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IDA MEMORANDUM REPORT M-445

INNOVATIVE SCIENCE AND TECHNOLOGY (IST) IN SUPPORT OF SDI BM/C^3

Bohdan Balko, *Project Director*

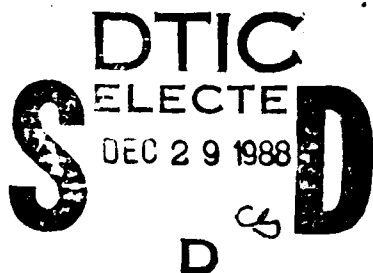*Committee Members*
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Battle Management and Command, Control and Communications (BM/C^3) issues in the Strategic Defense Initiative (SDI) context were discussed at a two-day workshop at the Institute for Defense Analyses (IDA). Another workshop probed civilian systems which require handling of large amounts of data and which have fault-tolerant features that may be useful in resolving the SDI BM/C^3 problems. The findings are summarized in this report, with special emphasis on possible research to be supported by the Innovative Science and Technology Office of SDIO.

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PREFACE

In May 1987, Dr. Dwight P. Duston, Deputy Director of the Innovative Science and Technology Office (IST) of the Strategic Defense Initiative Organization (SDIO), requested members of the IDA research staff to reexamine that part of the SDI program referred to as Battle Management/Command, Control, and Communications (BM/C^3). The IDA staff members were to establish a working definition of BM/C^3, delineate research areas which were not being satisfactorily addressed, and identify important new research initiatives for IST that might significantly affect BM/C^3 over the long term.

The SDIO has a "systems" side and a "technical" side. Within the systems organization, there is a BM/C^3 Office which has supported most of the SDI work in this area. The technical organization includes the Innovative Science and Technology Office. As its title indicates, IST supports basic research and technology programs that offer innovative approaches to the work of the other offices. It is in this context that IST has charged the IDA staff to reassess BM/C^3 problems with an open mind and to identify areas where there are gaps or needs that could be best filled by a research effort.

To prepare for the task, IDA staff members performed a variety of studies. Following a review of selected basic documents, they were briefed by in-house experts in BM/C^3 and also by corporate experts who are among the leading SDIO contractors in the field.

As part of this effort, the IDA team and consultants also examined the currently accepted scenarios for a strategic defensive war. It was clear that a typical architecture would involve platforms in geosynchronous orbit as well as many in orbits much closer to the earth. These platforms would house sensors, computers, kinetic- and directed-energy weapons or probes, and possibly other assets. If an attack were initiated by the enemy, within minutes there could be several hundred thousand objects on a ballistic trajectory toward CONUS targets, and a significant percentage of these would have to be tracked, identified, and destroyed. In addition to the U.S. space assets, there could also be suites of land- and sea-based defensive weapons, probes, and computers. The exchanges of

information among the various platforms, the analyses of the data contained therein, and the decisions that would have to be based on these analyses were perceived to constitute an enormous challenge. This awareness led the team to the next step.

It was decided that, to better understand the scope of the challenge, the team should examine as many possible analogues to the BM/C^3 problem as could be found through a relatively brief search in the public and private sectors. Missile defense systems already in existence in the military services would also be studied. This search could only be carried out using at least preliminary definitions of BM/C^3. The working definition developed is based on the assumption that the U.S. had already deployed a strategic defense system, and that future events, outside our control, initiated a global conflict. Further, this study does not deal with the process of strategic warning; it merely assumes that our deployed strategic defense system has detected the launches. How we would wage war from the initial detection of ballistic missile launches, to the use of sensors to form tracks of objects, to discriminating RVs from decoys, to ordering defensive weapons to engage targets, and finally, to deciding that the war is over--all of this identifies the functions of Battle Management. The C^3 portion of BM/C^3 includes human oversight, if any, and utilization of all of the software and hardware involved in the interchanges of information and directives among platforms.

In the effort to learn from analogues, five systems were identified whose functioning involved on-line handling of large volumes of data. All of these systems require updating of large amounts of memory and utilize fault-tolerant software containing, in some cases, millions of lines of code. They require rapid decisions to be made in real time, based on the flow of usable data. Representatives from the companies operating these systems were invited to workshops to brief us. A synopsis of the knowledge gleaned from these workshops was treated as one input to a larger two-day workshop on BM/C^3.

This report presents a review of the work done preparatory to the two-day workshop. We also summarize the findings of the workshop and make specific recommendations to IST for future work. The authors, while acknowledging valuable inputs and insights gained from the workshop participants, bear full responsibility for the contents of the report. The report has not been subjected to formal review.

ABSTRACT

Battle Management and Command, Control, and Communications (BM/C^3) issues in the Strategic Defense Initiative (SDI) context were discussed at a two-day workshop at the Institute for Defense Analyses (IDA). Another workshop probed civilian systems which require handling of large amounts of data and which have fault-tolerant features that may be useful in resolving SDI BM/C^3 problems. The findings are summarized in this report, with special emphasis on possible research to be supported by the Innovative Science and Technology Office of SDIO.

