW sensor is to provide early warning of a BW attack, which implies that the detection will be made near the dissemination source. Therefore, aerosol concentrations will be many orders of magnitude higher than point sensor sensitivity requirements for detection of the BW aerosols downwind of the dissemination source location.

RECOMMENDED DEVELOPMENT PROGRAM

We propose two UAV BW sensor approaches that address the problem of BW early warning. Both approaches use the BAS technique and differ only in the instrumentation complexity required for BW discrimination. The simpler instrument (BAS-2) can be operated on very small UAVs, while the more complex BAS-2 will require a larger UAV.

1. BAS-1 (AGENT DETECTION AND DISCRIMINATION)

The BAS-1 is based on the SRI Desert Storm PBS Outward Looking sensor illustrated in Figure 2a. The sensor has four bandpass-filtered detectors, as shown in Figure 2a, which provide four detection thresholds to be set between 300-400 nm for signature matching. An internal processor can be programmed to provide robust detection algorithms for signature discrimination between agents or biological aerosol interferences. The potential to provide biological aerosol discrimination is critically dependent on the development of a database of BW agent signatures and fluorescence cross sections. SRI has been funded by Edgewood Research, Development, and Engineering Center (ERDEC) to develop the required bioagent database required for

[1]BG spores (along with B. Cereus) are currently the only bioagent simulants that have been quantitatively characterized for fluorescence cross-section and fluorescence signature. This work was first performed in 1984 by SRI and recently was repeated as part of a follow-on effort after Desert Storm.

discrimination analysis.

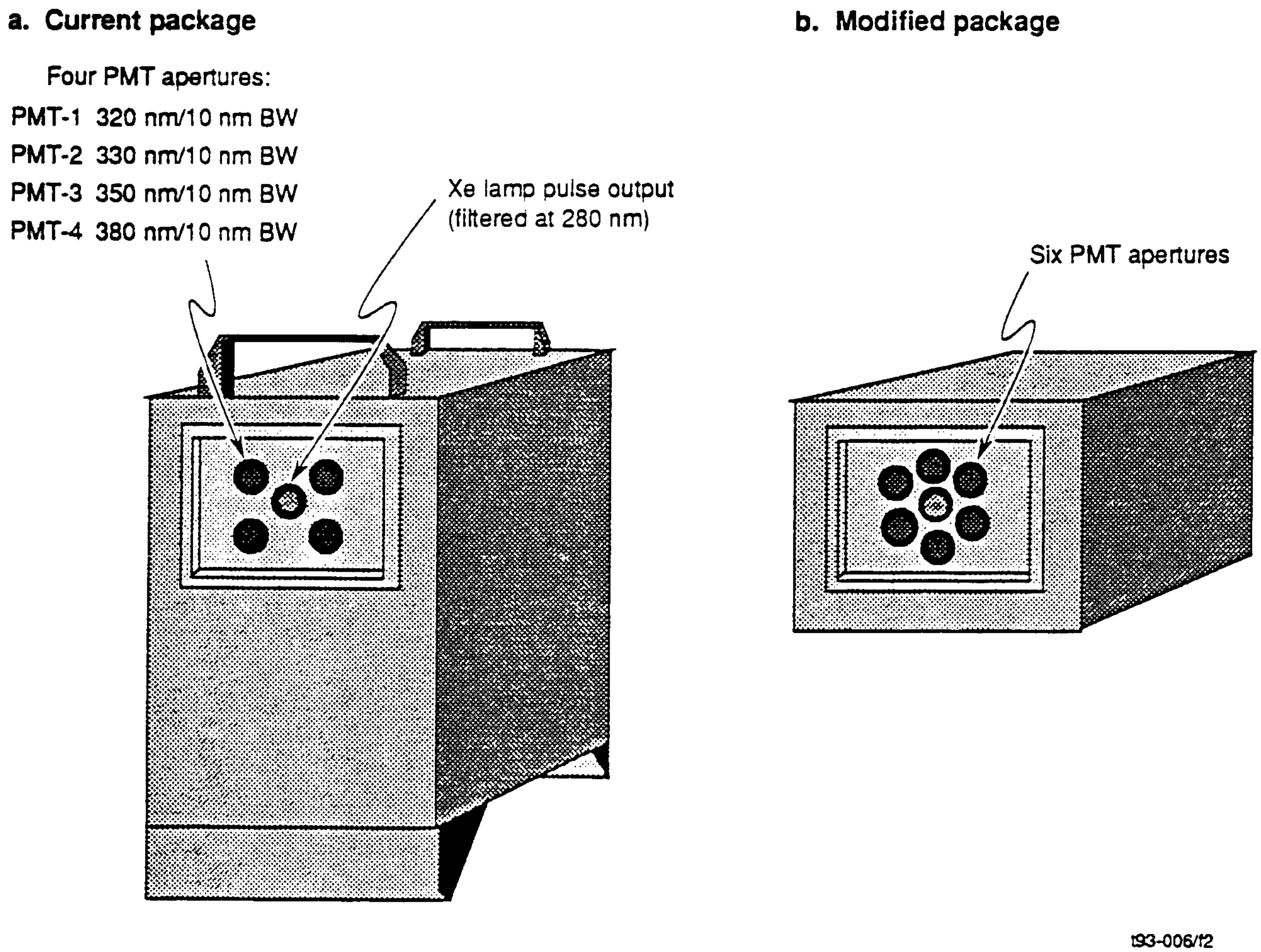

Figure 2 BAS SENSOR CONFIGURATIONS

The BAS-1 in its current (Desert Storm) package weighs less than 45 pounds, has a volume of 2.25 ft^3/package, and is operated from a 12 or 28 V dc power source common to most UAVs. The current packaging can be used on a number of UAV platforms for demonstration purposes or can be easily modified to reduce size and weight for smaller UAV systems. We propose that a

BAS-1 system be developed that will be housed in a 1.5 ft^3, 25 pound package. This will be accomplished simply by reconfiguring the system components and housing. In addition, BAS-1 modifications will be made to improve aerosol discrimination by addition of two PMTs to provide a total of six narrow detection bands in the 300-400 nm spectrum. A conceptual view of the modified package configuration is illustrated in Figure 2b. This straightforward modification will provide a convenient test system; however, we expect that final engineering will produce a system packaged in a volume of 1 ft^3 and weighing 10-15 pounds.

A conceptual view of the proposed modified BAS-1 system mounted in the payload compartment of a Pioneer type UAV is illustrated in Figure 3.

2. BAS-2 (Detection Only)

A reduced size and weight BAS-2 system will be designed to detect fluorescence from biological organisms without bioagent signature discrimination. The BAS-2, however, will be capable of discriminating between aerosols of biological origin and nonbiological aerosols such as dust, water, and smoke. For discrimination of nonbiological aerosols the sensor will probably require only two filtered PMTs. The sensor will be packaged in a volume of approximately 0.2 ft^3 and weighing 2-5 pounds. A conceptual diagram of the proposed package is shown in Figure 4.

The BAS-2 type sensor is envisioned to be used with an expendable UAV such as the AV Pointer which is a hand-launched miniature system controlled by a ground observer with a hand-held radio frequency (RF) link controller. In this application the UAV becomes more than an eye-in-the-sky forward observer; it can detect the presence of biological aerosols along its flight path. An example application is in surveying an area for BW aerosols in advance of troops moving into the area. Another application, which would have been of use during the Persian Gulf war, is the survey of the target impact of a Scud missile to determine if the missile was carrying BW weapons. This will be especially useful if the missile impact location is inaccessible by land vehicles. An example of this application is illustrated in Figure 5.

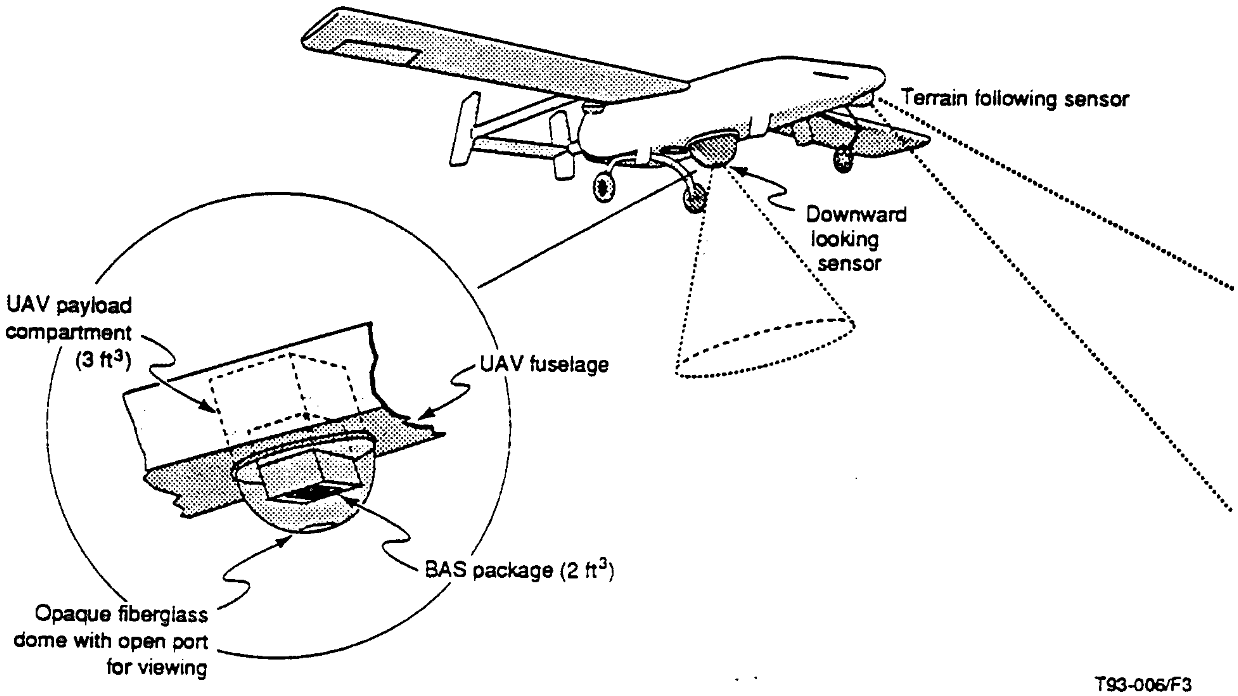

Figure 3 UAV MOUNTED BAS SYSTEM PACKAGE

1. Filtered PMT-1
2. Filtered PMT-2
3. UV filtered source

Packaging weight: 2 to 5 pounds

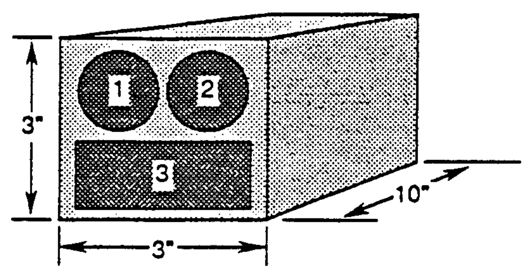

Figure 4 CONCEPTUAL BAS-2 SYSTEM PACKAGING

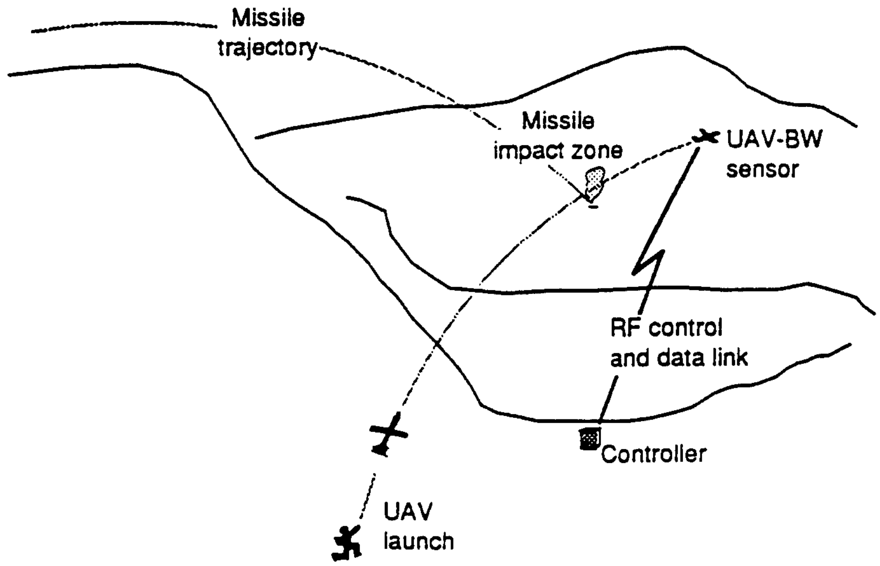

Figure 5 BAS SENSOR CONFIGURATIONS

SRI International

April 8, 1996

BIOLOGICAL AGENT BATTLEFIELD SURVEILLANCE AND COVERT COLLECTION

APPLICATIONS OF UPCONVERTING PHOSPHOR-DIODE LASER TECHNOLOGY

White Paper

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SUMMARY

The detection and identification of biological materials associated with the proliferation of biological weapons pose significant technical challenges for point and remote sensor systems. SRI International developed a new technology, based upon the use of upconverting phosphor tags in immuno- and nucleic acid-based diagnostic assays, that shows promise for economical, compact, robust, high sensitivity, near real time, multiple BW agent detection systems. Feasibility studies conducted at SRI have shown that single sub-micron phosphor particles can be detected using near-infrared semiconductor diode lasers and relatively simple optical systems. Furthermore, the proposed detection methodology is essentially background free because the upconversion process is rare in nature. This feature distinguishes the proposed approach from current systems that use fluorescent, electro-chemiluminescent, and potentiometric methods. Different upconverting phosphor materials, each of which has a unique emission signature, means that up to 20 agents can be detected simultaneously. Phosphor tags used in conjunction with standard immuno diagnostic methods promise sensitive and rapid detection and identification of a variety of pathogenic organisms and biotoxins using a single compact instrument.

The upconverting phosphor program at SRI captures previous commercial application work, focuses efforts on development of hardware for field demonstrations, and drives technology towards miniaturized, parallel (i.e., array configuration) diagnostic capability. The goal is to address the highest priority shortfalls in operational biological detection capabilities in battlefield surveillance, foreign intelligence (nonproliferation), and domestic intelligence (counter terrorism). The upconverting phosphor technology, under development since 1992 for clinical applications, is the only technology that can meet this goal. The technology exploits the unsurpassed sensitivity and specificity of antibody and nucleic acid probes being developed by the DOD and intelligence communities. This technology shows the potential to significantly improve the performance of existing and planned bio-sensors, as well as lead to a whole new class of immuno and nucleic acid diagnostic sensor systems.

INTRODUCTION

The proliferation of weapons of mass destruction (WMD) is a serious threat to the security of the United States. Biological weapon proliferation is particularly disturbing, and the threats it poses can be far more devastating than nuclear. Critical elements of United States efforts to reduce and counter this proliferation include: (1) the location and characterization of biological weapons facilities and capabilities worldwide; (2) the ability to rapidly detect and identify the use of biological weapons for effective warning and reporting on the battlefield; and (3) the capability to mitigate the deleterious consequences of an incident through effective protective and medical treatment measures. These elements constitute difficult technical challenges. A number of technologies to achieve success are being exploited, and include sampling, remote sensing, and point detection approaches. Sampling, in which a sample is collected and taken to a laboratory for analysis, is the most accurate approach, but also is the most time consuming. Remote sensing, i.e., detection at a distance from the contamination, provides early warning, but is very limited in its ability to identify what the substance is. Point detection systems involving either antibody (immuno)- or nucleic acid (DNA)- based assay techniques show the best potential for the precise identification of microorganisms. In systems compatible with unmanned aerial vehicle (UAV) payloads they can provide early warning.

Current diagnostic techniques available for the detection of biological materials typically involve the screening of multiple samples. This process is not only time consuming and expensive, but also tedious, thereby increasing the potential for technical errors. SRI developed a proprietary diagnostic detection technique that shows great promise of achieving significant improvements in detection times, sensitivities, and specificities. This new technology is based on upconverting phosphors that are chemically linked to probe units to produce a reagent with a high degree of certainty to the biological agent to be detected.

The phosphor system was demonstrated in a variety of immuno and nucleic acid assays for clinical applications. Excellent sensitivities were achieved using phosphors with a simple battery-powered diode laser detector with direct visual observation against complex backgrounds such as blood, sputum, urine, and soil slurries. Also, single molecular binding events were seen using instrumented systems. Other unique advantages, demonstrated in clinical applications, include large dynamic range, rapid response time, safety and environmental stability. This technology is unique in its ability detect multiple agents simultaneously. Collectively, these features are particularly suitable for small, real-time detection devices that could aid in the detection of biological agents. Furthermore, using microelectromechanical system (MEMS) fabrication techniques, miniature integrated systems that provide a complete detection and identification capability are possible.

This paper describes the upconverting phosphor technology, its uniqueness and advantages, and potential applications to intelligence, defense, battlefield, drug interdiction, medical, food quality control and environmental monitoring problems.

BACKGROUND

All diagnostic assay systems can be characterized as having three essential components: probe, reporter, and detector. The probe - either an antibody (Ab) or nucleic acid sequence (NA) - is designed to interact as strongly and uniquely as possible with the target biological agent (antigen); that is, it should bind tightly to the target antigen but not to other antigens in order to minimize false detection rates. The reporter consists of a material with chemical, physical, or optical properties that can be observed by some type of detector. It is important that these properties are unique to the reporter (i.e., are not contained in or demonstrated by the sample to be tested) to minimize background or competing signals. Linking (conjugating) the probe to the reporter produces the probe-reporter reagent that enables detection of target analyte (e.g. antigen or gene). The detector is the device or instrument used to determine the presence of reporters, and therefore the targets, in the sample.

UPCONVERTING PHOSPHOR DETECTION SYSTEMS

Phosphor Reporters

The SRI upconverting phosphor-based detection approach to diagnostic assays was developed to avoid the need for the traditional sample amplification procedure. Upconverting phosphors are rare earth (lanthanide series) inorganic crystalline particles. Rare earth emitting (e.g., Er, Ho, and Tm) and absorbing (e.g., Yb, Er, and Sm) centers are coupled by intercalation in the lattice of appropriate host crystals. They exhibit an unusual phosphorescence phenomenon in which the absorption of two or more incident photons of low energy (infrared) light produce a single emitted photon of higher energy (visible) light (Figure 1). This is a property unique to these man-made phosphors and is not found in biological materials. The advantage is that this type of phosphor produces visible light against a very low background, thereby greatly enhancing the sensitivity and dynamic range.

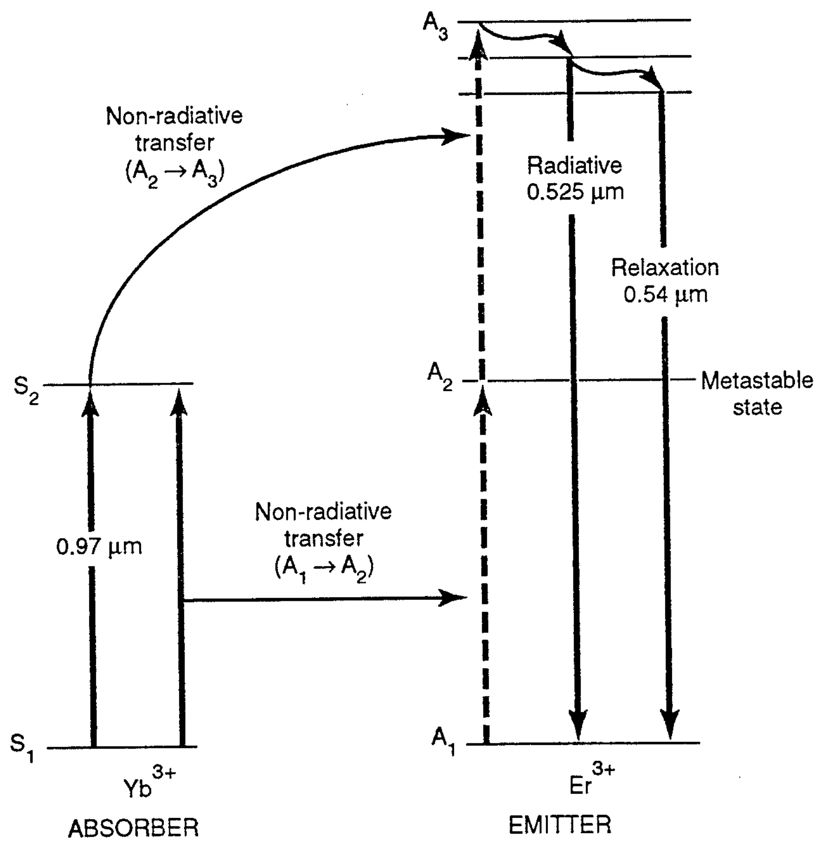

Figure 1 -- Two Photon Upconversion Process

The Multiplex Advantage

Using different dopant ion combinations, a wide variety of phosphor compositions are available, having the same absorption but different emission wavelengths, to yield unique colors (Figure 2). These colors, together with the widely separated absorption and emission lines of narrow bandwidth (typically 25-50 nanometers), permit multiple agents to be detected simultaneously in the same sample (i.e., multiplexed assays). Six spectrally unique phosphors have been developed and as many as twenty unique colors are possible.

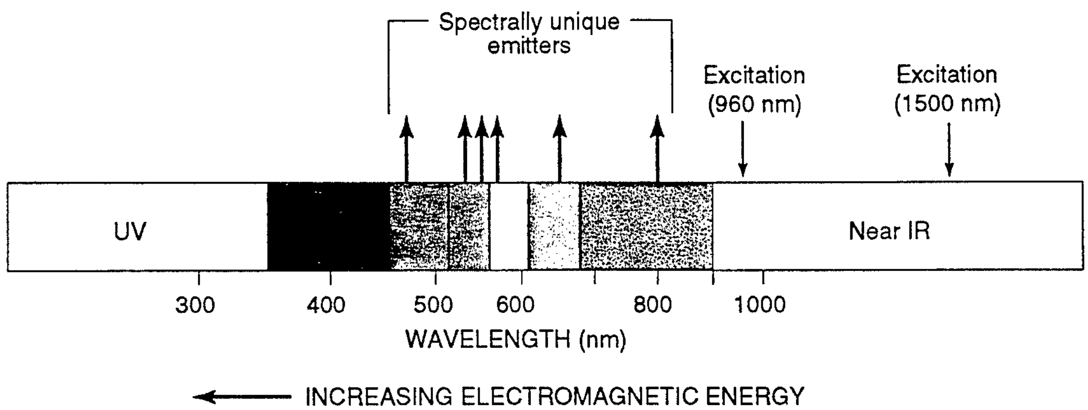

Figure 2 -- Unique Phosphor Colors Provide Multiplex Advantage

Detection Sensitivity Equals Detection Time

The phosphor reporters are especially well suited for this sensor application because they significantly lower (by orders of magnitude) the amount of material needed to achieve the minimum detection limit. The step in any detection system that ultimately determines the detection time is diffusion of the analyte to the detection surface. Since less analyte is required for detection above background signals, use of the phosphors leads to shorter detection times. Detection time can be further improved through the use of smaller capture surfaces as well as less sample quantity. The phosphors are the only reporter system whose detection sensitivity actually increases as the capture surface size is reduced. This benefit is directly attributable to the unique non linear (i.e., multiphoton excitation) required to achieve upconversion. In addition to the need for less sample quantity, the use of small capture surfaces permits system miniaturization and faster detection.

Probes

The phosphor reporter is chemically linked (conjugated) to a probe unit to produce a reagent to be used for the detection of biological agents (Figure 3). The probe is typically an

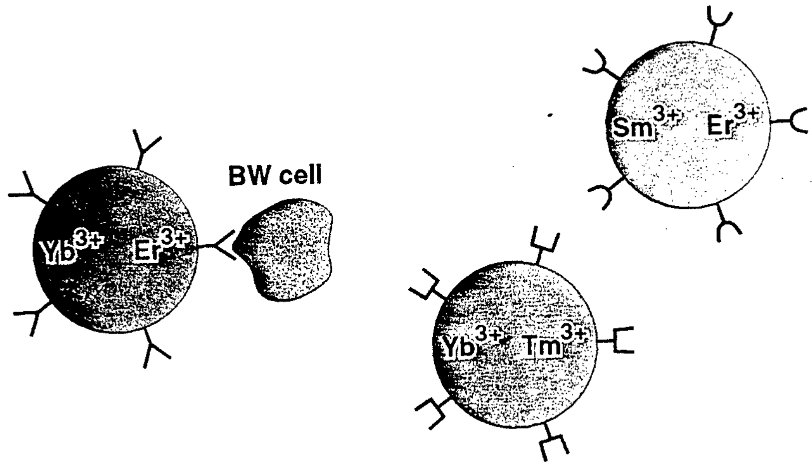

Figure 3 -- Conjugated Upconverting Phosphor Reagents

antibody or nucleic acid sequence which exhibits high sensitivity and specificity for the target antigen. Exposure of the reporter-probe reagent to the antigen will result in a binding of the reagent to the antigen in an essentially permanent complex. All antibody and nucleic acid probes available or currently being pursued by the services, universities and commercial enterprises can be used directly with the phosphor reporters.

Diode Lasers

The phosphors are excited by near infrared light (IR). The existence of upconverting phosphors and their compositions have been known for many years. However, the recent invention of infrared diode lasers - an energy efficient, high intensity, and low cost source of infrared light perfectly matched to the phosphor absorption line - enables the development of low cost and miniaturized detectors based on this technology. IR diode lasers are solid state devices, produced by computer chip manufacturing technology (similar to the diode lasers currently used in compact disc players), and are currently under evaluation as the next generation of fiber optic telecommunication devices.

Detection Process

A typical assay detection process (Figure 4) involves the use of capture surfaces prepared with capture sites for the target antigen. Target antigens are captured at these sites on the plate surface (step 1), followed with treatment by the probe-reporter reagent which attaches to the surface-captured antigens (step 2). The surface is then washed to remove any reporter-probe reagent not attached to the surface-captured antigens. Finally, a detector (e.g., a diode laser coupled with a photodiode detector) ascertains the presence of the reporters and, therefore, any antigens that are captured on the surface.

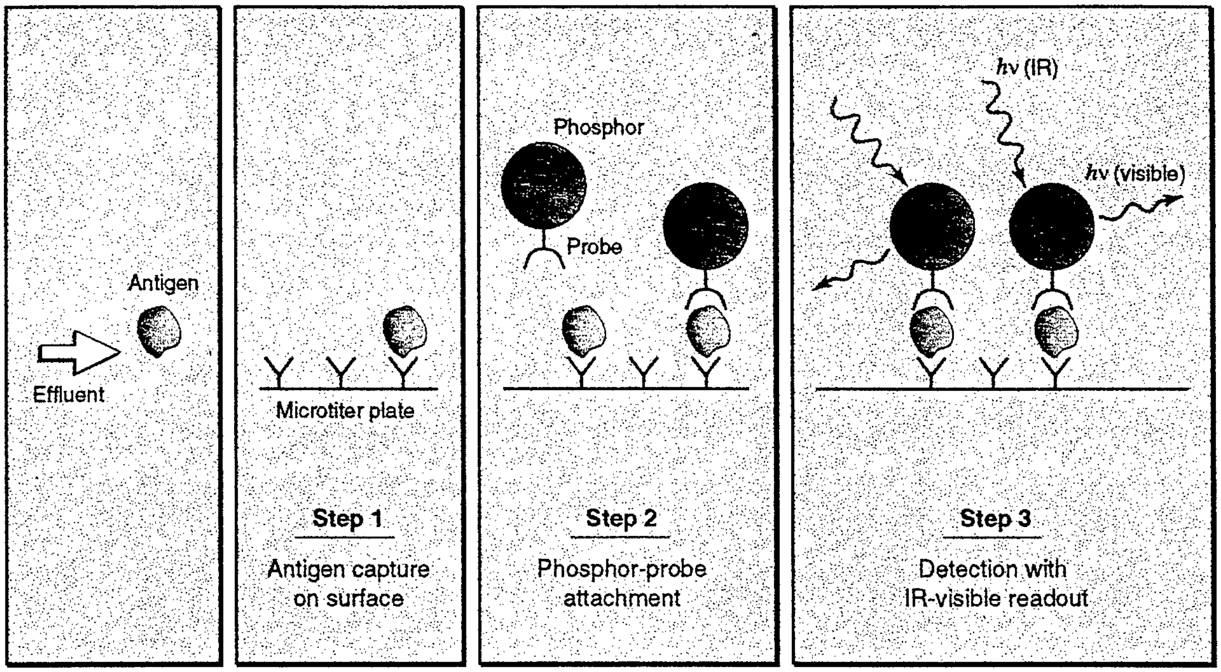

Figure 4: A Typical Phosphor-Based Detection Process

APPLICATIONS

SRI has licensed the upconverting phosphor technology for commercial end uses including human clinical diagnostics, substances-abuse diagnostics and environmental pathogen detection. The phosphor technology holds great promise for field detection of biological agents with the development of compact, fieldable, low-power, high-sensitivity, and real time multiple biological agent detection systems.

Nonproliferation

The Defense Advanced Research Projects Agency (DARPA) is sponsoring an upconverting phosphor effort in support of the U.S. nonproliferation thrust. The objective is to develop a low cost, high sensitivity, low power, hand-held detector and appropriate phosphor-conjugated antibody/nucleic acid reagents for simultaneous, real-time detection of biological agents. The initial phase, begun August 1995, is a proof-of-concept effort. It involves construction of a working breadboard detector and laboratory demonstration of the sensitivity for detecting the presence of at least 2 biological agents simultaneously in environmental samples (e.g., soil slurries, tap water, and river water). Thus far, the detector design is complete and its assembly initiated. Also, phosphor synthesis is complete with significant improvements in yield, particle size control, and upconversion efficiency. This effort ends in November 1996 at which time at least two assays will have been demonstrated with real world samples using the completed breadboard model. Variations of the envisioned device as unattended point detectors for air and down-stream applications are possible and will be pursued for funding as the technology matures.

Battlefield Detection

The U.S. Army Edgewood Research, Development and Engineering Center (ERDEC) has funded a two year effort that began September 1995 for the synthesis and characterization of new upconverting phosphor compositions. These phosphors will be configured to perform immunological and nucleic acid assays. Thus far, a new process has been developed to make submicron yttrium oxide and yttrium oxysulfide upconverting phosphor particles. These compositions have the highest optical efficiencies yet achieved, and show a hundred-fold improvement in yield of monodisperse particles. Work will continue on process optimization and development of new phosphors. These new compositions will increase the multiplex and sensitivity performance of detection devices in which they are used.

A variety of biological defense systems are possible including man-portable point detectors and payloads for mobile platforms. The technology promises to significantly improve the performance of existing and planned bio-sensors, as well as lead to a whole new class of immuno and nucleic acid diagnostic sensor systems.

Civilian Sector

Food safety applications were demonstrated with the U.S. Department of Agriculture (for food inspection). Other potential uses include: environmental field testing, toxicology applications, and more precise cancer diagnosis. Since the phosphors are physiologically inert, we expect these applications to lead eventually to direct in vivo use such as surgical imaging (e.g., to assist the surgeon in imaging cancerous tumors during an operation), and should serve as a wonderful adjunct to telepresence surgical systems currently under development. This latter application is not currently licensed.

Point detector devices are leading to an ability to perform infectious disease diagnostics in real time at the point of care (e.g., battlefield triage or doctor's office). A preproposal is under consideration by the U.S. Army Medical Research, Development, Acquisition, and Logistics Command at Ft. Detrick, the Executive Agent for medical biological defense. This preproposal concentrates on the development and clinical demonstration of a phosphor-based medical point detector for rapid identification of BW casualties.

The ability to tailor the resultant reporter-probe reagent to a wide range of target antigens suggests the phosphor technology can also be applied to the detection and identification of chemicals in a variety of applications such as:

- chemical agent detection
- illicit drug detection
- explosive detection
- forensic analysis
- chemical diagnostics
- environmental monitoring
- food quality control

ADVANTAGES OF UPCONVERTING PHOSPHOR TECHNOLOGY

The advantages of the upconverting phosphor-diode laser technology for the detection of biological agents are outlined below:

- This is a unique technology for *simultaneous detection of multiple agents* in a single solution (multiplexing).

- This technology has a *wide dynamic range* which gives this technology a unique and distinct advantage over existing technology. This means it can detect in a single solution, the concentration of which is unknown, a range from single molecules (bacteria) up to millions of molecules.

- The *level of sensitivity approaches single copy numbers*. Amplification of the antibody/antigen binding complex is not required. Essentially zero background is generated from biological materials (a unique feature of the upconversion process.

- This high sensitivity enables *faster detection times* by minimizing diffusional barriers.

- Phosphors *do not photobleach* like the organic dyes commonly used in fluorescence-based diagnostic assays, thereby allowing the assay to be reread, read continuously, or the phosphorescence to be time integrated to improve signal to noise.

- Phosphors are *water insoluble, chemically inert (buffer insensitive), physiologically inert (non-hazardous), and thermally stable*, thereby reducing operator error and need for repeat samples.

- Opportunity for *miniaturization* of equipment is enhanced due to increased sensitivity with reduced capture surface area (a unique feature inherent in the phosphor reporters), minimized processing (i.e. no washing steps) and simple detector technology (laser diodes).

SRI International

White Paper • May 1996

UNMANNED AIR VEHICLE - STANDOFF DETECTION OF CHEMICAL AGENT PLUMES

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SRI INTERNATIONAL
WHITE PAPER

UNMANNED AIR VEHICLE - STANDOFF DETECTION OF CHEMICAL AGENT PLUMES

High-altitude long-endurance unmanned aerial vehicles (UAVs) are gaining rapid acceptance for use in surveillance and reconnaissance missions over hostile territory. Several UAVs are under development that will provide payload size, weight, and power requirements for installation of complex sensor suites, including conventional (passive) video and (active) radar imaging sensors to detect, locate, and identify various targets, and to collect intelligence information on weapon manufacturing and testing for treaty verification. Another type of active sensor, the lidar (laser radar) can propagate high energy densities over long distances at optical wavelengths that strongly interact with volume and solid targets and therefore can provide target interrogations that are not feasible by conventional remote sensors in the military inventory.

Lidar systems have been successfully employed on ground-based and low-altitude airborne platforms to remotely detect and measure clouds and plumes of aerosols and gases that have military significance. Recently, a spaceborne lidar mapped global distributions of aerosol features with detection capability and spatial resolution greatly enhanced over that achieved by previous satellite sensors. These efforts clearly indicate that lidar techniques can be developed for high-altitude UAV application to a wide range of military surveillance and reconnaissance missions.

SRI International, under contract to the U.S. Air Force, conducted a study to establish the feasibility and limitations of a high-altitude UAV lidar system for detection of chemical plumes located near the earth's surface and to recommend the best system development and testing approach to demonstrate the methodology from a high-altitude aircraft within a three-year period.[1] That study led to a recommended high-altitude DIAL (differential absorption lidar) design - termed HI-DIAL - and testing approach that uses readily available and relatively inexpensive components.

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[1]E.E. Uthe, J.E. van der Laan, R.D. Kaiser, and R.E. Warren, "High-Altitude UAV CO_2-DIAL Surveillance System Development and Evaluation Plan," Draft Final Report, USAF Contract F19628-92-C-0179, SRI International, Menlo Park, CA 94025 USA (1995).

The recommended HI-DIAL approach is based on the use of a commercially available high-pulse rate (250 Hz), high-energy (500 mJ), low-pressure CO_2 laser employing a dual-discharge cavity with a common output coupler and a direct-detection (incoherent) receiver employing an optical amplifier spectrally matched to the laser emissions. The dual-discharge cavity and common output coupler can produce laser pulses at two selection CO_2 transitions with the same far-field optical axis and within critical pulse separation time intervals. The two-wavelength DIAL is recommended for initial testing with later extension to multiple wavelengths by use of frequency-agile tuning or by increasing the number of inter-cavity discharge elements.

The HI-DIAL low-pressure laser and optical amplifier receiver provides long-range target detection capabilities with relatively small weight, size, and power platform requirements and is also advantageous for operation at high-altitude ambient low pressures. It is recommended that initial high-altitude testing of HI-DIAL be conducted from manned aircraft. Preliminary designs have been developed for HI-DIAL installation in the Q bay of WB-57F and U-2 manned aircraft. Appropriate UAVs are currently under development that would be suitable for the following phase(s) of this program.

Performance of the recommended HI-DIAL system was estimated by using a CO_2-DIAL agent observation and modified for airborne long-range DIAL simulations. Because the modified code had not been validated against observations, performance simulations of HI-DIAL were compared to performance simulations by the code of a ground-based long-rate (16 km) CO_2-DIAL measurement reported in the literature. This analysis indicates that the recommended HI-DIAL sensor operating at an altitude of 60,000 ft (18 km) will have nearly the same detection capability as the successfully demonstrated DIAL. As part of the HI-DIAL simulation effort, an extensive atmospheric transmission database was generated using the USAF developed FASCODE model and the database is available for future lidar simulation studies. Aircraft-to-surface transmissions were evaluated at all the CO_2^{12} and CO_2^{13} laser lines for a number of aircraft altitudes, surface target distances from the aircraft nadir, and model atmospheric conditions. Laser lines ruled out by excessive water vapor and ozone absorption are identified.

Although the HI-DIAL approach appears well suited for high-altitude UAV surveillance and reconnaissance applications, risk-reduction experiments are also recommended. The low pressure laser produces a relatively long pulse width (5 μs) as opposed to previous CO_2-DIAL systems (150 ns). Arguments can be made for and against the use of long pulse widths for HI-DIAL topographic surface return measurements and this uncertainty needs further investigation. Expected performance of the optical amplifier used in a long-rage DIAL configuration also needs verification. The experimental results will provide a degree of simulation code validation as applied to the HI-DIAL system configuration and thereby enhance confidence of UAV HI-DIAL performance expectations.

The recommended HI-DIAL program schedule and milestones are given in Figure 1. The first-year program is directed to hardware procurement and to developing a HI-DIAL breadboard system designed to conduct ground-based risk-reduction experiments. The major component procurement items are the low-pressure laser and high-speed detectors. The breadboard system will be integrated into an existing van especially designed for transport and testing of lidar systems. The program schedule provides six months for component procurement and six months for breadboard system development.

Ground-based risk-reduction HI-DIAL experiments will be conducted during the first three months of the second year. These tests will be conducted at SRI and at a long-range lidar test site located near Los Banos, California. The experiments will prove the concept of the low-pressure laser/optical amplifier operation and will provide data needed to develop algorithms for long-range DIAL measurements with long-pulse lasers. The experiments will also provide horizontal path limits on pulse-to-pulse target return fluctuations and decorrelation of DIAL horizontal path limits on pulse-to-pulse target return fluctuations and decorrelation of DIAL pulse pairs. Depending on the results of the horizontal path experiments, similar experiments may be conducted with long slant paths. The results of these tests will provide the data needed to justify the development and testing of a high-altitude airborne HI-DIAL. The results of the risk-reduction experiments will be reported as input to the decision to proceed with a WB-57 or U-2 HI-DIAL program. As shown by Figure 1, the data will also be effectively used to design the airborne HI-DIAL configuration.

The schedule presented in Figure 1 provides nine months for development and ground-based testing of the WB-57 or U-2 HI-DIAL. During the latter part of the HI-DIAL development period, an aircraft integration and test plan will be developed and submitted for review. The HI-DIAL schedule provides three months for aircraft integration, three months for high-altitude test and evaluation, and three months to develop final conclusions and recommendations for implementing a high-altitude UAV HI-DIAL capability.

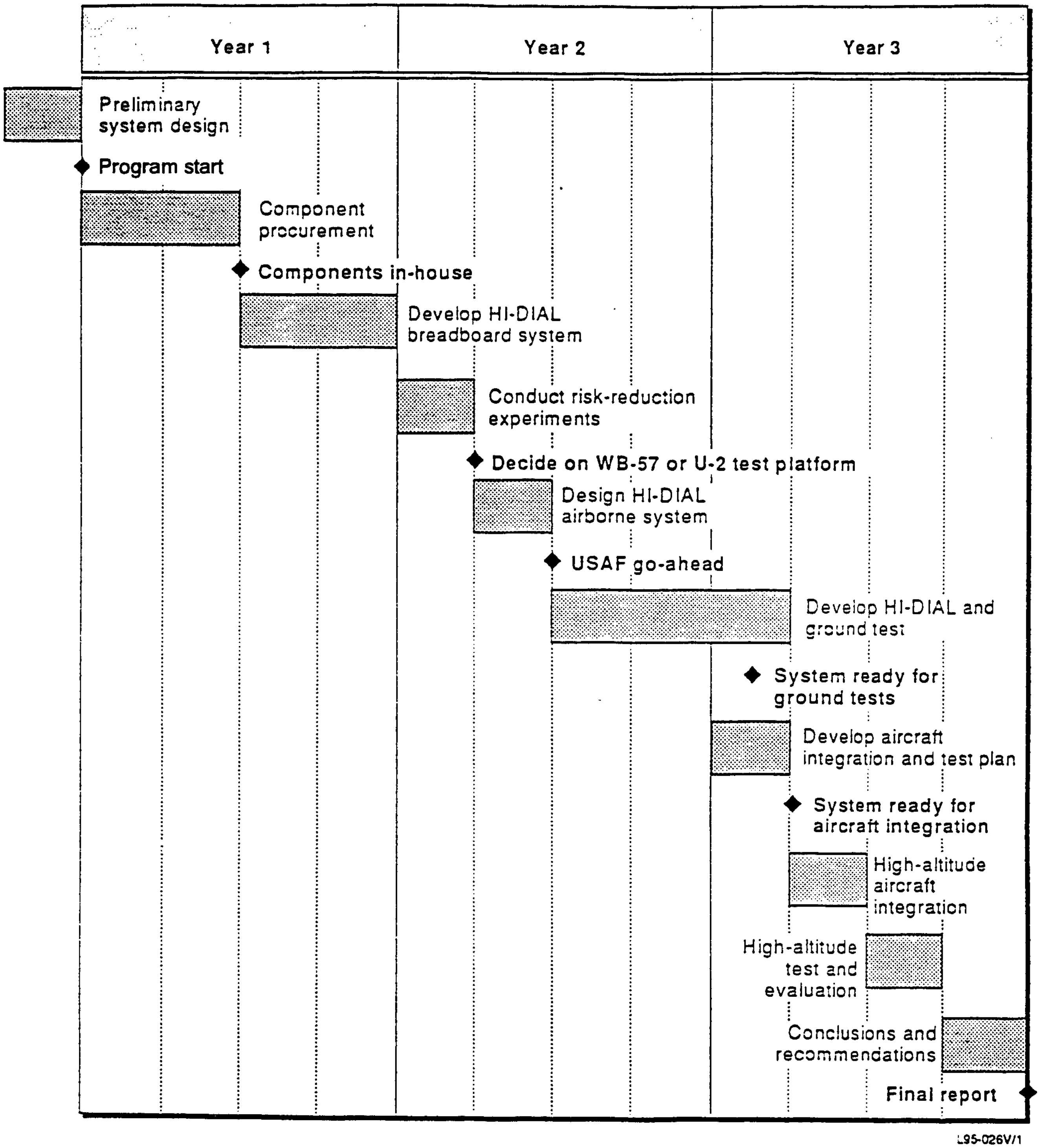

Figure 1 HI-DIAL PROGRAM SCHEDULE AND OBJECTIVE

The Problem of Landmines for Future Forces

A White Paper

Prepared by

Sandia National Laboratories

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The Problem of Land Mines for Future Forces

Outline

1. The Evolving Threat
2. Evolving Countermeasures Technology
3. Likely Consequences
4. The Situation at Twenty Years
5. Steps That Should be Taken

1.The Evolving Threat

Landmines are a particularly troublesome threat to offensive operations. They can be used to deny access to desired territory, multiply the effective firepower of a smaller force, channel offensive movements into corridors that are easier to defend, and create a psychological state of anxiety, caution, and trepidation for the attacker. They are low value ordnance that extracts a high price from the opposition.

Landmines in use today are - for the most part - simple mechanical devices operated by direct pressure or by tension in a tripwire. As such, they discriminate among targets by the force required to operate the fuzing mechanism. Thus, anti-vehicular mines will not be fuzed by human footsteps, but smaller mines will be triggered by foot traffic or vehicles. Depending on the particular mine, effects may be created by blast, throwing metal impactors against a vehicle, firing a shaped charge or explosively-formed projectile, or by scattering shrapnel.

Landmines targeted against vehicles are typically buried beneath roadbeds, 10-30 cm deep, often by hand but also by mechanical trenching and depositing machinery. They may contain 5-10 kg of HE. Anti-personnel mines typically contain 0.1 to 0.2 kg of HE, and are deployed in a number of ways. They may be scattered by aircraft or from vehicles, buried 1-15 cm deep, set on stakes driven into the ground, or attached to trees or buildings. The latter two types are trip-wire triggered and usually disperse shrapnel, encased steel balls, or fragments.

These simple devices are extremely easy and inexpensive to make. Many are constructed of cast TNT dip-coated with a plastic resin for environmental protection. A simple mechanical striker released by a pressure plate impacts and initiates a primary explosive pellet that intitiates the main charge. They can, therefore, be almost devoid of metal content and very difficult to detect by any means. This is especially true of the smaller, anti-personnel mines.

Sophisticated armies emplace their landmines in minefield arrays or as perimeter defenses that are constructed to create optimum effectiveness. These minefields may be marked, but will almost certainly be geographically mapped. On the other hand, irregular forces or guerillas may - or may not - use sophisticated emplacement, often use mines to protect their encampments or retreat along paths or trails, and will frequently make no records of mine locations. They may use mines for entirely different purposes from armies of regulars, such as for intimidation of the local population or denying them access to agricultural fields or roads.

As weaponry evolves, so will mines. A few mines today have anti-tamper mechanisms that cause them to explode if discovered and moved. More of these kinds of mines are being encountered and more can be expected. A few landmines have electronic fuzes or an ability to discriminate on signals other than force or pressure. Magnetic sensors are easily added to anti-vehicular mines. Fiber-optic and light-beam fuzes can replace tripwires.

Sea mines are, perhaps, several decades ahead of landmines in sophistication and thus offer a glimpse of the future. Sea mines available from several sources are now capable of fuzing from pressure transients, sound, and magnetic influences. Some release a target-seeking torpedo that homes on sonar. Some will not fuze on the first target, but can be programmed to count the passage of a number of targets before selecting the target to attack. In addition, sea mine shapes are being modified to disguise their identity and sonar-absorbent materials are appearing. There are analogs to all these functions in landmines, and some are being exploited by current US R&D on standoff and area-control weaponry.

Other evolutionary changes in landmines are already underway:

- the incorporation of non-metallics for more and more components, ultimately for such things as firing pins (which are currently the only sensible metal objects in some mines).

- incorporation of anti-tamper or detection penalties. Mine builders will add a detection penalty that will cause the mine to detonate when interrogated. Some landmines currently have such features that respond to motion, probing, or the signal of a mine detector. This, of course, also offers a possibility for a countermeasure, that is, using the anti-tamper signal to detonate the mine remotely.

- incorporation of stealth technologies that reduce optical, radar, infra red, or electro-magnetic signatures.

So-called standoff anti-vehicle mines further challenge countermine operations. These mines are autonomous weapon systems which can be emplaced many tens of meters off to the side of a road and set to activate when a vehicle passes. Unlike a standard mine which attacks from below a vehicle, standoff mines attack from a distance through the vehicle side or top. This type of weapon has a variety of advantages for the user. First, these mines can be concealed off-route, which greatly increases the difficulty of countermine reconnaissance. Second, because of the standoff capability, each single mine can now defend much more area than a single mine of conventional design. This greatly decreases the density of mines needed to cover a given area, which reduces the logistical and man-power burden of the mine laying force while again complicating countermine reconnaissance. A third advantage lies in the significant on-board computing power present in the more modern standoff mine designs. In the future, this should allow much more sophisticated control of mine activation, and it is possible to imagine dispersed groups of standoff mines acting in concert to attack whole convoys with high efficiency along a segment of road. Conventional mines with little or no lethal range, acting independently, and scattered in typical fashion to cover an area cannot engage a moving enemy column with the same potential effect.

The first generation of standoff anti-vehicle mines consisted of little more than tripod-mounted versions of hand-held infantry anti-tank weapons, coupled with sensors (usually magnetic and/or passive infrared). When the sensors are triggered by a passing vehicle, the weapon fires an anti-tank rocket into the side of the vehicle. Modern devices like the US Wide Area Mine, or WAM, have been designed from the beginning as an autonomous standoff area control weapon. The WAM has a limited capability to distinguish vehicle types, and can execute a lethal attack in any direction by lobbing a submunition into the air above its selected target.

What has not been addressed in the past and may become more important in the future is the ability of the mine-builder to disguise his product for use in more environments. A Chinese anti-personnel mine lying in the grass is hard to see, but on a sidewalk is clearly visible. We have not seen a great deal of attention given to mines specific for use in urban environments, but the possibilities for new variations are large. For example:

- devices that attach to the underside of manhole covers or mimic man hole covers, mimic pipe end closures, mimic street lamps or street apertenances, etc.

- devices that make use of the electrical power available in cities to perform functions not ordinarily associated with mines, including intelligence, communication, discrimination, or non-standard weapon effects.

Most of these schemes also qualify as urban terrorist devices. In the future, US forces can be expected to encounter the full range of landmines, from simple wooden boxes of explosive to the sophisticated standoff weapons. Forces depending on ground mobility to achieve their objectives will be vulnerable to these unless countermeasures not yet identified are created. These countermeasures will not come cheaply, will possibly be less than completely effective, and will probably add a combat and logistic burden that is not being borne today.

2. Evolving Countermeasures Technology

Countermeasures technology used by the US today has evolved from two key military needs:
- rapid advance by armored forces or assault troops; and
- securing captured territory that must be made safe for daily operations.

Mine countermeasures supporting rapid advance or assault have relied heavily on intelligence or visual surveys to locate mine*fields* rather than individual mines. The objective is to then avoid these areas, if possible. Minefield detection is problematical; thus the location of mines and minefield boundaries are not always known.

When avoidance of landmines is not possible, heavy equipment, including scraping blades, ground flails, and rollers are brought to bear in an attempt to detonate the mines ahead of advancing armor or to bulldoze them out of the way of following vehicles. Earthmoving technology is effective against small, anti-personnel mines but can be vulnerable to large anti-vehicular mines. Alternatively, explosives such as Bangalor torpedoes may be used in an attempt to shock-initiate mines in a minefield; however, many mines are insensitive to shock and will not fuze or detonate when explosive countermeasures are employed.

The result is that in-stride mine countermeasures often are less than complete, casualties and equipment loss ensues, and progress is impeded. Finally, US countermeasure technology has not discriminated between urban an rural environments. This may be a significant vulnerability in the future.

The Army and Marine Corps have actively sought means for improving on this situation and have solicited several national calls for technology support. More noteable products of this national effort include:

- the emergence of highly capable electro-magnetic hand-held detectors for manual surveying that can sense the few grams of metal in the firing pin of a mine buried several inches deep.

- the evolution of ground penetrating radars, singly and in arrays that are tuned for detection of near-surface objects of landmine size, and the developing of signal processing to improve detection limits.

- the evolution of sophisticated infra-red (IR) and laser radar (LIDAR) systems for detecting minefields by thermal disturbances created by the mine or soil disturbances associated with burial. The result is the Airborne Standoff Mine Detection System, ASTAMIDS, which is being developed for deployment from a remotely-controlled pilotless vehicle (UAV). Synthetic Aperture Radar (SAR) has possible future application to the ASTAMIDS concept but is, today, untested.

- the advanced development of infra-red and laser detection systems and ground penetrating radars with some capability for detecting surface and buried mines.

- the advanced development of shaped-charge-containing nets that can be rocket-deployed over a suspected minefield and detonated in an attempt to initiate or neutrallize mines.

- the actual deployment of dog teams trained to detect mines by their chemical signature.

These detection methods can be highly effective against exposed or shallow-buried metal mines and against most anti-tank mines. Their performance tends to degrade when wet soil or foliage is present, and they become less effective and sometimes useless against small, buried, non-metallic mines. The challenge facing us is whether technology can improve upon this situation, regardless of the time horizon. As was discussed earlier, the next generation of landmines will only get harder to detect and more discriminating of their targets.

At least two technologies have not been fully investigated and are currently the subject of R&D in the Department of Defense. These are ground interrogation via penetrating radiation and chemical sensing. Thus far none of the techniques has been shown to be effective. Penetrating radiation can, in principle, distinguish between mine-like materials and the surroundings, but suffers from several problems:

- a radioisotope source, if used, could be fragmented and scattered should there be a mine detonation. These sources and their shielding are heavy, cumbersome, and create transport, handling, and personnel safety problems.

- power sources tested thus far have been very large and unwieldy, unsuitable for field deployment.

- all the methods tested thus far suffer from weak signals that require long dwell times over the target for reliable identification, making them unsuitable for in-stride mine detection.

Chemical sensing is widely discussed within the countermeasures community, but to date no reliable chemical specie has been identified for sensing, and no sensor capable of detecting the minute amounts expected has been demonstrated. Some evidence indicates that explosive molecules themselves may be an appropriate specie to attempt to detect, and the Navy is taking steps to verify this possibility. It seems likely that large gains will be made in this area, mainly due to the following enabling developments:

- improvements in micro-analytical methods, including on-chip devices that can be deployed close to the target mine.

- studies of ways to chemically mark mines or the molecules they exude may be successful

- in concert with other detectors, chemical sensing may provide enough of the missing link in the data to make confirmation of a mines presence possible.

The other enabling development that may improve mine detection is the rapidly evolving field of signal processing, image extraction, sensor fusion, and data analysis. None of the mine detection methods, either existing or under study, provide positive detection under all circumstances. Often the ambiguity for a given field situation extends over the range of signatures obtained from all sensors. Signal processing can usually improve the performance of individual sensors, and with appropriate processing of the data from multiple sensors it may be possible to dramatically increase the reliability of detection schemes. This work is just beginning within the landmine countermeasures community, and is expected to yield large improvements.

The capabilities of standoff mines such as the WAM may require a different countermine approach, some aspects of which may be applicable to conventional mines as well. Rather than attempting to find and destroy the individual standoff mines that threaten a route of march, it may be more productive to deal with these devices in a more indirect manner. The more sophisticated, longer-range standoff mines will depend on sensors to identify targets within their engagement range. It may be possible to defeat this sensing process by a combination of active and passive means. Generally speaking, sensors can be jammed (overloaded with noise) or spoofed (fed a false signature) or decoyed (deliberately triggered on a false target); vehicles can also be made more stealthy (lowering their intrinsic signatures) or perhaps made to mimic the signatures of other types of vehicles (for advanced standoff mines which attempt to discriminate their targets). If the mine launches a submunition with a seeker on board, flares and obscurants could be dispensed to interfere with the ability of that seeker acquiring a target. Finally, it may be possible to assist the defense against standoff mines by continuing the development of new types of armor or new vehicle designs to add additional protection to the sides and top surfaces of vehicles.

The joint US Army and Marine Corps Off-Route Smart Mine Clearance (ORSMC) program is currently under way to provide some protection for US forces against smart standoff mines. According to published reports, the ORSMC system consists of an unmanned ground vehicle with an attached trailer. The ground vehicle spoofs the mines it passes by to alert status, while the inexpensive trailer serves as a decoy to attract the actual munitions fired by the alerted mines. This Advanced Technology Demonstration (ATD) program calls for the ORSMC system to operate at a speed of 16 km/h while neutralizing 90% of the standoff mines within 100 meters of the system.

3. Likely Consequences

Our ability to detect newly-laid, buried mine*fields* is likely to increase dramatically over the next 20 years. Standoff capabilities currently being developed for aircraft deployment will provide a significant step forward. Radar technologies may be extendable to satellite deployment, making it possible to cover wider areas or new locations on short notice. The result is that detection of buried mine*fields* may become a reliable operation that can provide real-time information to field commander intent on rapid movement.

It is difficult to see the situation as clearly or with as much confidence for individual, widely spaced, buried mines. These devices may remain beyond our ability to detect and neutrallize during in-stride operations. The principal problem facing the field commander is the limitations of time and resources. (This is analogous to the problem facing the technologist attempting to discover the remedy.) Currently, the time allowed for in-stride neutralization is less than the time required by the best available technology to detect a buried mine and deal with it. This is by far the most challenging technical problem in countermine operrations, and progress will depend upon significant technological advances in sensors, sensor fusion, sensor platforms, and remediation methodologies. Maximum return on invested R&D dollars mandates that the technologies in each of these subsystems be defined and integrated according to system-level objectives.

4. The Situation at Twenty Years

The objective of this DSB study is to predict battlefield requirements in twenty years. Therefore, in this section we attempt to extrapolate the threat and the countermeasure developments that were outlined in the first three sections.

Engagements with sophisticated forces using up-to-date technology will put our forces at risk in the same way that we will threaten an attacker. Offensive mines will remain a difficult obstacle, and early detection and avoidance may continue to be a preferable option. The variety of devices and means for deploying them will force us to develop multiple means for detection of:

- buried or scattered mines
- surface emplaced or above ground mines with passive fuzes
- standoff mines with active fuzes
- standoff mines with passive fuzes
- standoff mines with intelligent counting and discriminating mechanisms

Improved standoff detection of mines and buried minefields will have the most impact on operations if it can be achieved. It will aid operational planning, facilitate movements, and result in the lowest logistic burden for assault units. Standoff detection assets can be centrallized, shared, and made to communicate with local area commanders. Ground-based detection systems, on other hand, are vulnerable to landmines, have limited areal coverage, and require a large logistic burden (devices, spares, operators, training, etc.)

It will also become more necessary to develop mine-related tactics specific to the type of forces being fought. Today, regular and irregular forces use many of the same devices. In 20 years, we can expect large differences between regular forces deploying sophisticated standoff mines and smart mines, and guerrilla forces who may only be able to field today's technology -- still lethal but quite different in deployment and detectable signature.

Urban engagements are likely to see an increasing use of mines, and mines of greater sophistication. It is not clear whether the technologies being developed today are applicable to an urban environment with extensive manmade materials, high-metal-content backgrounds, and high electromagnetic fields. These background "noise" sources are termed "cultural noise" by geoscientists, and some of the emerging technologies from that discipline may be applicable to the countermine problem.

Defensive countermine operations will be essential to the future US force which is the subject of this Defense Science Board Study. The widely distributed, small, light US units postulated will have to be mobile and fast: mobile to be able to maneuver against an enemy's weak points while avoiding close combat with heavy units; and fast to hold the initiative, achieve surprise (a potent force multiplier), and increase shock value at the point of attack. Rapid, efficient countermine support will be needed to avoid attrition and to preserve force mobility and operational tempo in the face of an increasingly sophisticated enemy mine threat.

An adversary will use mines for a variety of purposes. In the past, mines have been used to counter mobility, to cause attrition, and to serve as a defensive force multiplier. Increasingly, they are being used politically, for terror purposes and for the systematic assault on a country's agricultural and commercial infrastructure. Depending on the circumstances, future US forces will have to be prepared for countermine operations to defeat increasingly sophisticated mine technology employed for any one of this broad spectrum of potential uses. The following paragraphs discuss some examples, and point out special issues specific to the small distributed units postulated for the study.

In wartime, mines are often used to "make the ground sticky", that is to fix a small, agile force in place for ambush or so that a large heavy force can close on it and destroy it in close combat. Future US units in combat situations must keep moving to survive. Twenty years from now they must be supported by the capability to do route reconnaissance for mine fields far enough in advance of their movement so that any mines discovered can be destroyed or neutralized, or so that the units have time to avoid the mine field by selecting an alternate route of travel before they actually encounter the mine field.

In-stride demining is not the preferred choice here. Mine reconnaissance and neutralization should take place as much as possible before the moving unit comes into contact with the mine field, and probably should be under control of a remote countermine unit assigned to support the combat unit. This scheme will allow the unit in the field to remain focussed on its main functions, i.e. maneuvering and fighting. Countermine operations will require large amounts of sophisticated, special purpose equipment controlled and maintained by highly trained personnel. Attempting to equip each future combat unit organically with all the equipment it might need to defeat a future mine threat would greatly increase its size and the complexity of its training, maintenance, and logistics burden. It would also likely slow the combat unit and expose it to the dangers of close contact with mine fields as it attempts its own clearing operations. Therefore, in twenty years we should count on the demining specialists to get their job done remotely from centralized support facilities elsewhere in the theater, with the use of specialized UAVs to fly route reconnaissance for conventional mine fields, UGVs (future ORSMC systems) to spoof standoff mines, and special systems - yet undeveloped - for the remote delivery of mine neutralizing ordnance.

Of the three elements of remote mine reconnaissance and neutralization listed in the preceding paragraph, preliminary versions of two are currently under development by the US Army and Marine Corps, while the third is not. The ORSMC standoff mine neutralization UGV has been described earlier. The Joint Countermine Advanced Concept Technology Demonstration Program is developing the Airborne Standoff Minefield Detection System (ASTAMIDS), which is based on a Hunter UAV platform. A variety of sensors on the UAV will capture images which will be sent back to the UAV ground control station for fusion in a high speed Minefield Detection Algorithm and Processor (MIDAP) system. Candidate airborne imaging technologies include the DARPA Hyperspectral Mine Detection (HMD) system, and Ground-Penetrating Synthetic Aperture Radar (GP-SAR) systems under development by Sandia Laboratories and SRI International.

The third element of the remote countermine suite would be some remote means of delivering ordnance or other mine neutralization means to clear a lane through a conventional mine field discovered by a reconnaissance UAV, in case no alternate route was available for the unit in the field. Existing high-speed standoff mine lane clearance systems require specialized equipment, and are mounted on engineer vehicles or special trailers. Examples include the US Catapult Launched Fuel-Air Explosive (CATFAE) system and the British Giant Viper and US MICLIC (Mine Clearing Line Charge) systems for dispensing lane-clearing explosive line charges. A new system currently under development for the US Army and Marine Corps is the Explosive Standoff Minefield Breacher (ESMB), which uses a rocket-launched net to deliver a 145 m by 5 m array of miniature shaped charges to blow a lane through a mine field. The ESMB requirements are neutralization of 99% of all mines in the cleared lane, including anti-tank mines buried to 20 cm.

Remote delivery of lane-clearing devices by a centralized countermine support unit would entail new developement work. For example, a single MICLIC line charge is over 100 m long and weighs approximately 1 metric ton. Delivery of such a device remotely would require not only the capability to handle the weight of the device, but also a means of spreading it out in a line correctly positioned and oriented to clear the necessary lane through the mine field.

In Military Operations Other Than War (MOOTW), the future US units in the field could be facing an opponent intent on using mines to terrorize the civilian population in the area and disrupt farming and other essential occupations. Here the time pressures on finding and neutralizing the mine fields are not as severe as in a combat situation, and additional development work may provide the means of clearing whole areas of even small, low-signature plastic explosives. What is not being looked at today are other approaches to solving the problem. For example, in twenty years, our vision of a US force will be one which has unprecedented awareness of everything which goes on in its area of interest. Is it possible to understand the signatures associated with the minelaying process itself, and attempt to react quickly to interfere with an opponent conducting such an operation before the mines are in place? If the force can't react fast enough to prevent mines from being laid, can sensors be dispatched to watch the process in detail to obtain a thorough map of the new mine field as a guide to subsequent clearing operations? Either one of these outcomes would be a significant help in combatting terror mining of civilian targets, and is much preferable to the alternative of letting the local population locate new minefields through the loss of life or limb.

5. Steps that should be taken

Several new technology areas which need investigation were pointed out in the last section. In general, we can say that the technologies being pursued by the DoD are insufficient in scope and depth to deal with the growing landmine problem. This is clear from our inability to deal with mines effectively during naval operations in the Gulf War and landmines in Bosnia. We are not alone - - no other country is making as much progress as we are, but it is not enough.

The current DoD program does not allow for enough basic studies of the physics of detection, the limits of detectibility, or pursuit of all phenomena. Studies of interrogation by penetrating radiation have been highly empirical, and after the expenditure of many millions of dollars the evaluation of the effectiveness of those techniques remains largely conjecture.

A number of labs within and outside of DoD have proposed chemical means for interrogation, but there has been little activity in this arena, and not enough to allow a coordinated study of the processes of detection and development of appropriate sensors. Neutralization by other than brute force means has been given insufficient attention.

As the landmine problem becomes more sophisticated, the need for very basic studies of the phenomenology related to signature generation and detection will increase.

A systems analysis of the coming evolution of mines is needed. We are trying to find the mines that were being built for the last war. True, they are still around and will continue to be used far into the future; but, new landmine designs are emerging, equally easy to build or procure, and more difficult to detect. This systems analysis is needed to guide the investment into techologies that will aid future detection and neutrallization.

International moral pressure is already reducing the number of countries which permit manufacture and trade in landmines. This trend will certainly continue; however; it is unlikely that all countries will abide by international agreements. As long as explosives are readily available, landmine technology will be easily exploited by insurrectionists or rogue states unconcerned with international convention. It is also clear that technologists will seek to subvert international agreements by renaming new landmine devices as something else in order to justify their development and use.

Future Land Mines
A White Paper for the DSB Summer Study

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1. Introduction

Land mines are autonomous, fixed, area control and denial weapons. Current mines basically consist of some type of sensor coupled to ordnance capable of projecting disabling or lethal effect against a target which comes within range and triggers the mine by activating the sensor. Simple mines are easy and inexpensive to manufacture, and require little training and no special equipment to use. They are currently produced by some fifty different countries.

Despite their simplicity, mines are a highly effective weapon system. During this century, studies have shown that a surprising proportion (as much as 25%) of military vehicles destroyed or disabled during wars were lost because of mines. The effectiveness of mines goes beyond what they can achieve in isolation. Land mines historically have been a significant force multiplier when integrated as part of a combined arms battle plan. For example, General Erwin Rommel, commander of the German Afrika Korps and a World War II leader famous for his skill in lightning armored campaigns, made adroit use of mines in many of his operations. In a typical encounter with the British Army in North Africa, Rommel would use mine fields to slow and fix attacking British columns. When a British column bogged down, it was worked over by towed German anti-tank gun batteries pre-positioned to cover the mines with direct fire. While the British armor was being destroyed in the mine fields, counterattacking German armored units were released to sweep around the flanks and attack the British rear areas.

The current Defense Science Board Summer Study postulates a future US force which twenty years from now will consist of small units widely dispersed in the area of operations, which must work together and in conjunction with out of area support forces to achieve a variety of military objectives. Based on historical precedent, we can state that land mines will be essential for the survivability of these dispersed US units, and will remain an important force multiplier. However, just as the remainder of the military force must evolve to support this new concept of operations, land mines must also change to remain effective. This white paper will attempt to indicate the mix of missions land mines will support on the future battlefield, discuss the capabilities mines must have to accomplish those missions, and indicate the technology development which must take place to provide those capabilities in the twenty year time frame of the study.

Within the past several years much concern has arisen over the use of land mines and the question of whether or not they are inhumane weapons. This issue is obviously of great importance for this paper, since the US is likely to adopt some official policy banning the manufacture and use of certain types of mines, and may even become signatory to an international treaty in that regard. At the present time, these concerns appear to be focused on the use of anti-personnel mines, particularly those varieties which are small and deliberately made from non-metallic materials so as to make demining costly and difficult. Such mines have been used extensively in many third world countries with the objective of attacking the civilian population and disrupting agriculture and commerce in the regions where mines have been laid. As has been openly stated by experienced US military leaders such as General Schwartzkopf, such mines have little or no military utility and are really being used as terror weapons against civilian targets. A future ban on their development, sale, and use would be welcome on moral grounds.

These justifiable international humanitarian concerns about land mines and their deliberate or unintentional impact on non-combatants imply several important points regarding the future mines discussed in this study. First of all, the current mix of US mines must be changed. Lethal anti-personnel mines in the current inventory must be replaced by future mines which can serve as non-lethal area control weapons producing no deaths or permanent injuries. Conventional US anti-vehicle mines, which by and large attack their targets indiscriminately, must be replaced by future smart mines which have the capability to distinguish specific types of military vehicles as targets. An explosive charge capable of destroying a tank will certainly also destroy a civilian vehicle; the objective in future mine design should be to make sure that the civilian automobile is not attacked to begin with.

Secondly, as a country which plans to use land mines as part of a future regional contingency, the United States should bear some of the responsibility for ensuring that any mines actually deployed will not remain as a disruptive, dangerous legacy for the civilian population for years after conflict ceases in the region. This means that the US should design future mines and mine deployment systems as if US forces will be involved in the actual post-conflict demining (as they may be, depending on the circumstances). Mines and mine deployment systems should facilitate careful automated record keeping and map making of actual mine locations. Modern US mines already have built-in "expiration dates" beyond which they will go inert; in the future, it should also be possible to command-disable a mine field with a high degree of surety as soon as it is no longer needed in the conflict. Disabled mines, which may still contain significant amounts of lethal ordinance, should also contain the means to mark themselves to make locating them easier for post-conflict demining teams. The marking system should also serve as a danger warning to the local civilian population, to keep innocents away until the ordnance is removed.

The US will need to make these changes if it plans to use mines in contingencies twenty years from now. The challenge to mine technology developers will be to accommodate these legitimate humanitarian concerns while preserving the important military utility of the land mine.

2. Basis of the Summer Study

As stated previously, the current Defense Science Board Summer Study is focused on one future vision of a US force which would be utilized in twenty years' time in regional contingencies, either for combat or for Military Operations Other Than War (MOOTW). This force is postulated to consist of limited numbers of widely distributed US units on the ground in the region, which will work together in a highly coordinated manner to achieve their objective. These units can count on support from additional remotely located US forces which will provide force multipliers as needed, such as precision fire support, additional sensors to ensure complete situational awareness, just-in-time logistics support, and so on. The study includes additional assumptions as well, e.g.: that future US combat make free use of Weapons of Mass Destruction (WMD); and that US actions should not cause significant collateral damage and civilian casualties.

These assumptions place a variety of constraints on the nature of the dispersed ground units and the equipment they have with them. Three of these constraints will be mentioned here. First, the ground units must maintain a large edge in mobility over the forces that oppose them. They cannot for instance allow an opponent's heavy units to come into contact and force them into close combat, particularly in terrain unfavorable to the use of the US units' force multiplying sensors and weapon systems (e.g., in forests and urban areas). Second, the organic capabilities and equipment of the US ground units must be slimmed down and simplified, with most logistics-intensive support activities handled remotely. For example, the ground force may consist mostly of maneuver units equipped with advanced direct fire and infantry assault weapons; indirect fire support could be accomplished from offshore floating missile platforms or orbiting aircraft carrying fast standoff weapons. Third, to protect the US ground force and minimize casualties among the local civilians, US forces will need to control crowds and prevent their formation, and deny civilian access to combat areas. Non-lethal means will be required to meet these goals.

Future mine technology can address these three concerns. Land mines have always been viewed as a part of countermobility operations. They will be necessary to interfere with the free movement of an opponent's forces to preserve the desired US edge in mobility. New mine and mine delivery system designs will reduce the logistics, manpower, and time burdens normally associated with emplacing mine fields, perhaps by allowing land mine operations to be run from a central support point remote from the US forces on the ground. In coordination with the dispersed ground units, mines could be delivered remotely from the central point on an as-needed basis. Mines equipped with non-lethal effects packages will be needed to help control crowd formation and serve as active barriers in urban areas to control civilian movement. These and other missions will be discussed in more detail in the following sections.

3. Missions for Land Mines

3.1. Current Mines

Traditionally, land mines have been used in support of countermobility missions; that is, missions to interfere with or limit the freedom of movement of an opposing force. For example, mines can be used to block chokepoints in roads or in an opponent's main Lines of Communication (LOCs). Such an operation would halt traffic flow, at least temporarily, and force an opponent to move countermine equipment to the area to clear the LOC. With current mine removal technology, which relies on man held equipment, mine plows and flails, or the detonation of line charges to clear lanes through the mine field, countermine operations can be slow and fatiguing and can cause casualties and damage the equipment of the mine clearing force.

As alluded to earlier in the discussion of General Rommel and the World War II North African campaign, mines can also be an offensive force multiplier, if their deployment is part of an integrated plan of offensive action. Small units can deploy mines to fix a larger force for an attack from ambush. Forces capable of deploying remotely deliverable scatterable mines can quickly lay down mine fields during an attack to isolate areas of the battlefield to maintain a local force superiority and prevent the timely arrival of enemy reinforcements or reserves to the threatened area. Scatterable mine fields laid in behind a defending force can be used to trap the force in place and interfere with its retreat in the face of an attack. Rather than being able to pull back in good order to some new pre-planned line of defense, the withdrawing force may be fixed in place for some time and compelled to take additional losses from the successful attack on the original position.

Mines are also a force multiplier for the defense. A defender can employ a mine field for the simple hope of causing a low level of attrition to an opponent's forces. This creates a general level of "friction" which must be accommodated by the opponent in his operations, arising from the unexpected losses of men and vehicles, and the steady burden on casualty evacuation and treatment facilities, vehicle recovery and repair facilities, etc. Mines specifically used for the defense of some fixed location (like a firebase) provide early warning of perimeter locations under attack when their explosive detonates. They also complicate an attacker's job by forcing him to deploy specialized troops and equipment forward for countermine operations before the attack can proceed. In addition, shock value is lost from the attack since its tempo is slowed by the presence of the mine fields.

A defender can also use mines to constrain an opponent's ability to maneuver. For example, mine fields can be used to create what are in essence "terrain features" in an otherwise flat and barren desert combat environment. Mine fields used in this way can force an opponent to maneuver laterally while under fire in order to find a clear approach through the fields. Mine fields also serve to channelize the approach of an attacker, either by deliberate plan where the defender leaves open a path into a pre-established kill zone, or just from the way countermine operations tend to clear narrow, one-vehicle wide lanes through mine fields. In the latter case, the attacker is forced to approach the defended position in single file; this is generally much less favorable than approach along a broad front since the lead vehicles may be masking targets from the rear vehicles, or obscuring those targets by stirring up dust clouds.

Finally, mines are also used to deny an opponent access to important facilities. The classic example of this is runway and airfield denial. Bomb damage to a runway can often be repaired very quickly. Including scatterable mines in the munitions mix used in the runway attack makes these repairs much more hazardous, and slows the process until most of the mines can be removed.

3.2. Mine Missions in Twenty Years

The military uses for mines described in the preceding section are important and should still be valid for the postulated future US force of this summer study. It is unlikely that land mines will be asked to do less in twenty years than they are now. However, with potential advances in technology during that time span which are reasonable extrapolations of existing technology trends (e.g., the continuing development of more computationally powerful microelectronics), it is reasonable to expect that mines will be put to important new uses by the future force. Four of these potential new mission areas are discussed in the following section.

<u>Mines as Battlefield Sensors:</u> The expected availability of higher-performance lower-voltage microprocessors will make future mines much smarter and more discriminating than they are currently. Simple mines already have a sensor of some form on board which is triggered when a vehicle target passes by with a signature (weight, magnetic field, etc.) that exceeds some threshold level. Smart mines will have the on-board computational capability to analyze that signature, identify the vehicle's type, and decide on a course of action, with "immediate attack" being only one possible choice. Another choice might be to report the contact to some remote monitoring station.

This combination of lethal land mine and sophisticated ground sensor could be used for the difficult problem of hunting for Time Critical Targets (TCTs) such as an opponent's surface to surface missile launchers (Transporter / Erector / Launchers, or TELs). While undeniably of high value, TCTs are by their nature fleeting targets which will rarely be exposed away from hide sites. The time lines for attacking TCTs are therefore very stringent; significant delays between the time these targets are acquired by a sensor and then attacked by a shooter eliminate the possibility of a successful engagement. One obvious fix for this problem is to put the identifying sensor and the attack mechanism on the same platform; future smart mines will have precisely this combination on board. Such mines could be seeded along the roads in suspected TEL operating areas to "hunt" for TCTs. This could be done completely independently of any deployed ground forces, and yet provide important protection for such forces by destroying and disrupting an opponent's ability to employ long-range weapons (with possible WMD warheads) against friendly troops.

<u>Convoy Ambush:</u> Future smart standoff mines could be equipped with low probability of detection communications capabilities, both for local area coordination and for long haul reporting to some remote monitoring point. Such mines could then work together and with remote forces to execute autonomous ambushes on convoys. Currently, a convoy moving along a road and encountering a previously unknown conventional mine field stops at the edge of the field once the first mines detonate, with losses pretty much limited to the lead vehicles. Smart standoff mines spread out along the road, however, could coordinate their attack to strike at the entire length of the convoy, destroying many more vehicles.

Such ambushes might work as follows. Individual mines would wait until the convoy was in the midst of the field; at that point the standoff mines within range could divide up the available targets, with particularly valuable targets perhaps garnering the attention of multiple mines. The mine ambush would then be executed along the length of the convoy. Alternatively, pairs of mines working together, but more widely separated along the road, could allow a convoy to get into the gap between them. They could then attack the first and last vehicles to fix the convoy in place while it is struck by remote fires called in by the mines themselves. If necessary or desired, human in the loop approval could be preserved in either case by having the mines present at the ambush site working as advanced ground sensors to provide reports to a remote human controller. The human operator would have the opportunity to confirm the identity of the vehicles in the possible target convoy before any ambush is sprung.

Smart Mines in Urban Warfare: Urban terrain is a very challenging environment for future high-tech warfare. The environment confuses sensors with miscellaneous man-made clutter, limits communications and data exchange because of line of sight restrictions and interference, and severely constrains the performance of weapons systems because of the high chances of producing collateral damage. Smart mines may be a solution to delivering munitions to military targets in this type of environment. The fact that they are "on the spot" systems gives them several advantages. Their sensors will be working in close proximity to their potential targets, which may help with the background clutter problem; assuming they have good discrimination capability they can function autonomously without need for external communication; and they can deliver their lethal effect against their chosen vehicle targets with great precision (again because of their proximity to their targets), limiting collateral damage. The constrained nature of urban terrain also works in favor of mine use.

Civilian Control: Future smart mines may also be excellent platforms for the delivery of non-lethal means for controlling crowds and proactively denying civilian access to combat areas, particularly in urban environments. Groups of mines could work together to maintain virtual barricades to stop civilian vehicle or pedestrian traffic flow into such an area, by disabling approaching cars, dispensing sticky-foam, spraying anti-traction liquids on streets and sidewalks, etc. Alternatively, mines could be dispersed along a street and used to emit audible or visible warning messages, or noxious smells, or high-volume noise to keep the local citizenry indoors and out of the way while the street is used for military purposes. Smart mines might also be made to sense when crowds begin to form in their vicinity, which would then trigger them to employ similar control effects for dispersing crowds quickly.

4. The Current State of Mine Technology

4.1. Conventional Mines

Most land mines manufactured today fall into the category of hand-emplaced conventional mines. These are simple devices which by and large rely on a single target characteristic for fusing. Typical anti-vehicle mines are activated by pressure, magnetic influence, or through the use of a tilt-rod which detonates when pushed sideways by contact with a vehicle. Conventional anti-vehicle mines generally attack the underside of their targets; since many are made to destroy tanks, this attack is executed by detonating a shape charge upwards to penetrate the tank's comparatively thin belly armor. Alternatively, pressure-activated anti-tank mines can be designed to cut tread, and thereby disable a tracked vehicle.

Typical anti-personnel conventional mines are activated by pressure, trip-wires, or handling (as an anti-tampering defense). They will either detonate a small internal explosive charge at ground level, or, for bounding mines, pop a submunition upwards to create an above-ground burst with a wider effects radius.

Laying a conventional mine field by hand is a time- and manpower-intensive process. Many modern armed forces have come to rely on automated systems to quickly scatter specially-packaged conventional mines for rapid (and possibly remote) mine field emplacement. These scatterable mines can be delivered locally from mechanical dispensers or remotely from what are basically cargo carriers fired by artillery or dropped from aircraft.

The systems currently used by the United States are good examples of the current state of scatterable mine technology. The US Army has several devices for mechanically dispensing mines. The Modular Pack Mine System (MOPMS) can be broken down into four man-portable sections and reassembled in the field to serve as a quick means of laying a small defensive mine field to support an infantry position. The heavy-duty Army mine dispensing system is known as the Volcano; this can be mounted on a truck or helicopter, and holds up to 960 Gator conventional mines. Gators come in two types: the BLU-91 anti-personnel mine and the BLU-92 anti-tank mine.

The Army can also scatter mines remotely using standard 155 mm howitzers. These artillery pieces can fire cargo rounds which break open above their target areas and dispense a cluster of mines. These cargo rounds come in two main types: the Area Defense Artillery Round (ADAM), which carries 36 anti-personnel mines; and the Remote Anti-Armor Mine (RAAM) round, which carries 9 anti-tank mines.

The Air Force and the Navy can dispense mines from high-performance fixed-wing aircraft. The standard Cluster Bomb Unit CBU-89 Tactical Munitions Dispenser can be loaded with Gator mines (either 600 BLU-91 or 94 BLU-92). When dropped from an airplane, the CBU-89 opens on its way to the ground and spills out its mine cargo over an area that normally spans 200 m by 300 m.

4.2. Standoff Mines

Standoff mines constitute a different category of land mine devices. These mines sense targets at some distance (50 m or more away) and when activated, project their effect in the target's direction. The simplest of these devices can be made merely by mounting an infantryman's anti-tank rocket launcher on a tripod, and arranging a sensor system to trigger the device when a vehicle rolls past the front of the launcher. The Panzerfaust Off-Route Mine is such a device, consisting of the German Panzerfaust 3 anti-tank rocket coupled to a combination infrared and acoustic activation sensor. By their nature, most standoff mines attack their targets directly from the side. An exception to this is the US Wide Area Mine (WAM) which will be discussed later in this section.

Standoff mines have several advantages compared to conventional mines. Their ability to act at a distance greatly decreases the number of mines needed to cover an area compared to very short range conventional mines. Their range also makes standoff mines much more difficult to detect during countermine reconnaissance. For example, to cover a road with a scattered conventional mine field, mines must end up sitting right on the road surface. If the same road were covered by standoff mines, these would be located well off the road to either side; there would be no visual indicators of a mine threat on or very near the road itself. This greatly increases the area which much be searched in support of countermine operations. Standoff mines are also immune to the use of mine plows and other simple mechanical devices employed on vehicles to clear lanes through conventional mine fields. As a matter of fact, standoff mines can be used effectively to guard such fields by attacking the vehicles equipped with plows and flails from the sides as they attempt to breach the field.

The US WAM, mentioned earlier, is probably the most advanced standoff mine design today. The WAM is a small, upright cylindrical device which contains a battery pack, an anti-vehicle submunition in a turnable launcher, several different types of sensors, and some controlling microelectronics including a Digital Signal Processor (DSP) chip. The WAM is omni-directional; unlike the simple Panzerfaust standoff mine discussed above, which is pre-aimed in a fixed direction during deployment, the WAM is capable of attacking targets in any direction. It also has the capability to be selective in the targets it chooses. When a vehicle comes within detection range of the WAM's on-board sensors, the DSP is used to process the vehicle signature to see if it matches that of a preassigned target type. If it does, the WAM estimates the target's track and determines the range, bearing, and time of the vehicle's Closest Point of Approach (CPA) to the mine. Just before the vehicle reaches CPA, the WAM aims its launcher in that direction and pops out a submunition timed to pass above the target at CPA. The submunition, similar to an Air Force Skeet bomblet, has a look-down sensor on board which searches for the target in flight. When it finds the target, the submunition detonates and fires a single-slug Explosively Forged Penetrator (EFP) down through the top of the target.

A hand-emplaced version of the WAM is nearing its Initial Operational Capability (IOC). This will be followed in a few years by a version suitable for use in the US Army Volcano mine scattering system. Additional plans call for the development of a Deep-Attack WAM, which would be scattered in a remote area from an Army Tactical Missile System (ATACMS) missile. Also under development is a WAM spin-off known as the Anti-Helicopter Mine (AHM). This device would use its sensors and signal processor to identify the nearby nap-of-the-earth hover or passage of a preselected type of helicopter. When activated, the AHM would toss a submunition up in the air in the direction of the helicopter. In this case, when the submunition acquired the target, it would detonate and spray multiple slugs like a large shotgun blast in the direction of the helicopter.

5. Transition to the Future Smart Mine System

The previous section summarized the current state of the art of land mine and land mine delivery technology and gave an indication of current US capabilities. These capabilities in general fall well short of the smart mine system which would be needed to accomplish the suite of missions described earlier for land mine support to the future US force postulated in this study. That is the bad news. The good news is that the basis for the necessary future mine system does exist now, and the changes necessary to address the technology shortfalls look to be evolutionary, rather than revolutionary in nature. The following sections summarize the requirements for a future smart mine system based on the policy considerations and mission needs discussed in previous sections, mention several programs which are beginning to take the first steps toward developing these future smart mine capabilities, and indicate the critical technology areas which will require additional investment in order to complete the transition of the current mine inventory to future smart mines within the twenty year period specified by the Defense Science Board study.

Future Mines Should Discriminate Specific Target Types: Future mines must not attack targets indiscriminately. Changes which will occur in US policy in the next twenty years will force mines to become much smarter than they currently are to ensure that civilian targets are not attacked with lethal force. Beyond this reason however, lies the fact that smart mines which are able to maintain surveillance in their local areas of the battlefield will become valuable additions to the theater Command, Control, Communications, Computing, Intelligence, Surveillance, and Reconnaissance (C4ISR) architecture and will help to achieve the high level of situational awareness needed by the postulated future US force. Mines must become ground sensors not only capable of reporting specific details of enemy convoy traffic at their locations, but also able to take decisive action if necessary, as in immediately attacking any passing vehicles identified as WMD carriers.

The ground work for this future mine capability has already been laid in the WAM and AHM programs and in development programs for the next generation of deep battlefield ground sensors. WAM already has some limited ability to discriminate the different types of tanks and heavy armored vehicles which constitute its principle target set. The Department of Defense coordinating office for Measurements and Signatures Intelligence (MASINT), the Central MASINT Office (CMO), is extending current WAM sensing and discrimination technology as part of its Unattended MASINT Sensor (UMS) advanced ground sensor program. UMS field tests have already demonstrated increases in effective sensor range and in the types of vehicles which can be identified, and new combinations of sensors have been tested. The Defense Advanced Research Projects Agency (DARPA), with its Internetted Unattended Ground Sensor (IUGS) program, is currently looking into other types of advanced MASINT technology to increase the suite of sensor types available for vehicle discrimination, and is set to feed new technology into UMS development and field testing. Results and advances from these ground sensor programs can be used to improve the existing

WAM design. Continued investment by the Department of Defense (DoD) in MASINT sensor research and testing is essential to develop the full advanced target discrimination capability needed for the future smart mine goal.

Progress in target discrimination will require more than the creation of broader suites of more sensitive sensors and new algorithms for vehicle signature recognition and data fusion. Processing ever-larger amounts of sensor data with more sophisticated and demanding algorithms will require increasingly capable on-mine microelectronics. The ground sensor / mine application introduces important constraints however, in terms of small package size, the need for ruggedized designs, and most critical, the need to preserve platform life with low power operation. Commercial trends appear favorable in the near term: 3-volt digital signal processors and supporting components are beginning to become commercially available, and can now supplant the much more power-hungry 5-volt components which had to be used previously in such devices. Still lower-power 1.8 volt DSPs have been announced by various manufacturers and should be available in the next few years. The Department of Defense should encourage this trend by funding continuing research and development on the production of high-performance, miniaturized, low-power microelectronics.

<u>Future Mines Must Communicate:</u> This paper has suggested that future mission needs will have smart mines (1) serving as surveillance assets within the overall C4ISR architecture; (2) attacking the enemy in coordination with other smart mines and with remote fire support elements as appropriate; and (3) remaining under active human control when applying lethal force, depending on the regional rules of engagement. All of these potential needs will require near-real-time communications capabilities both in their local area, and extending throughout the operational region. These communications must be two-way, with smart mines sending out data and receiving additional information and commands in return. The outbound communications must be Low Probability of Detection (LPD) so that the mines do not disclose their presence, and low power to preserve mine lifetime. For long-haul communications, relay platforms will need to be used. Candidates for this task on the future battlefield will include unmanned aerial vehicles (UAVs), manned aircraft, loitering unmanned high-altitude balloons, and satellites.

Several different programs are beginning to look into how such communications capabilities should be provided. The current WAM program for instance has a P3I element which will incorporate at least a receiver on the mines for rudimentary command and control (activation and disablement). Various smart mine field programs sponsored by DARPA and the US Army Engineer School (USAES) have looked into issues surrounding local communications for groups of cooperating mines. The CMO UMS advanced ground sensor program mentioned earlier has nearly identical needs in long-haul communications and will be field-testing several options for such links.

As in the previous case of advanced mine "smarts", the very early basis for this future communications capability is being developed now, but will never achieve operational readiness in twenty years unless actively pursued and put in place through Department of Defense investment. Much additional work is needed on the development of a cohesive communications architecture capable of supporting autonomous sensor systems including smart mines and advanced ground sensors. Large numbers of such devices may need to be deployed throughout the depth of the operational region in order to support operations of the US force postulated by this summer study. Designing miniaturized low-power communication devices for use on the mines and sensors themselves is just one aspect of the problem. The need to couple these devices, dispersed throughout a theater, to future relay platforms with communications protocols that ensure critical information from many similar sources is passed in real- or near-real-time within the constraints of available bandwidth and with low probability of detection is still a major concern.

<u>Future Mines Must be Deployed Precisely and with Dispatch:</u> The missions for future mines described earlier in this paper envision them being used on an as-needed basis in support of a dispersed US force in theater. Future mines in these circumstances will be expected to operate on their own if need be at a variety of locations throughout the entire theater for a variety of purposes.

The forces actually on the ground may not have access to all the places mines are needed; nor should they actually have to undertake minelaying under the scheme postulated in this summer study. Such a job would unnecessarily increase the size and complicate the operations of the dispersed ground units. On the battlefield postulated in the study, minelaying should be handled by centralized facilities with the resources to handle mine logistics for the theater, plan and coordinate mine deployments, and ensure precise, remote mine delivery, even in time-urgent situations. Precision placement of mines will be necessary to: (1) conserve mine and mine deployment assets and reduce the associated logistical burden of mine operations; (2) increase the efficiency of deployed mines by optimizing laydown for the local need (e.g., spreading mines out linearly alongside a straight road rather than scattering them into an elliptical area nearby); and (3) achieve successful mine deployment in difficult terrain (as in mountainous regions or urban areas).