CONTENTS

Not included with this report but available upon request:

ADDENDUM 1--Copies of Vugraphs Presented at the One-Day Workshop
on Data and Information Flow in Civilian Systems

ADDENDUM 2--Copies of Vugraphs Presented at the Two-Day Innovative
Science and Technology Workshop on SDI BM/C^3

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EXECUTIVE SUMMARY

To be effective, the Strategic Defense System (SDS) must have the capacity to evolve and must allow primary human command and control functions to be exercised expeditiously and unambiguously. The SDS can be thought of as consisting of three primary parts, to wit: (1) the hardware and software which make up the suite of sensors, battle stations, weapons, communication links, and algorithms for carrying out detailed system functions; (2) the hardware and software comprising the means by which human oversight and control of the system is established and maintained; and (3) the human cadre that monitors and controls the operational goals. Except in making the recommendation for training, testing, and feedback of desirable system modifications, the Program Committee did not address the third item. In the context of this partition, and in view of the general requirement for SDS, the Program Committee has identified three primary research areas which are important in SDI BM/C^3 and which should be undertaken by IST. They are discussed in detail in Chapters II and III, and they may be briefly portrayed as follows:

- *We recommend research on methodologies which can be used to compare appropriate command and implementation structures and to select those which yield robust systems subject to reliable and flexible control by the senior command level. Measures of effectiveness should involve consideration of performance in a highly variable and ambiguous peacetime environment, as well as the performance appropriate to a hostile encounter.*

- Human control over the SDS is to be exercised at several levels, for diverse purposes and on disparate time scales. *We recommend development of analytical and computational tools which will help define and facilitate the role of the human decision maker at all levels in this highly variable system.* This research should include, but not be limited to, the assessment of training protocols and the development of decision aids based upon innovative approaches to data assimilation to cover all aspects of operation and maintenance of system hardware and software as well as operation of the system in the event of an attack.

- The payoff in mathematics is often very high. *IST should support mathematical research in areas such as system and control theory for very large*

systems, as well as in novel computational techniques such as fundamental mathematical aspects of parallel computing and applications of neural networks, all of which may conceivably lead to major breakthroughs in the design, understanding, and handling of a BM/C³ system. Conceptual research dealing with the underlying mathematical structures is well worth pursuing in the basic research program.

Additional topical studies and specific recommendations relating to hardware development are listed in Chapter IV of this report. These recommendations were compiled from a set solicited from a broad community of experts.

Some specific recommendations of the committee are as follows:

1. There is a clear need to study the panoramic aspects of BM/C³ as contrasted with the current emphasis on the behavior of the numerous subsystems. Stability, adequate execution of the design objectives, etc., are all properties of the complete system and require a system level study. It has been suggested that what is needed is a search for the "essential parameters" for SDI BM/C³, similar to the concepts of RCS and of drag coefficient, both of which are used to make sense out of large amounts of data."[1]

2. The role of the human operator as an integral part of the system architecture has been inadequately explored. In the systems discussed at the workshop, the central position of the operator was emphasized repeatedly, but there was not a sense that the human/computer interface had been determined on a rigorous basis. This seems to be due in large part to the lack of a dynamic model for the human which is compatible with the rest of the system. This modeling effort is made more difficult by the fact that human decision makers will play several distinct roles in the SDS. At the highest level, the NCA is charged with making competent all-encompassing decisions in a timely manner. In other situations, the human decision maker works on tasks that are so well defined that his replacement by an algorithmic surrogate might seem wise. The quantification of the performance of a human in the proposed operational environment should be studied under conditions of uncertainty and delayed information, with strict adherence to the needs of the ultimate users of the SDS. The National Test Bed (NTB) would be a useful facility for testing alternative human roles.

3. Research on the local algorithms necessary to support the proposed system architectures is a fundamental need. Several suggestions for specific areas which warrant attention have been made. The problem of tracking has not

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[1]   F. Sevcik, "Comments on the SDIO/IST Workshop on BM/C³," IDA letter dated Nov. 27, 1987.

been adequately addressed, and it is time that many of the simplifying assumptions made by the contractors should be dropped; e.g., perfect scan-to-scan correlation. Other areas come immediately to mind, to wit, distinguishing the target from the plume and other debris during the boost phase, target assignment, and missile typing (for example, S18, S24, ASAT). Work on passive algorithms is currently in progress as part of the IST program. This effort needs to be expanded to include active algorithms which make use of the ability of the system to reconfigure its communication assets in the best possible manner. Because of its ravenous appetite for data, the need for maintaining a "birth-to-death" file for every detectable object should be explored and reevaluated.

4. The current efforts in high-speed computing, sensing, discrimination, and signal processing have direct application in SDI BM/C^3. Higher sensitivity and better resolution detectors would have a profound impact on performance because they would permit the design of sensors with higher update rates, and the difficulties encountered in the multiple-target-tracking problem would be diminished. While the committee does not believe that the IST should support a significant effort in the design of special-purpose computers, there are several computational issues that should be confronted. There is a need to develop space-qualified, hardened, general-purpose computers. To support the functions of the SDS, a programmable message-interface module should be developed. These should be physically hard against a nuclear space environment (NSE), space-qualified, and capable of handling very large data packets.

5. There is a need for research into the question of the degree to which a modular design philosophy constrains performance. We believe that the communications network will create the primary limit on performance under full-stress conditions. Thus, not only should the detailed comparisons of alternative communication links (RF vs. laser) be continued, but more basic studies of the effects of communication overhead and delay should be performed. The human decision makers should have the flexibility to modify the communication organization when appropriate. This requires basic research on mathematical techniques for the development and assessment of strategies for managing a space-based network for data transmission. As part of this study, the explicit influence of the system architecture on measures of effectiveness can be deduced, and the contrast between implicit coordination and its more hierarchical counterparts is made more apparent.

The evaluation and listing of important research topics described above is based on a very limited access to major development efforts in SDIO that relate to BM/C^3 functions.

For this reason, we believe that selected additional IDA evaluations along the lines presented in this report may be appropriate.

I. INTRODUCTION

While all military BM/C^3 systems share similarities, the SDI environment tends to emphasize the importance of integrating the logical and physical architectures of BM/C^3 functions. Generically, Battle Management (BM) and Command, Control and Communications (C^3) involve a collection of functions which are performed in a hierarchical fashion at many levels, ranging from individual weapons platforms, through the military structure, up to the National Command Authorities (NCA).[2] These functions are carried out using equipment, algorithms, and communications organized as subsystems ranging from space-based sensors to field radios.

To be effective, the Strategic Defense System (SDS) must have the capacity to evolve. The system will reach initial operational capability (IOC) with an initial set of functional elements. During its lifetime, these elements will be multiplied, modified, or replaced, and their roles expanded or constricted as changing demands are placed upon the system. Hence, a flexibly implemented system, subject to reevaluation on the basis of technological improvements and changing missions, is an indispensable requirement.

System control and management during the transition to full capability will be exercised by the Strategic Defense command structure interfacing with the National Military Command System (NMCS). Upon achieving full operational capability, means will be provided for overall direction by the NCA through the NMCS, with day-by-day operations under the control of the Strategic Defense commander. The system must allow this primary human command and control function to be exercised expeditiously and unambiguously. A possible command structure has been laid out in IDA Paper P-1928 and is diagrammed in Appendix E.

Even when the particular needs of one element of the multilayer SDS are studied, virtually the entire domain of system components and locations must be considered. For example, at the level of an individual missile-launching platform, BM/C^3 functions are

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[2] The National Command Authorities (DoD) are the President and Secretary of Defense and their duly deputized alternates or successors. Commonly referred to as NCA--JCS Pub. 1, 1 April 1984.

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performed by subsystems that process data from both on-board and remote sensors along with weapon-status information to determine whether and where to launch interceptors. A panoramic view of BM/C³ includes not only the specified subsystems, but also the communication links (and their support) that supply information and are used at the control and management centers.

In the global system, there are numerous decisions to be made in the allocation of BM/C³ functions to different levels within the hierarchy and to different nodes within a level. This allocation is made considering cost, sensitivity to countermeasures, and uncertainties in the workload that each node might face. In addition, a flexible architecture is essential to permit the inclusion of advanced subsystems and components as technology permits.

The role of the human decision maker in the SDS does not alter this fundamental view of BM/C³. Some BM/C³ functions can be performed either by a human or by an algorithmic surrogate. Obviously, any task involving quick processing of large quantities of data is beyond human capabilities. However, it is unlikely that computers can be programmed to handle every contingency. With judicious aggregation of data, however, humans can learn to make or assist in critical decisions upon which the success of the SDS may depend. And, clearly, invoking changes in rules of engagement, demonstrating national will and resolve, placing the SDS on alert status, and authorizing the engagement of targets by the SDS are human decisions that must be referred to the NCA and the Strategic Defense Commander acting in a direct management role.

A broader definition of BM/C³ is useful in scoping the tasks to be done. Paraphrasing from Ref. 1: *Battle Management/Command, Control, and Communications (BM/C³) is the military organizational structure that exercises authority and direction over the available forces in the accomplishment of a specific mission.* Battle management functions are performed through an arrangement of equipment, communications, facilities, and subsystem interactions which are employed in directing, coordinating, and controlling forces and operations in accomplishment of the mission.

While necessarily couched in general terms, this definition captures the ubiquitous nature of BM/C³ and focuses attention on the need to apportion BM/C³ tasks at various levels in a hierarchical SDS. An "operational" definition is that BM/C³ is the mapping of assets into actions to *accomplish desired goals.* When this statement is interpreted in the SDS context, it is apparent that the BM/C³ architecture is stringently tied to system physical

architecture. Arguments about the scope of BM/C^3 (Does it extend "from detectors to debris" or is it confined to the decision-making environment of the NCA?) can be viewed as disputations about the domain and range of the *mapping*, rather than about the fundamental character of BM/C^3.

The Program Committee for the IST Workshop on SDI BM/C^3 tried to identify issues in BM/C^3 that were both SDI-specific and not being currently addressed by the IST research program. One approach was to hold a workshop during which presentations were made by people involved with the design and operation of complex civil systems that share features with SDI BM/C^3, such as wide geographical dispersal of activities, high data rates, and uninterrupted operation for extended periods. These meetings helped identify some of the system-level problems that must be addressed in the SDI BM/C^3.