As described in the earlier section on current mines, the US presently has the capability to scatter mines remotely using artillery cargo rounds, dispensers on helicopters and aircraft, etc. The deep-attack version of the WAM will extend that capability to long-range delivery by ATACMS missile within the next decade. These existing capabilities obviously provide a starting point for the development of deployment means for future smart mines. However, in each case, the system works because relatively large numbers of mines are scattered into elliptical areas surrounding the locations at which the mines are needed. Further work is necessary to understand how to "spot" the mines to optimize placement. Possible solutions include creating special mine dispenser racks for low-flying UAVs or delivering mines via cruise missile. It may also be possible to borrow precision delivery technology from other efforts like the Joint Direct Attack Munition (JDAM) program. Mines released from aircraft or surface to surface missiles above the target area may then be able to steer themselves to their optimized final positions on the ground with very high precision. Department of Defense investment will be required to develop and test the actual precision delivery means, to ruggedize the future mines for such delivery on to normal terrain, and to investigate means of softening the landing when future smart mines must be deployed in unfavorable terrain (rocky areas or paved / built-up urban locations).

Future Mines Should be Able to Deliver Non-lethal Attacks: As described earlier, future smart mines can play an important role in MOUT operations, where combat may take place in the midst of large numbers of civilians. In these circumstances, mines will need to serve as remotely-deliverable barriers to close streets and other arteries to vehicle and pedestrian traffic, and as autonomous means of controlling and dispersing crowds. The US policy of seeking to prevent civilian casualties and minimize collateral damage will mean that mines with lethal effects will not be used for these purposes. It will be necessary to ensure that non-lethal technologies suitable for these missions will be developed and packaged as future mine payloads.

Workers at a variety of laboratories in the US have begun the development of such non-lethal technologies in support of various existing DoD and Department of Energy (DOE) programs. These have been highlighted recently in feature stories in various national and defense-related magazines. Further work is required to expand the suite of technologies so that the optimal attack mechanism is available to suit the local circumstances (e.g., a sticky-foam barrier may be the best choice for temporarily closing a narrow alley, whereas anti-traction liquids may be the best way to deny access to a hilly road). DoD investment will also be necessary to package the non-lethals in ways that will fit in the small form factors of the future mines, and ensure that any power requirements will be met adequately from the mines' on-board storage.

Non-lethal technologies will not generally discourage people from repeated attempts to bypass or subvert the control they impose. Unlike their lethal-attack brethren, the non-lethal mines may have to stay in place and maintain an aggressive posture with repeated attacks during the course of a multi-hour period. The payload packaging and power requirements should be designed with this in mind. For controlling actively hostile citizenry it may be necessary to seed several different non-lethal mines into the same point so that they can cooperate together to alternate the attacks to maintain an element of surprise and achieve best effect.

Future Mines Should Incorporate Demining Aids: For humanitarian reasons, future smart mines should incorporate demining aids and all aspects of US mine operations should be conducted as if US forces will be actively involved in mine cleanup when the conflict is over. Maintaining a centralized support organization responsible for planning and executing minelaying operations will help right from the outset with the bookkeeping necessary to understand the areas where US mines have been laid. However, the planned deployment area may not be specified tightly enough to help find the small, camouflaged mines out in the field. Mine delivery platforms and the mines themselves must be given the ability to shrink the location errors still further so that demining teams waste minimal time in search. Flashing lights, audible tones, beacon signals, etc. which can be turned on by command post-conflict will also help locate the mines and should be included in future mine design.

Modern US mines like the Gator system are designed to deactivate a certain set time after their deployment. In terms of current programs looking to go beyond that minimal capability, the Smart Mines Technology Project, sponsored by the DoD Office of Munitions is currently developing an Electronic Safe and Arm Device (ESAD) for use in the WAM P3I program to allow reliable command disabling of those mines. The ESAD will provide two levels of command safing: the first (meant to allow emergency passage of friendly units) would allow command re-arming, while the second (meant for mine recovery) would require mechanical intervention in order to re-arm the mine. Since troops will actually be handling mines during recovery, the challenge for the project is to meet the stringent requirement of better than six 9's safing reliability set by the Army Fuse Board.

The Smart Mines Technology Project is an important example of exactly the sort of development program which must be pursued by the DoD to address mine recovery issues. However, support for demining operations goes beyond mine disablement, and this area will require further investment from the DoD if future smart mines, and their delivery systems, are to be designed to make post-conflict demining not only safe, but more efficient and more certain.

6. Summary

This paper has attempted to show that smart mines will be essential to future US military operations of the sort postulated in this study. Humanitarian concerns about the future use of mines are justified, but technologies already under development should allow the DoD to phase out the worst offenders from the current mine inventory and replace them with mines which will not kill or permanently disable civilians.

The capabilities of the future smart mines needed to support the postulated US forces of this study will go well beyond current mine capabilities. At a minimum, the future mines will be able to serve as remote sensors and be an important part of the future theater C4ISR architecture. They will be able to attack their targets either alone or in cooperation with remote fire support assets. The remote delivery means will exist to put the future mines on the ground precisely where and when they are needed. Various mine payloads will be available to suit the current mine mission, including advanced non-lethal weapon packages. Finally, the future mines will incorporate various features to help with post-conflict demining operations.

In order to provide these capabilities, the DoD must: (1) continue research on MASINT sensor technologies and signal processing algorithms to support reliable vehicle discrimination; (2) develop low-power, high-speed, micro-electronics for on-mine computational power; (3) provide an architecture for long-haul two-way communication between the mines and remote theater C4ISR facilities including low-power, miniaturized, on-mine electronics, an accessible communications relay platform, and a protocol for moving time critical information between the mines and the theater in near-real-time; (4) create a mechanism for optimally emplacing mines in remote areas at precise locations in response to urgent needs; (5) develop low-power non-lethal attack mechanisms in small packages suitable for use as mine payloads; and (6) invent additional components to add in to mine systems to assist post-conflict demining teams to quickly locate disabled mines. A promising beginning has been made already on most of these items, but continued DoD investment will be necessary to produce this highly-capable future smart mine in the twenty-year span considered by the summer study.

The Explosive After Next

A White Paper Prepared for

The Defense Science Board Summer Study

on

Tactics and Technology

for

21st Century Military Superiority

Submitted By

Los Alamos National Laboratory

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The Explosive After Next

Los Alamos National Laboratory

For over a hundred years, the standard explosives used in military munitions (TNT, RDX, and HMX) have basically been unaltered. Now, with major advances in chemistry and physics, and sophisticated modeling, it is possible to envision a spectrum of explosives which provide higher energy in smaller packages and can be tailored to the needs of a specific weapon system and application. In the nearer term these explosives are called HEDMs or High Energy Density Materials. They can provide as much as twice the specific energy as RDX (5kj/kg) and their rate of burn can be varied so that for the first time energy can be coupled to the target in modes that optimize damage to the target. One example of these materials which will be described in this paper is Metastable Interstitial Composites (MICs). In the longer term it is possible to envision very compact sources based on direct drive fusion or antimatter which are also discussed.

MICs A MIC material is a *constructed* energetic material consisting of two or more chemical species that are exothermically reactive with each other; e.g., pyrochemical or thermitic species. Specific examples include Al/MoO_3, Al/Teflon, and $Al/KClO_4$. The reactions of such materials release more energy than explosives. The MIC is fabricated such that the reactant species are almost atomically intermixed to form a metastable reactive system. The near atomic-scale proximity of the reactants minimizes distances over which the molecules must diffuse in order to react, resulting in a dramatically increased reaction rate relative to conventional powdered mixtures. Los Alamos has developed MIC materials that exhibit performance characteristics encompassing the entire range between high explosives and conventional thermite. Current laboratory scale production amounts to tens of grams of material per day. Scaled-up production approaches for more substantial amounts of material are judged to be straightforward.

As an enhanced weapon payload, MIC materials offer several advantages over explosives, including the following: 1) MIC reaction-zone temperatures are typically three times greater than temperatures produced by detonating explosives thus producing a large thermal loading; 2) most MIC reactions produce solid products not gases, minimizing target venting problems; 3) MICs release more energy than explosives, allowing more efficient energy packaging in the enhanced payload weapon; 4) MIC energy-release rates are widely adjustable, permitting optimum coupling of the released energy to damage modes in the target; 5) the MIC composition can be adjusted to produce ceramic/abrasive particles and/or metallic/conductive particles for mechanical and electronic hardware destruction, and 6) MIC ignition characteristics are tunable, enabling a wide variety of ignition scenarios.

Pure Fusion Conceivably, a pure fusion device may be possible by either initiating the fuel with a higher energy density explosive than currently exists or by utilizing combinations of magnetic fields to assist in initiation. Both of these concepts could currently be evaluated in the near term.

The theoretical yield of D-T fusion is 80 tons/g or 335,000 MJ/g. Thus, about 2 tons of energy would require 25 milligrams of fuel if completely converted. With expected conversion efficiencies, the required fuel mass would still be tens to hundreds of milligrams. The difficulty to obtaining the energy lies in initiating the fusion reactions.

Experimental work performed over the past five decades has created a wealth of expertise in the physics of thermonuclear reactions. The results of these efforts, coupled with the computational modeling capability developed in the nation's nuclear weapons program, would allow the feasibility of a pure fusion system to be assessed. In addition, the benefit of development of a chemical explosive with higher energy content than current HE could be assessed with regards to enhancing the possibility of driving a fusion fuel to ignition.

In summary, the capability exists now to assess the potential of developing a system that could offer extremely high specific energy sources. Computational modeling combined with future High Energy Density Materials may allow a wholly new energetic system to be considered.

<u>Antimatter</u> Antimatter possesses the highest energy per mass ratio of any material currently known to mankind. At ninety trillion joules in every gram of antiprotons, the specific energy of the material is a factor of 1000 higher than fission and 100 larger than fusion. In addition, the interaction of antimatter and matter is a 100% efficient reaction. Thus, conceptually, small, efficient weapon systems could be developed that are powered by extremely tiny masses of antiprotons. Previous studies indicate that some of these concepts may be feasible depending upon the desired effect. Collateral explosions may be difficult to produce and would probably require quantities of antiprotons not currently available in this country. Very intense radiation sources of neutrons, gamma rays, pions and electrons could be developed relatively straightforwardly. The critical issues to all of these applications are production, storage, and energy conversion.

Antiprotons are currently produced at high energy in several facilities around the world. The Fermi National Accelerator Laboratory in the US has the highest production level, 10^{15} to 10^{16} per year (roughly 1 megajoule of contained energy), but delivers the particles only at very high energies for fundamental physics experiments. The CERN/LEAR facility in Europe is the only source of low energy antiprotons worldwide. Antiprotons are also produced at high energies at Brookhaven National Laboratory (US) and KEK (Japan) at lower rates. Of these facilities, only the LEAR site has demonstrated the capability to capture and store antiprotons.

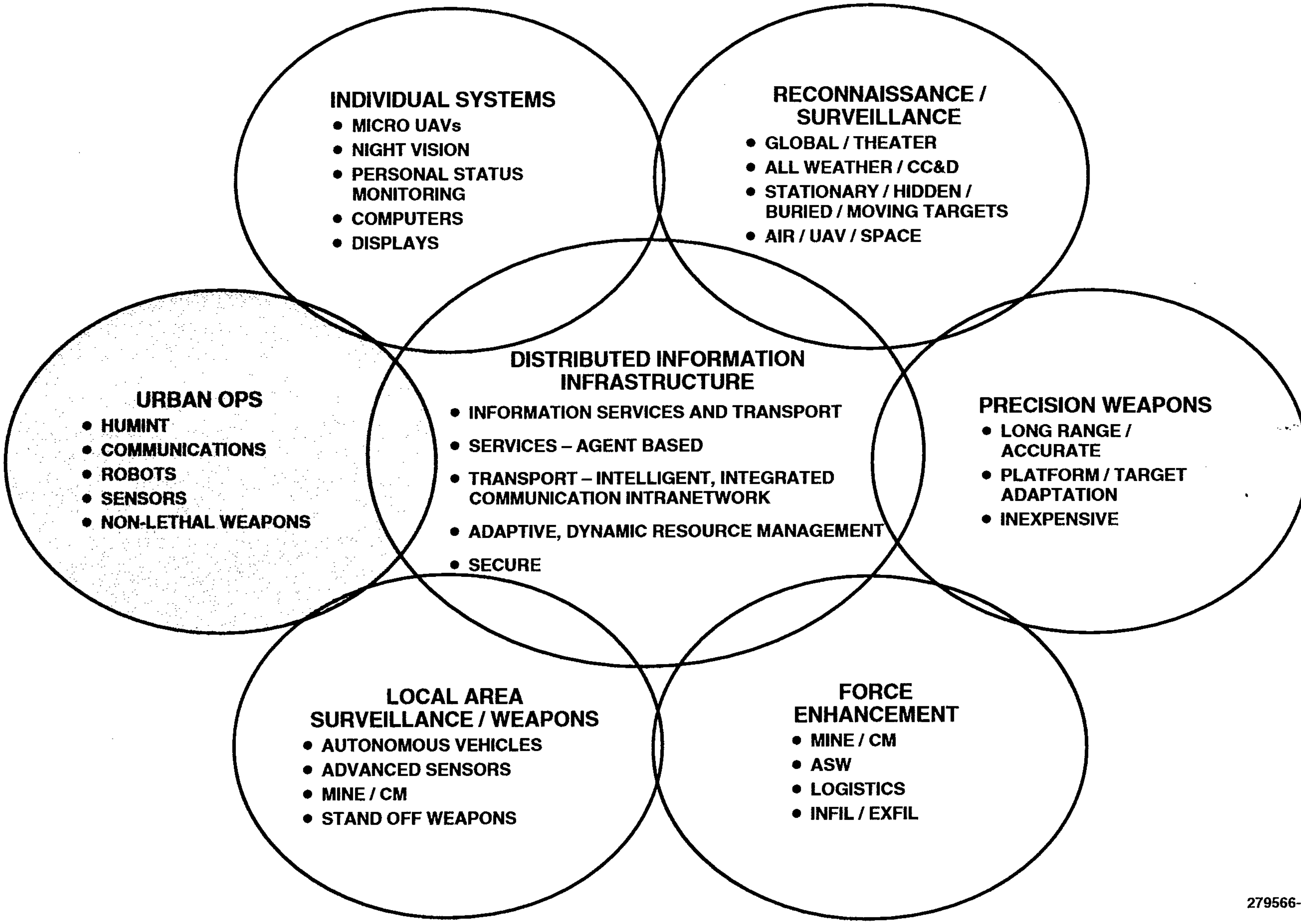
In general, the size of the storage device for antimatter is determined by the energy of the particles confined. The lower the energy, the smaller the storage system. Recent successes in trapping antiprotons at LEAR at CERN suggest that applications of small, portable sources of antiprotons may be near. In 1991 Gabrielse trapped and held 105 antiprotons for several months. In 1993 Holzscheiter trapped 7.8×10^5 antiprotons from a single beam burst at LEAR and plan to trap up to 10^7 antiprotons within the next two years. Conceptually, extensions of the Penning trap technology could allow up to 10^{13} antiprotons to be stored in a portable system. Development of a portable trap is currently being pursued at Pennsylvania State University under sponsorship from the USAF and NASA. Development of the Penning trap technology allows a source of very low energy antiprotons to become available so that other, higher energy density storage schemes can be investigated.

Efforts are currently underway to create antihydrogen using the Penning trap as a reaction volume. By accumulating the neutral antihydrogen into frozen, micro-crystals and suspending the crystals diamagnetically, hundreds of megajoules of energy could be stored in extremely tiny volumes.

With the advent of high density storage. several applications of antiprotons can be envisioned. Even though the specific energy is high, however, the conversion of the reaction products to usable form is nontrivial in some cases. Antiprotons react with normal matter to create charged pi-mesons and gamma rays. The average energies of the mesons and gamma rays are 256 MeV and 200 MeV respectively. These are extremely penetrating, long-ranged particles. Consequently, they do not deposit energy locally to create an explosion in the normal sense. The particles can, however, be captured in intense magnetic fields where their kinetic energy can be used to excite lasing media or to produce neutrons and electrons. Thus, the unique characteristics offered by the reaction products can be used to produce unique effects in the local environment.

TACTICS AND TECHNOLOGY FOR 21st CENTURY MILITARY SUPERIORITY

TECHNOLOGY CONCEPTS PANEL



279566-3T

TECHNOLOGICAL INNOVATIONS TO SUPPORT MILITARY OPERATIONS IN AN URBAN ENVIRONMENT

A White Paper
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Wade Ishimoto
Dori Ellis

SYNOPSIS:

This paper responds to the Defense Science Board's 1996 Summer Study Task Force on Tactics and Technology for 21st Century Military Superiority. In particular, it addresses technology needed to support our military forces in a most formidable setting, that of conducting military operations in an urban environment. Urban operations are singularly unique with constraints that require different tactics and equipment to enhance mission success. US military forces have little experience in these environments; thus it is difficult to state definitively which technological innovations will be most useful. However, it is certain that the more tools that are available to the warfighter, the more likely he will be able to successful execute his mission. The unusual nature of urban operations is examined in this paper, along with potential technologies that may provide the warfighter with a combative edge by the year 2015.

TYPES OF MILITARY OPERATIONS IN AN URBAN ENVIRONMENT:

Military operations in an urban environment may span the entire spectrum of warfare, with both tactical and strategic implications. The very nature of an urban area presents unique challenges to military forces not found elsewhere in land, sea, or air battles. The density of population, high-rise buildings and skyscrapers, restrictions on mobility, and the numbers of potential ambush locations hinder the use of tactics and equipment that are quite practical in other arenas.

Adding to this difficulty is the fact that urban operations include Operations Other Than War (OOTW), small-unit, special operations like surgical counterterrorist actions, full-scale land warfare using armored and infantry forces, and stand-off attack using artillery, naval gunfire, and land or sea-based aircraft with conventional or nuclear armament. The missions assigned to our military forces may require minimal use of force and less-than-lethal weaponry,with a desire to produce minimal damage to a city, preserving its population and infrastructure. These difficulties place a premium on the use of precision strike weapons systems and specialized technology.

The diversity of missions, environments, and potential constraints placed on our forces in urban operations, make it difficult to generalize technology needs. Each may require specialized tactics and equipment. For example, battlefield sensor systems like IREMBASS or the Internetted Unattended Ground Sensor System (IUGS), under current development by DARPA, are principally designed for use in a rural environment. In an urban area, other sensor systems are required for use by covert intelligence collectors to track and locate personnel, to determine specific activities within a building, to secure intelligence against deep underground structures, or for use in a counterterrorist operation.

In addition to sensor systems, other important technology needs include communications other than line-of-sight, individual soldier equipment, mobility, planning, training, and rehearsal tools; and weaponry systems.

UNIQUE CONSTRAINTS SURROUNDING URBAN OPERATIONS:

The unique constraints found in an urban setting must be understood by those developing technology. There are three significant considerations which greatly impact mission performance, tactics, and equipment. These are:
1) the effects on the population,
2) the infrastructure found in an urban area, and
3) what this paper characterizes as "line-of-sight" problems.

Population:

The density of population within an urban area causes great concern over casualties to non-hostile civilians. Avoiding mass casualties places a greater burden on intelligence gathering and weapon precision. Lessons learned in Somalia, e.g., demonstrate the adverse political and public image implications if non-combatants become casualties. The problem is exacerbated when the adversary chooses to use the people as hostages or human shields. Damaging infrastructure in an urban area also has the potential to cause unacceptable difficulties for civilian non-combatants. It is much more difficult to forage for food, water and fuel for heat than in a rural area. Riot and crowd control are also likely scenarios.

Infrastructure:

Reducing damage to infrastructure places a premium on intelligence collection and analysis. Enemy forces can hide their activities within large buildings. Extensive and deep underground structures would defy our current ability to attack them without causing massive collateral damage. A built-up area provides plentiful ambush and sniper locations which pose problems for smaller units. In addition, the very nature of an urban area masks targets from artillery and air attack. There may also be a desire to avoid excessive collateral damage to an urban infrastructure for the purpose of allowing a reconstituted government to more rapidly assume governmental control. To this end, it would be desirable to protect industry, commerce, and government. Accordingly, there may be a desire to preserve fire-fighting systems, communications, safety systems, power, water, and food facilities and to avoid destruction of important public records.

Precision attack of the adversary and the facilities they are using may be required. Our forces may be required to clear large buildings and underground structures room by room, floor by floor, consequently placing them at greater risk and adding to the time and difficulty of their task.

Line-of-sight problems:

In an urban environment, communications between individuals and units is greatly reduced, since most current systems rely on line-of-sight devices. Visual communications become difficult, and radio communications have reduced reliability and distance. Command and control is much more difficult under these circumstances. The ability to "see" in a location (e.g., underground) without any ambient light, or where there is no desire to use an illuminating device, is a severe limit on the use of clandestine force options.

TECHNOLOGY TO ENHANCE SUCCESS IN AN URBAN ENVIRONMENT:
What technologies show promise or are likely to be available within the next twenty years to assist our military in solving these vexing problems?

Intelligence and Sensor Systems:
A new family of sensors combined with analytical tools to turn data into knowledge are needed for covert or clandestine use by intelligence collectors or surgical forces. They must confirm the presence or absence of Weapons of Mass Destruction that a strategic system may not be able to pinpoint. Other miniaturized, remotely guided sensor systems, along with through-the-wall viewing systems, will assist in gathering intelligence within buildings and underground structures. There are several technologies which hold promise. They include small, robotic devices using micro-electronic machines (MEMS), gravity gradiometry systems, and penetrating radar. New sensor systems must also be aimed at gathering information unique to the urban environment. For example, monitoring power usage within a building may indicate that it is a command and control center. Sensor systems mounted on unmanned aerial vehicles (UAVs) may assist in providing more reliable communications and situational awareness.

Analytical systems are required to process all-source information into useful intelligence. Accurate, real-time, three-dimensional modeling systems are well within the realm of possibility within the next 20 years to assist commanders with their planning. The use of situational awareness enhancements and virtual reality also hold promise as analytical and planning tools. By incorporating utility, power, and transportation information with adversarial data, they may allow the field commander to decide among alternate means of attack.

Communications:
One of the keys to success when operating in a built-up area is the ability to communicate and rapidly redirect troops. Radio communications around buildings and underground require significant improvements in reliability. This is not a new problem. The issue was raised almost 20 years ago by our national counterterrorist forces. Although improvements have occurred, the same degree of reliability found in field communications systems is not available. Therefore, the need to develop small-team communications systems and improved communications with headquarters remain a significant technology need.

Another facet of communications is language barriers. Translators are currently in the R&D phase to perform translations for communicating with indigenous persons or with allies who are not fluent in English.

Other communications technology improvements which may provide our military with an advantage should be available for fielding within the next 20 years. These include:

- Long-life batteries for voice, data, and sensor communications.
- Low-Probability-of-Intercept/Low-Probability-of-Detection and burst communications with data compression.
- Advanced encryption systems to enhance security.
- Improved antenna size and functionality.
- Higher power satellite communications (e.g., nuclear powered) to provide improved bandwidth, processing power and reliability.

Weaponry to include Non-lethal weapons:
The desire to reduce casualties to non-combatants and to avoid collateral damage when possible is a goal that appears achievable. There are a large number of initiatives already occurring. Obscurants to assist in crowd control or to provide force concealment are available. Access delay devices such as dispensable caltrops are available for use against wheeled vehicles or personnel, and sticky foam can be used (as in Somalia) to slow the advance of hostile forces.

Other promising technologies currently being examined include:
- Pulsed high-frequency sound to confuse or cause pain.
- RF technologies that are tunable and directional to disrupt command and control, communications, and intelligence systems.
- Directional, high power acoustics using phased array or parametric antennas to cause pain or confusion.
- Holograms to confuse and cause panic.
- Microwave to stop moving vehicles.
- Wide area concealed weapon detection (metal detection with advanced computing to eliminate clutter) for use in crowd control situations.
- Custom "bugs," e.g.., biologicals that attack fuels, plastics, metals selectively.
- Low-observable technologies suitable for urban environment to increase force survivability through decreased detection of activities.

Information Warfare technology to deceive, channel, or frustrate adversarial forces is another area that is undergoing development. This type of weaponry shows promise not only for attacking command, control, communications, computer, and intelligence systems, but also for use in psychological operations and physical infrastructure attack.

Planning, training, rehearsal:
The use of smaller forces in situations which often require rapid planning and deployment call for the development of advanced planning, training, and rehearsal systems. Again, there are a number of initiatives which show great promise and are likely to be fielded within the next 20 years. Virtual reality systems will allow real-time scenario building with subsequent use by individual troops and their commanders to plan, train, and rehearse actions. Virtual reality advances include sensory enhancements in visualization,

feeling, and hearing. Decision support models using digitized data and three-dimensional modeling are well on their way to success along with other planning, modeling, and simulation software developments.

CONCLUSION:

The dawn of the 21st Century is almost upon us. In many ways, the world has become a much more unpredictable place to live. Although super power conflicts cannot be ignored, it appears that the future will likely hold smaller conflicts, many in urban environments. Our enemies will be more likely to have access to advanced technologies. This implies an increasing need to stay on the leading edge of technology. Agility in planning, training, and rehearsing will be needed to anticipate the tools that the warfighter must have available in each scenario. Equipment must be made modular to provide exactly the right set of capabilities for each situation.

SRI International

White Paper • May 1996

ULTRA-WIDEBAND RADAR APPLIED TO SURVEILLANCE

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Prepared for:

Technology Panel
Defense Science Board Summer Study

Approved:

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SRI WHITE PAPER

ULTRA-WIDEBAND RADAR APPLIED TO SURVEILLANCE

BACKGROUND

A number of experiments have been performed since 1990 in which ultra-wideband, synthetic aperture radar (UWB/SAR) has been used to detect concealed or buried targets under camouflage, forest cover, or shallow soil. Funding for these projects has largely come from the intelligence community, with some later substantial support from ARPA. The results have been quite positive. Vehicular targets have been detected with a high probability of detection (POD) and low false alarm rate (FAR) in a variety of forest and camouflage cover situations. A recent report[1] by a government team of experts confirms these findings. Shallow buried targets have also been detected with UWB/SAR on a fixed-wing platform from 3000 ft altitude. Deeper buried targets have been detected using downward-looking UWB radars, (non-imaging) from other platforms at lower altitudes. In order to achieve these results, the radar must operate in a spectral region where forest canopy scattering and soil absorption is low, and yet where reasonably good resolution (1 meter or better) can be maintained. This turns out to be the region from 100-500 MHz. Instrumentally, this is a difficult region in which to work, since the required antenna dimensions and integration times are significantly larger than in conventional (higher frequency) radars, and the long-term flight track recovery becomes a technical challenge. To date, the UWB/SARs have produced high quality imagery up to 11,000 ft altitude (AGL). The question arises as to whether the technology can be implemented at higher altitudes without degradation of the system performance. The overall field of UWB radar applied to surveillance problems is sufficiently

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[1] Robert R. James and Lawrence E. Hoff, Naval Command, Control and Ocean Surveillance Center Report, "Investigation of SAR Target Detection Algorithms Using Narrowband and Ultra Wideband Sensors," 15 May 1993.

complex that it will take a trade-off study to determine the areas of highest pay-off to the government. In particular, the technical problems in implementing a high altitude UWB radar, although known, need to be defined thoroughly in a systems study that would precede any substantial investment in hardware.

POTENTIAL FOR UWB/SAR

The areas in which UWB/SAR working in the VHF/UHF is known to succeed are

1. Detection of vehicles under camouflage (Fig. 1)
2. Detection of vehicles under foliage
3. Detection of small rivers, pathways under forest canopy
4. Detection of drums, vehicles, large mines under shallow soil cover (0 - 1m)
5. Detection of modest-sized buildings under foliage (Fig. 2)
6. Detection of shallow-buried bunkers/caches (Fig. 3)

Thus the UWB/SAR, as a wide-area surveillance sensor, offers potential for moderately high resolution imagery of concealed targets because of its unique capability to penetrate various forms of cover, including camouflage, in all-weather operation.

AREAS OF REQUIRED STUDY

1. Frequency

Most UWB work in the last three years has been conducted at VHF/UHF (SRI and others) with a small effort being conducted at X Band (NRL). The SRI work has covered foliage penetration as well as camouflage and soil penetration. (The NRL work has been directed at detection of sea-skimming missiles from deck height.) For applications where penetration is required, the VHF and even lower frequencies are essential. The Swedish government for example, has recently attempted to use a novel design called CARABAS, operating from 20-90 MHz, for sub-surface imaging, but to date have had only limited success. This spectral region should not be ignored in the study, since it potentially offers much greater penetration at the expense of poor (4 x 3m) resolution. The difficulty with the

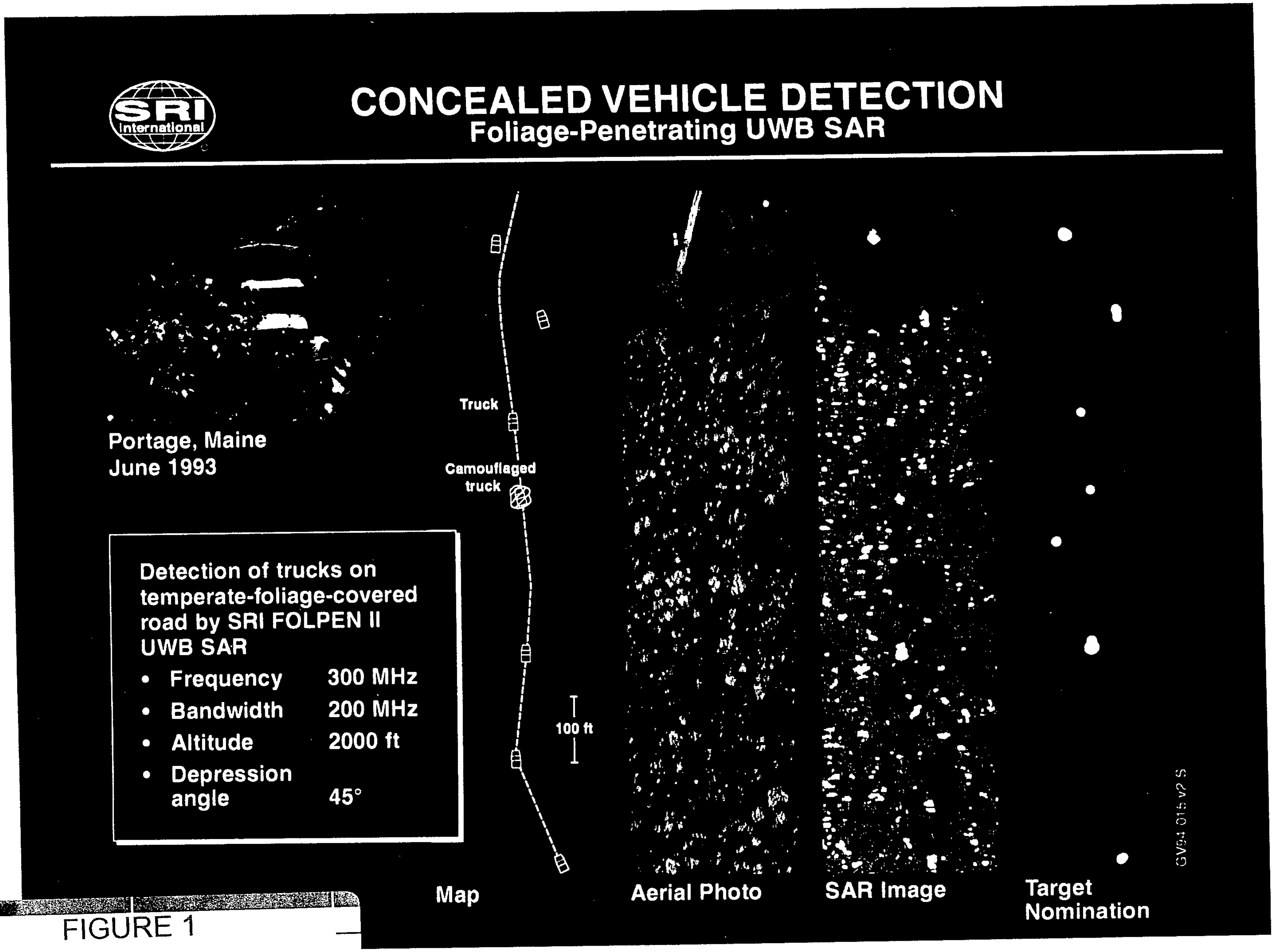
CONCEALED VEHICLE DETECTION
Foliage-Penetrating UWB SAR
SRI International
Portage, Maine
June 1993
Truck
Camouflaged truck
100 ft
Detection of trucks on temperate-foliage-covered road by SRI FOLPEN II UWB SAR
• Frequency 300 MHz
• Bandwidth 200 MHz
• Altitude 2000 ft
• Depression angle 45°
Map
Aerial Photo
SAR Image
Target Nomination
GV94 015 v2 S

FIGURE 1

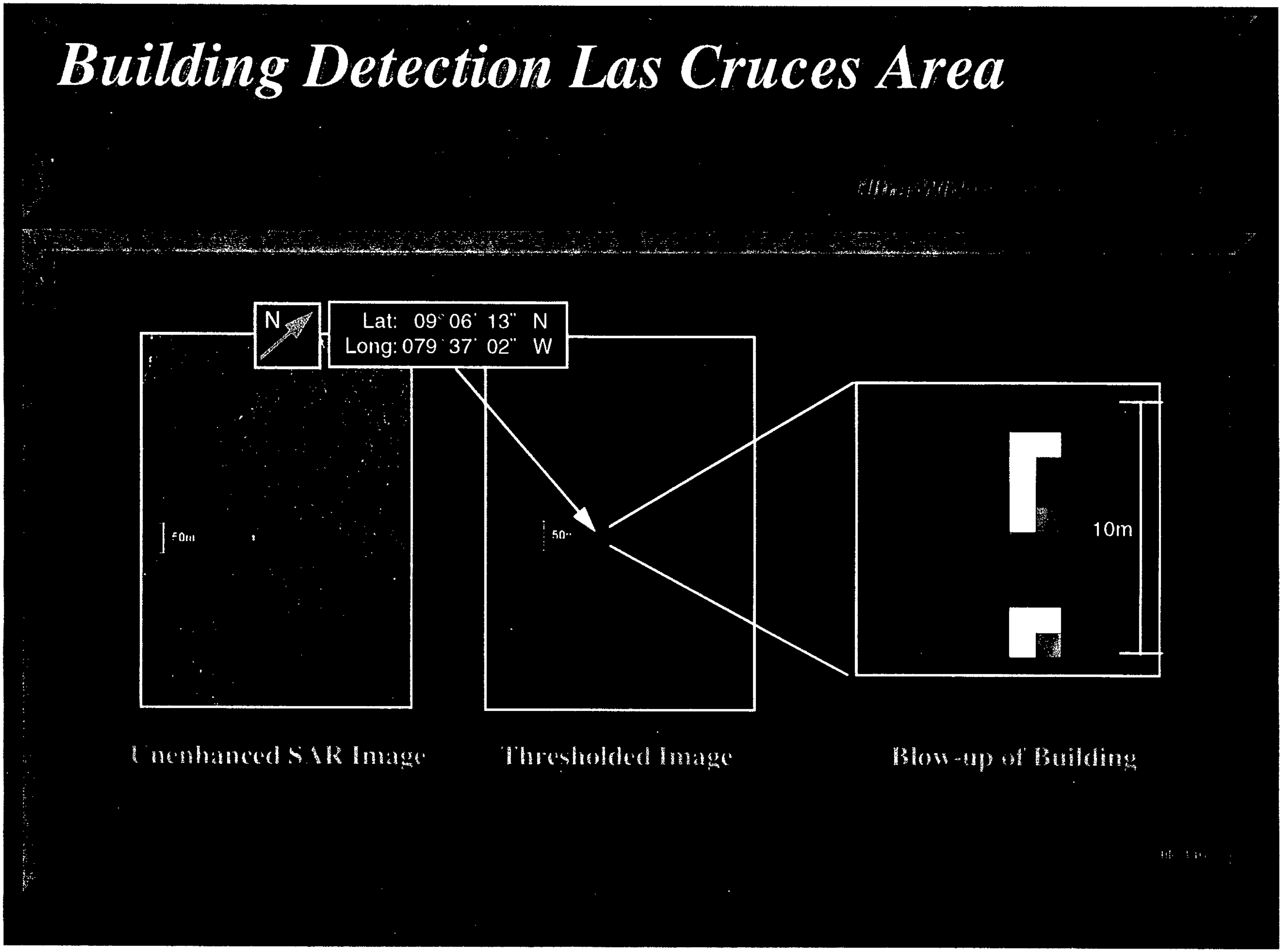
Building Detection Las Cruces Area
N
Lat: 09° 06' 13" N
Long: 079° 37' 02" W
50m
10m
Unenhanced SAR Image
Thresholded Image
Blow-up of Building

FIGURE 2

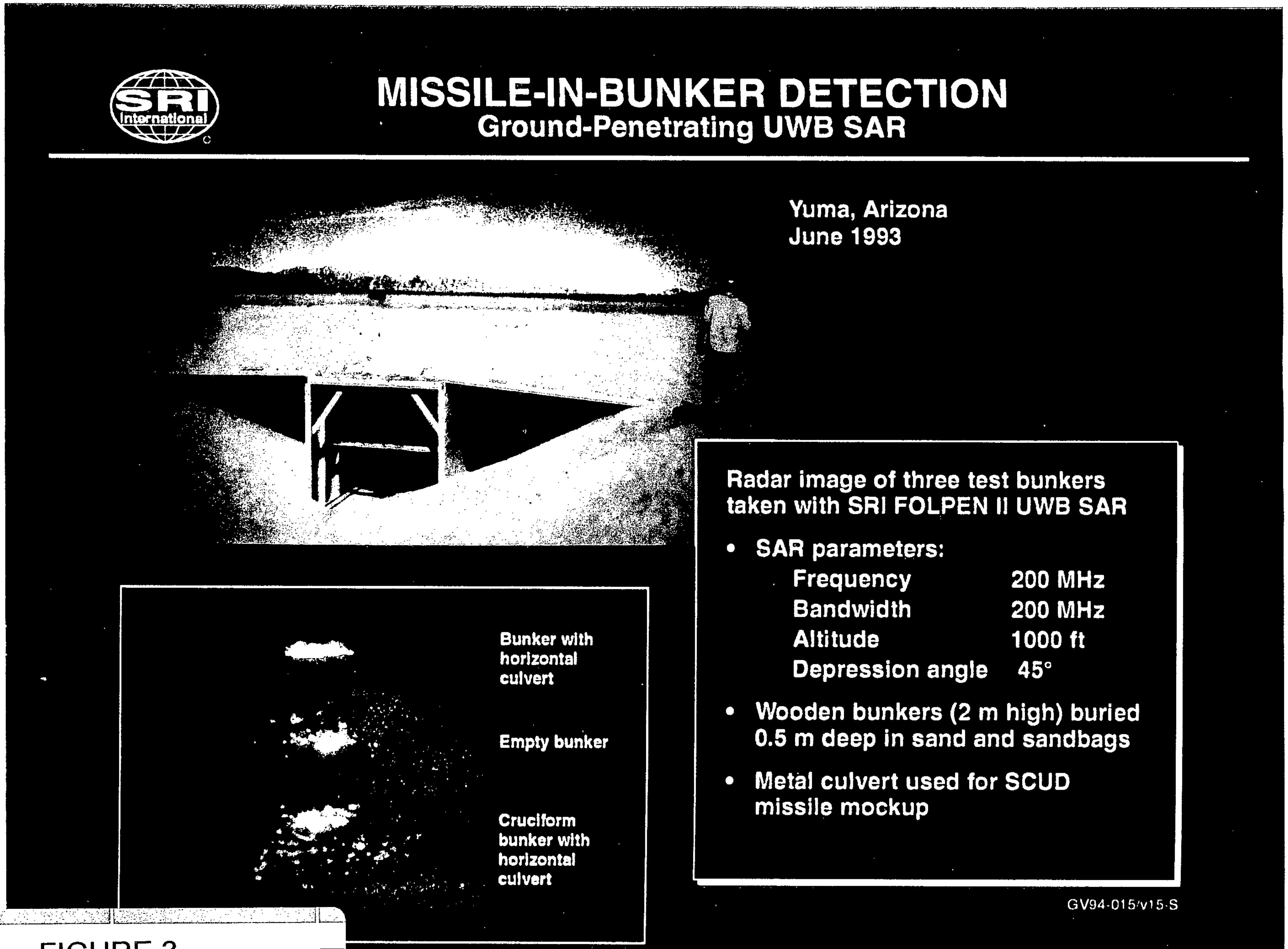
SRI International
MISSILE-IN-BUNKER DETECTION
Ground-Penetrating UWB SAR
Yuma, Arizona
June 1993
Bunker with horizontal culvert
Empty bunker
Cruciform bunker with horizontal culvert
Radar image of three test bunkers taken with SRI FOLPEN II UWB SAR
• SAR parameters:
Frequency 200 MHz
Bandwidth 200 MHz
Altitude 1000 ft
Depression angle 45°
• Wooden bunkers (2 m high) buried 0.5 m deep in sand and sandbags
• Metal culvert used for SCUD missile mockup
GV94-015/v15-S

FIGURE 3

Swedish system has been the mechanical design of the antennas, and their perceived need to use proprietary processing to form the SAR image. In fact, conventional processing of CARABAS data works quite well, as has been demonstrated by Lincoln Laboratory. The feasibility of other radar implementations in this frequency band should be studied.

2. Radar Equipment.

The major radar element affected by the choice of frequency is the antenna. The size of the antenna is roughly proportional to the longest wavelength employed in the radar; thus, the design for airborne antennas operating at VHF and lower frequencies can be quite challenging. The choices of antenna design are further limited by the airspeed and altitude for any planned survey operations . A major element of any UWB/SAR study should be the available classes of antenna design versus the speed and altitude of the survey platform. For space applications, the problems of wind loading and stress are replaced by ones of structural rigidity, size and weight.

3. High Altitude Operation.

The required product of transmitter antenna gain and transmitter power (P_tG_t) goes up rapidly with altitude. For a single point source, a factor of ten increase in operating altitude necessitates a factor of 1000 in P_tG_t. While this can be obtained, up to some limit, by using more powerful transmitters and physically larger antennas, the real gains beyond that limit are to be had by design of the transmitted pulse so as to take advantage of processing gain (pulse compression or correlation gain). In this way, a longer pulse can be transmitted to increase the average power, and the resolution is recovered by relatively standard processing techniques.

High altitude operation (30,000 ft and above) is therefore quite feasible with today's state-of-the-art technology. Ten watts of average power produces acceptable SNR at 10,000 ft altitude even in areas with significant man-made noise. Thus 30,000 ft operation could be achieved with 1 KW of average power. SRI currently operates a number of 1.3 KW transmitters in the 100-500 MHz band which are more than adequate for the airborne task.

Other considerations for high altitude operation are (1) the antenna design requires less vertical beamwidth is required, so the aperture could be increased in that dimension, platform constraints permitting; (2) the UWB noise field at high altitude has not been studied in any depth, and would be expected to be less than at low altitude since most high power transmitters in this band are TV and FM, which illuminate with a pancake-shaped beam over the terrain in the immediate vicinity. (There is no money to be made by radiating TV energy skyward). (3) Motion compensation is always a limiting factor on SAR operations, and at high altitude there is the advantage of smooth air, but the disadvantage of very long integration times. For example, a 1m resolution image at 30,000 ft and 45° depression with a center frequency of 300 MHz would require an integration time of 100 seconds. (4) Real time processing of such an image is a challenge since it would require integration of some 15,000 pulses as opposed to the 2,000 we currently integrate. However, rapid advances in processing and memory speed are diminishing the challenge.

4. Altitude and Coverage Rate.

The coverage rate of UWB radars designed for penetrating concealment is governed by many factors, including flight speed and swath width. With a flight speed of 150 kt and the standard swath of 2 Km, the coverage is 540 Km^2/hour. To achieve wide area coverage the swath can be increased; then the bottleneck becomes data flow and storage. Currently data storage devices are coming on the market with capacity and rate capabilities 4-6 times what is used in the current SRI FOLPEN series of radars. Thus a new design could be implemented today which would achieve up to 3000 Km^2/hour. Over the next decade, this data capability is certain to increase, probably up to an order of magnitude. Conservatively then, one could expect within the decade to achieve 10,000 Km^2 at 1m x 1m resolution.

Typically the penetration requirement entails use of high depression angles, which in turn give lower coverage per flight mile than conventional SARs. Coverage rates can therefore only be increased by either flying higher or faster. As with any high resolution imaging system, the available platform data rate also limits the average coverage rate, although bursts of high rate, high resolution coverage are always feasible. Thus a trade-off study should be made of the radar coverage rate versus system parameters, in which the platform flight envelope, the average raw power available, the processing power required, the communications link bandwidth, and the data storage and retrieval mechanism are all considered.