While the commercial systems discussed share a range of challenges with military BM/C^3 systems, their permissible reactions to these challenges is relatively less restricted. For example, the American Airlines SABRE system has a brittle software architecture and has had to be completely shut down for brief periods in the past under emergency conditions. It has evolved over the years that it has been in service by *ad hoc* responses to new needs or unexpected predicaments. Such a pattern of development is clearly to be avoided in the context of the SDI mission. The SDS is expected to remain in place for decades. An "open" architecture, which permits the exploitation of advances in technology, in sensors, communications, and processors, is important if the system is not to be unduly degraded by sophisticated countermeasures that were not foreseen when deployment started.

We believe that some BM/C^3 concerns affect design at the subsystem level. This point was emphasized in the Eastport Study (Ref. 2). This Committee endorses the view that "designing the system first and then writing the software to control it is the wrong approach for SDI." Rather, the performance of subsystem elements must be gauged in terms of quantitative measures of effectiveness related to the ability of the system to accomplish its objectives. The nonexistence of such quantitative measures of effectiveness makes the isolated examination of BM/C^3 issues as research topics or as aids to system synthesis more difficult than it would otherwise be.

The current IST program organization reflects the ambiguity with which BM/C^3 is widely viewed (Fig. 1). Research in such areas as "Sensing, Discrimination, ..." and "High Speed Computing ..." is clearly supportive of SDI goals. Furthermore, each topic

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within "Sensing, Discrimination, ..." has a well-developed conceptual framework within which a quantitative assessment of research alternatives can be made. A similar framework is not available for BM/C^3 as a topic.

The need for such a viewpoint is made clear by Van Trees (Ref. 3). Discussing C^2 systems, he says:

> The utility of communications, intelligence, warning, surveillance and reconnaissance cannot be determined without casting these systems in a command and control systems context and understanding ... the dependencies and interrelationships which exist among these contributing subsystems. The ability to evaluate and understand command and control systems which are working properly as designed in situations that are correctly anticipated is not enough. The increasing investment which our adversaries are making in developing countermeasures and in their own command and control systems heightens the need to understand how our systems would operate at diminished levels of capacity and capability and the impact of this reduced performance on our fighting capability.
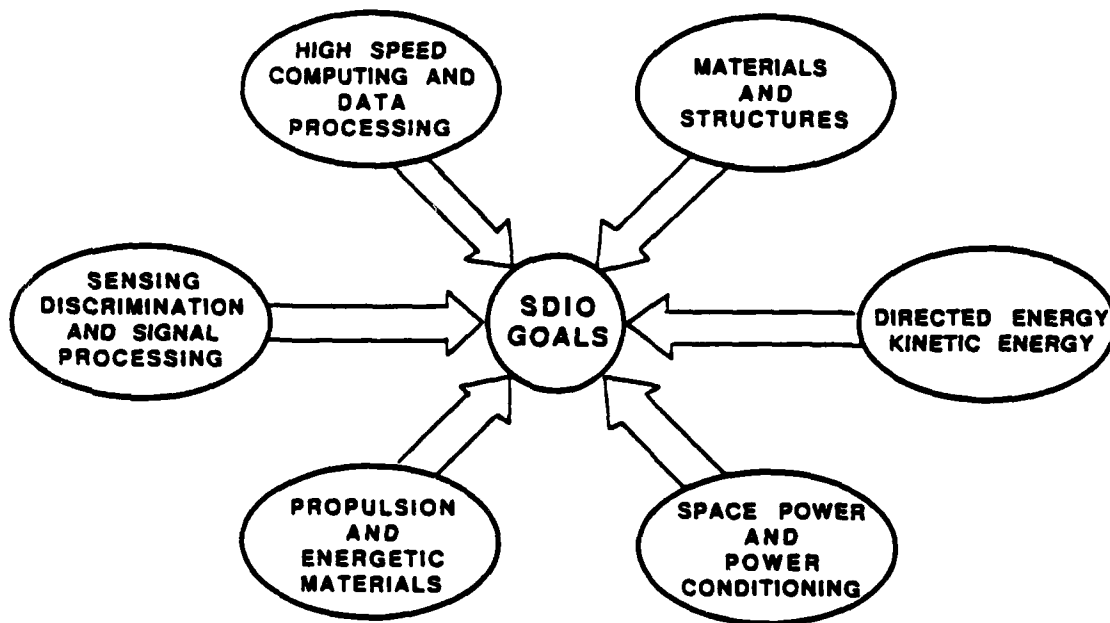
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Figure 1. SDIO/IST Program Organization

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II. ARCHITECTURE, ALGORITHMS, AND COMMUNICATIONS

The study of BM/C^3 leads naturally to an investigation of system architectures. Indeed, a system's logical and physical structure is an explicit manifestation of a BM/C^3 concept. Logical architectural forms range from those that are highly centralized to those that are nearly autonomous. The former are very vulnerable to particular countermeasures directed to disabling the central authority, and they may also introduce possibly unacceptable time delays. However, they generally represent efficient resource allocations. The latter may be more survivable, but they pose difficulty in assuring that scarce resources are used efficiently (Ref. 4). There is a spectrum of choice between these extremes. The current preference is for *implicit coordination*[3] to be achieved by a highly autonomous structure. Before a final decision is made to take this approach, important questions remain to be answered.