4. Ancillary Requirements.

If the UWB radar is to operate at long (VHF) wavelengths, there is a demand on the platform track recovery (positioning) system which is significantly more stringent than for the more conventional SARs. For example, whereas an X Band radar has a real beamwidth of a few degrees and requires an integration time of only a second or two, a UWB/SAR in the VHF/UHF has a beamwidth of over 90° and requires integration times in excess of 30 seconds. From the positioning standpoint, such a long-wavelength radar requires less short term accuracy, but requires that departures of the flight line from a theoretical straight line be accurately tracked for up to a minute. This places a severe stress on inertial systems, even with GPS supplements. Recent flights of a UWB radar in Panama showed that with 20 second integration and no positioning correction, the resolution dropped from 1 x 1m to worse than 3 x 3m. Addition of differential GPS information brought the 1 x 1m resolution back over the entire flight path.

SUMMARY

There are many diverse considerations in assessing the potential of UWB/SAR systems. Sufficient performance information is now available to show that the technology offers significant new intelligence information, and should be developed further. The first phase should be an evaluation that considers the range of possible missions, altitudes and platforms that would be appropriate for the technique. Then the required performance figures and technical specifications could be derived. Extrapolation of the development rate of various component sub-systems, such as the transmitter, the positioning, and the data handling systems should be carefully carried out, resulting in a believable prediction of what could be built and operated in the next few years. Since there are very few centers of excellence in this area, most of the information needed for such a study is available from a relatively small number of sources. We estimate that a comprehensive study could be completed in six months, with about a six man-month effort.

Following the evaluation phase should be a second phase to speed the development of the "long-pole" technologies necessary to move the technique from its current capability of modest altitudes with research scientist staffing to high altitudes (even space platforms) in a (near) operational wide area search mode. Included in this phase would be experimental verification and demonstration of the solution to all technology "stretches." One should expect that some of the "long-poles" will be mission or platform dependent, e.g., antenna configurations, power availability, space and weight constraints. Other "long poles" may relate to technology progress in such areas as GPS/INS track recovery accuracy over long (100 seconds) time intervals.

The substantial wide-area surveillance capability of the "penetrating" radar appears to offer sufficient benefits to warrant additional investment.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

THROUGH-THE-WALL 3-D CSAR SYSTEM CONCEPT

David F. Sun
Jay R. Sklar

Through-the-Wall Radar

1. Introduction and Summary

Effectiveness of many small unit operations would be enhanced by a synthetic aperture radar (SAR) image of the scene on the other side of an obstructing wall. Propagation phenomenology does permit radar energy to penetrate walls constructed of many common building materials if the operating frequency is sufficiently low (below 400 MHZ). But with such a long wavelength, target resolution is usually inadequate. Recent development of High Definition Vector Imaging technology has shown that operationally useful resolution can be obtained with a radar operating at these low frequencies. A radar able to "see" inside a building can be installed in a delivery van; another man-portable design can "see" inside the next room. Although this technology is in its early development stages, such capabilities should be available in a ten-year time frame. This paper describes this technology and outlines the projected system options.

This through-the-wall imaging radar has the potential to satisfy search, surveillance, and strike support missions in counter terrorism and built-up area operations. Pacing system requirements include:

1. image resolution sufficient to detect and track concealed weapons;
2. image capture rates sufficient to limit blurring to less than one pixel due to typical human motion;
3. high mobility, including both man-portable units for deployment in large building complexes, and covert vehicle-mounted systems;
4. image update rates sufficient for near real-time support to strike forces;
5. ability to penetrate typical building wall materials; and
6. low cost for widespread deployment among small units operating worldwide.

This paper describes a through-the-wall imaging radar system concept and provides the results of a first order analysis to quantify system parameters. The principal design features are:

1. the use of a Circular Synthetic Aperture Radar (CSAR) to avoid the cost burden traditionally associated with electronically scanned array approaches to radar image formation;
2. the use of a high rpm rotary joint CSAR with a single revolution image capture for minimum blurring due to uncompensated target motion;

3. the use of High Definition Vector Imaging[1] (HDVI) to achieve resolution sufficient to detect military weapons as small as handguns while operating at low enough microwave frequencies to insure building penetration[2]; and

4. the use of a parallel multiprocessor architecture such as one based on the SHARC digital signal processing chip for high throughput image update rates at affordable cost.

A three phase development plan has been proposed to ARPA. Phase I, Proof of Concept, is intended to establish feasibility through development and measurements focused on the principal risk areas, notably through-the-wall resolution. The Phase II field Demonstration is intended to provide imagery representative of an operational system for representative operational scenarios. The Phase II system will contain none of the processing subsystems required for real time operation, but system including image processing as a post mission function. The Phase III prototype Demonstration will focus on development and field testing of prototype transportable and man-portable versions. Both versions will include a near real time processing capability. A four year development schedule suggests that this capability could be in hand by the 2005 era.

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[1] G.R. Benitz, "Preliminary Results in Adaptive High Definition Imaging for Stationary Targets", Project Report AST-34, M.I.T. Lincoln Laboratory (4 November 1994).

[2] For purposes of this paper the most stressing requirement is that of penetrating concrete.

2. Transportable Through-the-Wall 3-D CSAR System Concept

Figure 1 shows the scenario that calls for the transportable system. This system will be a vehicle-based system for needed mobility. It will have its own motor generator for prime power and will operate across the street from the building of interest. The CSAR antenna consists of a 5 cm antenna element forming a 2 m diameter circular synthetic aperture. This system will have four interchangeable sensor heads for operation at four frequencies, 18 and 35 GHz for high resolution imagery, and 10 and 6 GHz for effective penetration through a concrete wall.

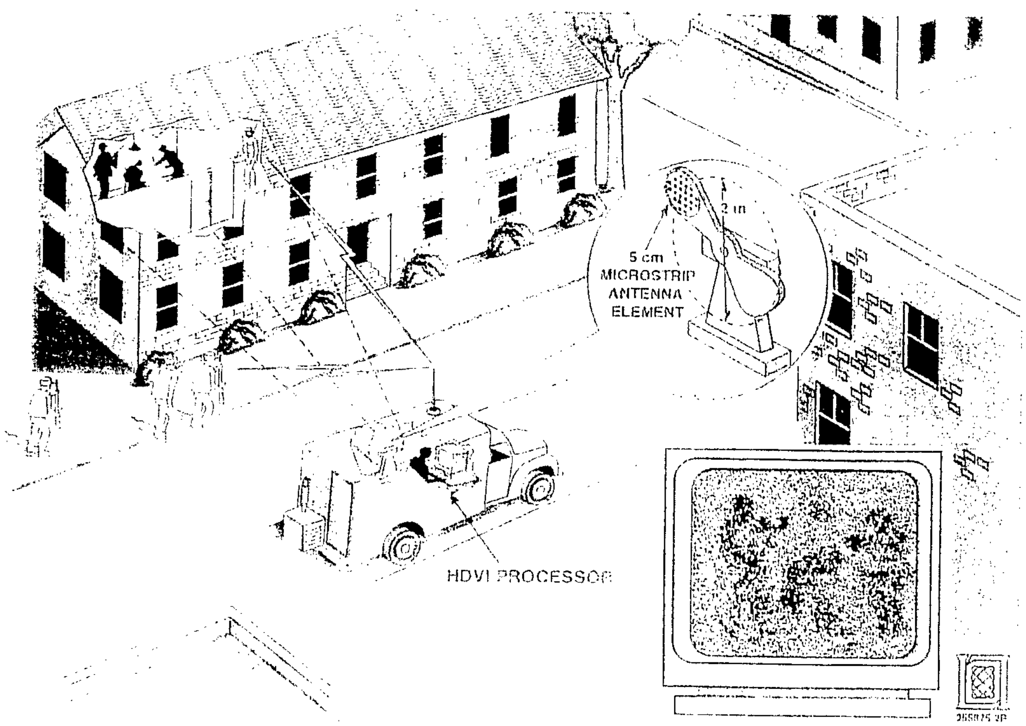


Figure 1. System Concept For Transportable Through-The-Wall 3-D CSAR

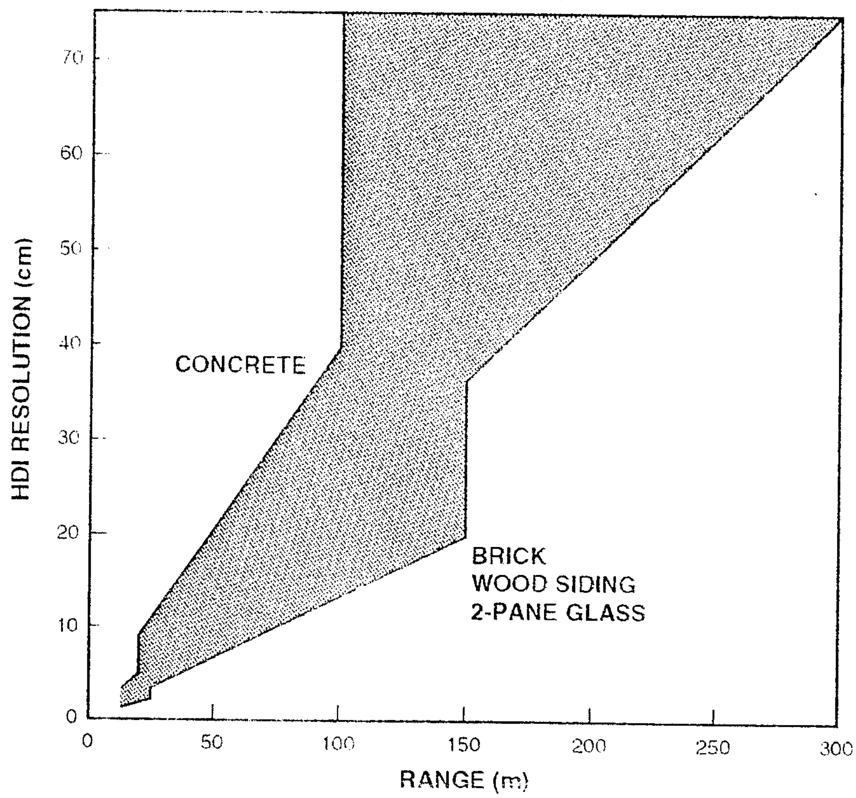


Figure 2. Transportable System Image Resolution Versus Operating Range

Its nominal operating range will be about 100 m for a typical 2 - 3 story building. As shown in Figure 2, excluding concrete walls, extended operating ranges can be achieved by sacrificing image resolution. High resolution 3-D images will be output from a COTS digital signal processor running the HDVI algorithm. With the HDVI processing, image resolutions of 1.8 cm, 3.5 cm, 6.2 cm and 10.4 cm are expected from this system operating at 35 GHz, 18 GHz, 10 GHz and 6 Ghz, respectively, for the nominal range of 25 m. With reasonable data rate, these images can also be transmitted to nearby commanding officers for real-time scene visualization.

The imaging environment here requires microwave signals to penetrate through various building walls. Thus, for a through-the-wall radar system, transmission loss through building

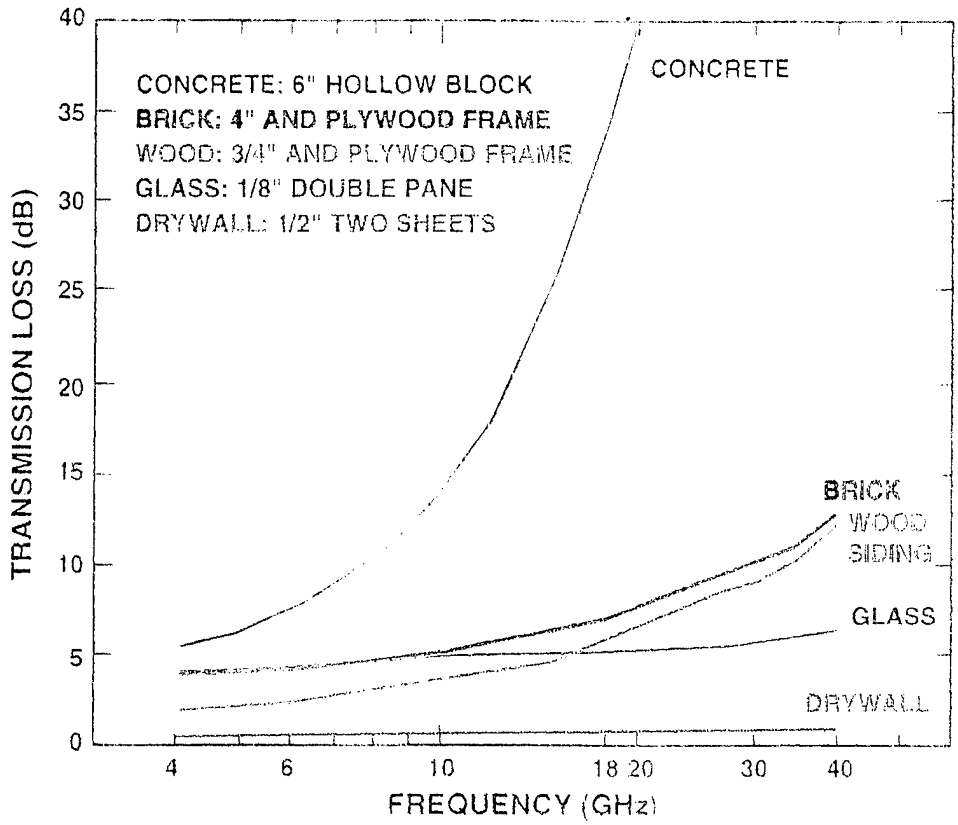


Figure 3. Measured One-Way Transmission Loss Through Walls

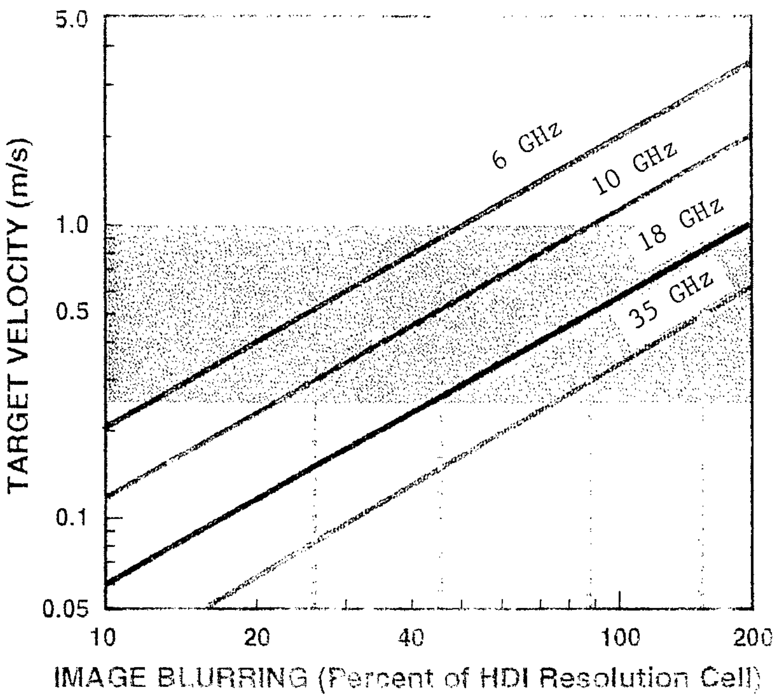
walls will be one important factor in system design consideration. Figure 3 shows the one-way transmission loss for five typical building walls[3]. It is quite clear that the transmission loss through the concrete wall increases rapidly for frequencies above 12 GHz, i.e., about 20 dB at 12 GHz and 40 dB at 20 GHz. For the other walls, the loss barely exceeds 10 dB below 35 GHz. For the concrete wall, this system will be set up to operate at 10 and 6 GHz. For the other walls, two more operating frequencies at 18 and 35 GHz will be provided for improved resolution.

---

[3]These curves have been constructed using measured data published by General Dynamics for loss through various material. Except for glass wall and drywall, these walls all consist of four layers of materials. That is, behind the outer layer of concrete, brick or wood-siding, it is a typical building framing, formed with 3/4" of plywood, 3-1/2" of insulation and ½" of drywall.

The choice of a circular synthetic aperture is dictated by the need to minimize the image blurring due to possible target motion. In particular, image capture time needs to be as short as possible. With the circular synthetic aperture, image capture time of 60 ms can be realized with available 1000 rpm RF rotory joints. As will become clear in the following example, the aperture scan rate of 1000 rpm not only will provide high resolution and reasonably unblurred imagery for this system but will also provide an attractive operational performance envelope with no more than 100 watts of transmitter power.

As an example, performance trade-offs are evaluted at a range of 25 m. Figure 4 presents an evalution of blurring for the four operating frequencies of the transportable system.



RANGE = 25 m
APERTURE = 2 m
APERTURE SCAN RATE: 1000 rpm

FREQUENCY (GHz)	HDI RESOLUTION (cm)
6	10.4
10	6.2
18	3.5
35	1.8

Figure 4. Moving Target Image Blurring: Transportable System

Two things about the image blurring can be easily understood from Figure 4. First, for a given aperture scan rate, the faster the target moves, the blurrier the image will be. Second, for the same target speed, the finer the image resolution, the blurrier the image will be. Here, it can be seen that for a person walking at a pace of about half a meter per second (faster than 1 mph), image blurring should be acceptable, at less than one HDI resolution cell for the image with resolution down to 3.5 cm and at 1.5 HDI resolution cell for the image with 1.8 cm resolution.

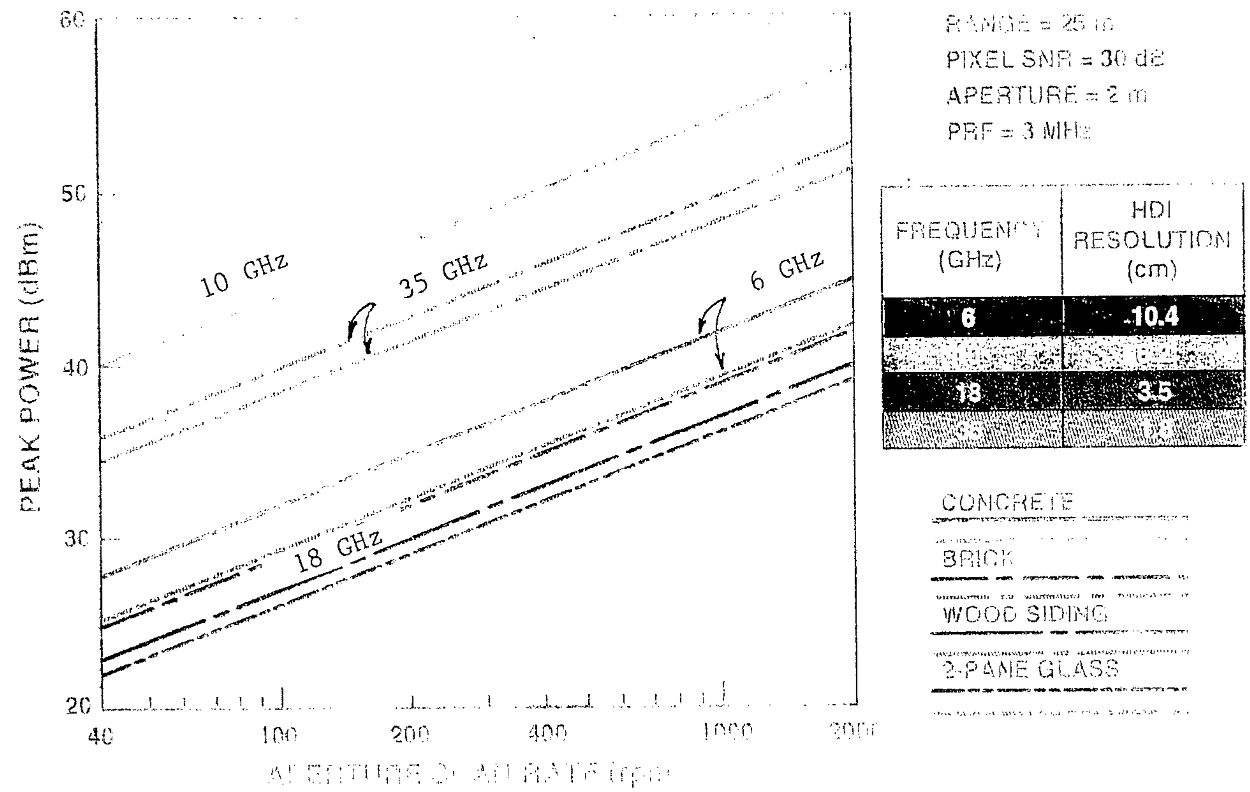


Figure 5. Required Transmitter Power for Transportable System

Figure 5 shows the required transmitter power to provide high resolution imagery at 30 dB pixel SNR. With a 10 watt transmitter power, this transportable system can image at 1000 rpm through a 2-pane glass wall at its limiting resolution of 1.8 cm, through brick or wood-siding wall at 3.5 cm resolution and through concrete wall at 10.4 cm resolution. For a brick or wood-siding wall, it will take about 80 watts of transmitter power at 1000 rpm to achieve 1.8 cm resolution. Achievement of 6.2 cm resolution through concrete walls requires 200 watts of transmitter power at 1000 rpm.If the transmitter power is limited to 100 watts, 6.2 cm resolution can be achieved through a concrete wall by slowing down the aperture scan rate to 400 rpm.

Rapid image update is important for applications such as strike support. Image update rate depends on computation requirements for a given image processing algorithm. The HDVI processing for the transportable system takes about 100K real operations per HDI pixel. This kind of computation load can be handled by the SHARC MeshSP which has recently been

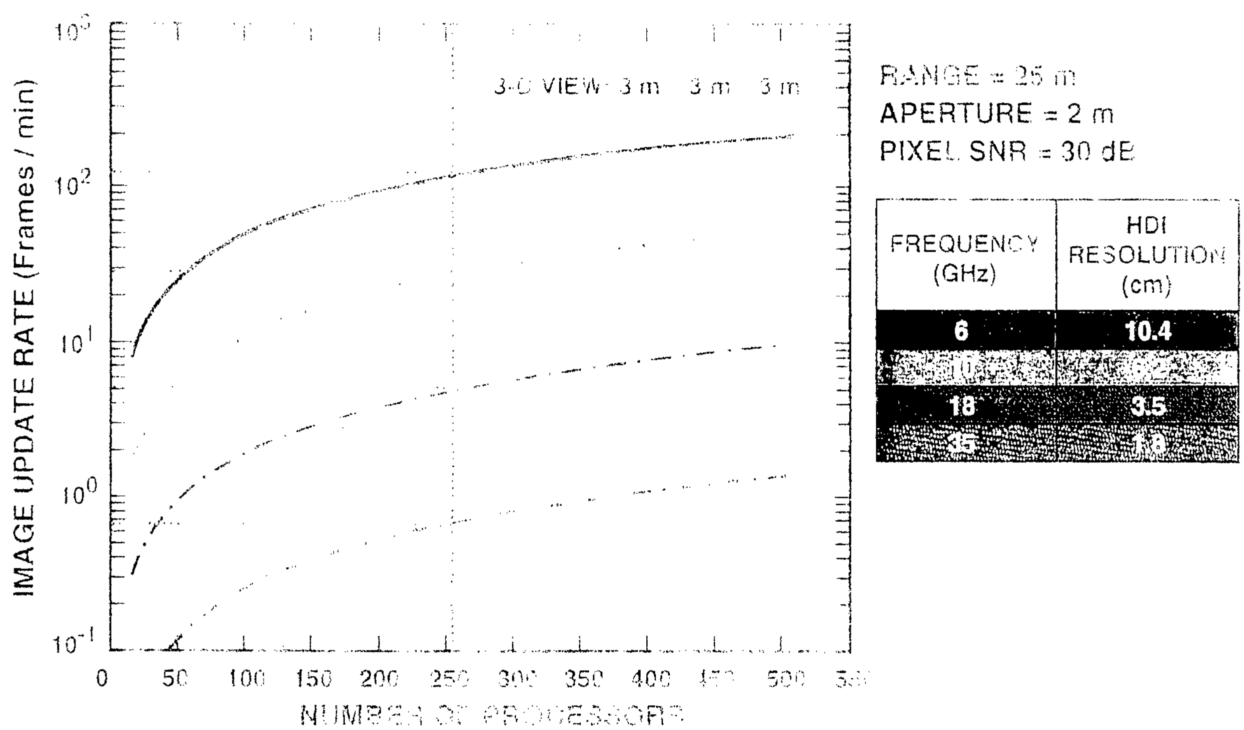


Figure 6. Image Update Rate for Transportable System

developed at Lincoln Laboratory and will soon be in production. Figure 6 shows the image update rate as a function of the number of SHARC processors for the transportable system operating at 25 m range, as described in the above example. For a given image resolution and a fixed viewing volume, the image update rate almost entirely depends on the number of digital signal processors to be used. For example, as indicated in Figure 6, 256 chip SHARC processors[4] provide a 3-D high definition image for a 3m x 3m x 3m room at an update rate of 0.7 and 5 frames per minute at a resolution of 1.8 and 3.5 cm. For a medium resolution of 6.2 cm, an image update rate at 30 frames per minute can be achieved.

[4]These only amount to 4 SHARC MeshSP cards.

3. Man-Portable through-the-Wall 3-D CSAR Sytem Concept

The man-portable system concept is depicted in Figure 7. This system can operate on local power when it is deployed inside the target building in a nearby room at a range up to 25m. As indicated in Figure 8, extended range can be achieved at reduced resolution. This system employs a circular aperture of 1 m in diameter for portability. A folding mechanism would facilitate transport in standard suitcases. It will be equipped with a 5 cm antenna element operating at 10GHz. At its nominal operating range of 12m, high resolution 3-D images with 6cm resolution can be obtained using HDVI processing.

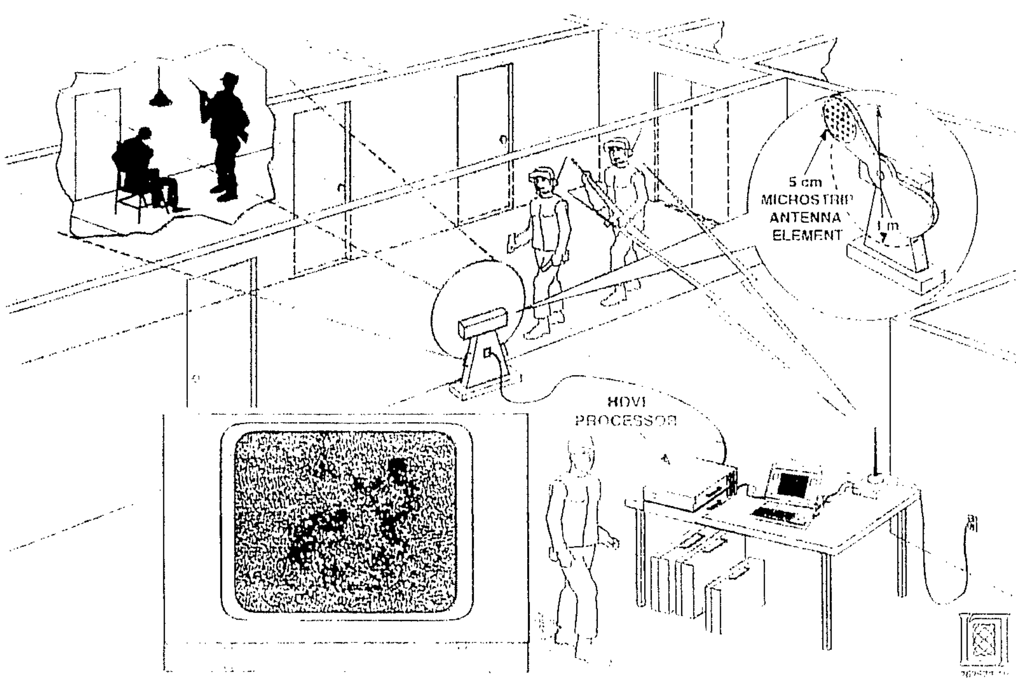


Figure 7. System Concept for Man-Portable Through-The-Wall 3-D CSAR

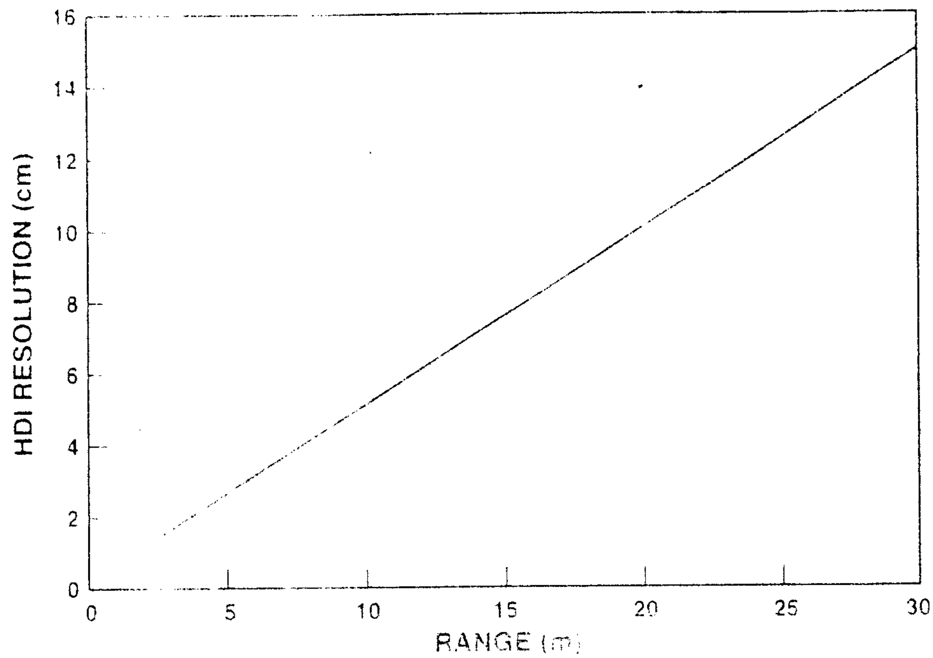


Figure 8. Man-Portable system Resolution Versus Range

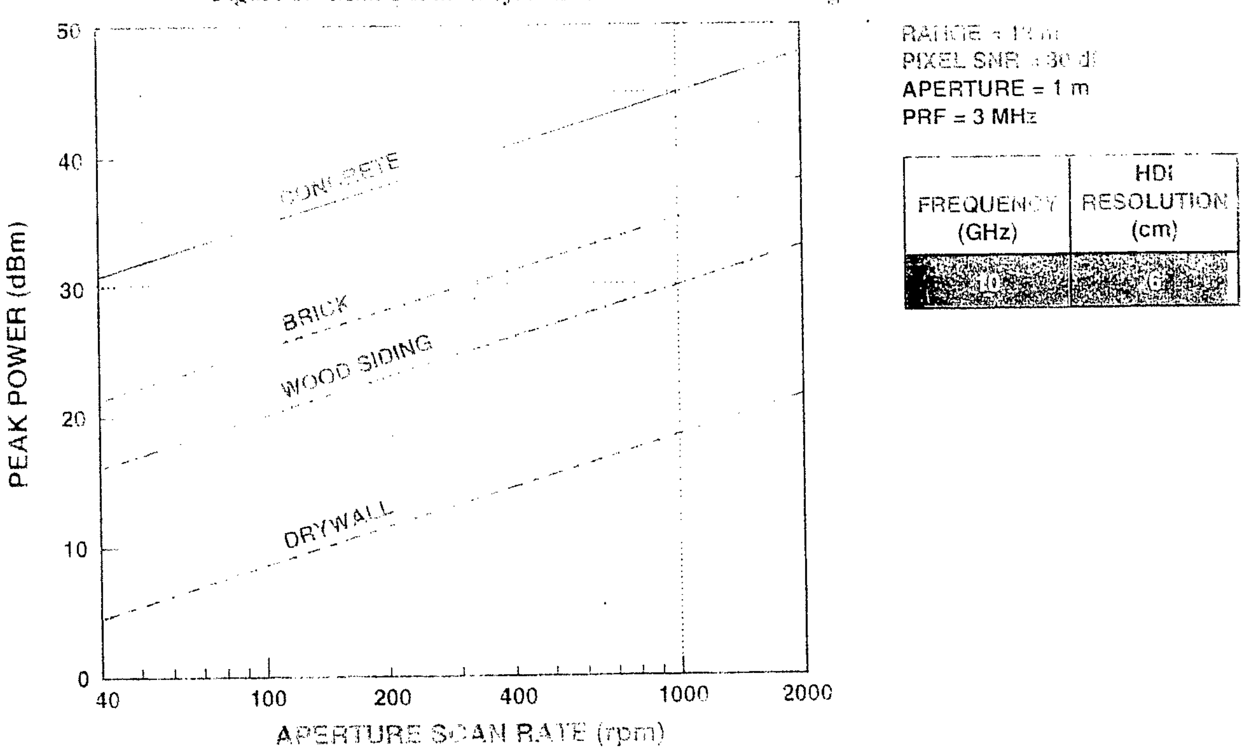
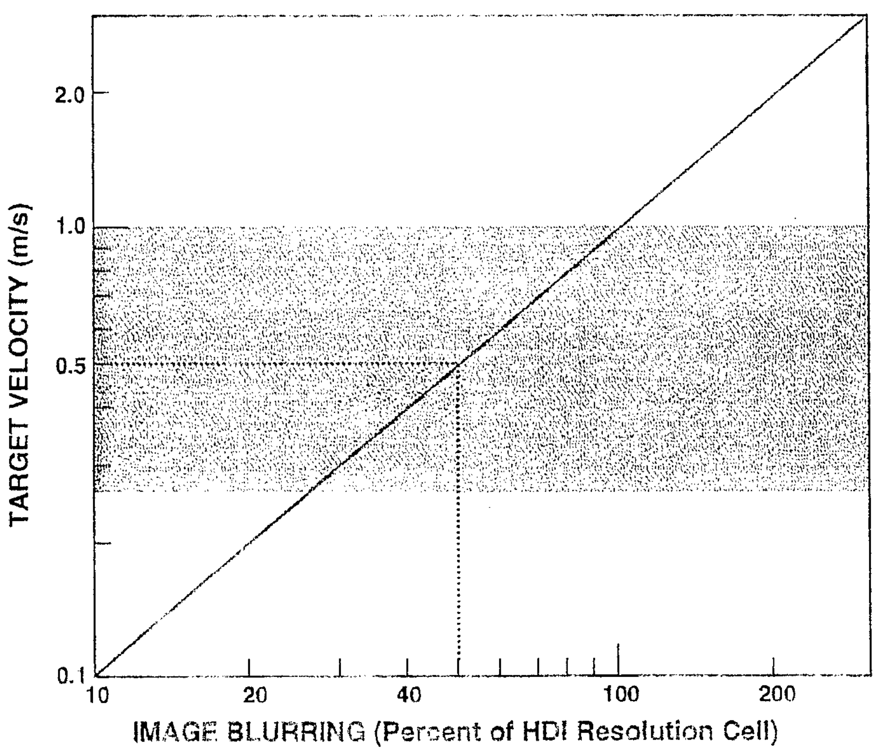


Figure 9. Required Transmitter Power for Man-Portable System

The required transmitter power to achieve 30 dB pixel SNR at a nominal 12 m range is shown in Figure 9. For an aperture scan rate of 1000 rpm, 10 watts of transmitter power will suffice for drywall, wood-siding or a brick wall. For a concrete wall, 30 watts will be required. However, if this ystem is constrained to operate with a maximum transmitter power of 10 watts, the aperture scan rate can be reduced to 300 rpm. Slowing down the aperture scan will result in a blurrier image only if target motion is significant. Figure 10 shows the degree of image blurring due to target motion for this system operating at 1000 rpm aperture scan rate. For half meter per second target velocities, the image will only be blurred by about half of a HDI resolution cell.

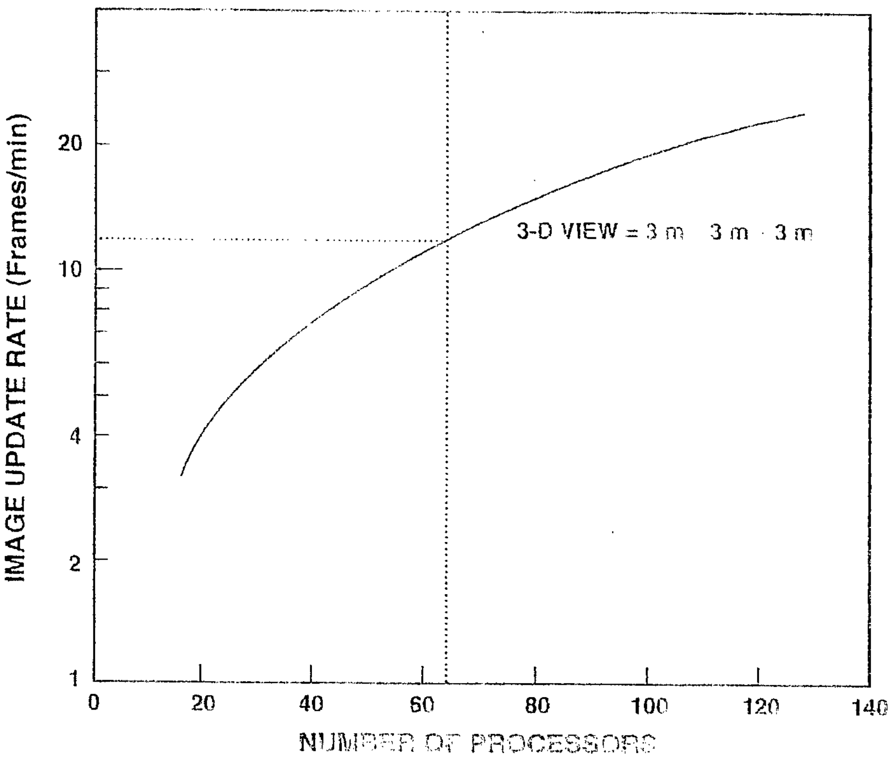
Figure 11 shows the image update rate as a function of number of SHARC processors for a 3m x 3m x 3m room for an operating range of 12 m. As indicated in Figure 11, one SHARC MeshSP card of 64 processors can produce a 12 frames per minute image update rate.



APERTURE = 1 m
RANGE = 12 m
APERTURE SCAN RATE:
1000 rpm

FREQUENCY (GHz)	HDI RESOLUTION (cm)
10	6

Figure 10. Moving Target Blurring: Man-Portable System



RANGE = 12 m
APERTURE = 1 m
PIXEL SNR = 30 dB

FREQUENCY (GHz)	HDI RESOLUTION (cm)
10	6

Figure 11. Image Update Rate for Man-Portable System

4. System Specifications

Table 1 summarizes specifications for the two candidate CSAR systems. The system performance in terms of image resolution, update and SNR should be more than adquate for their designated mission applications. The importance of HDVI processing is illutrated by considering the requirements for a conventional rail SAR design. To achieve a 1.8 cm resolution, such a system without HDVI processing would require a 6 m aperture and a 8.4 GHz bandwidth.

Table 1. Candidate System Specifications

	Transportable	Man-Portable
RANGE (m)	20-100	2-25
WALLS	EXTERIOR: CONCRETE BRICK, WOOD, GLASS	INTERIOR: CONCRETE BRICK, WOOD, DRYWALL
APERTURE (m)	2	1
ANTENNA ELEMENT (cm)	5	5
APERTURE SCAN RATE (rpm)	1000	1000
FREQUENCY	35, 18, 10, 6	10
BANDWIDTH (MHz)	2800, 1440, 800, 480	833
PRF (MHz)	< 1.5	< 6
PULSE WIDTH (ns)	< 130	< 13
TRANSMITTER POWER (watts)	100	10
NO. OF SHARC PROCESSORS	256	64
PRIME POWER	20	1.8
VIDEO DATA RATE (Kbits/s)	150	30
HDI RESOLUTION (cm)	1.8, 3.5, 6.2, 10.4	6.0
IMAGE BLURRING (% pixel)	150, 80, 50, 20	50
TARGET PIXEL SNR (dB)	> 30	> 40
3-D IMAGE UPDATE RATE (fpm)	0.7, 5, 30, 110	12

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

SNIPER DETECTION RADAR

Jay R. Sklar
H.D. Goldfein

29 March 1996

Sniper Detection Radar

Introduction

Snipers are a constant threat to small unit operations. Acoustic and optical approaches to detecting and locating snipers are currently funded at ARPA. Both approaches suffer some critical shortcomings, primarily that they are subject to tactical countermeasures which prevent the sensor from having a line-of-sight view of the sniping weapon muzzle. In addition, accoustic sensors have poorer accuracy than IR or radar sensors. Several radar system concepts have been explored to overcome this difficulty. The radar tracks the sniper bullet along a portion of its trajectory and extrapolates back to the firing point which need not be in view of the sensor. Typical radar deployments would focus on the area to be protected rather than on the locations where snipers might be located. The radar options allow the use of lower power transmitters with small antennas suggesting hardware costs can be low. This paper outlines the technologies involved and summarizes the capabilities of radar systems based upon them.

Figure 1 illustrates the sniper shooting geometries. Hidden snipers operating from inside buildings or from bunkers avoid accurate location by acoustic sensors or IR sensors which depend on muzzle flash for detection/location.

Radar System Concepts

Several radar system concepts have been assembled based on these objectives:

1. High accuracy sniper location determination, with a 5 foot maximum horizontal error;
2. Operation with partly obscured bullet flight path, with the required accuracy being achieved with 100-300 m observation of a 1 km flight path being visible;
3. Capability to detect, backtrack, and locate the first bullet;
4. Sufficient sensitivity to handle 5.45 mm to .50 cal bullets;
5. Operationally appropriate size.

Various radar concepts, differing in their overall tracking configuration, have been examined: range and angle track, multiple netted radars for multilateration tracking, etc. The more promising of these will be described in this paper.

Figure 2 provides some details on six system concepts. The first two are based on detecting and tracking the sniper bullet for a portion of the trajectory and then backtracking this trajectory estimate to locate the sniper. Both systems use an electronically scanned array (ESA) to form multiple beams and develop a track from the ranges at which these beams are cut as the bullet passes through them sequentially. Performance is strongly affected by beamwidth; thus

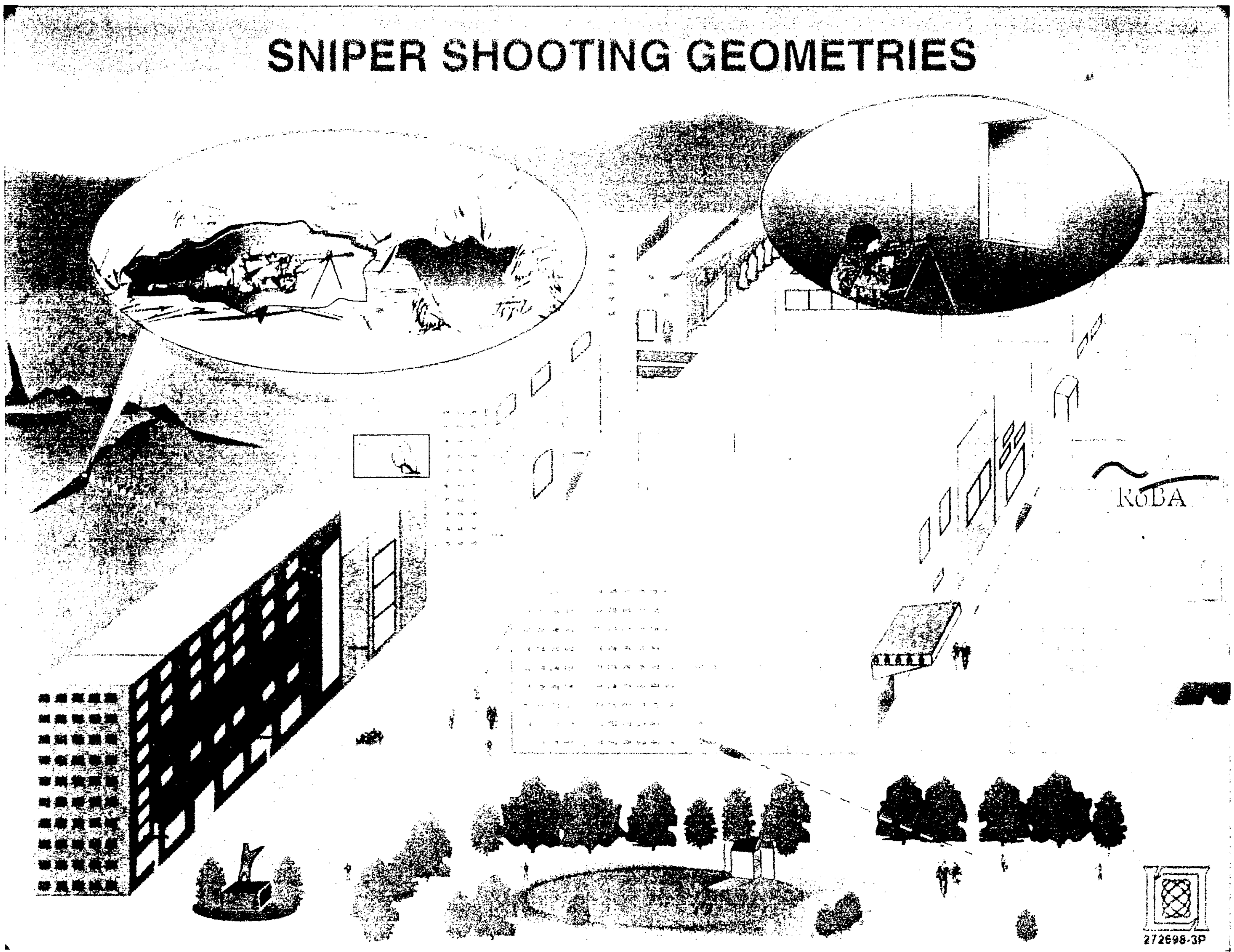
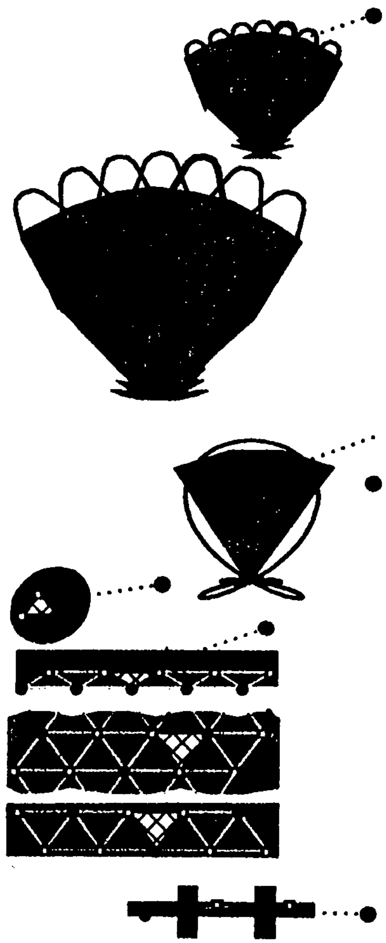


Figure 1

SNIPER DETECTION AND LOCATION
RADAR BASED OPTIONS



ANGLE MEASUREMENT	ANTENNA SIZE	BEAMWIDTH (degrees)	POWER (Watts)	RANGE (meters)
RADAR	10 ft; 27-45 in × 9 in; 1.5 in	3.3, .5	20	500
	40-56 in × 9 in	2.5	12	500
RADAR Direct sniper visibility	14-30 in × 18 in	6.5	70	1000
IR	1.5 in × 8 in	60-180	4-40	500
RADAR range based multilateration	1 in × 10 in	360	150	800 triangle edge
corridor geometry	8 in × 8 in	10	2-4	800 short triangle edge

BDSUMM

Figure 2

one of these backtracking radar options uses a large, though unfilled aperture to enhance angular measurement accuracy.

The third option uses a single beam, and is therefore less complex than the first two, but it requires the sniper location to be within radar detection range.

For comparison, an angle tracking IR system is included.

The final two options require a net of range-only radars, with the attendant high data rate communications requirements. One of these options assumes an advantageous net geometry, relieving requirements for angular accuracy; the other is constructed for operation in a narrow corridor such as in a highly built-up area, with a deployment which limits the opportunity for minimal geometrical dilution of precision.

Electronically-scanned Array Radars

Figure 3 illustrates an ESA radar installed on a HMMV. As indicated above, the design driver is the antenna system. Tracking analysis has shown that an azimuth accuracy of 0.025 to 0.1 degrees is required, depending on the geometry in order to meet the backtracking goal of a 1.5 m location uncertainty at the sniper location. If options are limited to easily deployed antennas, at frequencies where the bullet radar cross section is sufficient for reliable tracking, a beam-splitting capability of 20:1 to 100:1 is demanded. Such beam-splitting requires 1) precise calibration, 2) no radome distortion, and 3) minimal degradation from multipath. The antenna pattern must have low sidelobes to counter ground clutter. These antenna demands give rise to a split aperture such as that included in the second ESA option.

Coherent processing of multiple radar pulses is required to achieve adequate sensitivity. But during the required 50 ms coherent processing interval (CPI), there is considerable bullet motion. This motion sharply limits the number of independent array samples required to resolve and suppress clutter through adaptive antenna processing. On the positive side, these multiple array samples reduce calibration error through error averaging.

Table 1 summarizes the critical design parameters for several ESA radar designs. One should view this table as a set of five examples, an existence proof that a workable set of parameters can be found. None of these examples should be considered optimal. Figure 4 is one conceptual antenna design for such a radar; Figure 5 is a comparable design for a radar designed to detect the sniper position without backtracking a portion of the bullet trajectory.

Autonomous Radar/IR System

Figure 6 illustrates this concept. This operates as an autonomous system using a widebeam radar antenna for range measurements and a co-located passive IR sensor for angle measurements. The two sensor modalities complement each other, relieving requirements for a large radar aperture associated with strictly radar-only systems. A new IR sensor, capable of providing angle measurements which are accurately time-aligned with the radar range measurements would be required. Figure 7 show two examples of broad azimuth, narrow elevation beam antennas; the antenna gain needed to provide adequate radar sensitivity would be

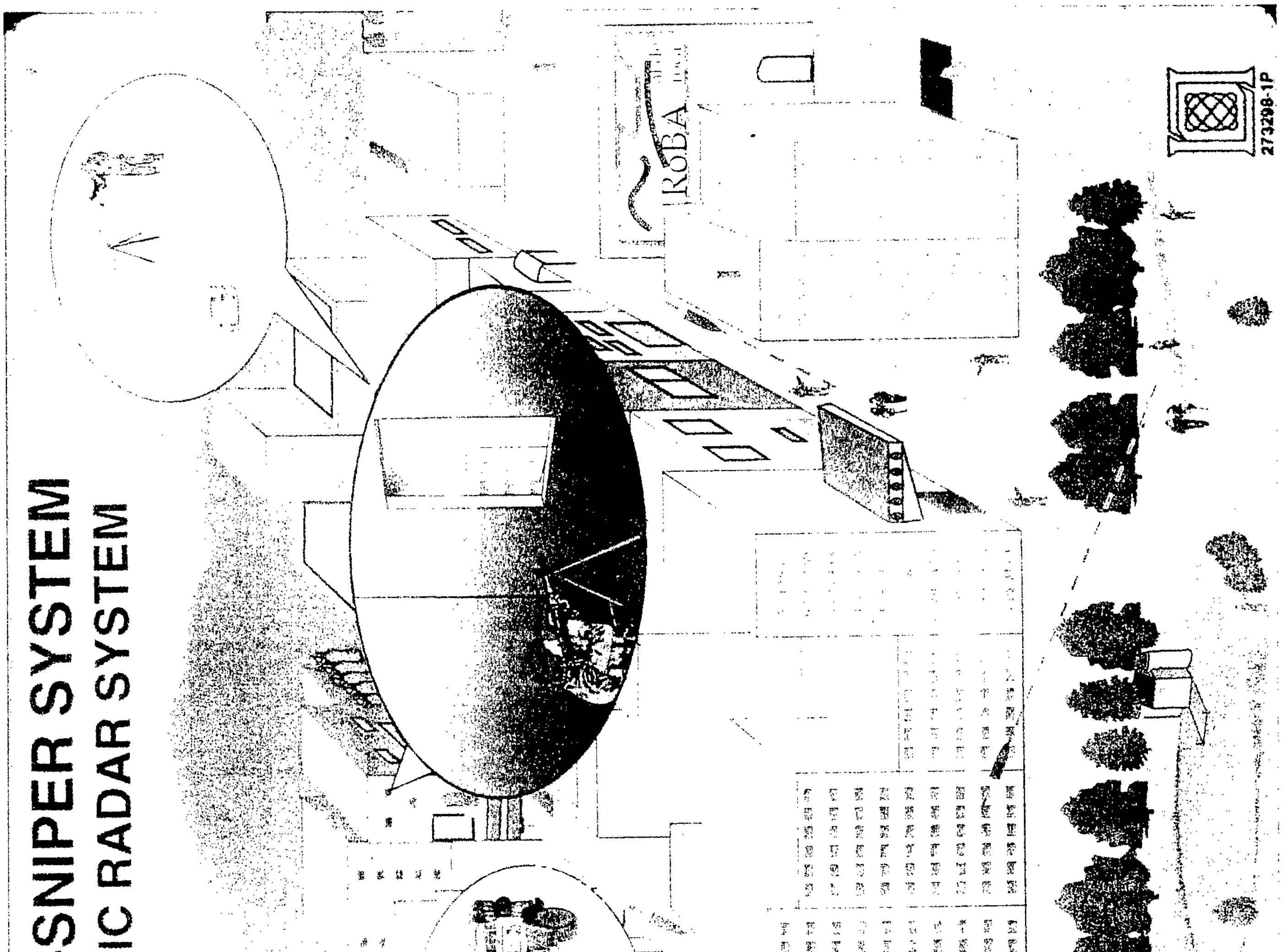

COUNTER-SNIPER SYSTEM
MONOSTATIC RADAR SYSTEM
ROBA
273298-1P

Figure 3

Table 1

ESA DESIGN POINT EXAMPLES

- 5.56 mm Target, Coverage 120 deg × 100 m

Frequency (GHz)	Range (m)	Beam Width (deg)	Beam Split Ratio	Average Power (W)	Antenna Size (m)	Blind Velocity (m/s)
10.5	1000	6.5	65	27	.56 × .3	70
10.5	500	2.5	100	2	1.5 × .15	95
10.5	500	3.5,.6	35,25	4	1,3 × .15	85
14.5	500	2.2	88	5.5	1 × .11	100
35.0	500	1	40	110	1 × .042	100

- Many sources of X band T/R modules; At least one Ku band source; 35 GHz availability is unknown

60223-03

DIRECT SNIPER OBSERVATION RADAR

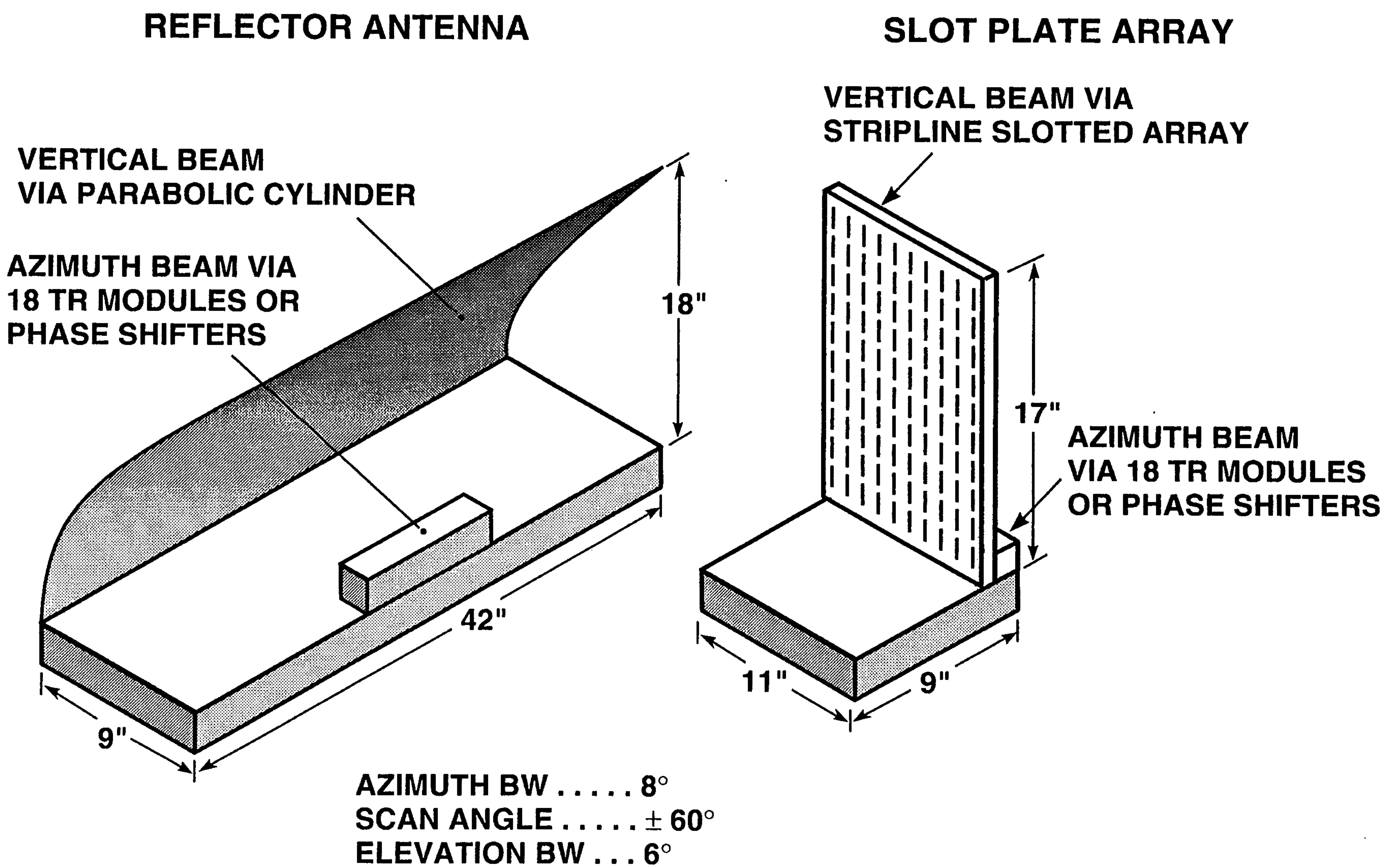


Figure 4

SHORT RANGE RADAR FOR BACK TRACKING LOCATION DETERMINATION

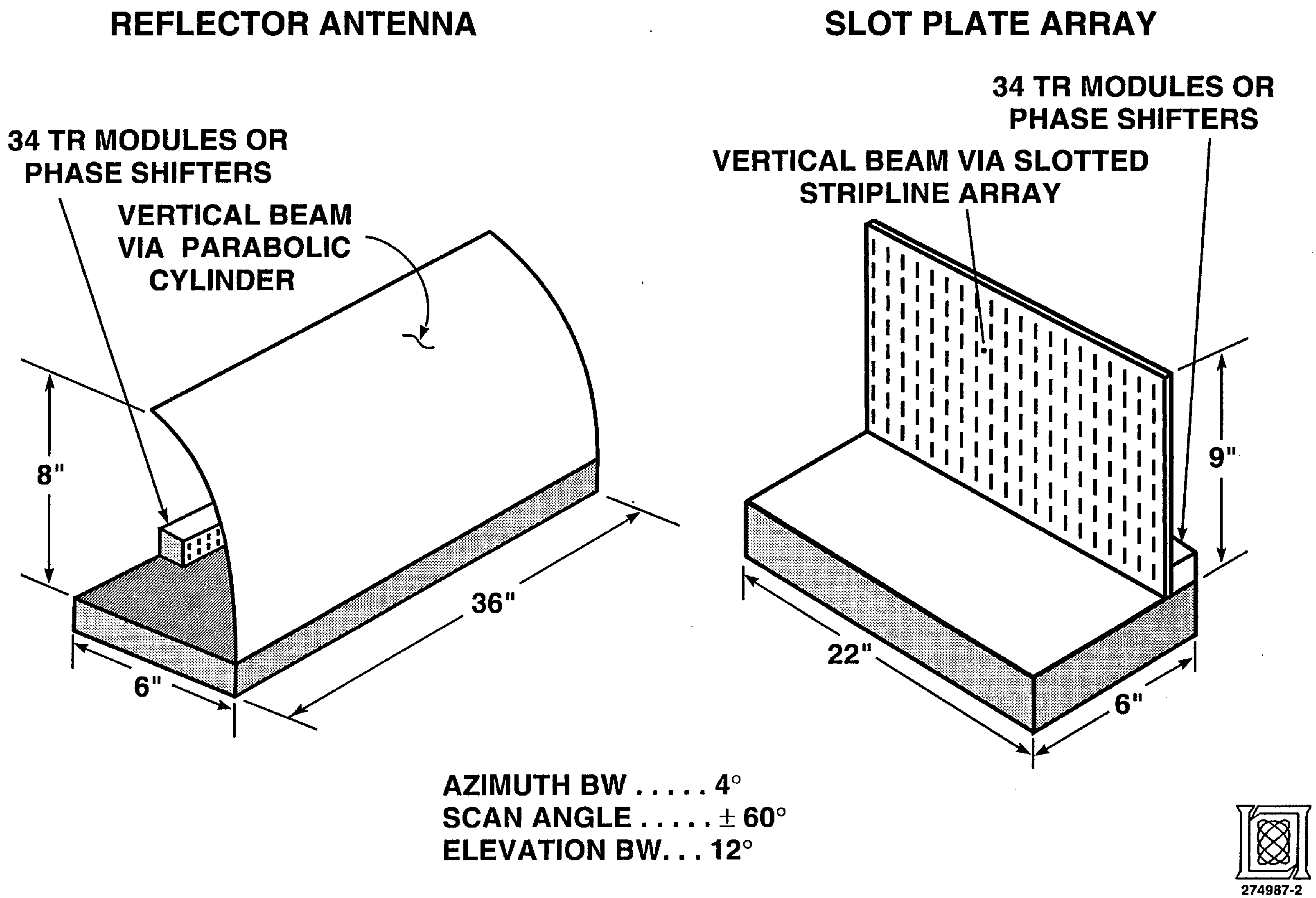


Figure 5

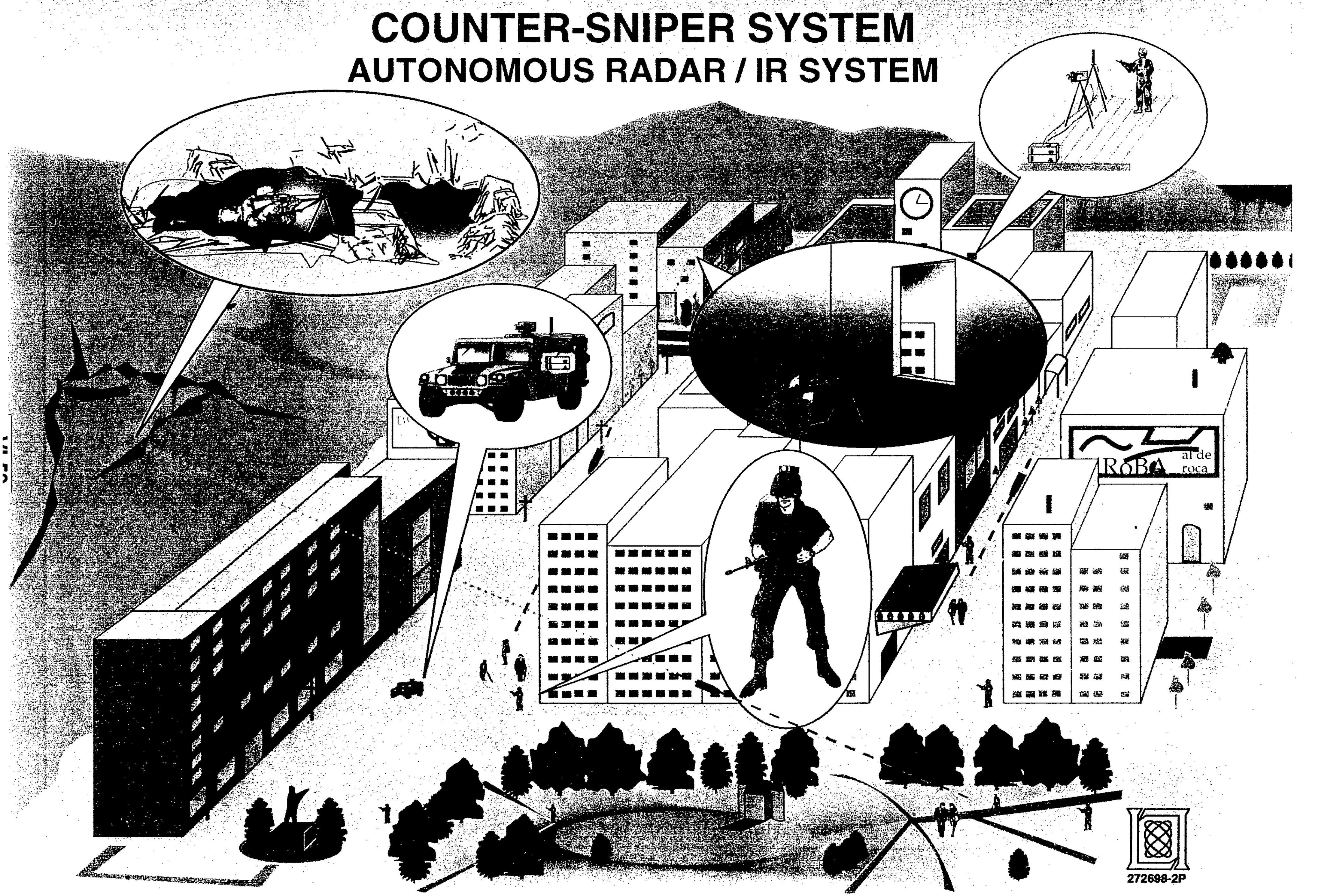

COUNTER-SNIPER SYSTEM
AUTONOMOUS RADAR / IR SYSTEM
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Figure 6

BROAD AZIMUTH BEAMWIDTH ANTENNAS

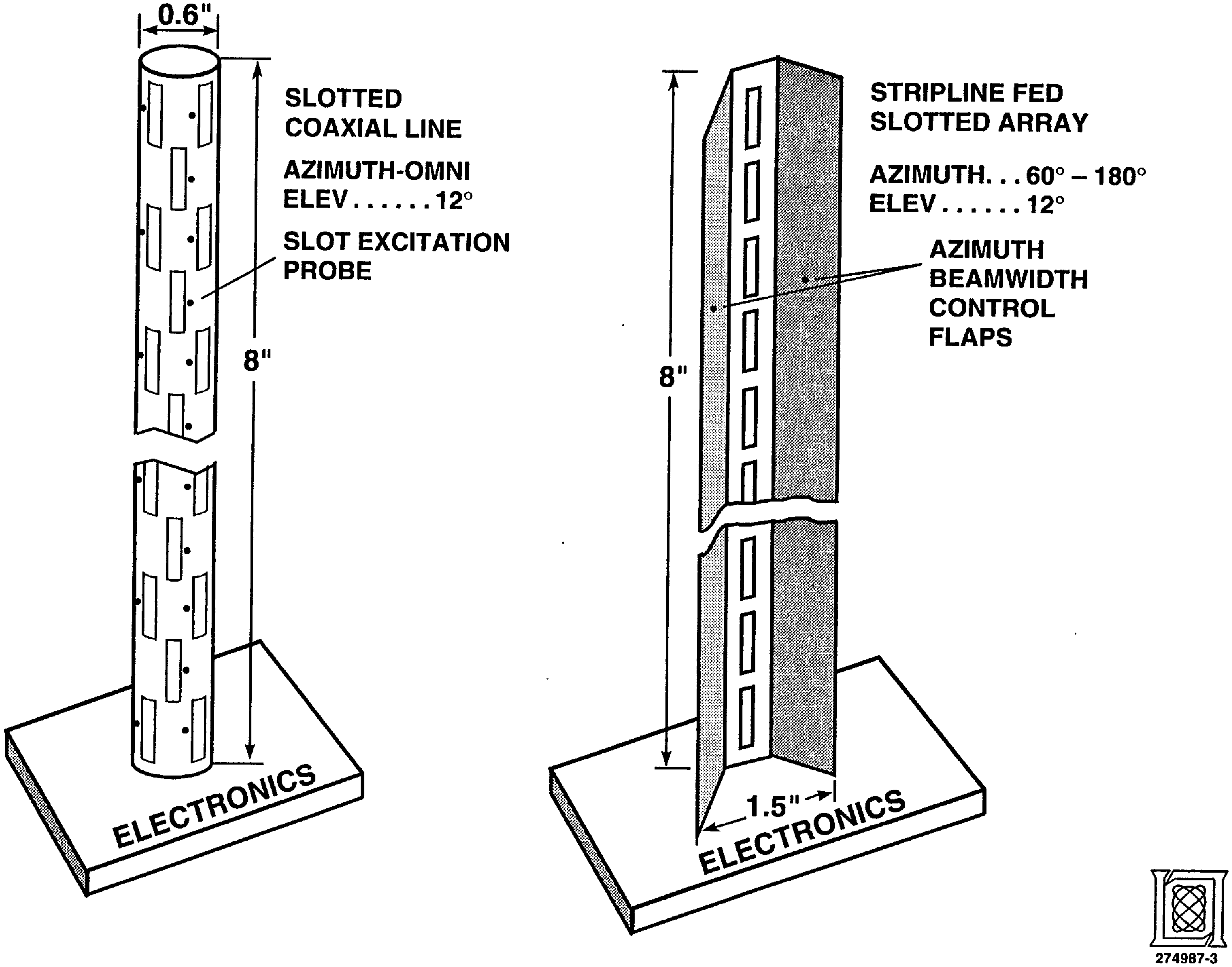


Figure 7

have to be limited if the broad azimuth coverage were to be obtained. As a result, the transmitted radar power may be higher than with the ESA systems.

Multi-site, Bistatic Radar Systems

Two systems using a single radar transmitter and a set of netted receivers are described in this section. Figure 8 illustrates this concept showing the transmitter/receiver mounted on a HMMV and several receivers; telephone pole, in-building, and head-mounted receivers are included as alternatives. If the system is to operated in a limited corridor, a restricted field-of view antenna such as the one shown in Figure 9 could be used to provide a narrow beam in both azimuth and elevation directions; the advantage is lower transmit power requirements.

These multilateration systems operate bistatically for minimum cost. Precision siting of the receivers can be easily accomplished with GPS receivers. Since each radar receiver will have autonomous detection processing, communications will be limited to very low rate data packets which can be accommodated by standardized communications gear; no dedicated communications system is required. Since there is a single radar transmitter to cover an entire area, the cost of the system will be low.

The geometry of this system is very flexible. Many options have been considered in sufficient detail to show that the same system components can be used in a variety of geometries. Interactions with the user community is necessary to select a few specific cases for detailed analysis. Figure 10 shows some of the geometries already examined.

A corridor geometry has been examined for built-up areas. It is important to point out that the corridor geometry presents significant problems since the multilateration payoff is poor. Geometrical dilution of precision forces the radar to wide bandwidth for extremely short range cells. It will be difficult to deploy the receivers in a geometry which avoids this large bandwidth and the associated high signal processing cost. Since the corridor is narrow, a limited beamwidth antenna could be used to reduce transmit power, a potential cost saving. Very short flight path visibility will complicate the coverage of snipers on cross streets. Interactions with potential users would help in focusing a corridor coverage design.

Conclusions

A radar based sniper detection and location system can be assembled based on any one of three different architectures: autonomous radar, netted radars with range-only measurements, and a radar/IR hybrid.

With autonomous radars, there will be angular accuracy degradation due to multipath propagation. Signal processing to support the required precision beam splitting while minimizing the physical size of the antenna will be a challenge. The cost of an array antenna to support the multiple simultaneous beams will be high.

A netted system has the potential for lower transmitter cost due to the bistatic viewing of sniper bullets. A radar with an average power of no more than 150 W and omnidirectional coverage provides adequate performance; substantial power reduction is possible for more limited

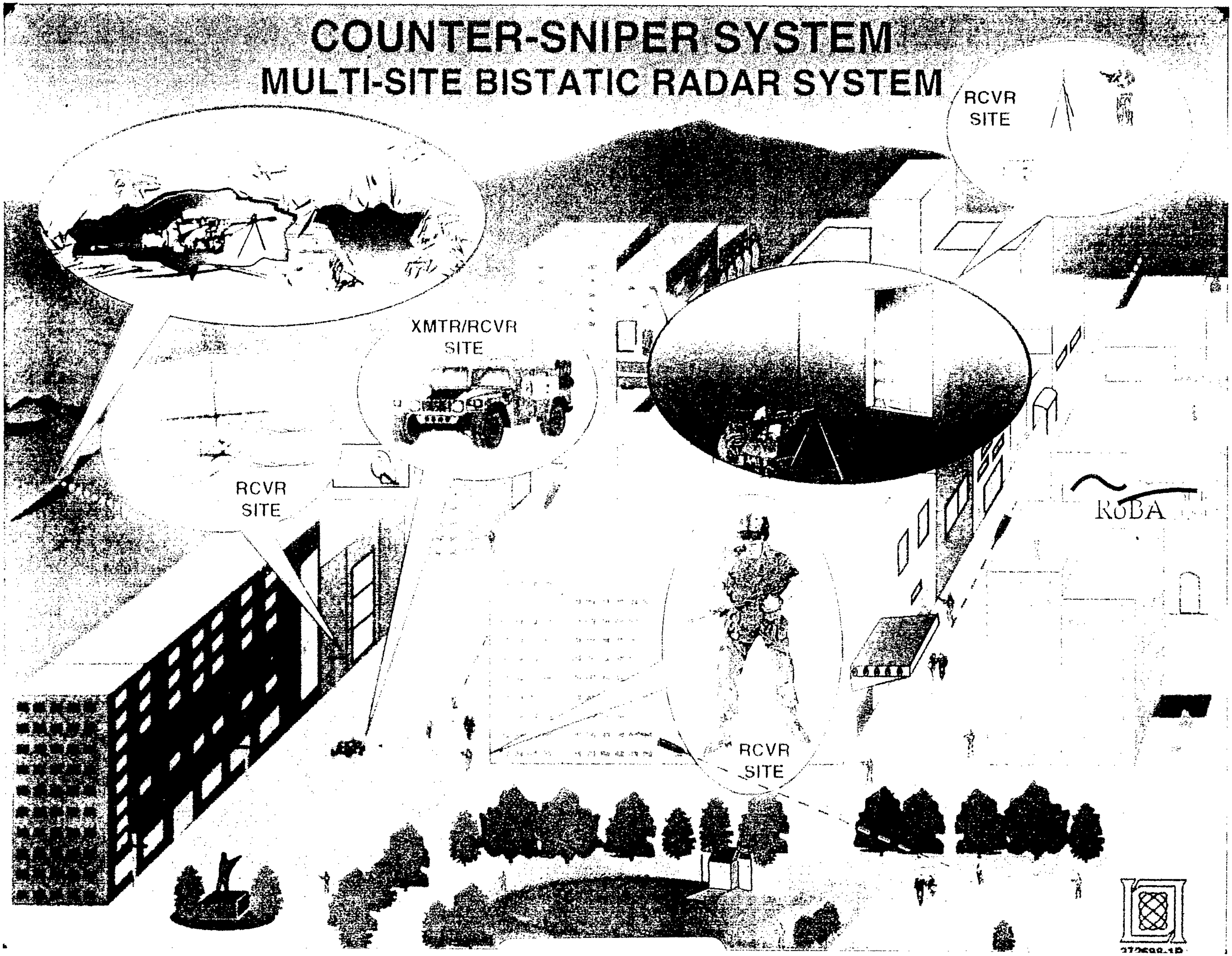
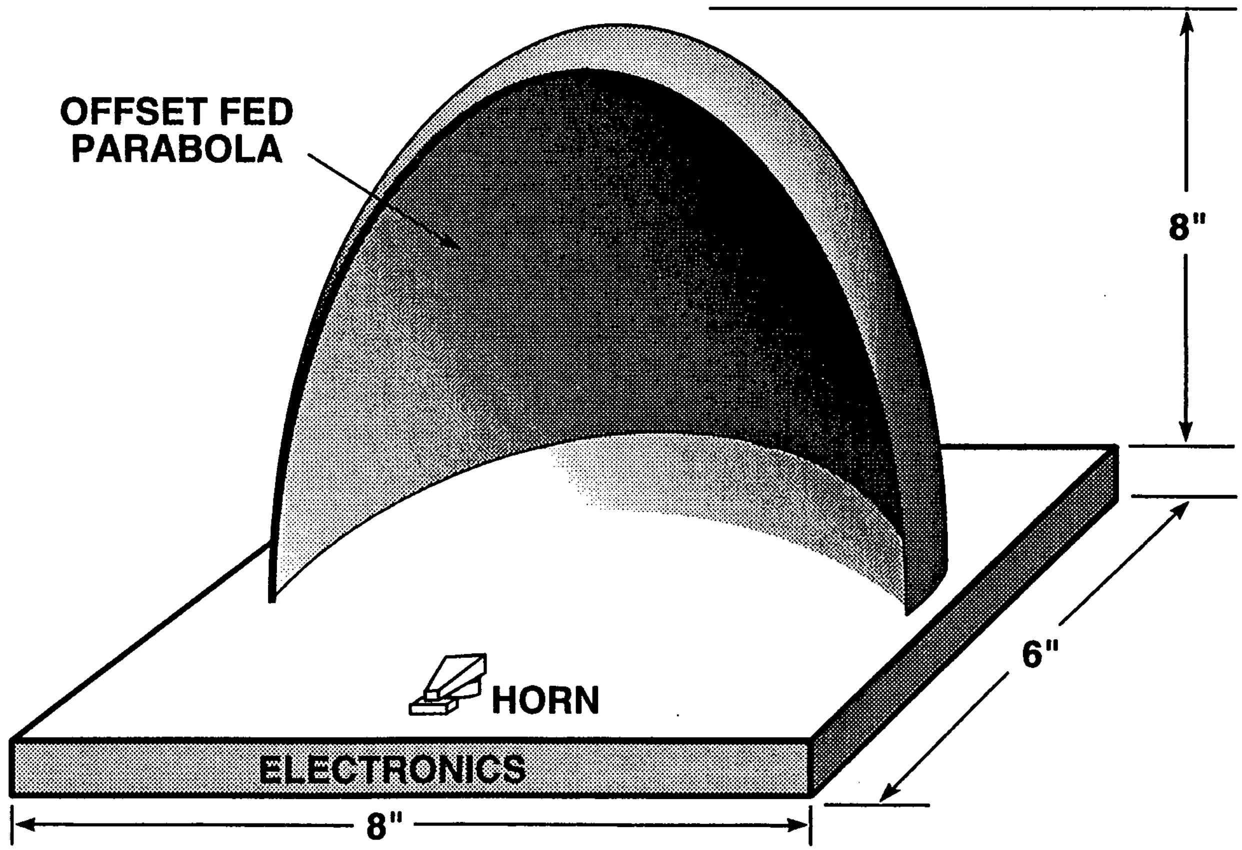

COUNTER-SNIPER SYSTEM
MULTI-SITE BISTATIC RADAR SYSTEM
RCVR SITE
XMTR/RCVR SITE
RCVR SITE
RCVR SITE
RoBA

Figure 8

CORRIDOR RANGE ANTENNA



AZIMUTH. . . 10°
ELEV. . . . . . 12°

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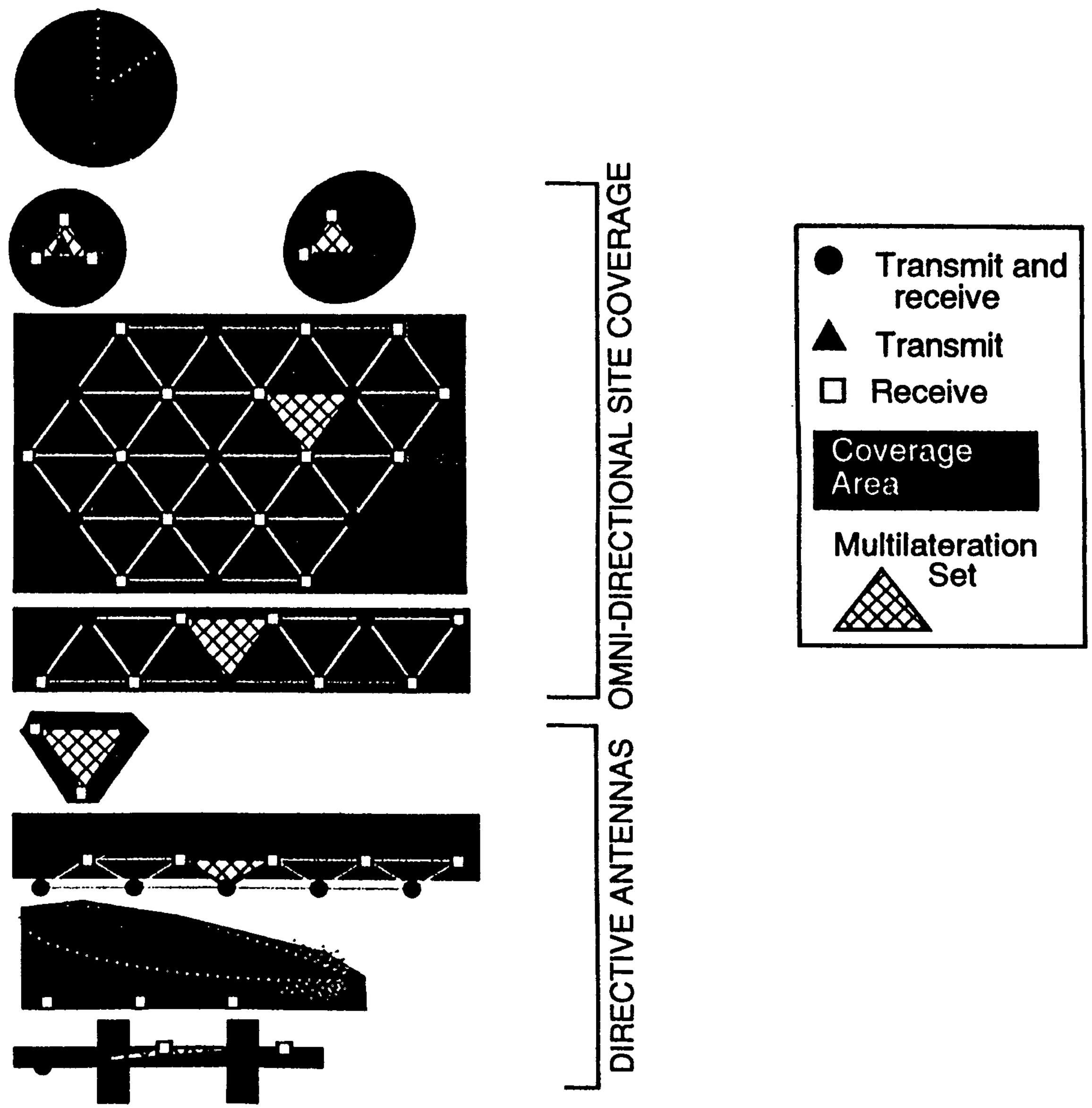
Figure 9

BULLET DETECTION AND TRACKING RADAR - GEOMETRY OPTIONS

- SINGLE SITE
  R, θ
- ISOLATED MULTILATERATION
- AREA COVERAGE
- LINEAR BARRIER
- ISOLATED MULTILATERATION
- LINEAR BARRIER
- ISOLATED LINEAR BARRIER
- CORRIDOR



coverage requirements. The accuracy degradation due to multipath will also be a problem for this construct.

The hybrid radar (for range measurements) and IR (for angle measurements) takes maximum advantage of the two sensor modalities. It will require development of an IR angle measurement sensor which can produce angle estimates accurately aligned with the radar range measurements.

Despite these challenges, there appear to be several radar-based options for a successful sniper detection/location system. By the 2005 time frame, one or more of these should be available to support small unit operations.

PORTABLE SNIPER LOCATION SYSTEM

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A. PROBLEM

The detection, localization, and suppression of sniper activity continues to be an unresolved problem for our armed forces. Peacekeeping operations and modern warfare situations where our troops will be faced with sniper threats and terrorist attacks, require an innovative yet cost-effective method of directing immediate counterfire or suppressive action. New requirements for Small Unit Operations (SUO), reconnaissance teams, and peacekeeping forces demand innovative technology that will encompass situational awareness, portable remote sensing, mobile internetted unattended sensors, and combatant survivability. This paper will examine a concept for a portable, wide-area, Sniper Location System (SLS) that will provide deployment flexibility and sniper location accuracy. Figure 1 illustrates the portable SLS concept.

B. SYSTEM CONCEPT

SRI's investigation of acoustic gunshot-location technology over the past 2-1/2 years has culminated in the installation of a semipermanent gunshot location experimental testbed at SRI's Menlo Park, California, facility. Throughout its investigation, SRI has conducted numerous gunshot tests at a facility near Los Banos, California, at local rifle ranges, and with blank "starter" pistols in Menlo Park. In many of the tests, a real-time display was used at the test site to successfully demonstrate accurate gunshot location. In all tests, the acoustic data were recorded for later, detailed analysis and were used as test signals for optimizing real-time displays.

The existing SRI acoustic outdoor testbed facility utilizes fixed sensors. Seven acoustic sensors are currently hardwired to a central processing computer while one acoustic sensor is connected through a wireless link Since the sensors are installed on fixed surveyed buildings, their locations are accurate to 1 m. The portable SLS concept discussed here will utilize differential GPS instead of map-grid point surveying to record the sensor positions and to maintain overall operational accuracy requirements.

GPS is known to have an accuracy window that depends on a number of factors, including environment and period of integration. Differential GPS has a range of accuracy between 1 and 10 m. Since the target positional accuracies are proportionally related to sensor positional accuracies, this effect should and will be quantified. Furthermore, prior investigations have shown that the geometric topology of the sensors directly affect the target positional errors. Clearly the geometric topology of the sensor network (soldiers' positions) is in flux and potentially in non-optimal configurations. At present, the SRI SLS algorithm automatically discards the data from the active sensors with "poor goemetry."

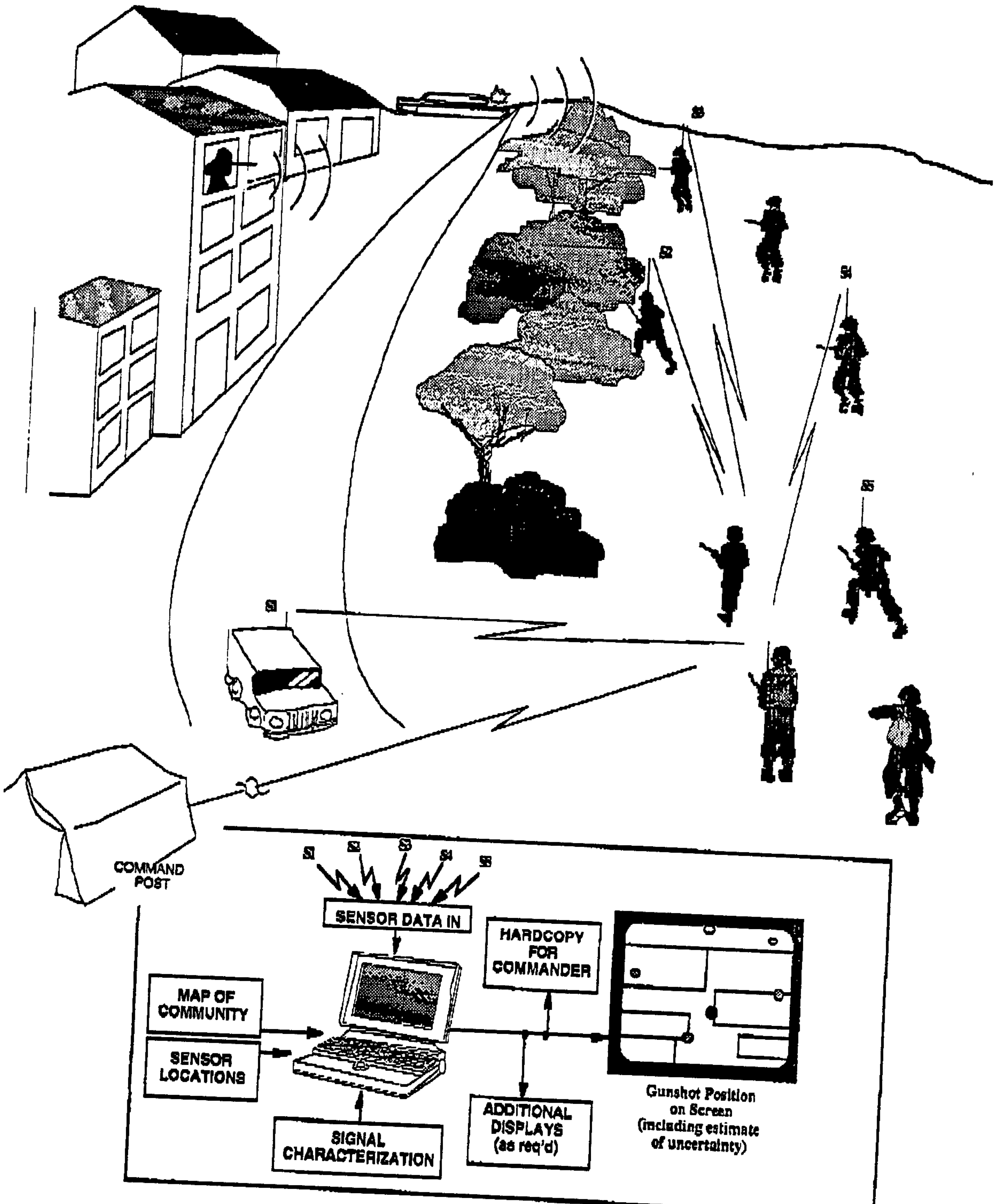

FIGURE 1 PORTABLE SNIPER LOCATION SYSTEM CONCEPT

During 1993, at the direction of and with funding from ARPA, CECOM established an integrated Commercial Communications Technology Testbed (C2T2) project to evaluate existing and future personal communication system (PCS) technology. The C2T2 system was successfully utilized by the 2-87 Infantry and the 10 Special Forces Group to distribute operation orders, plans, friendly situation data, and intelligence data among the battalion, company, and platoon leadership as part of the Warrior Focus Advanced Warfighting Experiment (AWE) conducted in November 1995. C2T2 successfully concluded with JRTC 96-02. The concepts and technologies developed are being transitioned to the ARPA Small Unit Operations program and will be utilized by the Marine Corps in TF XXI.