The committee identified two fundamental issues which should be addressed soon because their resolution may determine if implicit coordination or any of its proposed variants will be viable characteristics of an SDS architecture. The first issue concerns the complexity of the algorithms which must be developed to perform the required data manipulation. The second relates to the communications capability required to support the needed data flow.

Here, the term communications is to be interpreted generically. Communications technology is fundamental to all BM/C^3 functions. Any communications architecture must simultaneously support a sensor architecture, a weapons architecture, and a command and control architecture. That is, information required at any node will be assumed to be transmitted to that node unambiguously and with minimal delay. While it is evident that

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[3] Implicit coordination is a term used to describe architectures which minimize information transfer requirements for operational coordination by assuring (1) all BM/C^3 decision elements operate from a common information base, and (2) all such elements use a common set of algorithms for resource-allocation decisions.

communications by themselves do not convert algorithms into command and control functions, critical battle-management issues arise when the communications are incomplete or not transparent to all users.

The synthesis of appropriate algorithms is, in turn, related to the communications architecture in ways that are frequently overlooked. For example, multiple-target tracking requires input data from at least two sensors.[4] To date, numerous tracking algorithms have been developed, but these are restricted to a relatively small number of targets and low target densities. Typically, these algorithms have been designed to accommodate processing data from multiple sensors. Even for these special cases, there are shortcomings with existing designs, especially in the presence of target maneuvers and structured clutter. The timeliness and quality of multiple-sensor inputs will influence the operation of a tracking algorithm.

In the SDS environment, there will be multiple-sensor configurations, and hence a variety of processing chains is possible. In multiple-target tracking, the architecture, the processing resources required, and the performance will depend on algorithm design, as well as on sensor configuration. Candidate algorithms must therefore be developed and evaluated before overall system performance can be predicted.

Even the criteria for evaluating multiple-target estimation performance are not without controversy. The adequacy of an estimator depends upon the performance of the weapon subsystems. Tracking errors when predicting ahead to the interceptor target impact time must provide an error volume smaller than the divert capability of the interceptor. Furthermore, the analytical structure which underlies the design of trackers in the multiple-target environment is not well developed. This conclusion contrasts with single-target tracking for which error analysis techniques are available to put tight bounds on potential tracking accuracy, without regard to the specific algorithm used. Complications such as misassociation do not occur in single-target tracking. The consequences of misassociation include reduced tracking accuracy, increased acquisition time, and increased numbers of false and missing tracks. Misassociations corrupt track purity, which is important for discrimination where correlated observations are used over a period of time. The number of misassociations depends upon the threat characteristics, sensor design, configuration timeliness, quality of sensor data, and the specific algorithm employed. System synthesis cannot be on a firm footing without an understanding of these algorithmic issues.

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[4] This requirement is necessary to obtain range information from passive sensors.

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Although SDIO is currently addressing many of these problems, IST could make an important contribution by supplying innovative approaches to these issues.

Another important architectural issue in SDI BM/C^3 is that of the organization and management of the available communications assets. This topic is not restricted to the bandwidth needed in the communication links or ECM vulnerability, as typified by the RF vs. laser debate. Rather, this subject should be expanded to include the desirable topological properties of the communications network.

When attention is focused on the vexing algorithmic difficulties at the nodes of the system, it is easy to lose sight of the fact that a basic limitation on the effectiveness of the system rests jointly on its ability to guarantee that the requisite quality and quantity of information is available at each node, and on the provision of the required processing capacity at the nodes. The communciations assets of an SDS are too limited, too expensive, and too vulnerable to invite a logical architecture that dedicates assets to specific users. More appealing is an approach to communication which permits a reallocation of idle channel capacity. This approach should improve survivability and flexibility by not requiring critical users to be fully dependent upon nonredundant communication links.

It was suggested at the workshop that the IST research initiative on BM/C^3 emphasize the control and management aspects of the system rather than the performance of its various subsystems. The SDS must perform in an environment where data traffic requirements and external stress (due to jamming and countermeasures, among other things) may vary by orders of magnitude over short periods of time. Although the traffic flow pattern can be anticipated reasonably well under "nominal" conditions, the external stresses occur unpredictably and may arise anywhere in the system: at the sensors, the processors, the communications elements, and the displays at monitoring stations.

The processing algorithms at each node of the SDS network should be designed with consideration of the communications network that supplies the node. Clearly, the communications needs of a node depend on the functional requirements to be met at that node, i.e., on the degree of autonomy with which the elements of the system perform their functions. There is, therefore, a need to consider algorithmic design in the context of its data links. The current research effort is focused upon what might be termed "passive" algorithms. This research has led to techniques that derive "good" conclusions from marginal communication links. What is needed is the development of "active" algorithms which can clarify anomalous data and seek missing data. To perform these functions, an

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algorithm at a given processing node must be able to infer the network state and then decide how best to obtain the needed data.

Concurrently, the committee members believe that a study of dynamic network control should be initiated. Network control balances traffic loads and queues with the available communciations resources in response to user needs and the availability and fidelity of the links within the network. The ability to perform dynamic network control is essential if information flow is not to be restricted to an unacceptable degree when the system is subject to countermeasures.

An important judgment in designing a dynamic communications architecture is how and where the control decisions are to be made. Experience with currently operatonal systems, both civilian and military (e.g., the SABRE[5] system and NORAD), has demonstrated the importance of human operators for making structural decisions; we know no way of avoiding such an arrangement in strategic defense. Thus, this type of research leads directly to the issue of how to evaluate the impact of a human as an integral element of the system in functions ranging from the sequencing of diagnostic, training, and maintenance operations to the direct control of the system to respond to decisions at the highest human level. Although any high-speed changes in the communication network must be made automatically, its overall structure falls within the purview of a human operator. To make the most of such an organizational structure requires further study of an operator's ability to rearrange assets in a cluttered and time-varying environment. If neither the automatic algorithms nor the human operator can make an optimum response, the system must be designed with a realistic understanding of potential limitations.

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5   See Appendix C.

III. THE HUMAN/SYSTEM SYMBIOSIS IN SDI BM/C^3 DECISION MAKING

In the presentations made during both phases of the workshop, the function of the human decision maker in system operation appeared in various contexts. The need for a human presence is a controversial theme in discussions of complex systems, both military and civil. For example, the SABRE system includes data processing and support for aircraft and crew dispatching. Orders are issued by a duty team in a central location designated as a "war room." The team is, in turn, supervised by a central dispatcher, a classical hierarchical management structure involving human supervision, monitoring, and decision making, as well as algorithmic data manipulation. Similarly, space-shuttle flights are under human control except for the ascent and descent phases. In NASA, there is such a lack of trust in the ability of computers to detect nonnominal operating conditions automatically that computers are not permitted to turn off other computers. This can only be done by a person responsible for making such decisions.

The ambiguous role of the human was seen again in B. Brown's presentation on the NORAD system. This system provides the closest operational analogue to parts of an SDS. The principal operating decisions are all made by humans working individually or in teams. Although anecdotal evidence suggested that some of the most untoward system errors (false alarms) were caused by operator errors, the ability of the well-trained monitors on duty to sense that something was wrong and to diagnose the problem quickly has reinforced the conviction that human oversight is essential. Indeed, proposals from both NASA and NORAD suggest increasing the human presence by providing decision aids to enhance human effectiveness. It is the ability of people to reason in the face of uncertainty, malfunctions, missing data, and unexpected situations that reinforces this reliance on human oversight and ultimate control.

In many discussions of complex systems, the human is not thought of as an integral part of the system architecture, but is rather given an external position as a "user" of data or an "input" to the rest of the system. This view of the human as extrinsic has led some investigators to relegate the human to a very limited position in the SDI BM/C^3 functions.

In Ref. 4, for example, it is suggested that "the tactical system will have to operate in an automated mode simply because there is no time for humans to evaluate the huge amounts of sensor information to arrive at superior weapon engagement in the short time available." While this is undoubtedly true for many of the operations and processes of an SDI system at the detailed level, it does not address the management and operation of the BM/C^3 functions at the global level.

It is the view of this Committee that such a circumscribed role for the human may turn out to be unsatisfactory for the SDS mission. Indeed, there has been a consensus from early on that at some levels human involvement in strategic defense decisions is essential. Admittedly, there are significant practical limits to the roles that humans can play. A research issue is how to define and support the role of human decision making, given the characteristics and limitations of human information-processing capabilities. Early incorporation of human factors analysis is highly recommended.

It is possible that, even with such analyses, the role of the human may remain only loosely defined. Superficially, it may appear that any precisely defined task assigned to a human could be performed automatically by an algorithm which mimics his input-output relationship. But, such emulations have proven unsatisfactory in many respects. The unique contributions that can be made by humans stem from uniquely human competence in: (1) decision making in semantically rich problem domains, (2) analogical reasoning and problem structuring, and (3) information processing and application of heuristics (Ref. 5).

The human brings distinctive skills to the operation of a complex system. What is sought is a system that uses the best combination of automated and human decision making to accomplish the mission requirements, while at all times recognizing the overriding need for a political decision maker to direct the strategic posture of the nation. While there is a continuum of different possible roles for human decision makers, four are evident. (1) The NCA will determine the appropriate response to any given strategic situation and establish or select rules of engagement. The BM/C^3 system should be so structured as to supply the requisite information to make the decisions easier and to make the expected consequences of these decisions readily available. (2) A decision maker will allocate or release for use specific resources and formulate defensive strategy, *at least in broad terms*. (3) In addition, *man in the loop* "will oversee conduct of the battle management process, overriding, as necessary, the automated response processes when the situation exceeds the parametric bounds for which the battle management process was designed" (Ref. 6). (4) After proper

training, human interpretive skills may perhaps be used to advantage in such functions as midcourse discrimination, which has relatively long timelines of 15 min or more.