The AWE success was made possible by the innovative, SRI-developed distributed database system at the heart of the C2T2 system. The asynchronously replicated and distributed database system is optimized for use in unreliable, low-bandwidth communications environments. Each node of the system (in this case an individual soldier's computer) maintains a copy of the database with full rights and privileges to access and modify the data. Each node includes a Global Position System (GPS) receiver. Thus, each soldier's position is automatically logged in a common database. The portable SLS concept leverages the C2T2 infrastructure onto the existing gunshot location algorithm, thus providing a portable concept of operations. The existing prototype demonstration SLS utilizes fixed point sensors which transfer the data to a central processor. This system would be identical, except for a central processor which dynamically reads the locations of all the sensors through the database prior to determining the target sniper location. All sensor to main processor communications will be wireless.

C. SNIPER LOCATION ALGORITHM

The accuracies of the standard location methods of time difference of arrival (TDOA) and angle of arrival (AoA) have been extensively studied [Torrieri, 1984; Wax, 1983; Gavish, 1992; Reddi, 1993; Ho and Chan, 1993]. It can be shown theoretically—and SRI has demonstrated—that if the sensor locations are well known, these methods can locate acoustic impulse sources with sufficient accuracy to resolve the sniper location problem (within several meters) in open environments.

The choice of which approach, TDOA or AoA, depends on operational concerns such as the deployment "cost" (e.g., mobility requirements, securing the sensor location, existing structures available to mount a sensor, availability of power at sensor site) and the sensor "cost" (e.g., hardware cost, calibration and alignment time, ruggedness). (TDOA and AoA methods can be combined to improve positional accuracy, but this approach is computationally more difficult [Foy, 1976].) TDOA sensors are simpler to implement, easier to field, require no azimuthal alignment, are more compact, can be made more covert, are easier to implement in moving vehicles, and require less sensor processing than AoA sensors. For these reasons, SRI has initially selected a TDOA-based approach for the SLS. However, field tests have shown that direct application of standard, available TDOA or AoA location algorithms in the SLS scenario can result in significant errors (hundreds to thousands of meters) 30% to 50% of the time. Computer simulations indicate that these errors are caused by delays in some signal arrival times due to path blockage and multipath.

To reduce the number of extreme position errors, SRI has developed a unique proprietary SRI SLS algorithm, which incorporates adaptive thresholds, correlations with key parts of gunshot signatures, TDOA techniques, sensor geometry criteria, and specialized analysis techniques. The routine is efficient and runs in real time on a PC. The algorithm determines the most probable gunshot position and develops a confidence ellipse showing the estimated position error. Extensive computer simulations and field tests in urban-like environments have demonstrated that this algorithm consistently achieves accuracies of between 1 and 13 m.

D. LOCATION ACCURACY

SRI invoked simulations and experiments to investigate and evaluate the performance of the SLS. The simulation scenario had 25 sensors uniformly spaced 2.5 km apart, covering a 10x10-km area. The gunshot source position was varied to 160 random positions inside the grid. The sensor positions and the sonic velocity were assumed known without error. The simulation used parametric models of acoustic propagation based on SRI's acoustic experiments in an urban environment. The gunshot amplitude at each sensor was assumed to vary with the square of the gunshot/sensor distance, along with an additional blockage loss factor that varied randomly from -20 to 0 dB. The fraction of paths with blockage was varied. The noise level at each sensor was adjusted so that the maximum detection distance was 3.5 km (2 km in one case). In this system, the sensor detects a shot if the signal-to-noise ratio (SNR) exceeds a certain threshold. When blockage occurs, the SNR is reduced, the sensor often does not detect the shot, and time-of-arrival is not available to help locate the gunshot. The signal time of arrival contained random errors from 0% to 10% of the true time because of blockage and multipath. The fraction of paths with time errors was varied. These data were passed to the SLS algorithm and to the conventional TDOA algorithm [Reddi, 1993] to determine the gunshot locations.

Table 1 shows the mean location errors for four cases with different acoustic path errors. Case 1 had a maximum detection range of 3.5 km, 20% of the paths had time errors, and 30% of the paths had blockage losses. The SLS algorithm had a mean error of 1.18 m, while the standard TDOA algorithm had a much larger error of 48.7 m. As the acoustic path errors increased (Cases 2 and 3), so did the location errors, but the SLS algorithm still outperformed the TDOA algorithm. Decreasing the maximum detection range (Case 4 compared with Case 1) did not significantly affect the SLS location errors, because the SLS is insensitive to multipath errors if the maximum detection range exceeds a certain value. With the TDOA algorithm, reducing the maximum detection range steadily increased the location error. Not only can the SLS algorithm locate lower amplitude shots, it also requires fewer sensors than the TDOA algorithm. The field tests were conducted in a realistic scenario in which 5 and later 8 sensors were mounted atop various buildings at SRI Menlo Park facility. This site has both single-and multi-story buildings and is prone to acoustic multipath. A .32 caliber starter pistol was fired at various locations within the sensor grid. Figure 2 compares the locational error probability using the SRI SLS algorithm and a conventional TDOA algorithm. As can be seen, the SRI SLS algorithm determined the shot location with high accuracy, while the conventional algorithm made significant errors in many cases.

Table 1 LOCATION ERRORS USING THE SLS AND STANDARD TDOA LOCATION ALGORITHMS WITH ACOUSTIC PATH ERRORS

Case	Maximum Detection Range (km)	Paths with Time Errors	Paths with Blockage	Mean Location Error (m) GLS	Mean Location Error (m) TDOA
1	3.5	20%	30%	1.18	48.7
2	3.5	30%	30%	1.83	60.7
3	3.5	20%	40%	1.38	51.7
4	2	20%	30%	1.18	58.7

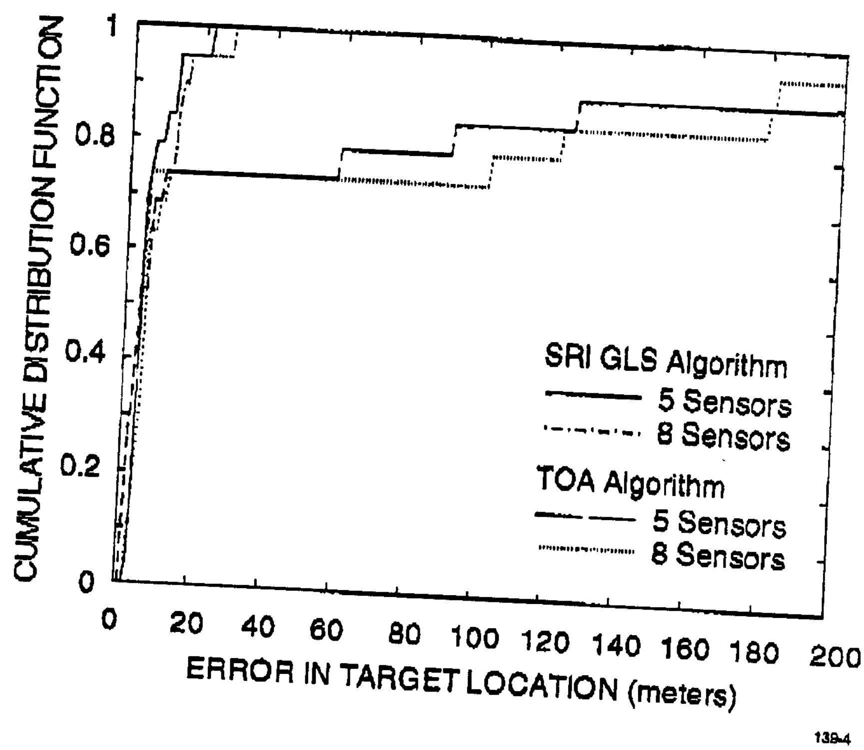

FIGURE 2 MEASURED GUNSHOT LOCATION ERROR PROBABILITY IN AN URBAN ENVIRONMENT: 5 AND 8 SENSORS

E. PERFORMANCE AND IMPLEMENTATION ISSUES

The SLS range (or, equivalently, the maximum sensor spacing) is determined by the desired location accuracy, acceptable false-alarm rate, weapon amplitude level, ambient noise level, amount of anomalous signal attenuation, strength of multipath signals, and environmental effects. Sensor spacing determines the required number of SLS sensors and hence is a key system parameter. SRI has conducted both computer simulations and experiments in urban and rural environments to estimate the maximum SLS range in the presence of the above effects. Experiments in an urban environment (SRI facility) described previously demonstrated excellent SLS performance with a sensor spacing of slightly less than 500 m with a .32 caliber pistol. Using this scenario as our baseline case (Case 1 in Table 2), we were able to conservatively estimate the maximum sensor spacing for other cases.

Table 2 SENSOR SPACING ESTIMATES

Case	Scenario	Noise	Noise Level (SPL)	Weapon	Relative Weapon Amplitude (dB)	Max. Sensor Spacing (m)
1*	Urban with multi-path	High urban (SRI)	56 dB	.38 pistol	-25	500
2		Low urban	46 dB	.38 pistol	-25	1580
3	Urban with multi-path	High urban (SRI)	56 dB	.306 rifle	-15	1580
4		Low urban	46 dB	.306 rifle	-15	3000
5	Rural	Low rural (Los Banos)	36 dB	.38 pistol	-25	2000
6			36 dB	.306 rifle	-15	5000

*Baseline

Case 2 is an urban environment with 10 dB less noise than experienced at SRI. With this improved SNR, sensor spacing can be increased until the signal level drops by 10 dB at each sensor. We assume that the gunshot signal strength is reduced by the increased sensor distance in proportion to the square of the sensor/gunshot distance, which is valid if the sensors are mounted high enough that no new obstacles block the signal path. The resulting maximum sensor spacing is 1580 m. Cases 3 and 4 are also urban environments, but with a .306 rifle. (The .306 rifle and .32 pistol amplitudes were measured at SRI's Los Banos test site.)

In a rural environment, the maximum detection distance of different weapons can be measured directly. Cases 5 and 6 in Table 2 show conservative, maximum detection ranges determined using correlation techniques for a .32 pistol and a .306 rifle in a low-noise, low-wind rural environment. However, to achieve high gunshot location accuracy at these long ranges, the wind speed along the path must be estimated and accounted for in the location algorithm.

F. PROBABILITY OF DETECTION AND FALSE-ALARM RATE

The SLS algorithm uses a threshold on the acoustic signal strength to decide if an event occurred. If the threshold is too low, the algorithm triggers on noise or spurious events (e.g., car backfires, low-flying aircraft). If the threshold is too high, probability of detection degrades. A practical system must have a threshold level that meets the required detection and false-alarm probabilities. The SRI SLS algorithm minimizes false alarms by a combination of correlation processing and the use of data from multiple sensors. Using these techniques, SRI has operated its SLS over multiple days and experienced very few false alarms.

G. SLS OPERATIONAL UTILITY/FLEXIBILITY

The SLS will provide the soldier of the future a useful, practical, flexible system. Because it uses TDOA techniques, the SLS could be used on mobile platforms using a differential GPS receiver at each sensor and a wireless communications link. Another possible scenario is locating semiportable sensors (at fixed, but flexible locations) using one common differential GPS receiver. In either case, the SLS algorithms are ideally suited to the mobile scenario. To cover a very large area, additional subnetworks at different frequencies could be added to the base station to handle the increased load. To cover a small area, only four sensors would be needed.

H. CONCLUSIONS

SRI has conducted extensive successful internal investigations and now desires federal fund- ing to develop a prototype portable sniper location system that will improve the response time and effectiveness of military personnel in dealing with sniper shooting episodes. The potential SLS military applications include location of sniper, mortar, and field artillery sources involving full military and limited peacekeeping situations. The fully developed SRI SLS concept will immedi- ately provide the location of such weapons, enabling rapid and accurate countering fire. The SLS concept discussed herein would pinpoint a gunshot source (to less than 10-30 m, depending on the acoustic environment and sensor layout), allowing friendly forces to focus immediately on the source area. Other potential applications of the SLS include location of gunshots in high-crime urban areas involving local law enforcement agencies as well as federal law enforcement such as the FBI, DEA, ATF, Secret Service, and the U.S. Park Service for use in national parks, where poaching activities are known to occur. A significant benefit of the SLS in these applications is that it could establish probable cause for a search for concealed weapons in or near the gunshot source region. In both law enforcement and military applications, the SLS can also provide limited weapon type classification, with an estimated confidence factor. Depending on the operational scenario both fixed and mobile/portable versions of the SLS are feasible. Finally, the system could permanently record pertinent acoustic, source location, and environmental information for off-line analysis to permit ongoing improvements in system performance, to aid the development of multisensor fusion approaches, and, as appropriate, to document and support legal actions.

The Department of Energy Non-Lethal Programs

A White Paper Prepared for

The Defense Science Board Summer Study

on

Tactics and Technology

for

21st Century Military Superiority

Submitted By

Los Alamos National Laboratory

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The Department of Energy Non-Lethal Programs

The Department of Energy and its technology laboratories have had initiatives in the area of non-lethal technologies for a number of years. These activities initially focused on DOE's needs to provide safeguards and security for its nuclear weapons facilities and the safe transportation of critical nuclear materials. In recent years, the DOE Laboratories have provided non-lethal technologies to assist Department of Defense forces in conducting peacekeeping and humanitarian assistance operations. Other non-lethal technologies have aided the Department of Justice and the Nation's Law Enforcement Community in their missions. Many of these technologies have been successfully transferred to American industry for production and distribution. The Department of Energy also maintains excellent test and evaluation facilities at its Nevada Test Site. The Site is capable of testing a variety of components and systems. It can conduct full scale Blue Team and Red Team-type testing to validate non-lethal technology operational performance.

The DOE continues to be a unique resource of near-off-the-shelf and advanced technology concepts which can support missions of the Department of Defense. It is currently providing both technologies and technical assistance in areas such as the development and deployment of non-lethal land mines, drug transport tracking and interdiction, and Southwest U.S. border protection, detection, and control. Smart sensor technologies and software and hardware for sensor data fusion being developed at the DOE Laboratories have many applications in Department of Defense operations. Technical personnel from the DOE Laboratories are presently assisting OSD in developing new antipersonnel land mine policies, establishing infrastructure assurance strategies, and the selection, training, and deployment of non-lethal technologies to U.S. peacekeeping forces in Haiti and Bosnia. User involvement is critical in establishing the requirements and fielding the technologies. DOE technical personnel are working closely with the operational side of the Defense services to assure that technical developments meet the needs of the user.

The following is a brief outline of DOE technology developments which have been or are being developed in accordance with the Department of Defense's evolving non-lethal requirements.

<u>DoD Requirement</u>	<u>DOE Applicable Technology</u>
1. Close-in Engagement Scenarios	
• Crowd Control:	- Acoustic Generators - Non-Lethal Projectiles - Labeling and Marking Materials - Entanglements and Nets - Projected Thermal Beam
• Uncooperative Subject:	- Entanglements and Nets - Sticky Foams - Flash Bangs - Non-Lethal Projectiles - Air Bag Restraint

- Hostage Situations:
  - Flash Bangs
  - Obscurants
  - Non-Lethal Projectiles
  - Foams
  - Through-Wall Detectors
- Equipment Neutralization:
  - Encapsulates
  - Foams
  - Super Corrosive Materials
- Stopping Vehicles:
  - Tire Damage Devices
  - Dazzling Light Sources
- Land Mine Neutralization:
  - Rigid Foams
  - rf and Beam Disruption Devices

2. Long Range Battlespace (>200m)

- Assembly and Movement of Large Groups of Aggressive Individuals:
  - Non-Lethal Projectiles
  - Phased Array Acoustic Systems
  - Obscurants
- Keep Out Zones:
  - Non-Lethal Land Mines
- Vehicle Movement:
  - Chemical Agent Degrading Materials
  - Combustion Prevention Systems
  - Dazzling Light Sources
- Sensors and Radars:
  - Obscurants
  - Dazzling Light Sources
  - Focal Plane Array Disabling Techniques
- Projectile Tracking
  - Infrared Sensing Devices

3. Wargame Models and Training Tools

- Modeling and Simulation
  - Non-Lethal Technology Representations

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Brief Technical Descriptions

DOE Nevada Test Site: The Nevada Test Site offers an expanse of federally controlled land in a remote region of southern Nevada and is surrounded by other federal lands. The geology, hydrology, meteorology and radiological environment of the 1,350 square mile site have been extensively characterized making it an ideal location for carrying out projects and experiments in complete safety. The infrastructure of the test site is made up of extensive facilities and expert scientific personnel which can support any test, evaluation, and validation of non-lethal technologies.

Acoustic Generators: Acoustic Generators are portable generators which produce high power, low frequency acoustic sound waves. These sound waves couple with an individual's body cavity causing pain, nausea, and loss of control of bodily functions. **Phased Array Acoustic Systems** can focus high intensity sound wave nodes at specific distances from the generator for controlled zones of effectiveness.

Non-Lethal Projectiles: These special rounds are designed to be shot from conventional guns, such as 12 gauge shot guns or 40 mm grenade launchers. The rounds are filled with various less-than-lethal projectiles such as small, soft rubber pellets, wooden slugs, bean bags, or foam projectiles. These rounds are non-penetrating, thus, safer than traditional large hard rubber bullets.

Labeling and Marking Materials: These materials are generally launched from a conventional gun such as a 12 gauge shot gun, and are used to mark individuals (such as leaders) in unruly crowd situations. They consist of bright dye or florescent materials which cannot be readily removed.

Entanglements and Nets: As the name implies, these are net-like fabric structures that can be deployed around a keep out area or propelled from a gun-like launcher system. When deployed on the ground, the nets entangle the feet of a individual passing through the area. The launched system can be deployed over an individual to capture him.

Projected Thermal Beam: A projected thermal beam is an off-the-shelf carbon dioxide laser which is felt as heat when pointed at an individual. The beam provides a thermal standoff zone; the closer the individual is to the source, the hotter the thermal beam feels. Standoff zones of up to 50 feet are reasonable for such a device.

Sticky Foams: Sticky foams are urethane foam systems which have been specially formulated to maintain a high degree of tack. When an individual comes in contact with the material, he is unable to break free from the material. These foams can be deployed from a gun-like system to either provide a method of restraining an individual or establishing a keep out zone. Sticky foams can also be water-based.

Flash Bangs: Flash Bangs are grenade-like devices which provide an extremely bright flash and a very loud acoustic sound when they go off. They are generally used as a distracting device in forced entry situations by law enforcement officials.

Air Bag Restraint: An inflatable air bag type device for restraining an occupant in the rear seat of a patrol vehicle if the occupant becomes violent during transportation.

Obscurants: Particulate or aerosol fogs.

Aqueous Foams: Water-based "soap-like" foams which can be used to block passages and fill rooms. When an individual becomes surrounded by these foams, they become disoriented.

Through-Wall Detectors: Radio frequency detectors that can monitor and assess personnel and objects on the other side of structural walls.

Encapsulates: Resinous or plastic-like materials which can foul moving parts or equipment when the equipment comes in contact with the materials. Encapsulates generally harden a period of time after application.

Super Corrosive Materials: Extremely strong acid or basic liquids which rapidly "eat" through substances when exposed to these liquids.

Tire Damage Devices: Spiked Barrier Strips used to puncture tires of fleeing vehicles. Chemicals which rapidly soften the rubber of tires when put on the tire is also included in this category.

Dazzling Light Sources (Dazzlers): Very bright light sources which deny vision of an individual exposed to it by washing out his field-of-view. Used to distract or disorient an aggressor because he looses the ability to resolve objects when "dazzled". Dazzlers are, generally, eye safe systems.

Rigid Foams: A hardened urethane-type foam which can provide a protective cap over lethal explosive devices such as land mines, rendering them non-lethal.

Non-Lethal Land Mines: Land mines that do not permanently injure or kill when set off by an individual. These mines can consist of simple pepper spray type devices to acoustic and entrapment devices.

Chemical Agent Degrading Materials: Chemicals which rapidly soften the rubber of tires when put on the tire.

Combustion Prevention Systems: Chemical materials which prevent the burning of fuel in an internal combustion engine or jet engine when the engine is exposed to these chemicals in aerosol or vapor form. Halon materials can prevent the combustion of fuel when it is mixed in the intake air. Sticky polymer aerosols can plug air filters on engines when exposed to "fogs" of the material.

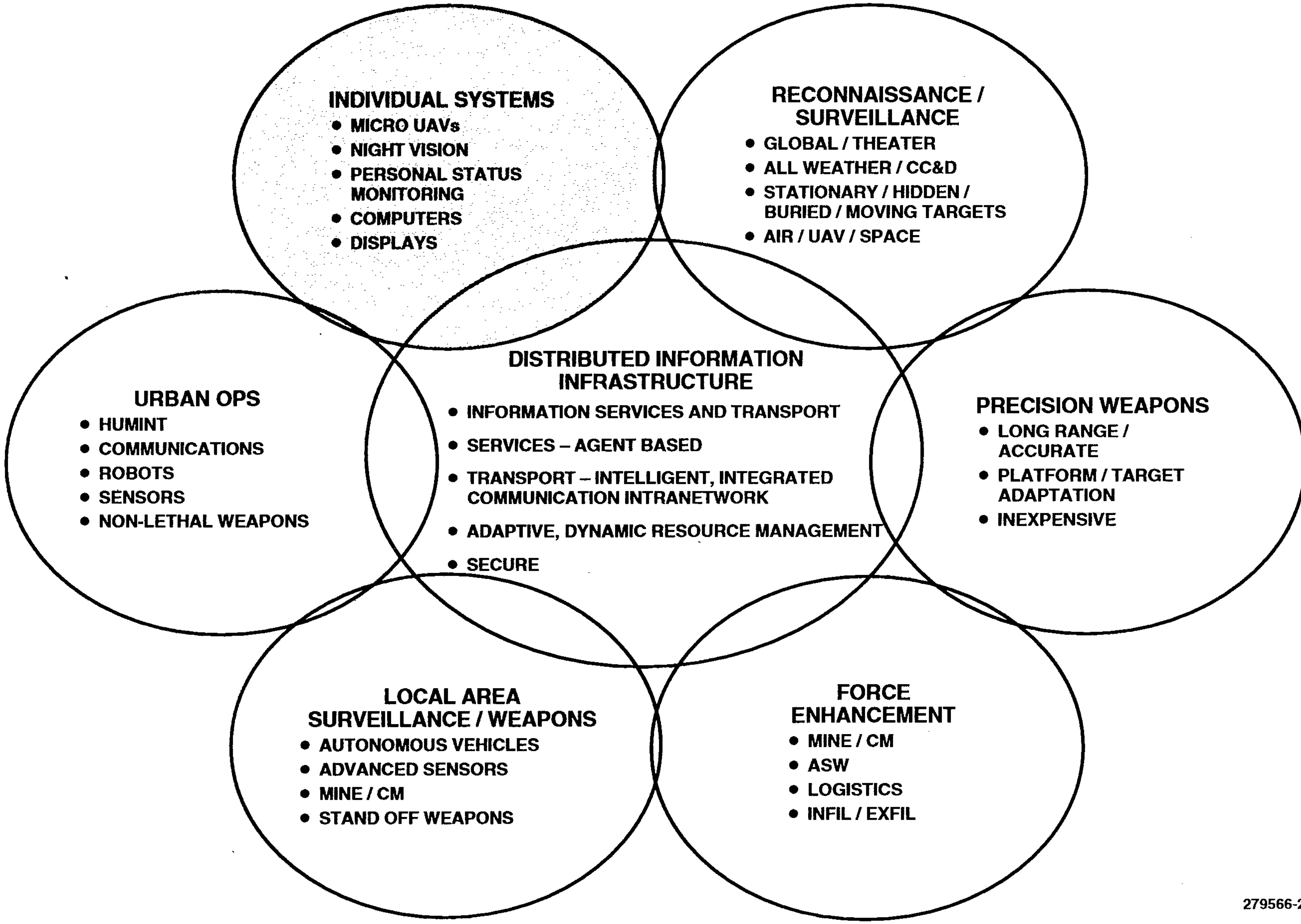
Focal Plane Array Disabling Techniques: Exposure of focal plane array sensors to high intensity light or laser sources can temporarily "blind" or "burn out" the optical sensors.

Projectile Tracking Systems: A system of state-of-the-art infrared detectors and computational hardware and software which trace the path of a projectile. This system is extremely useful in tracking the projectile back to its source.

Non-Lethal Technology Representations: Non-lethal representations are codes which are compatible with all existing wargaming models. These codes give accurate performance characteristics of non-lethal technologies under all conditions being considered when they are plugged into wargame simulations. These codes can give a commander a realistic feel for the deployment of the non-lethal technology in the scenarios he is simulating.

TACTICS AND TECHNOLOGY FOR 21st CENTURY MILITARY SUPERIORITY

TECHNOLOGY CONCEPTS PANEL



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SOLID STATE COLOR NIGHT VISION:
FUSION OF LOW-LIGHT VISIBLE AND THERMAL IR IMAGERY

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SOLID STATE COLOR NIGHT VISION: FUSION OF LOW-LIGHT VISIBLE AND THERMAL IR IMAGERY *

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ABSTRACT

We describe an apparatus and methodology to support realtime color imaging for night operations. Registered imagery obtained in the visible through near-IR band is combined with thermal IR imagery using principles of biological opponent-color vision. Visible imagery is obtained using a Gen III image intensifier tube fiber-optically coupled to a conventional CCD, and thermal IR imagery is obtained using an uncooled thermal imaging array, the two fields of view being matched and imaged through a dichroic beam splitter. Realistic color renderings of a variety of night scenes are illustrated. We also demonstrate both grayscale and color fusion of intensified-CCD/FLIR imagery obtained from the U.S. Army NVESD. Progress in the development of a low-light sensitive CCD imager with high resolution and wide intrascene dynamic range, operating at 30 frames/sec is described. Example CCD imagery obtained under controlled illumination conditions, from full moon down to overcast starlight conditions, processed by our adaptive dynamic range algorithm is shown. The combination of low-light visible CCD imager and thermal IR microbolometer array in a single dual-band imager, with portable image processing computer implementing our neural net algorithms, and color LCD display, yields a compact integrated version of our system in the form of a solid state color night vision device. The systems described here have application to a large variety of military operations and civilian needs.

1. INTRODUCTION

Current night operations are enabled through imaging in the visible-near infrared band, as provided by Gen III image intensifier tubes in night vision goggles (NVGs), and the thermal infrared (IR) bands, supported by a variety of imaging FLIRs (both scanners and IR focal plane arrays) displayed on CRTs, the cockpit HUD, or combiner optics (Bull, 1992; Cameron, 1990). These dual sensing modalities are complementary, in that the intensifier tubes amplify

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reflected moon and starlight (primarily yellow through near infrared light); whereas the FLIR senses thermally *emitted* light (in the mid-wave or long-wave infrared), from objects in the scene. Each modality alone suffers from its own limitations which at times can be disorienting (Crowley et al., 1992), while alternating between these sensing modalities can be difficult, confusing and distracting (Rabin & Wiley, 1994). However, there is much utility in fusing this complementary imagery in realtime into a single image product. Prior to our work (Waxman et al., 1994, 1995a), existing methods for Visible/IR image fusion were based on local measures of image contrast, choosing between the visible and IR image on a pixel-by-pixel basis, attempting to maximize contrast (Toet et al., 1989; Toet, 1992). The result is a grayscale fused image product which combines features (and noise) present in each of the separate image bands. Texas Instruments Corp. has developed a similar system for the grayscale fusion of intensified visible and FLIR imagery (the methods of which are proprietary), and which has been tested by the U.S. Army NVESD under its *Advanced Helicopter Pilotage Program* (Ryan & Tinkler, 1995).

Recognizing that color vision evolved in animals for survival purposes, we describe in Section 2 a methodology based on biological opponent-color vision, to fuse registered visible and IR imagery in realtime in order to create a vivid *color night vision* capability, as shown in Section 3. Utilizing full (24-bit digital) color allows for simultaneous presentation of multiple fused image products. The user's visual system can then exploit this coloring to aid perceptual *pop-out* of extended navigation cues and compact targets (Wolfe et al, 1989; Grossberg et al., 1994). The ability to generate a rich color percept from dual-band imagery was first demonstrated experimentally in the visible *(red and white imagery)* domain by Land (1959a,b), and motivated his famous *retinex theory* of color vision (Land, 1983) which itself lacked any notion of opponent-color!

In Section 4 we summarize our work on the development of low-light CCD imagers, sensitive from the UV through near-IR, and operating at 30 frames/sec in controlled illumination conditions from full moon down to overcast starlight. These solid state imagers possess extremely high quantum efficiency and very low readout noise, which together yield an extreme low-light sensitivity and support a very large intrascene dynamic range. Their utility is increased by our retina-like computations which enhance visual contrast and adaptively compress dynamic range in realtime. These CCDs for night vision actually emerge from technology originally developed at Lincoln Laboratory (Huang et al., 1989; Reich et al, 1993) for high frame-rate applications (i.e., adaptive optics and missle seekers). They represent the beginning of the technology curve for solid state visible night vision. And they are nicely complemented by the newly emerging solid state "uncooled" thermal IR imagers (Flannery & Miller, 1992), as well as a variety of cryogenically cooled IR focal plane arrays.

Finally, we conclude in Section 5 with the importance of conducting human perception and performance testing on natural dynamic scenes in order to assess the true utility of Visible/IR fusion and color night vision for enhanced situational awareness and tactical efficiency.

2. VISIBLE/IR FUSION ARCHITECTURE

The basis of our computational approach for image fusion derives from biological models of color vision and Visible/IR fusion. In the case of color vision in monkeys and man, retinal cone sensitivities are broad and overlapping, but the images are quickly contrast enhanced *within bands* by spatial opponent processing via cone-horizontal-bipolar cell interactions creating both ON and OFF center-surround response channels (Schiller, 1992). These signals are then color-contrast enhanced *between bands* via interactions among bipolar, sustained amacrine, and single-opponent color ganglion cells (Schiller & Logothetis, 1990;

Gouras, 1991), all within the retina. Further color processing in the form of double-opponent color cells is found in the primary visual cortex of primates (and the retinas of some fish). Opponent processing interactions form the basis of such percepts as color opponency, color constancy, and color contrast, though the exact mechanisms are not fully understood. (See Section 4 of Waxman et al., 1995b, and Gove, Cunningham & Waxman, 1996, for development of double-opponent color processing applied to multispectral IR target enhancement.)

Fusion of visible and thermal IR imagery has been observed in several classes of neurons in the optic tectum (evolutionary progenitor of the superior colliculus) of rattlesnakes (pit vipers), and pythons (boid snakes), as described by Newman and Hartline (1981, 1982). These neurons display interactions in which one sensing modality (e.g., IR) can enhance or depress the response to the other sensing modality (e.g., Visible) in a strongly nonlinear fashion. These tectum cell responses relate to (and perhaps control) the attentional focus of the snake as observed by its striking behavior. This discovery predates the observation of bimodal Visual/Auditory fusion cells observed in the superior colliculus (King, 1990). Moreover, these Visible/IR fusion cells are suggestive of ON and OFF channels feeding single-opponent color-contrast cells; a strategy which forms the basis of our computational model.

There are also physical motivations for our approach to fusing visible and IR imagery, revealed by comparing and contrasting the rather different needs of a vision system that processes reflected visible light (in order to deduce *reflectivity* ρ) versus one that processes emitted thermal IR light (in order to deduce *emissivity* ε). Simple physical arguments show that spectral reflectivity and emissivity are linearly related, $\rho(\lambda) = 1 - \varepsilon(\lambda)$, which also suggests the utility of ON and OFF response channels. Thus, it is not surprising that often FLIR imagery looks more "natural" when viewed with reverse polarity (black hot as opposed to white hot, suggestive of *off channel* processing; Schiller, 1992). This simple relation strongly suggests that processing anatomies designed to determine reflectivity may also be well suited for determining emissivity; and so therefore will be computational models of these anatomies.

Figure 1 diagrams the multiple stages of processing in our Visible/IR fusion architecture. They mimic both the structure and function of the layers in the retina (from the rod and cone photodetectors through the single-opponent color ganglion cells) which begin the parvocellular stream of form and color processing. The computational model that underlies all the opponent processing stages utilized here, is the feedforward center-surround shunting neural network of Grossberg (1988; also see Elias & Grossberg, 1975). It is used to enhance spatial contrast within the separate visible and IR bands, to create both positive (ON-IR) and negative (OFF-IR) polarity IR contrast images, and to create two types of single-opponent color-contrast images. These opponent-color images already represent fusion of visible and IR imagery in the form of *grayscale* image products. However, the two opponent-color images together with the enhanced visible image form a triple which can be presented as a fused *color* image product.

The neurodynamics of our center-surround receptive fields is described at pixel *ij* by the equations,

$$\frac{dE_{ij}}{dt} = -AE_{ij} + (1-E_{ij})[CI^C]_{ij} - (1+E_{ij})[G_S*I^S]_{ij} \tag{1a}$$

$$E_{ij} = \frac{[CI^C - G_S*I^S]_{ij}}{A + [CI^C + G_S*I^S]_{ij}} \tag{1b}$$

where E is the opponent processed *enhanced* image, I^C is the *input* image that excites the single pixel *center* of the receptive field (a single pixel center is used to preserve resolution of the processed images), and I^S is the *input* image that inhibits the gaussian *surround* G_S of the receptive field. Equation (1a) describes the temporal dynamics of a charging neural membrane (cp. capacitor) which leaks charge at rate A, and has excitatory and inhibitory input ion currents determined by Ohm's law (the shunting coefficients ($1 \pm E$) act as potential differences across the membrane, and the input image signals modulate the ion selective membrane conductances). Equation (1b) describes the equilibrium that is rapidly established at each pixel (i.e., at frame rate), and defines a type of nonlinear image processing with parameters A, C, and size of the gaussian surround. The shunting coefficients of equation (1a) clearly imply that the dynamic range of the enhanced image E is bounded, $-1<E<1$, regardless of the dynamic range of the input imagery. When the imagery which feeds the center and surround is taken from the same input image (visible or IR), the numerator of equation (1b) is the familiar difference-of-gaussians filtering which, for $C>1$, acts to boost high spatial frequencies superimposed on the background. The denominator of equation (1b) acts to adaptively normalize this contrast enhanced imagery based on the local mean. In fact, (1b) displays a smooth transition between linear filtering (when A exceeds the local mean brightness, such as in dark regions) and ratio processing (when A can be neglected as in bright regions of the imagery). This is particularly useful for processing the wide dynamic range visible imagery obtained with low-light CCDs, as described in Section 4 below. Equation (1b) is used to process separately the input visible and IR imagery. These enhanced visible and ON-IR images are reminiscent of the *lightness images* postulated in Land's (1983) retinex theory (also see Grossberg, 1988, on *discounting the illuminant*).

A modified version of equation (1), with an *inhibitory center* and *excitatory surround* is also used to create an enhanced OFF-IR image (i.e., a reverse polarity enhanced IR image). Following noise cleaning of the imagery (both realtime median filtering and non-realtime *Boundary Contour/Feature Contour System* processing (Grossberg, 1988; Waxman et al., 1995b) have been explored), and distortion correction to ensure image registration, we form two *grayscale fused* single-opponent color-contrast images using equation (1b) with the enhanced Visible feeding the excitatory center and the enhanced IR (ON-IR and OFF-IR, respectively) feeding the inhibitory surround. In analogy to the primate opponent-color cells (Gouras, 1991), we label these two single-opponent images $+Vis\ -IR$ and $+Vis\ +IR$. In all cases, we retain only positive responses for these various contrast images. Additional application of equation (1b) to these two single-opponent images serves to sharpen their appearance, restoring their resolution to the higher of the two (usually visible) used to form them. These images then represent a simple form of *double-opponent color-contrast* between Visible and ON/OFF-IR.

Our two opponent-color contrast images are analogous to the *IR-depressed-visual* and *IR-enhanced-visual* cells, respectively, of the rattlesnake (Newman & Hartline, 1981, 1982); they even display similar nonlinear behavior. In fact, with the IR image being of lower resolution than the visible image (in the snake, and for man-made uncooled IR imagers), a single IR pixel may sometimes be treated as a small *surround* for its corresponding visible pixel. In this context, our opponent-color contrast images can also be interpreted as *coordinate rotations* in the color space of *Visible vs. IR*, along with *local adaptive scalings* of the new color axes. Such color space transformations were fundamental to Land's (1959a,b, 1983) analyses of his dual-band *red and white* colorful imagery.

To achieve a natural color presentation of these opponent images (each being an 8-bit grayscale image), we assign the following color channels (8-bits each) to our digital imagery: (1) enhanced *Vis* to *Green*, (2) $+Vis\ -IR$ to *Blue*, and (3) $+Vis\ +IR$ to *Red*. These channels are consistent with our natural associations of *warm red* and *cool blue*. Finally, these three channels can be interpreted as *R, G, B* inputs to a color remapping stage in which, following conversion to *H, S, V* (hue, saturation, value) color space, hues can be remapped to alternative "more natural" hues, colors can be desaturated, and then reconverted to *R, G, B* signals to drive a color display. The result is a *fused color* presentation of Visible/IR imagery.

3. DUAL-BAND VISIBLE/IR IMAGERS AND FUSION RESULTS

We have developed a dual-band imaging system to collect registered visible and long-wave IR imagery in the field at night, as shown in Figure 2A (Waxman et al., 1995a). The visible imagery is obtained using a Gen III image intensifier tube optically coupled to a conventional CCD (supporting a resolution of 640x480 pixels), while the thermal IR imagery is obtained using an uncooled ferroelectric detector array developed by Texas Instruments Corp. (supporting a resolution of approximately 320x240 pixels), the two fields of view (about 30° wide) being matched and imaged through a dichroic beam splitter. An alternative LWIR imager we are pursuing is the silicon microbolometer array originally developed by Honeywell Corp. (Flannery & Miller, 1992). For long stand-off distance (narrow field of view) imagery, we plan to use a cryogenically cooled IR imager. In the field we record synchronized dual-band time-stamped imagery on two Hi8 videotape recorders for later processing back in our lab. We perform realtime computations on a PIPE parallel computer (from Aspex Corp), and have recently mapped our algorithms onto the new TMS320C80 multi-DSP processor chip from Texas Instruments. We are also designing a low-power compact portable processor dedicated to these computations. For compact portable systems, head-mounted display will utilize solid state high resolution color LCD display on a chip, such as being manufactured by Kopin Corp. For vehicle-based applications, where the user is behind a windscreen (which does not transmit thermal IR light), the dual-band sensor must be placed in an external turret or pod with an appropriately transmissive window, while the realtime fusion results can be displayed on color helmet-mounted displays.

We are planning to shrink our dual-band sensor down to a size of several inches, suitable for use as a hand-held or helmet-mounted color night vision device (or mounted as a gunsight) for the man on the ground. This will be achieved by replacing the image intensifier tube/relay optic/CCD camera with a low-light sensitive CCD imager, as will be described in Section 4 below. Conceptually, a compact dual-band color night vision scope could be layed out according to Figure 2B, in which much of the camera electronics has been remoted away from the CCD imager and microbolometer array (Waxman et al., 1994).

A dual-band Visible/LWIR scene of Gloucester, MA, is shown in Figures 3A-F, which includes three embedded low contrast (15% or less) square targets which modulate brightness but do not alter texture in the original visible and IR images. This imagery was taken under dusk (no moon) illumination conditions with our system in January 1995. Note the complementary information present in the visible and IR imagery, where the horizon and water line is obvious in the IR but not in the visible image, while the ground detail is revealed in the visible but not the IR. The enhanced visible, enhanced thermal IR, both opponent-color contrast (i.e., fused gray), fused color, and remapped fused color images are shown as Figures 3A-F, respectively. In the fused color images (3E,F), notice how clear the horizon is, as well as the houses and shrubs on the ground, water line on the rocks, and ripples on the water surface. The enhanced contrast afforded by the color now supports the perceptual *pop-out* of all three embedded targets, one of which (in the water) is weakened in the gray fused image (3C) and one (on the land) is lost in (3D). Also note that the fused color imagery inherits the higher resolution of the visible image. In the remapped color fused image (3F), the trees and shrubs corresponding to brown in the fused image (3E) have been remapped to a greenish hue with low saturation, and the blue water is brightened. In practice, the class of color remap selected by the user (in realtime) will depend on the kind of mission undertaken.

Figure 4 illustrates a scene taken at Nahant beach on the Atlantic Ocean, on an overcast night with near-full moon, in January 1995. We illustrate the enhanced visible (upper left), enhanced thermal IR (upper right), gray fused "blue channel" opponent-color (lower left), and unremapped color fused (lower right) imagery. In the color fused image, notice how the water and surf easily segment from the sand, and how clear the horizon is over the water. There is also a concrete picnic table and tar bicycle path in the foreground. Realtime processing of this scene is quite dramatic, as the incoming waves are clearly apparent. Notice that the gray fused imagery displays an enhanced surf but a very weak horizon. Clearly, even the low resolution and low sensitivity of the uncooled IR imager seems quite adequate in modulating the visible imagery into a color fused result. It will be of great interest to assess the utility of such a night vision system for search & rescue operations at sea.

Figures 5 & 6 present fusion results on data provided by the U.S. Army NVESD, Advanced Helicopter Pilotage Program. Here an intensified CCD provides low-light visible imagery and a cryogenically cooled 1st Gen FLIR provides high quality thermal IR imagery. In many respects, the FLIR imagery is more useful than the visible imagery. However, by inspecting the original visible (upper left) and original IR (upper right) images, it is easy to see how the sensors complement one another. The gray fused results (lower left) are shown next to the color fused results (lower right). In Figure 5 we see that the color fused result displays a clearer horizon, clearer tree shadows across the road, and a better sense of depth down the road, than does the gray fused result. In Figure 6, both fused results show a strong horizon, but the color fused result reveals more detail near the top of the tower and the communication dish on the ground, whereas the gray fused result more clearly reveals detail on the trailer.

We are currently preparing sequences of gray and color fused imagery for purposes of comparison and psychophysical testing. Such sequences could be provided to investigators wishing to conduct human performance testing.

4. LOW-LIGHT CCD IMAGER

Solid state, thinned, back illuminated, multi-ported frame transfer CCD imagers offer enormous benefits over electro-optic intensifier tubes, including excellent quantum efficiency (>90%), broad spectral sensitivity (0.3μ - 1.1 μ), high spatial resolution, sensitivity in overcast starlight, enormous dynamic range, anti-blooming capability, and near ideal modulation transfer function characteristics. Such CCDs with integrated electronic shutters have been fabricated and tested at Lincoln Laboratory (Huang et al., 1989; Reich et al, 1993). Our near-term target CCD imager has 1Kx1K pixels, 16 parallel read-out ports, supports 12-bit digital imagery at less than $2e^-$ read-noise level, operates at 30 frames/sec with integrated electronic shuttering and blooming drains, and requires only thermoelectric cooling (as does the non-cryogenic "uncooled" thermal LWIR imager) down to about 0°C. Nearly all of these capabilities have already been developed and demonstrated in different devices. We are currently integrating them into a single imager for night vision applications.

Figure 7A illustrates a variety of low-light CCD imagers (with size comparison to a quarter-dollar coin) including: (upper left) a wafer patterned with four large 1Kx1K pixel imagers and four smaller 512x512 pixel imagers, thinned to 10 microns for back illumination; (lower left) two 1Kx1K imaging chips inside open packages with one mounted for front and the other for back illumination; (upper right) two 512x512 imaging chips mounted in open packages; and (lower right) a mounted and sealed 128x128 pixel 4-port imager and an empty package showing the TE cooler upon which the imager is mounted. Figure 7B shows a laboratory prototype low-light CCD camera built around a back-illuminated 4-port 128x128 pixel imager. This camera operates in the dark at 30 frames/sec or less (and was actually designed to operate in excess of 500 frames/sec with adequate lighting). In front of the camera is a multi-chip module containing all the analog circuitry for the four read-out ports, in order to illustrate the potential to build far more compact devices. Further size reduction can be realized through the use of ASICs for the read-out and timing circuitry. This camera operates at 30 frames/sec with a measured read-noise of about $5e^-$.

Figure 8 illustrates imagery obtained in the laboratory with the camera shown in Figure 7B, under controlled lighting conditions from full moon down to overcast starlight (as measured at the scene with a photometer calibrated for a Gen III intensifier tube, using a light source with a blue-cut filter which actually deprives the CCD of the few available blue photons present in the night sky). The scene consists of a 50% contrast resolution chart, and a toy tank in the case of full moon illumination. All images, except for overcast starlight, were taken at 30 frames/sec; whereas for overcast starlight the frame rate was reduced to 6 frames/sec. Better quality imagery can be obtained at starlight or below if one is able to reduce the frame rate below 30 frames/sec, thereby integrating photons directly on the imager without the penalty of accumulating additional read-noise. Down the left side of Figure 8 we show the original 12-bit imagery scaled by hand such that the minimum pixel value is set to 0 and the maximum set to 255 on an 8-bit grayscale display. This is possible only because of the simplicity of the scene and uniformity of lighting. Down the right side of Figure 8 we show the corresponding images after processing the 12-bit data with the center-surround shunt processing of Equation (1b). In all cases we can see that contrast has been enhanced and the dynamic range has been adaptively compressed to only 8-bits. All images were processed exactly the same, and no hand "tweeking" was involved.

An example 640x480 pixel (cut-out) low-light CCD image is shown in Figure 9. The original image, taken at White Sands, NM, in Spring 1994 under starlight conditions, is approximately 1Kx1K pixels, digitized to 12-bits (4096 gray levels). This high resolution imagery was taken at a relatively low frame rate (5 frames/sec), in order to maintain low read-out noise over the imager's 4 read-out ports. Figures 9A & 9B are actually the same image shown at opposite ends of the 12-bit dynamic range. At the high end of the dynamic range, Figure 9A shows the stars in the sky and the horizon, but nothing is visible on the ground. At the low end of the dynamic range, Figure 9B shows the presence of vehicles on the ground, but the sky and dome are saturated white. This enormous dynamic range is a tremendous asset for night imaging where the moon and cultural lighting can dominate the bright end while objects and shadows on the ground may be apparent only at the low end of the dynamic range (and would ordinarily be lost due to the automatic gain control of an intensifier tube). The center-surround shunting neural networks of Equation (1b) can exploit the contrast inherent in the wide dynamic range CCD imagery, while adaptively normalizing the local data to a dynamic range well suited to only 256 gray levels (i.e., 8-bit display range). And the computations can be carried out in realtime with one frame latency, even at high data rates. The result of this neural processing is shown in Figure 9C, where one can easily see the stars in the sky, the buildings on the horizon, the vehicles on the ground, and the telescope dome, without any saturation at either end of the dynamic range.

5. CONCLUSIONS

We have described a novel approach to achieve color night vision capabilities through the fusion of complementary low-light visible and thermal IR imagery. Our approach to image fusion is based on biologically motivated neurocomputational models of visual contrast enhancement, opponent-color contrast, and multi-sensor fusion. Example imagery illustrates the potential of the approach to exploit wide dynamic range visible imagery obtained with new low-light CCD cameras, and to create a natural color scene at night which supports the perceptual *pop-out* of extended navigation cues and compact targets.

We have begun psychophysical testing on static imagery to assess the utility of color vs. gray Visible/IR fusion in terms of human *reaction time, accuracy, and false alarm rate* for detection of embedded low contrast targets and extended navigation cues (relevant to enhancing *situational awareness* and *tactical efficiency*). It will be essential to conduct such testing on dynamic image sequences of natural Visible and IR night scenes, before and after realtime fusion is carried out. This will require the development of new paradigms in psychovisual testing. If a small set of human perception parameters can be isolated from these tests (e.g., color and brightness contrast as a function of spatial frequency) which correlate well with human performance measures, then they can be incorporated into system models designed to predict overall performance under varying illumination and thermal conditions. Such models can then form the basis of future system design trade-off studies.

We anticipate that solid state, Visible/IR fusion, color night vision systems will offer many advantages over existing monochrome night vision systems in use today. They will play increasingly important roles in both military operations and civilian applications in the air, on the ground, and at sea. And because they are composed of all solid state components, they will be more rugged, last longer, and cost much less than systems currently in use.

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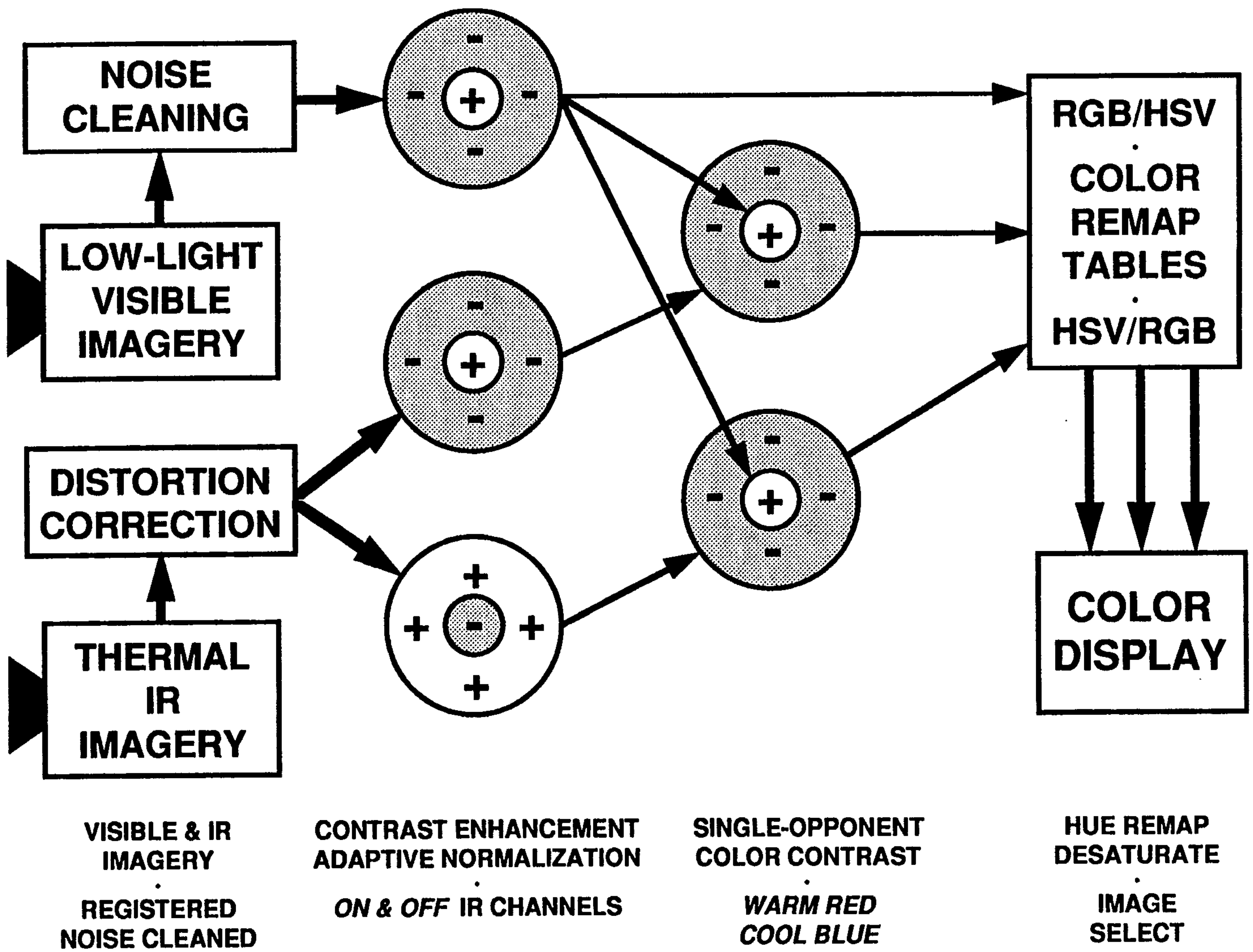
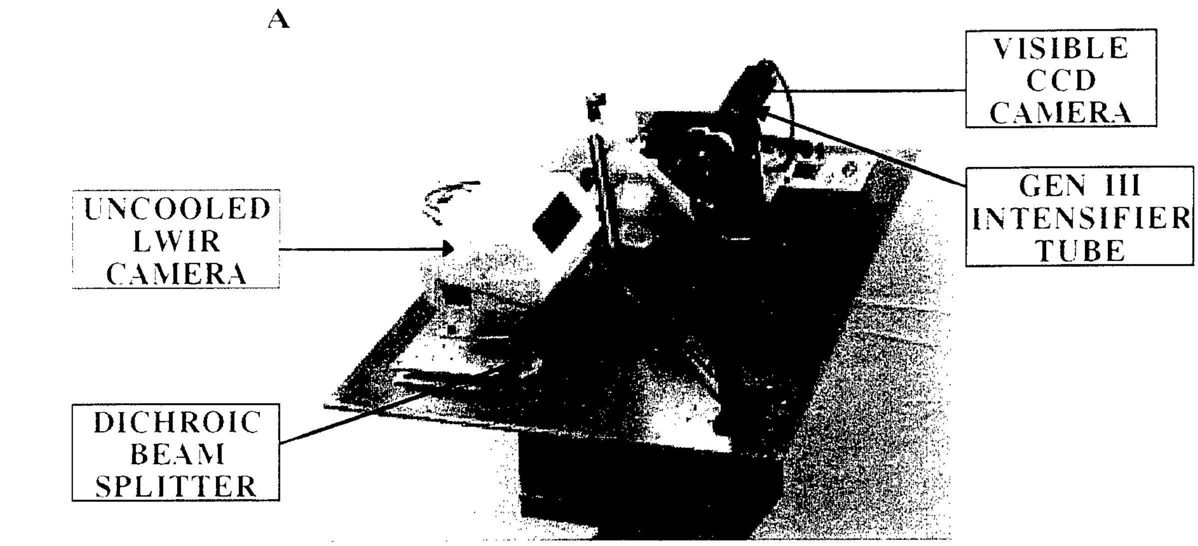


Figure 1. Neurocomputational architecture for the fusion of low-light visible and thermal IR imagery based on principles of opponent processing within and between bands.



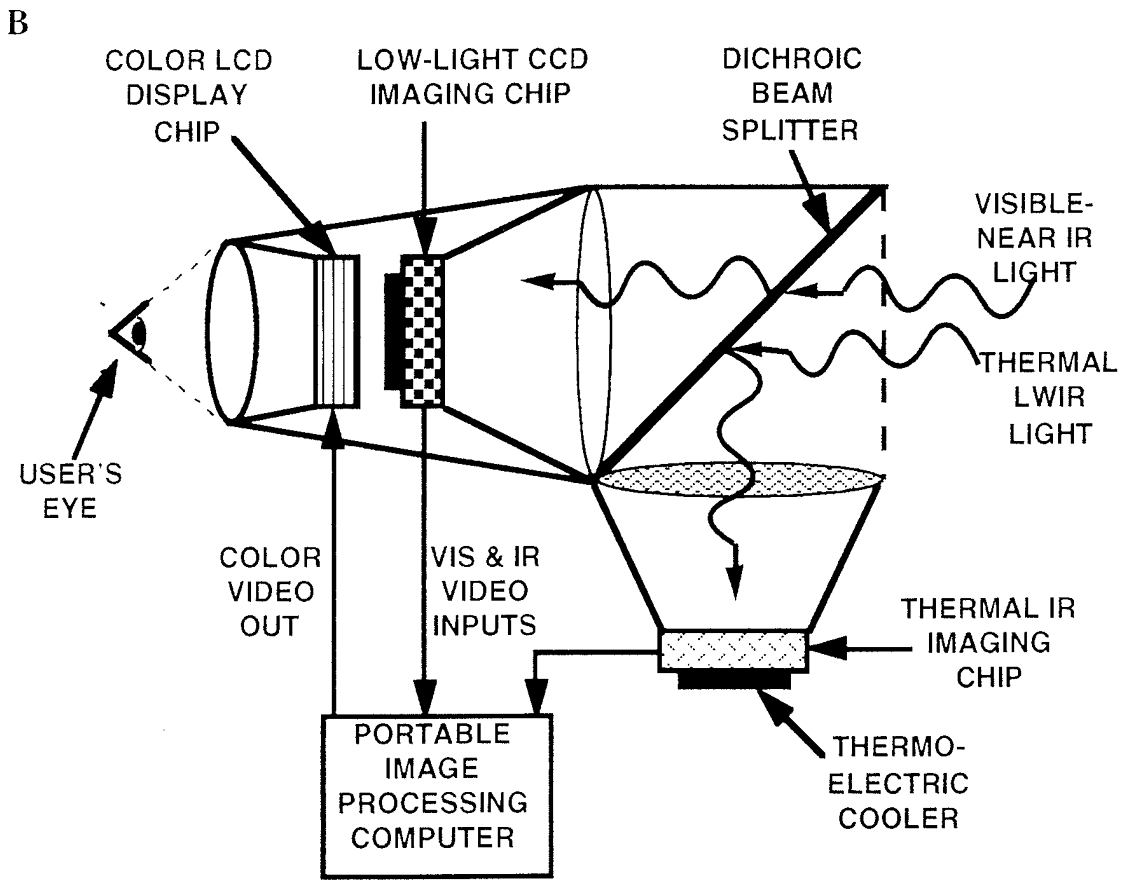


Figure 2. Dual-band Visible/LWIR imagers: (A) sensor pod used to image night scenes consisting of a Gen III intensified-CCD, an uncooled thermal IR imager, and a dichroic beam splitter; (B) design of a monocular solid state color night vision scope.

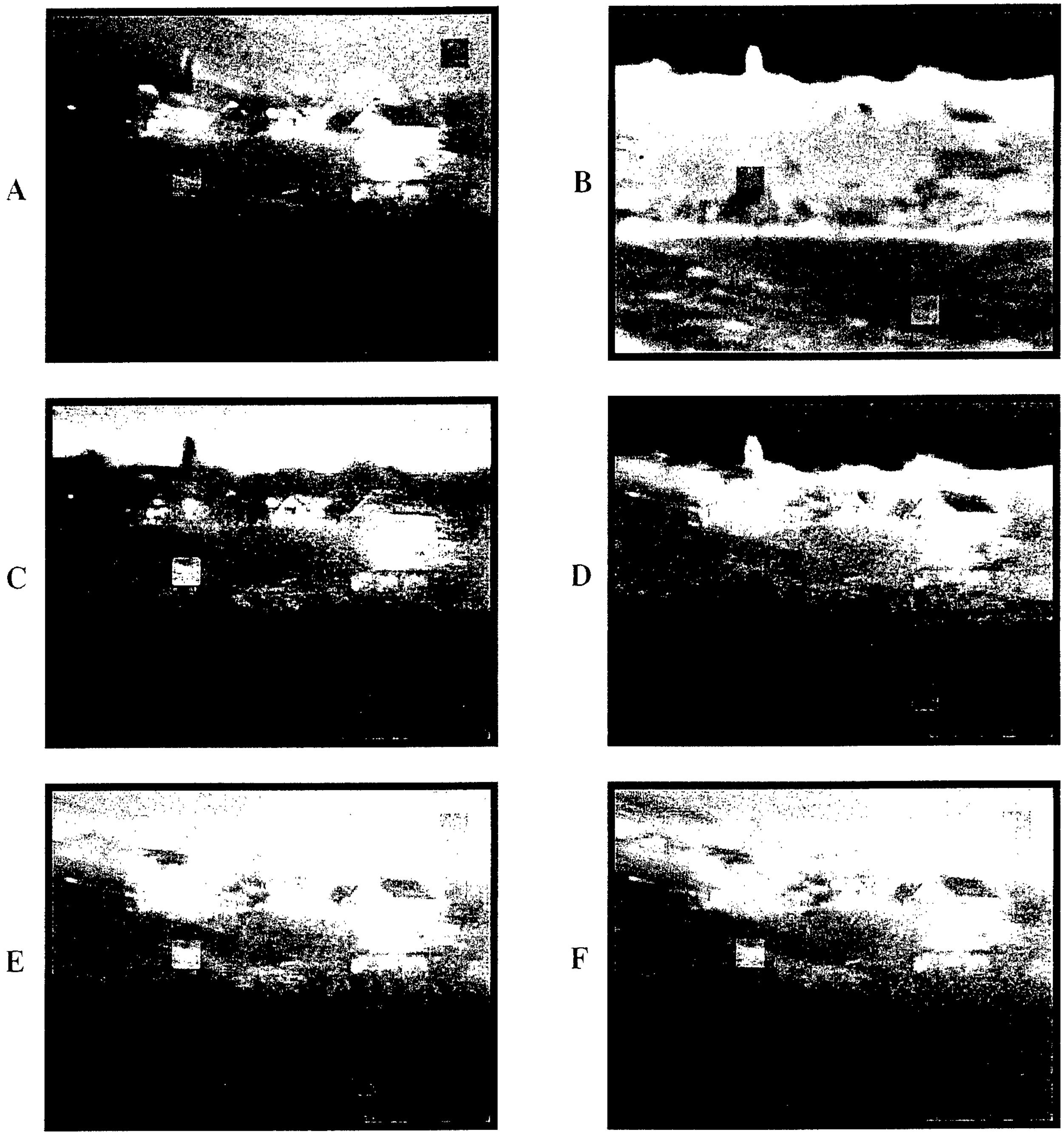


Figure 3. Dual-band imagery of Gloucester, MA, at dusk, with three embedded low-contrast square targets: (A) enhanced visible image taken with a Gen III intensified-CCD; (B) enhanced thermal IR image taken with an uncooled IR camera; (C) gray fused opponent-color (blue channel) image; (D) gray fused opponent-color (red channel) image; (E) color fused image; (F) remapped color fused image. Note that the color fused images support the perceptual *popout* of all three embedded targets.

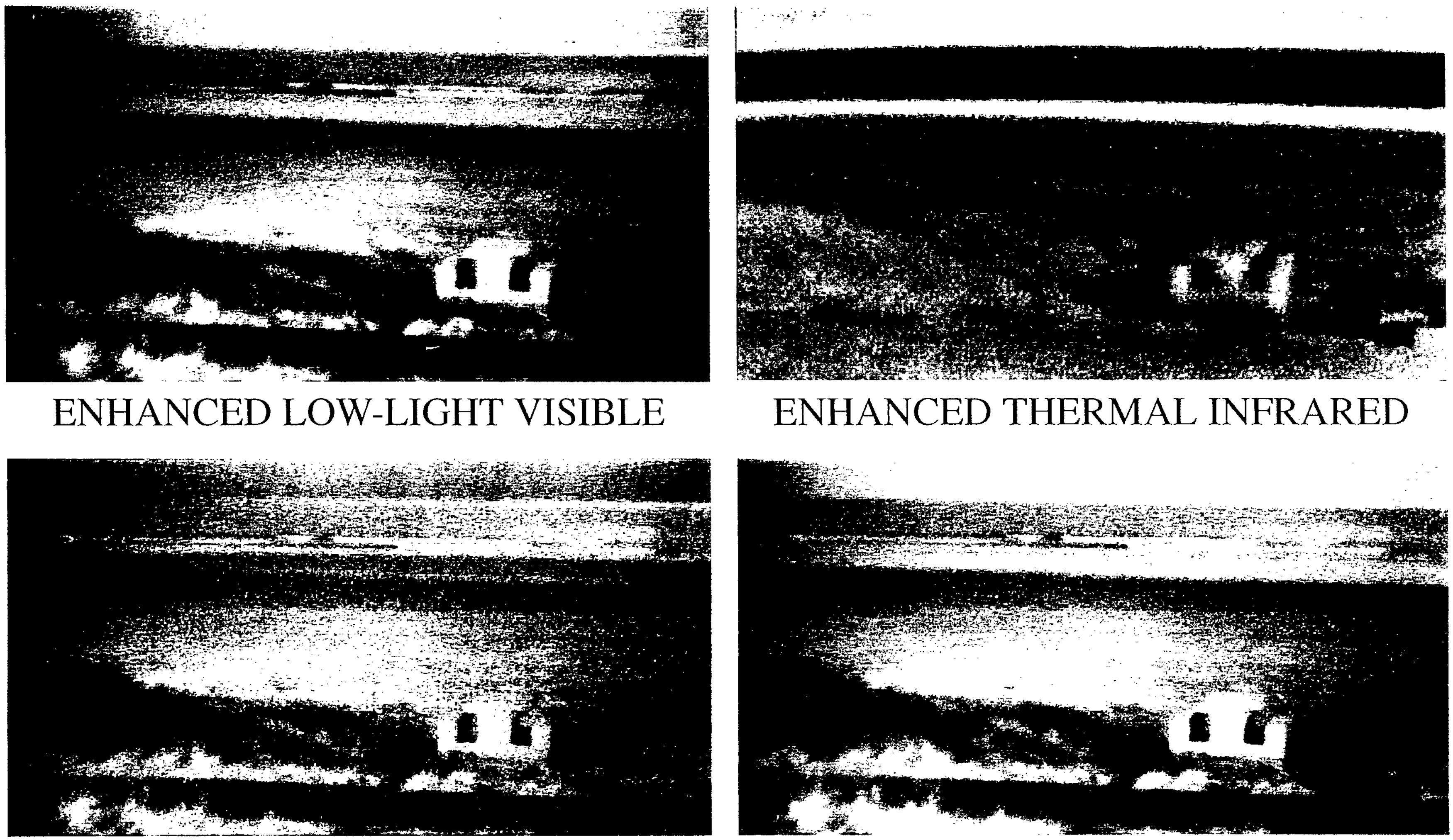
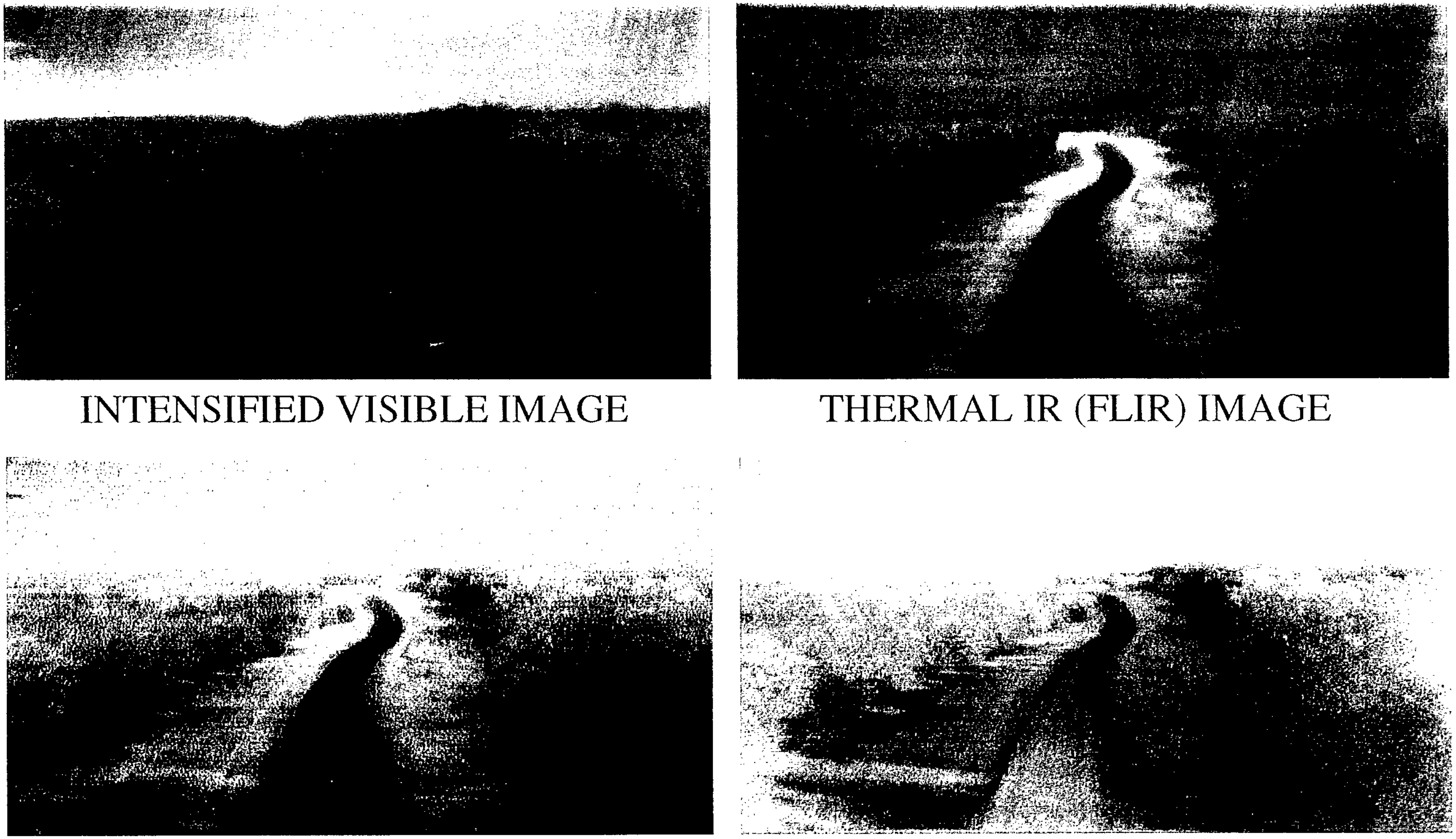


Figure 4. Nahant beach on the Atlantic Ocean in overcast full-moon illumination conditions. Dual-band visible and thermal IR imagery is combined to create grayscale and color fused images of the night scene.



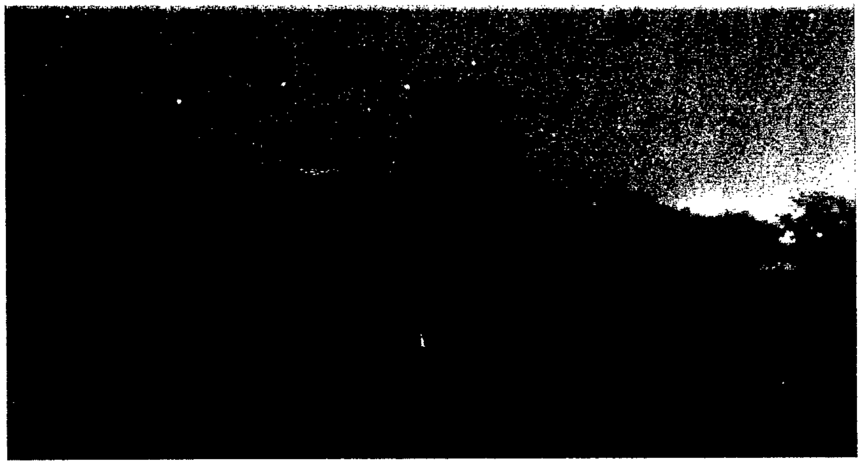
INTENSIFIED VISIBLE IMAGE

THERMAL IR (FLIR) IMAGE

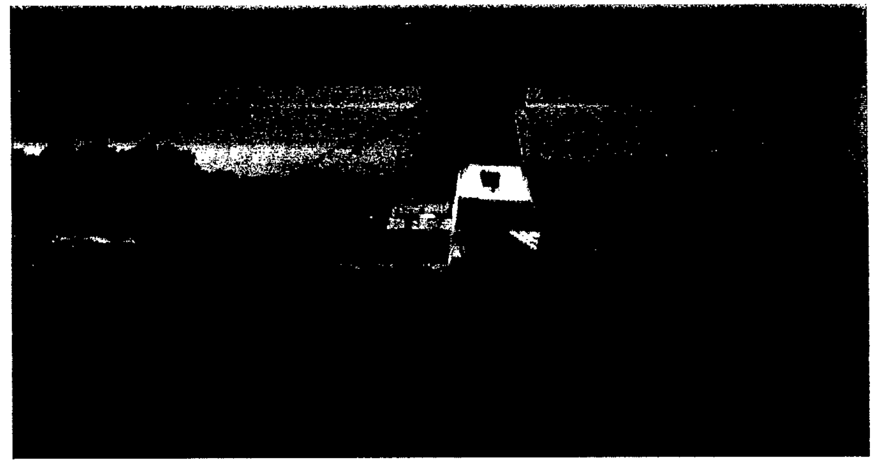
GRAY FUSED - "BLUE"

FUSED COLOR IMAGE

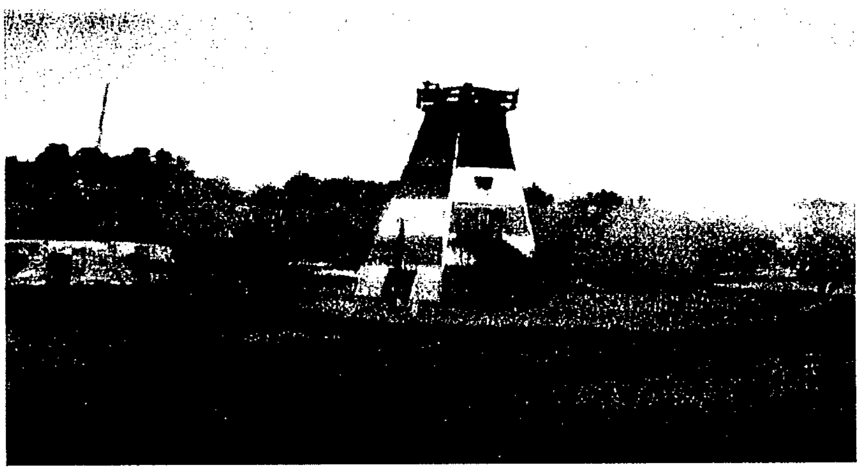
Figure 5. Road scene imagery provided by the U.S. Army NVESD. Dual-band visible and FLIR imagery is combined to create grayscale and color fused images of the night scene.



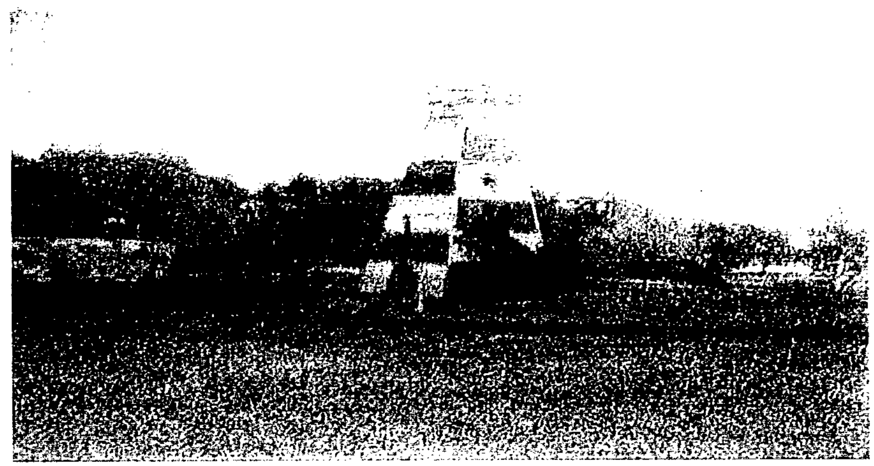
INTENSIFIED VISIBLE IMAGE



THERMAL IR (FLIR) IMAGE



GRAY FUSED - "BLUE"



FUSED COLOR IMAGE

Figure 6. Tower scene imagery provided by the U.S. Army NVESD. Dual-band visible and FLIR imagery is combined to create grayscale and color fused images of the night scene.

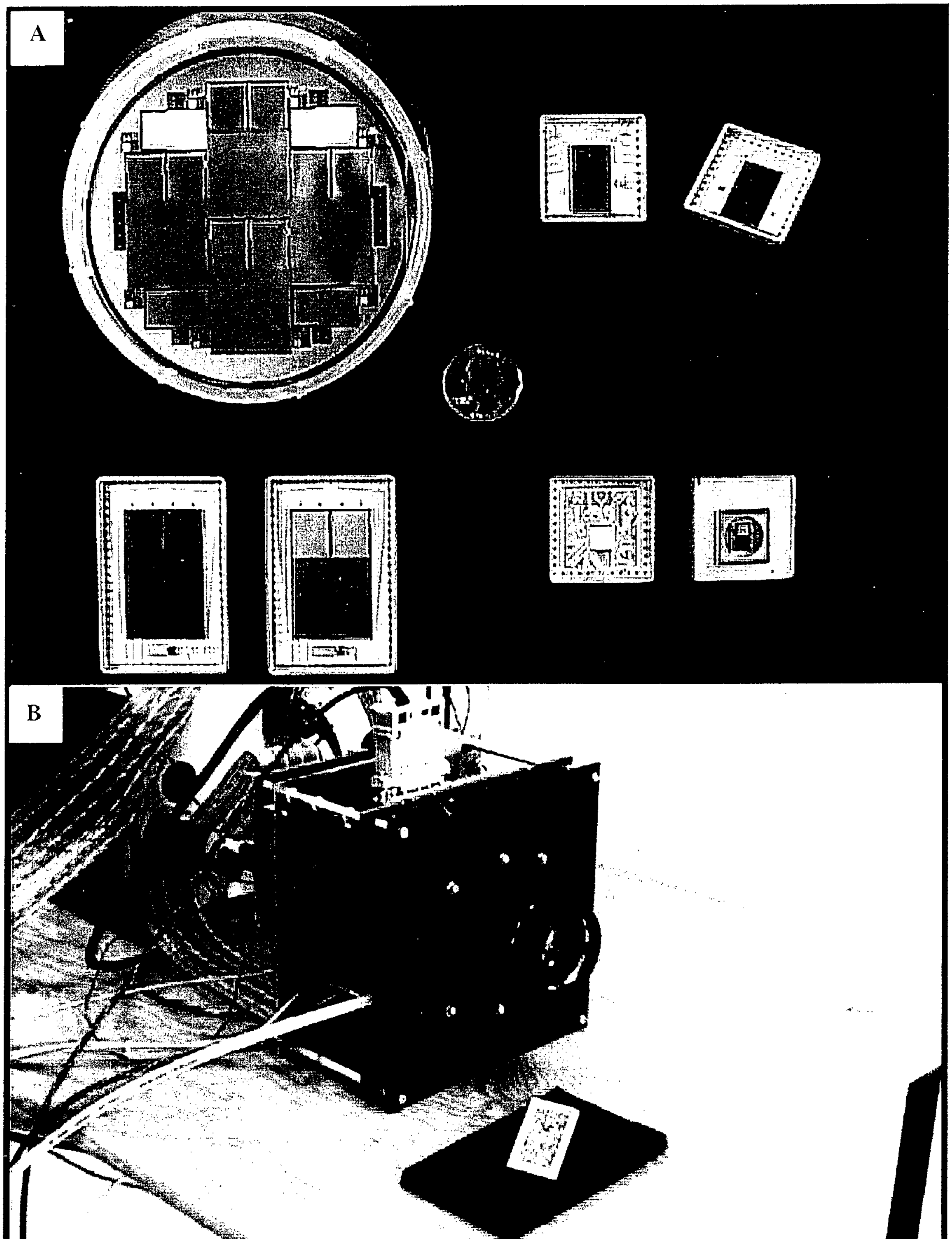
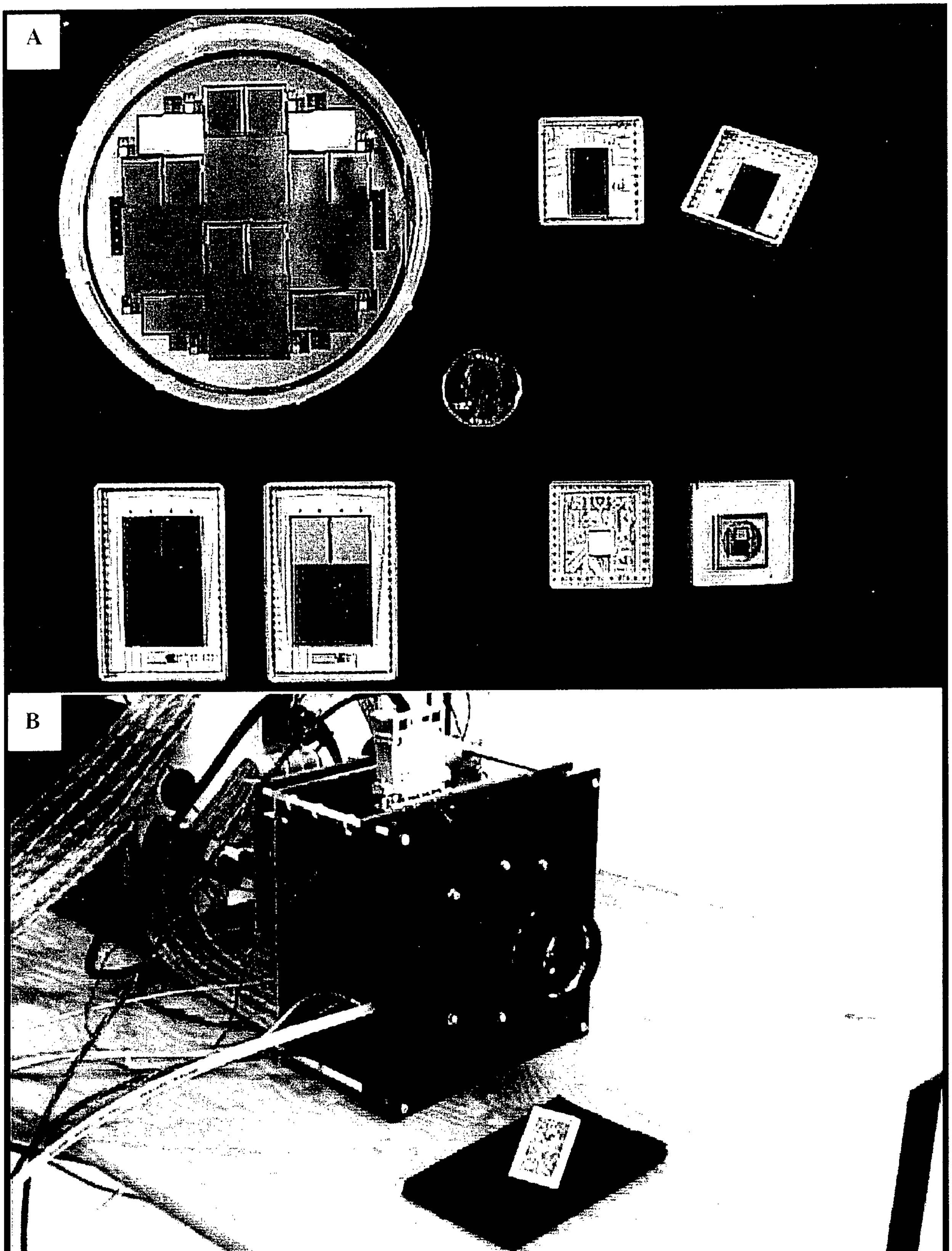


Figure 7. Low-light CCD imagers: (A) thinned wafer and packaged multi-ported CCDs with formats 1Kx1K, 512x512 and 128x128 pixels; (B) prototype low-light camera using 4-port 128x128 back-illuminated CCD, and analog circuit multi-chip module (shown in foreground).



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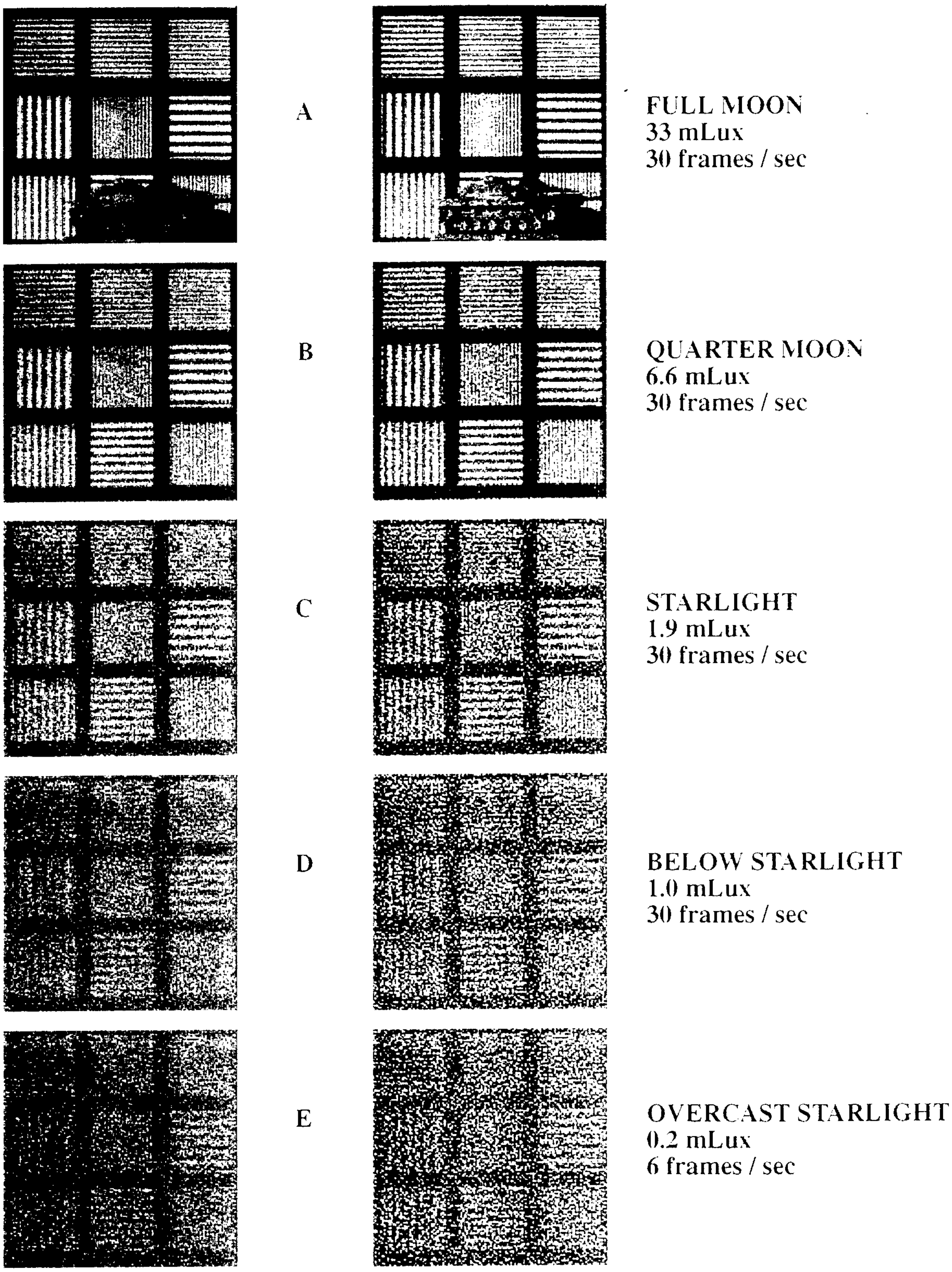


Figure 8. Low-light CCD imagery taken at video rates under controlled illumination conditions (A-E as indicated). Left column: raw 12-bit imagery scaled so *minimum* and *maximum* map to 0 and 255. Right column: corresponding 8-bit imagery obtained from center-surround shunt neural processing of original 12-bit imagery.

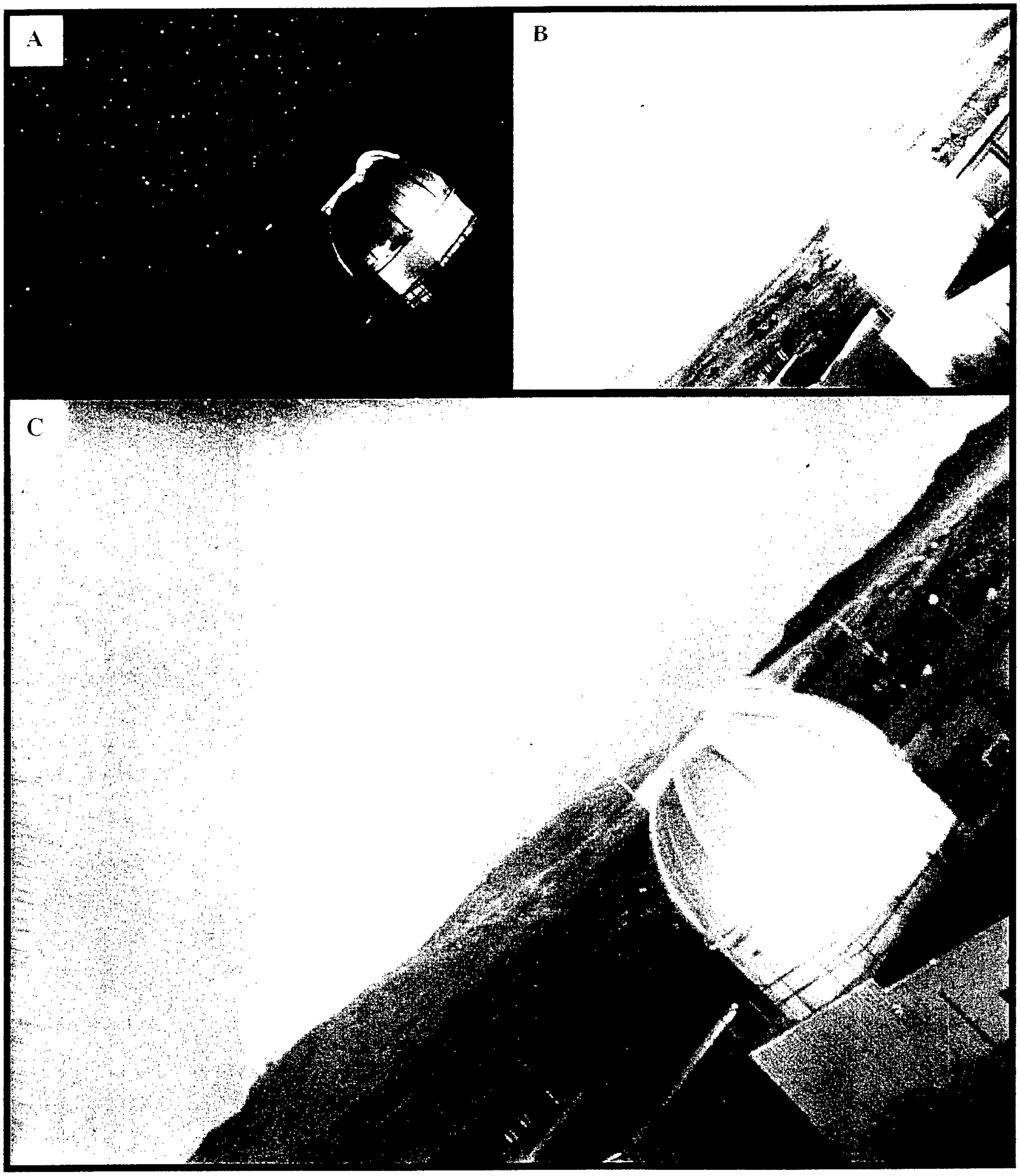


Figure 9. Low light CCD imagery of White Sands, NM, under starlight conditions, originally 1K x 1K pixels. (A) High end of 12-bit dynamic range. (B) Low end of 12-bit dynamic range. (C) Entire 8-bit dynamic range after center-surround shunt neural processing of original 12-bit imagery.