To assess SDI BM/C^3 performance quantitatively, it will be necessary to characterize the ability of an individual or a team to perform situation assessment, to deduce the "correct" response, and to include human response characteristics in the paradigm used to describe the rest of the system. Thus, a compatible quantitative description of human response is required.

Human performance attributes can be described in different ways. Some, quite promising for this application, are normative-descriptive models based upon the premise that the human decision maker strives to make the best possible decisions but is constrained by cognitive limitations and, to some degree, by temporal pressures. To be useful in simulation and analysis, the representation chosen must be compatible with other subsystem models so that they can be combined to form an all-inclusive system description.

Two such representations were discussed in the workshop. Each provides a quantitative indication of the ability of a human operator to perform the tasks that would be assigned to him in his SDS role. Furthermore, these models provide intermediate-state descriptions that can be used to test the utility of various decision aids. In each, there is an explicit decomposition of activities which corresponds closely to the functions performed by the human: information processing, hypothesis evaluation, option generation, and decision generation.

In one model, human response is described in terms of stochastic differential equations. The advantage of such a model is that it is compatible with the differential equation models used to predict the dynamic behavior of other SDS elements such as threats and countermeasures. Uncertainties about the way an encounter will evolve can be included directly, as can communications link uncertainties. This model has been used to provide a quantitative comparison of the relative performance of a human decision maker and an algorithmic surrogate (Ref. 7). The utility of this representation in the SDS setting is worthy of study.

Another approach discussed in detail in Ref. 8 uses a stochastic, timed, attributed Petri Net model of the critical decisions and information flows associated with the situation assessment in the command center. A powerful feature of this model is that it allows a sensitivity analysis of the time required to reach a decision after an event occurs, under

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different assumptions about the design of the command center, the architecture of the command control system, and the delegation of authority. This network model is useful for comparing different organizational forms.

Each of these models offers advantages, and their forms are complementary. Both are analytically tractable and can be simulated directly. They relate to different aspects of the operator's role in the efficient allocation of resources and in assessing changes in the encounter. It has been suggested that roughly half of the total life-cycle cost of a complex system accrues to personnel-related expenses, including base support costs, salaries, retirement, and family support. To spend this money wisely, careful study should be made of ways to use human sensory and interpretive functions and decision-making capability to best advantage.

IV. RECOMMENDATIONS

The IST Office should obtain proposals and fund selected studies dealing with the broad research areas identified in Chapters II and III. Although the pioneering role of IST within the SDIO and the search for high-risk, high-payoff research should be emphasized, there are gaps in the mainline program that IST can attempt to fill through its research program.

The committee believes that BM/C^3 concerns are paramount in making choices between alternative system architectures and subsystem elements. One participant in the workshop observed that "some projects in the SDS program are not adequately interfaced with others. As a result, when problems are encountered in one project, they are unilaterally declared to belong to another interfacing project (e.g., sensors interfacing with processors)." We believe that an effort which will articulate and quantify behavioral characteristics of candidate SDS architectures is warranted. This evaluation procedure should be sufficiently detailed to lead to improvements in technologies supporting system-element performance, such as propulsion and materials, which in turn manifest themselves as explicit improvements in the measures of effectiveness.

Research is recommended on methodologies which can be used to compare appropriate command and implementation structures. Those selected should yield a robust system subject to reliable and flexible control by the senior command level. Measures of effectiveness involve performance in a highly variable and ambiguous peacetime environment, as well as the performance appropriate to a hostile encounter.

Human control over the SDS is to be exercised at several levels, for diverse purposes and on disparate time scales. The relevant Unified or Specified Commander must be constantly apprised of SDS readiness and threat magnitudes at all stages of system implementation and operation. *We recommend research on the identification of analytical and computational tools which will facilitate the study of the role of the human decision maker in this highly variable system.* This research should include, but not be limited to,

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determination of the utility of training protocols, as well as guidance of the development of decision aids based upon advanced techniques, such as AI approaches to data assimilation.

The payoff in mathematics is often very high. The investment by the Air Force Office of Scientific Research in the work that led to Kalman filtering serves as an example that paid back the investment by several orders of magnitude. *IST should support mathematical research on very large integrated systems relating to system theory and control and estimation theory. In particular, novel computational techniques such as the mathematical foundations of parallel computing and also neural networking should be evaluated for possible applications to BM/C^3 systems. Furthermore, some conceptual thinking of underlying mathematical structures would be well worth doing in the basic research program.*

In order to facilitate this program-development schedule, we identify in the following enumeration examples of topical studies that we consider to be appropriate for IST-supported research.

(1) IST should encourage research on the algorithms necessary to support proposed system architectures. Work on passive algorithms is currently in progress as part of the IST program. This effort should be expanded to include active algorithms which lead to a system that will reconfigure its communication assets in the best possible manner. The need for maintaining a birth-to-death file for every detectable object should be explored and reevaluated in order to reduce the requirement for processing very large amounts of data.