Position Location Using B-CDMA

This White Paper discusses the use of Broadband Code Division Multiple Access (B-CDMA) technology as a supplement or replacement for GPS to provide position location capability to military users in future operations.

Requirements for Position Location

Providing position location capability to a communication system greatly supports many important military field objectives. Amongst these are:

- Accurately tracking mission forces on a timely basis.
- Directing support to the mission elements in its different phases.
- Providing supplies to the right places as required by the situation
- Guiding needed medical assistance to appropriate casualties.

To be effective the position location capability must function reliably, not only in open terrain, but in heavily foliated areas, and in built up urban environments such as in cities, tall buildings and factories.

In such environments the effectiveness of GPS in providing position location degrades rapidly. This is due to a combination of attenuation of the GPS signals by the foliage and overhead canopies and/or building materials, loss of line of sight to the required number of satellites and multipath interference produced by numerous reflections from buildings and within buildings by walls, floors and other obstructions.

These situations are expected to be encountered more frequently in future operations. A supplementary position location system or an alternative to using GPS is therefore required if operations in such tactical situations are to be effectively supported. Direct sequence spread spectrum transmission technologies solve many of these problems. In particular the use of broadband spread spectrum signaling, in which the transmission bandwidth occupied by the signal is made much larger than the underlying data rate, provides the needed capability. This technology shows superior performance in the presence of multipath, supports multiple users in the same band simultaneously, provides excellent range accuracy and has inherent LPI and LPD characteristics. In addition because of wide band processing it also provides significant AJ capability in the presence of interference.

This paper addresses these issues.

Position Location - Geometry

Figure 1A depicts three objects located on a planar surface. Two of the objects or base stations, BS_1 and BS_2, know positions relative to the coordinate system shown. The third object, MS (or mobile) does not know its position in this coordinate system -- nor do either BS_1 or BS_2. The problem for the system is to determine the location of MS. Figure 1B shows that given the distances MS/BS_1 and MS/BS_2, and drawing circles with these distances as radii about their respective base stations, the object MS must lie at the intersection of these two circles. These circles intersect, at most, in two points leading to an ambiguity in the position of MS. This ambiguity can sometimes be resolved by the particular circumstances of the situation or mission. However by using a third base station BS_3, in similar fashion, the ambiguity in position inherent in using two base stations is completely resolved as shown in Figure 1C. Thus for the situation where all the objects are located in a plane and all conditions are ideal, a minimum of three base stations are required to uniquely locate a mobile.

For the situation where the mobile and base stations are located in three dimensions, rather than a plane, a minimum of four base stations are required to uniquely locate an object in the coordinate system. In this case the intersection of four spheres must be considered rather than circles as in the planar case.

In either case there are three elements at minimum that must be present to affect position location:

- A sufficient number of base stations to receive and process the needed information.
- A parameter to be measured at each base station to estimate the range between the base station and the mobile.
- A system technology to ensure that the accuracy with which the range information is obtained is maximized. This guarantees that any errors which are introduced into the position location estimate by practical considerations, such as the behavior of equipment or a non-ideal environment within which the position location system operates, are minimized.

Optimal Parameter Measurement Processor

The range between two objects can be measured electronically by transmitting a signal from one object and observing that signal at the other object. This latter signal is delayed in time relative to the transmission due to the range, r, between the two objects and the finite velocity of electromagnetic propagation, c, (approximately 10^9 ft./sec.). The amount of delay, T, is then:

$$T = \frac{r}{c}.$$

In reverse, this states that the range, r, between two objects can be determined by measuring the delay T between the transmission and reception of a signal between the two objects.

The transmitted signal vs. time t is s(t) and the received signal component is s(t-T). This signal is obtained at the receiver in the presence of unwanted components including thermal noise. In the presence of thermal noise, estimation theory[1] shows that the optimal processor to use to estimate T is the correlation receiver (or matched filter). Thus in Figure 2 the input signal received from the transmitter is multiplied at the receiver by a reference waveform $s(t - \hat{T})$ where $\hat{T}$ is an estimate of the value of T. This product is integrated for a length of time T_I secs and the value of the integration is noted. The optimum estimate, $\hat{T}_0$, of T is that value of $\hat{T}$ which produces the maximum output from the integrator.

To affect the correlation receiver, (Figure 2), the receiver must a-priori know the waveform used by the transmitter, i.e., s(t) and the receiver must test different values of delay $\hat{T}$ until the optimum value is found. Testing the different values of delay constitutes a search of all possible delays. When the integrator output is maximized, the value $\hat{T}_0$ is obtained and the range between the two objects is estimated as $c\hat{T}_0$.

<u>Spread Spectrum and Minimization of Range Error Estimate</u>

The accuracy of the range estimate $\hat{T}_0$ made in the correlation process depends upon the nature of the signal s(t). Figure 3 shows two possible waveforms. Each is of length T_I secs. The main difference between the two waveforms is that the waveform in Figure 3B is broken up in time into integral "chip" segments with the smallest chip t_c (sec) in length. The accuracy or resolution of the delay estimate $\hat{T}_0$ is <u>proportional</u> to[2]

T_I secs	Figure 3A waveform
t_c secs	Figure 3B waveform

Clearly using the waveform shown in Figure 3B leads to better accuracy in the time estimate of $\hat{T}_0$ than the waveform shown in Figure 3A, even though both waveforms are of the same length. This is because $t_c < T_I$.

The waveform of Figure 3B is said to be a direct sequence spread spectrum waveform with a constant envelope. The bandwidth of the waveform of Figure 3A is proportional to $1/T_I$ while that of Figure 3B is proportional to $\frac{1}{t_c}$. The ratio of the bandwidth of the spread waveform to that of the non-spread waveform is $\frac{T_I}{t_c}$.

[1] *Statistical Theory of Signal Detection*, Helstrom, Pergamon Press, 1960, Chapter VIII, p. 203.
[2] *Ibid*, Chapter X.

The smaller the value of the chip length, the larger is the bandwidth ratio (also called the processing gain of the waveform[3]). Thus the larger the processing gain the greater is the accuracy of the range estimate between MS and BS.

In a practical system the value of T_I is determined by the data rate required for the system. Selecting the value of t_c (chip time) determines the range accuracy of the position location system.

Breaking the waveform into small continuous chip segments creates a waveform sequence (a pseudo noise sequence) with a bandwidth larger than the data rate. Such a waveform is called a spread spectrum waveform.

Broadband Spread Spectrum-Code Division Multiple Access (B-CDMA)

When the processing gain utilized is larger than about 15, the waveforms are said to be broadband spread spectrum waveforms. The larger the bandwidth of the spread spectrum waveform (for a given data rate), the greater is the accuracy of the range estimates that are made. Therefore broadband spread spectrum waveforms are the optimal waveforms to use in a position location system. By carefully selecting different sequence patterns for the chips over the given data time many different waveforms can be created. These waveforms can be selected to have relatively small cross correlations between them. This enables multiple users to access or transmit simultaneously in the same frequency channel with minimal mutual interference. A broadband spread spectrum communication system using such a technology is said to be a B-CDMA (Broadband Code Division Multiple Access) system.

Position Location Using B-CDMA

Figure 4 shows a B-CDMA sequence which is transmitted from each BS. Because of the different distances between each BS and the MS, the delay time experienced and measured by each BS is different. This delay time is measured in chips. For example using a chip time of 8 Mcps, the range r corresponding to a one chip delay is:

$$r = \frac{10^9}{8x10^6} = 125ft.$$

For purposes of calculation, assume the one way delay measured at each BS is:

BS_1 delay = 64 chips	Range = 64 x 125 ft. = 8,000 ft.
BS_2 delay = 77 chips	Range = 77 x 125 ft. = 9,625 ft.
BS_2 delay = 86 chips	Range = 86 x 125 ft. = 10,750 ft.

[3] Note that T_I/t_c is also equal to the number of chips in the waveform of T_I sec in length.

Using these ranges as radii about their respective BS, the location of the MS is uniquely determined as shown.

The pseudo noise sequences can be thought of as a long ruler with a resolvable increment in range equal to the chip time (in the example the resolvable range = 125 ft.). The actual resolution of the position location system is dependent both upon the chip length and the signal to noise ratio at the correlator output. Typical range accuracies, using 8 Mcps, of 15-20 ft. can be obtained.

Communications systems using B-CDMA can also provide position location capability. There are various ways this can be done. For example during pauses or programmed dead times in the communications, a position location communication process can be implemented using spread spectrum signaling. Thus the communication system and the position location system are practically transparent to each other.

Hand Off - Communications and Position Location

In a practical mobile system the MS is moving. In many cases the MS will move out of communication range with one BS and into communication range with another BS. To maintain communications it is necessary for the MS to affiliate or lock up to the new BS. It achieves this lock by monitoring a set of a-priori known BS pilot signals which are active in the region where the mobile is located. These pilot signals consist of pseudo noise spread spectrum sequences. Thus the MS is continually searching a repertoire of pilot signals using correlation processing as previously discussed. When the MS moves away from one BS and closer to another, the pilot signal of the closer BS will provide a larger correlation output -- thus indicating that the MS should switch pseudo-noise codes to that corresponding to the closer BS.

With this new sequence both secure communications and position location information can be maintained seamlessly as the MS moves.

Multipath Effects

One of the non-ideal environmental conditions which are present in the communication channel is multipath. Thus the signal received at a BS will consist of contributions made from multiple components coming from multiple directions or reflecting elements that are present between the transmitter and receiver. These components introduce errors into the location system. A B-CDMA signal structure is the optimal signal type to use in such a situation. This is due to the fact that a spread spectrum signal processor is capable of resolving, or distinguishing, between multipath components that are delayed from each other by amounts greater than the range increment corresponding to the chip time. The smaller the chip time the greater the resolution capability of the position location system.

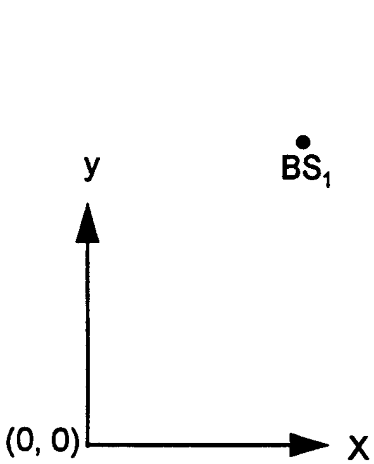
Thus a BCDMA position location system with a large processing gain minimizes multipath fading effects which introduce position location errors.

LPI, LPD, AJ Characteristics

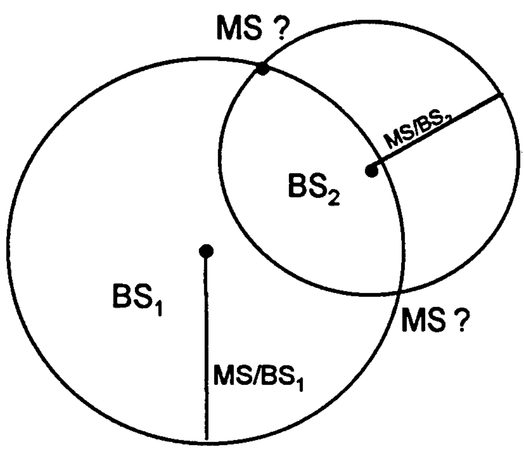
In spread spectrum signaling, the basic data bit is decomposed into an integral number of chip time epochs with amplitude of ± 1. The resulting waveform, a PN sequence, occupies a bandwidth much greater than the basic data rate. As an example, for the case of a spread spectrum chip rate of 8 Mcps and a data rate of 64 kbps, there are 125 chips per bit and the RF noise bandwidth of the transmitted signal is 8 MHz. For a fixed power transmission, the higher the chip rate the lower is the output power density of the signal as measured in watts per Hz. With sufficiently high chip rates, the transmitted power density can be designed to be less than the ambient thermal noise. In this situation the chance that this signal will be intercepted by a fielded radiometer type receiver are greatly reduced. Figure 5 illustrates the power density situation with and without spreading.

Simultaneously the complex structure of the transmitted waveform (with a large number of chips) provides assurance that only the intended user with the correct code will be able to effectively decorrelate the received signal. For those users, intended or not, who do not possess the correct code, the resulting output of the decorrelation process will be attenuated and the data will not be able to be obtained.

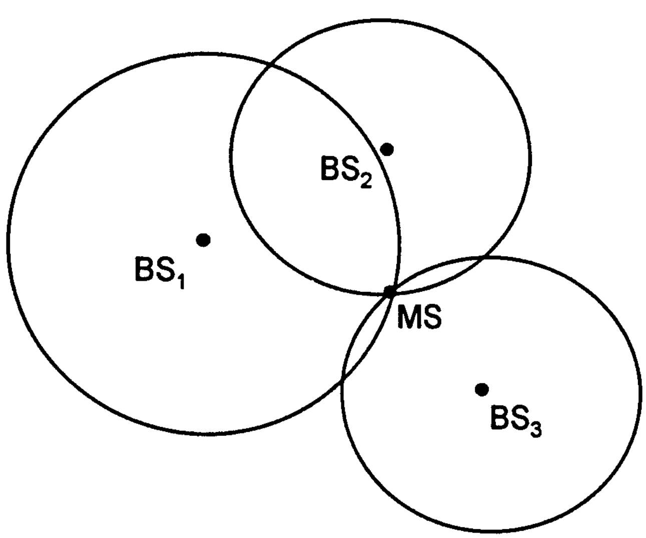
AJ is provided by the B-CDMA system because in the decorrelation process a narrowband interference with a fixed power will be spread over the full spread bandwidth. This reduces its power density at the input to the integrator. If the jammer is initially wide band, with the same power as the narrow band jammer above, then the same effect has been achieved since the jammer has reduced its own power density at its transmitter. Thus in either case, or anything in between, the jammer's power density has been reduced in the data bandwidth. For example, in the above case of 125 chips per bit, B-CDMA provides 21 dB anti-jam protection as compared with a conventional narrowband technology.



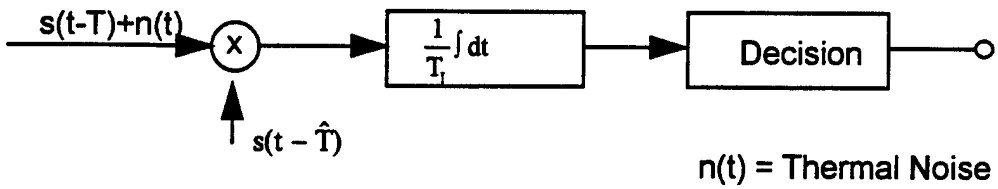
COORDINATE SYSTEM
FIGURE 1A



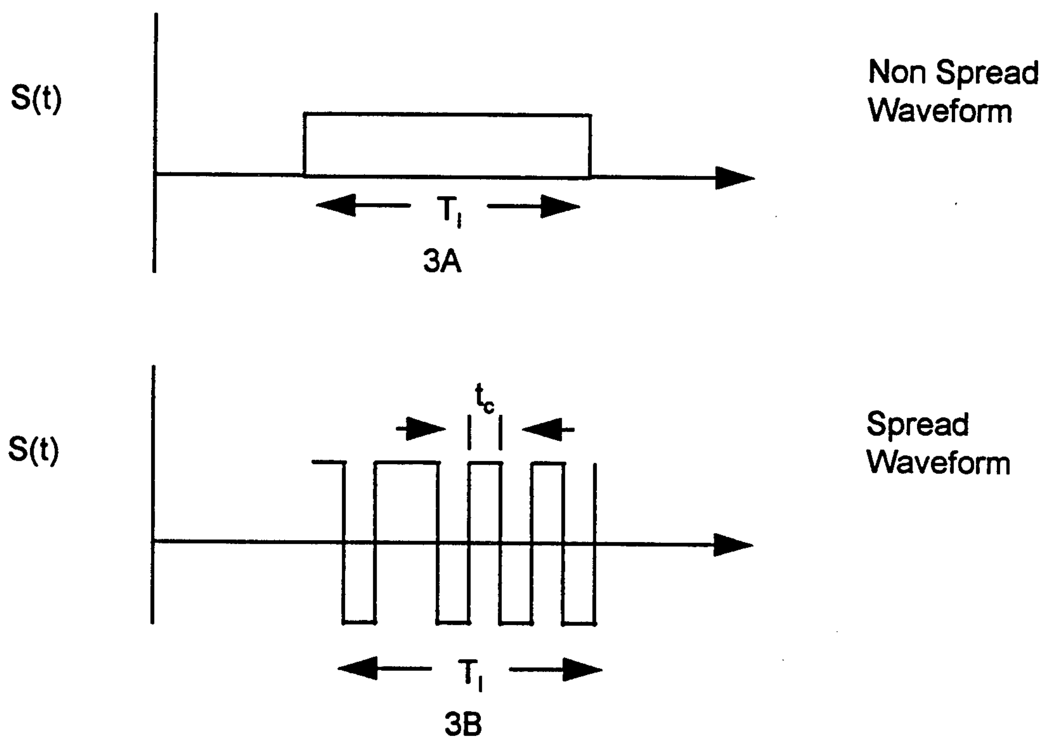
AMBIGUOUS POSITION LOCATION
FIGURE 1B



RESOLVING AMBIGUITY
IN POSITION LOCATION
FIGURE 1C

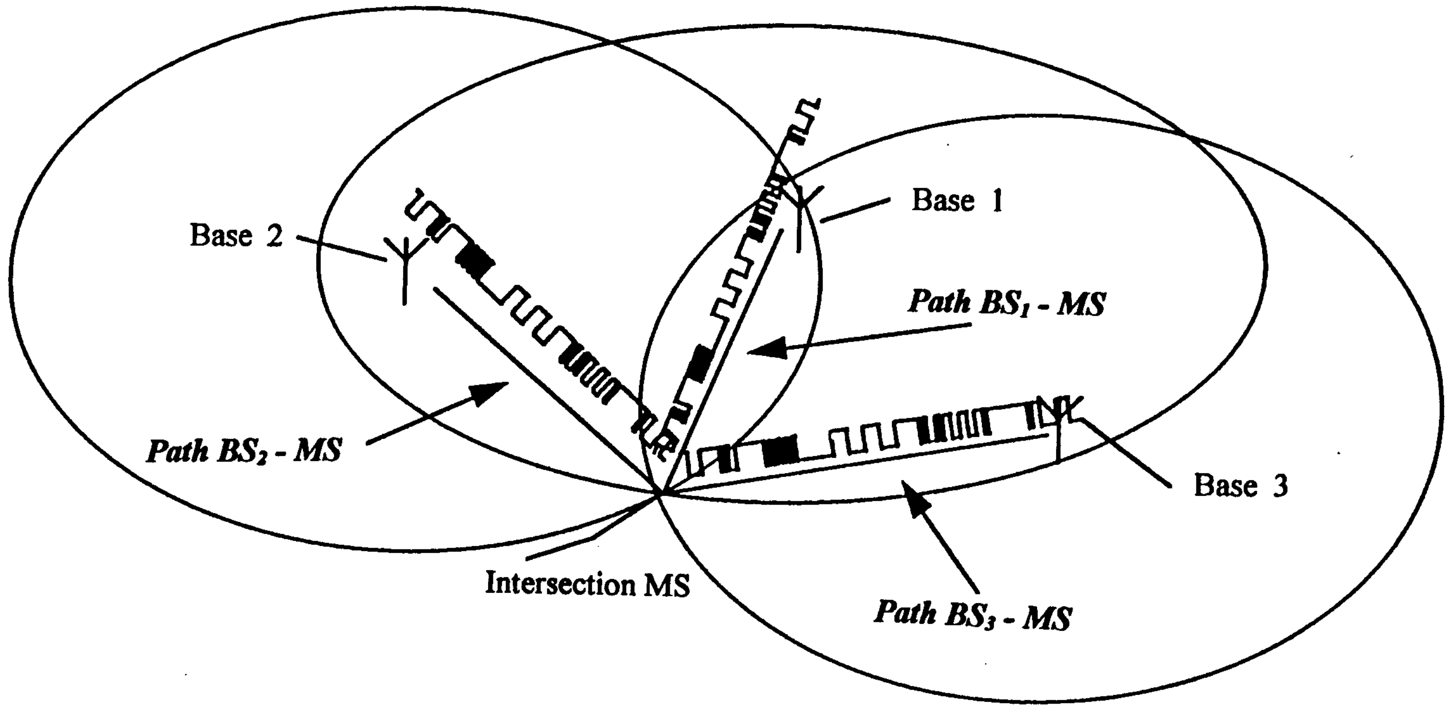


CORRELATION RECEIVER - OPTIMUM ESTIMATOR
FIGURE 2



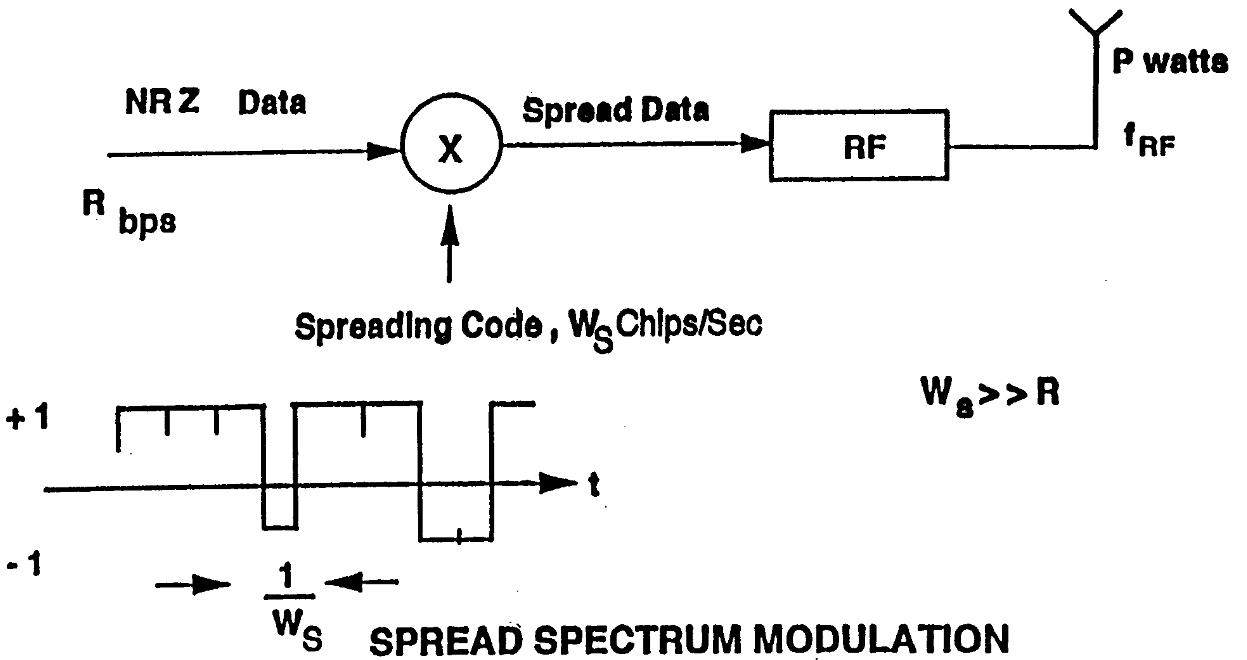
WAVEFORMS
FIGURE 3

Ranging to Three Base Stations

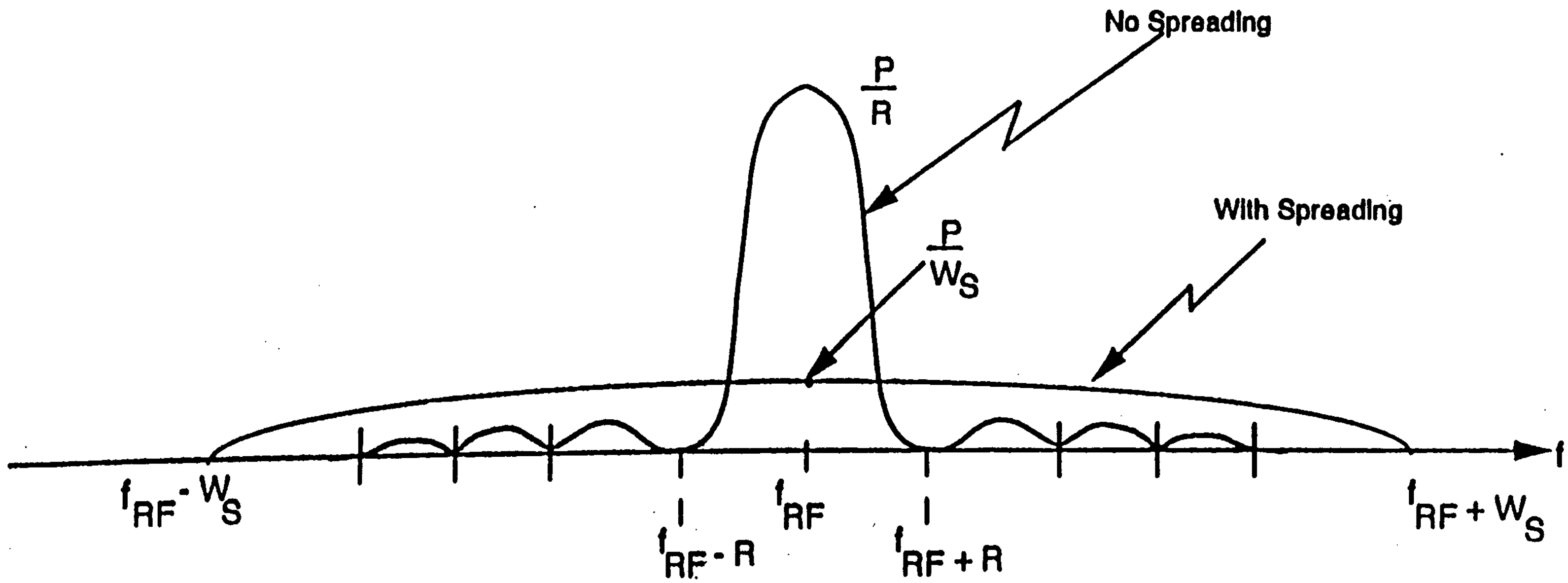


The PN Sequence Forms A Long Ruler Between The Mobile M1 and the Base Stations

FIGURE 4



SPREAD SPECTRUM MODULATION



OUTPUT POWER SPECTRUM - WITH AND WITHOUT SPREADING
FIGURE 5

DNA VACCINES FOR MALARIAL PREVENTION

RADM Noel Dysart

USN, N931

ABSTRACT

Malaria is a major disease in the world, resulting in 300-500 million cases per year with over 2 million deaths. Obviously, it is a very important threat to DoD worldwide military operations. Years of research starting with Walter Reed's work during the construction of the Panama Canal have yet to result in the successful fielding of an effective vaccine for this disease. Recent work has focused on a new vaccine process (DNA vaccines) which provide protection against infection with malaria for mice and non human primates.

DNA vaccines differ from all other vaccine technologies in that in all vaccines that have been used, the "foreign" material against which the body is asked to respond is inoculated and the body produces immunologic responses against this foreign material. In DNA vaccines the DNA encoding these foreign proteins, and the proteins are actually produced within the hosts' cells. This is a radical departure from standard vaccine methodologies.

An ATD to prove the safety and efficacy of this technique will begin in FY97 and has as its goal FDA approval of the technique and FDA permission to begin human trials. If successful, this same vaccine technique could have utility for the production of protection against diseases such as Dengue Fever and biological warfare agents.

ATD

DEVELOPMENT OF DNA VACCINES FOR COMPLEX MULTISTAGE PATHOGENS, AND AGAINST MULTIPLE PATHOGENS OF MILITARY IMPORTANCE

Start FY97

I. PROJECT OBJECTIVES

A. **Overall project objective:** To develop multivalent DNA vaccines designed to protect against complex, multi-stage microorganisms or against multiple simple pathogens by inducing protective antibody, and protective T lymphocyte responses against the proteins encoded by multiple genes, expressed either at multiple stages of the same organisms' life cycle, or by several different pathogens.

B. **Project technical objectives:**

1. Transition to advanced product development at least one multi-stage DNA vaccine against the complex malaria pathogen, *Plasmodium falciparum* from the following:

a. Sporozoite and liver stage malaria DNA vaccine

b. Liver and blood stage malaria DNA vaccine

c. Combined multi-stage, multi-immune response malaria DNA vaccine (sporozoite, liver, and erythrocytic stage)

2. Provide technological foundation for human testing of multivalent DNA vaccines against pathogens of military importance.

a. Infectious diseases (dengue, ETEC, etc.)

b. Biological warfare threats (anthrax, toxins, etc.)

II. CONFORMITY WITH HIGH-LEVEL DIRECTIVES

A. DON Science and Technology Requirements Guidance (STRG) June 95

1. First quartile: Develop single dose multivalent vaccines for operationally relevant diseases.

B. ATD Selection Meeting

1. DNA vaccines ATD ranked in top five by all CINCs

III. PAYOFFS

A. Warfighting Payoff

1. Background: In every war in this century, infectious diseases have caused far more hospitalizations than both non-battle and battle injuries combined. However, it is infection with malaria that has posed the greatest medical threat to field commanders. This is because malaria is the most important parasitic disease in the world, and one of the most important infectious diseases in the world. There an estimated 300-500 million cases of malaria and 1.5-2.7 million deaths caused by malaria annually. For example, in WWII, over 12 million man-days were lost due to malaria and in Vietnam the number was 1.2 million. During WWII in some theaters the malaria attack rate was 84% per annum and higher among forward troops. In both Wars, many units up to the division level were rendered completely ineffective due to malaria infection. Now 25 years later, the threat due to malaria is in many places worse than during WWII. Recently, in Somalia where the threat of malaria is relatively low and where troops were under supervised antimalarial prophylaxis, one Marine Corps unit sustained a 10% attack in one month. A deployment of 50,000 troops in the same area at that attack rate would represent over 5,000 cases of malaria each month, and over 50,000 per year. Forces from other nations are equally plagued by malaria infections. In the 1990s United Nations forces (Dutch and Australian) deployed to Cambodia sustained malaria attack rates between 9.5 and 16.6% on enforced chemoprophylaxis, and UN Forces deployed to Angola (Brazilian) had higher attack rates at 18% even though all were

taking the best antimalarial drugs available. The threat of malaria to U.S. Forces today is real. Of the last 7 major military deployments, 6 were to areas where malaria is endemic. The recent military action in Liberia highlights this fact. U.S. troops have never before faced as great a malaria threat as exists in sub-Saharan Africa, where the attack rates will be 10 - 100 times higher than in any previous conflict. The spread of drug resistant strains throughout the world limits even further our ability to defend our troops against malaria. With a reduction in our forces we will not have the backup personnel required to sustain operations that we have had in the past when we lost large percentages of our forces to malaria.

2. Preserve human life and manpower assets, and minimize morbidity, mortality and casualty rates: Vaccines are the single most efficient method of reducing infectious diseases. By using malaria to prove the principle that effective DNA vaccines can be developed, Navy Medical Research Institute (NMRI) scientists will develop a method to protect deployed forces against malaria, a disease with enormous mission aborting potential as described above, and provide the foundation for developing single-injection, multivalent vaccines against less complex pathogens including biological warfare agents.

B. Affordability

1. Economic impact: This vaccine will significantly reduce the costs of chemoprophylaxis and hospitalization of infected sailors and soldiers.

2. Reduce medical logistics and manpower requirements: Reduction of the threat posed by malaria and other infectious diseases and biological warfare agents by immunization will significantly reduce the requirements for training in and execution of effective measures to prevent, diagnose, and treat malaria and other infectious diseases. In addition, because this technology will enable development of a multivalent vaccine effective against several pathogens, and this vaccine will not require refrigeration, the logistical resources required for vaccine delivery will be significantly reduced.

IV. BACKGROUND

A. General Scientific Background

Since establishing 20 years ago that immunization of rodents and humans with radiation attenuated Plasmodium sp. sporozoites provides solid, sterile protective immunity, NMRI Malaria Program scientists have been working to:

1. Define the immune mechanisms responsible for this protection (6.1)

2. Identify the parasite proteins that are the antigen targets of this protective immunity (6.1).

3. Develop vaccine delivery systems that are able to induce the required immune responses against the identified targets so as to induce protective immune responses (6.2).

4. Develop experimental and natural malaria challenge models in humans so as to be able to optimally assess the protective efficacy of the vaccines developed (6.2).

5. Assess the protective efficacy of these vaccines in human volunteer studies (6.3).

This work has been necessary because it is completely impractical to immunize large numbers of individuals by the bite of thousands of infected mosquitoes as is required with the experimental vaccination with radiation attenuated sporozoites. Progress in this area has been remarkable over the years. NMRI scientists have identified the specific components of the humoral and cellular immune responses responsible for the protection, and discovered a number of parasite proteins that are the targets of this protection. They have refined the experimental challenge of human volunteers with malaria so that it is a safe, well accepted, and reproducible system, and through field studies at DoD laboratories in Indonesia and Kenya they have established the conditions for optimal testing of these vaccines under conditions of natural exposure. They have also conducted numerous safety, immunogenicity, and protective efficacy studies of experimental malaria vaccines in volunteers with only modest success (15-25% protection).

B. DNA vaccines; high risk/high reward technology

1. Standard modern vaccine development approaches: One of the major obstacles to success in the entire field of malaria vaccine development and modern vaccinology in general has been inadequate advancement in the area of vaccine delivery systems. This work for malaria has been summarized in a recently published book edited by the principal investigator (1). Over the last 10 years there have been great hopes for synthetic peptides, purified recombinant proteins, and live recombinant vaccines, but progress with these approaches has been disappointing in most infectious diseases. In the case of malaria, numerous proteins that are targets of protective immune responses have been characterized, but no existing vaccine delivery system has been reproducibly shown to generate adequate, long-lived protective immunity in malarious areas against even a single malaria protein. Since virtually all malariologists believe that a successful and sustainable malaria vaccine will have to induce protective antibody and T lymphocyte responses against numerous proteins expressed at different stages of the parasite life cycle, a versatile vaccine delivery system is of critical importance.

2. DNA vaccines:

a. Advances: The recently discovered technique of DNA immunization has the potential to revolutionize the field of vaccinology. NMRI scientists working independently demonstrated that DNA vaccines induced high levels of protection against malaria in their animal model systems (2,3). This cutting edge work and other studies conducted over the years has been published by NMRI scientists and has resulted in 3 issued patents, and 9 other patent applications. This strong foundation in 6.1, 6.2, and 6.3 research has paved the way for the 6.3 studies planned for this ATD, whereby DNA vaccines designed to induce the protective immune responses against the target proteins that NMRI scientists have spent so many years characterizing will be produced and evaluated. Recently, the journal *Molecular Medicine Today* highlighted the planned malaria DNA vaccine development work to be conducted under the ATD (4).

b. <u>Reasons for the enthusiasm</u>: **DNA vaccines differ from all other vaccine technologies in that in all vaccines that have been used, the "foreign" material against which the body is asked to respond is inoculated and the body produces immunologic responses against this foreign material. In DNA vaccines the DNA encoding these foreign proteins, and the proteins are actually produced within the hosts' cells. This is a radical departure from standard vaccine methodologies.**

c. <u>Advantages of DNA vaccines</u>:

1) Easy to produce and purify
2) Easy to modify
3) Can easily produce multi-gene (multi-antigen) DNA vaccines
4) Relatively inexpensive
5) May not require cold chain
6) No requirement for adjuvant
7) Highly immunogenic, especially for CD8+ T lymphocytes

NO OTHER VACCINE DELIVERY SYSTEM PROVIDES ALL THE POTENTIAL ADVANTAGES OF DNA VACCINES.

C. <u>Summary of Project</u> Using the biological discoveries and animal and human model systems established by NMRI scientists, and the basic discoveries regarding DNA malaria immunization made by NMRI scientists, the fundamental discoveries and capabilities of VICAL in this field, and the scale up, marketing, and distribution capabilities of Connaught Laboratories Inc. (CLI) , this **ATD** will plan to develop, produce, evaluate, and transition DNA malaria vaccines, and provide the technological foundation for production of vaccines against multiple infectious diseases and biological warfare threats.

References:

1. Hoffman, Stephen L., editor. ***Malaria Vaccine Development: A Multi-Immne Response Approach***. ASM Press, Washington, DC, 1996.
2. Sedegah M., R. Hedstrom, P. Hobart, and S.L. Hoffman. Protection against malaria by immunization with plasmid DNA encoding circumsporozoite protein. ***Proc. Natl. Acad. Sci.*** 91:9866-9870, 1994
3. Doolan D.L., M. Sedegah, R.C. Hedstrom, P. Hobart, Y. Charoenvit, and S.L. Hoffman. Circumventing genetic restriction of protection against malaria with multigne DNA immunization: CD8+ T cell-, interferon-, and nitric oxide-dependent immunity. ***J. Exp. Med.*** 183: 1739-1746, 1996.
4. Fricker J., Naked DNA for Malaria Vaccines, ***Molecular Medicine Today***, March 1996, p. 91

IV. MAJOR TASKS AND INTERNAL RELATIONSHIPS

1. **Develop sporozoite and liver stage DNA vaccines**
   a. Produce supplies of vaccines for pre-clinical safety, bioavailability, and immunogenicity studies
   b. Conduct pre-clinical safety, bioavailability, and immunogenicity studies
   c. Produce vaccine supplies for Phase 1/2 studies
   d. Submit investigational new drug (IND) application to FDA
   e. Conduct first set of Phase I clinical trials
   f. Conduct first set of Phase II clinical trials
   g. Conduct second set of Phase I and II clinical trials
   h. Transition successful vaccine

2. **Develop liver and blood stage DNA vaccines** (Same milestones as above)

3. **Develop combined multi-stage DNA vaccine** (Same milestones as above)

Further technology development has already resulted from success with this malaria vaccine project and will continue to occur. DNA vaccines against dengue fever and hepatitis E have been produced and shown to be immunogenic, and patents have been filed. Other standard infectious diseases of concern to the U.S. military, infectious biological warfare threats to the U.S. military, and single injection multi-valent vaccines important to the DoD and the private sector may be addressed by this technology. Both VICAL and CLI are financially sound and jointly can provide the resources necessary to develop and commercialize a naked DNA malaria vaccine.

The successful development of a malaria vaccine constitutes one of NMRI's principal missions. NMRI will benefit from this collaboration by gaining access to technology and material supplied by VICAL enabling the possible development of an efficacious malaria vaccine. VICAL will benefit by gaining access to NMRI's technology in malaria biology and pathogenesis and NMRI's ability to clinically test candidate vaccines. In the event a marketable malaria vaccine is developed, CLI will realize significant savings in time and cost of product development.

V. TECHNOLOGY BASE STATUS

The technology base status has been clarified through experimental work and meetings over the past two years. It consists of 1) An immunization technique likely to revolutionize vaccine development; 2)A Cooperative Agreement with Vical, Inc., the leading biotech company in the field (includes complete intellectual property rights for DNA vaccines (Vical), and malaria DNA vaccines (NMRI); 3) Proof that DNA vaccines protect against malaria in rodents; 4) Proof that P. falciparum DNA vaccines are immunogenic in rhesus monkeys; 5) A non-human primate (Aotus monkey) model to determine the protective efficacy of P. falciparum liver blood stage DNA vaccines; 6) An established core of physicians, immunologists, and molecular biologists with extensive experience in all aspects of malaria research including IND submission and clinical trials.

The following specific technical accomplishments have been achieved.

A. Gene identification, plasmid production, and murine studies: NMRI scientists have reported the first proof that DNA-based vaccines can protect against malaria in the rodent model. Mice immunized with a plasmid encoding the *P.yoelii* circumsporozoite protein (PyCSP) mounted specific antibody and cytotoxic T lymphocyte (CTL) responses and over 80% of these mice were protected against malaria. This level of protection is significantly greater than that achieved by any other subunit vaccine. Recently, we demonstrated 50% protection after immunization with as little as 2.5 ug of PyCSP plasmid DNA. These results have been extended using the gene encoding a malarial liver stage protein called PyHEP17 recently discovered by NMRI scientists. A DNA vaccine encoding a portion of the PyHEP17 antigen conferred protection against malaria in up to 86% of mice. Furthermore, mice immunized with a combination vaccine including both PyCSP and PyHEP17 had greater protection than achieved with either component alone, and 100% of BALB/c mice were protected by the combination. A DNA vaccine against a third sporozoite, liver stage protein discovered by NMRI scientists, SSP2, has also induced protection, and studies are underway with a trivalent vaccine in mice.

B. Studies in non-human primates:

1. Rhesus monkeys: Non-human primates. A number of vaccines have been shown to be immunogenic in mice, but not to be in primates. It was therefore considered imperative that we establish the immunogenicity of the P. falciparum DNA vaccines in non human primates before proceeding to human trials. The four plasmid DNA vaccines planned to be included in the first sporozoite liver stage vaccine trial have been used to immunize rhesus monkeys. All of the monkeys immunized with the mixture planned for humans responded. Most importantly they have all been shown to produce cytotoxic T lymphocytes against the malaria proteins.

2. Aotus monkeys: Aotus monkeys offer an advantage for the liver blood stage vaccine projects in that they can be challenged with Plasmodium falciparum and will die if they become infected and are not treated. They will be used to develop the optimal liver erythrocytic stage vaccine.

C. Production of human use plasmids under GMP conditions: Based on discussions that NMRI and Vical have had with the FDA, Vical scientists have produced a plasmid thought to be optimal for acceptance by the FDA. This plasmid expresses large amounts of antigen, provides high yields of DNA, and should be inexpensive to produce in large quantities. Production of GMP material will utilize methodology already developed by Vical, and be done in their GMP facilities

D. Immunologic studies in mice, monkeys, and humans: NMRI scientists have developed many assays to characterize antibody, CD4+ and CD8+ T cell responses induced by natural exposure to malaria or immunization in mice, monkeys, and humans. These assays are currently functional at NMRI.

E. Protocol development, IND submission, and safety, immunogenicity, and protective efficacy studies in humans: NMRI clinical investigators and VICAL collaborators have considerable experience with all phases of this process.

VI. TRANSITION PLANS

When Phase I/II clinical trials have established safety and protective efficacy, with concurrence of the OPNAV program sponsor (OP93), the vaccine(s) will be transitioned to 6.4 (PE/project 643807/808) for advanced development and conduct of "pivotal" studies required for application to the FDA for a product licensing agreement (PLA) and establishment license agreement (ELA). Support for advanced development to be provided by The United States Army Medical Materiel Development Activity (USAMMDA) PE/project 643807/808, Vical Inc., La Jolla, CA, and Connaught Laboratories Inc. (CLI), Swiftwater, PA. Manufacturing and commercialization will be carried out by Vical Inc. and CLI.

VIII. DELIVERABLES

A. The primary deliverable is a <u>DNA vaccine delivery system.</u>

B. At least one of the following malaria vaccines will be transitioned to advanced development:

1. A protective sporozoite and liver stage malaria DNA vaccine

2. A protective liver and blood stage malaria DNA vaccine

3. A protective combined multi-stage, multi-immune response malaria DNA vaccine.

C. Technology developed in this ATD will be transitioned to studies of multi-gene DNA vaccines against biological warfare and infectious disease agents (e.g. anthrax, dengue, etc).

IX. SUMMARY

All the pre-ATD objectives have been met (enormous progress), the tasks and milestones for the ATD are clearly established, cooperative agreements and CRADAs with industrial partners are in place, intellectual property rights are established, and a program execution plan is approved. We believe that the DNA vaccine technology in this ATD will lead to our having the capacity to produce effective vaccines against complex multi-stage microorganisms like malaria parasites, rapidly produce new vaccines against simple, single infectious and biologic warfare threats, and produce vaccines capable of protecting against multiple pathogens with the same injection. Because of its complexity and variability at each stage of its life cycle constructing a multi-antigen malaria vaccine is in essence constructing a single injection vaccine that protects against multiple pathogens. Proving the principle with this complex parasite, will provide the foundation for all other work. We have an opportunity with this ATD to create a revolution in vaccinology and protect operational forces against the most important infectious disease and biological warfare threats.