(2) IST-supported experimental and/or theoretical evaluations of laser and RF communication techniques are appropriate. Basic studies of the effects of transmission, routing, and processing time merit serious attention. Research should be undertaken to see how to exploit the greatly expanded bandwidth capabilities of a laser communication network.

(3) Human decision makers must have the flexibility to modify the communication organization when appropriate. Therefore, IST should support basic research on mathematical techniques for the development and assessment of strategies for managing networks for data transmission. As part of this research, measures of effectiveness should be developed and the explicit influence of the system architecture on these measures should be deduced. As a consequence, the contrast between implicit coordination and its more hierarchical counterparts may become more apparent.

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(4) While the Committee does not believe that the IST should support a significant effort in the designing of special-purpose computers, there are several computer requirements that should be confronted.

    (a) It is hoped that the SDI Phase-One Program will include space-qualified, hardened, general-purpose (GP) computers. To support the functions of the SDS and facilitate modification and evaluation, a programmable message-interface module should be developed. This module should be physically hardened against a nuclear weapons environment, space-qualified, and capable of handling very large numbers of data packets.

    (b) IST should support work in ultrareliable computers and networks with long lifetimes which, by virtue of cooperative behavior, may provide very significant advantages. Integration of multiple computers, with a distribution of effective lifetimes, may collectively, because of shared redundancy and distributed computational responsibility, achieve the kinds of reliable characteristics needed.

(5) IST should support research designed to provide a mathematical description of the underlying structure of BM/C^3. Research should be funded on system concepts, as well as system behavior. The designs of BM/C^3 system structures should be studied. These studies should include, as limiting cases, totally distributed and totally hierarchical control functions. Within this framework, IST should support mathematical research addressing the problem of defense-resource allocation under an attack whose structure is revealed sequentially, about which information is not complete, and in which information about the status of the defended target set is incomplete.

(6) Assuming that the results of IST-sponsored BM/C^3 research lead to products suitable for testing (e.g., algorithms and decision techniques), IST should study the utility of the NTB facilities in testing and validation experiments.

(7) IST should support research in a field loosely described as large system science and technology (LSST) with the goal of establishing an analytical framework for the integration of system components into large-scale systems. LSST encompasses the design, simulation, validation, and testing of large-scale systems which involve the interfaces and interactions of many smaller systems as an integrated whole. Again, some aspect of this effort could be carried out by using the NTB.

(8) IST should support research directed towards resolving the difficult problem of initiating, establishing, and maintaining tracks, especially in a dense target environment. An examination of neural networking should be considered in this context. IST should

also study the application of neural networking techniques to the problem of utilizing mutliple sensor fusion for midcourse discrimination.

(9) The hardware and software needed for monitoring system performance, displaying system status, and conducting tests while the system is in operation may become major cost items in the operation and control of SDS. This aspect of the problem should be examined closely in consideration of the new developments in human/machine interfacing characterized by novel multisensor display systems and interactive techniques.

This evaluation and study was performed with the intent of gaining a broad perspective on the major development efforts that relate to the SDI BM/C^3 function. We believe that selected additional evaluations of specific SDI BM/C^3 issues, along the lines identified in this report, are appropriate and necessary.

REFERENCES

1. A.H. Lewis and M. Athans, "The Quest for a C^3 Theory: Dreams and Realities," *1987 Symposium on C^2 Research*, National Defense University, Washington, DC, August 1987.

2. *Summer Study 1985, Eastport Study Group*, December 1985.

3. H.L. Van Trees, "Keynote Address," *Conference Workshop on Quantitative Assessment of the Utility of Command and Control Systems*, National Defense University, Washington, DC, January 1980.

4. M. Athans, "Command and Control (C^2) Theory: A Challenge to Control Science," *IEEE Trans. on Automat. Contr.*, AC-32, 286-293, April 1987.

5. J.A. Welch, "State of the Art of C^2 Assessment," *Conference Workshop on Quantitative Assessment of the Utility of Command and Control Systems*, National Defense University, Washington, DC, January 1980.

6. R.D. Turner, A.J. Perrella, Jr., A.W. Hull, and V.A. Mall, *Guidelines for Establishing a C^3 Assessment Facility for the Strategic Defense Initiative*, Institute for Defense Analyses, IDA Paper P-1852, January 1986.

7. K.S. Haaland, R.G. Hutchens, and D.D. Sworder, "Imaging Systems: Corporal and Autonomous," *Proceedings, of the 28th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 1987.

8. J. MacMillan and J.G. Wohl, *Human Roles in an SDI System: Situation Assessment During Peacetime and Transitions*, Alphatech Report No. TR-363, October 1987.

APPENDIX A

WORKSHOP PROGRAMS

PROGRAM OF THE INNOVATIVE SCIENCE AND TECHNOLOGY (IST) WORKSHOP ON DATA AND INFORMATION FLOW IN CIVILIAN SYSTEMS

November 10, 1987

(Four institutions, IBM, American Airlines, NASA, and AT&T, were invited to make presentations. All have programs that involve handling large volumes of data, extracting information from the data, and making decisions based on that information.)

Leslie Cohen, Chairman

IBM	Demos Gazis	Real time traffic control modeling and experience
American Airlines	Milton McIlhaney	Characteristics of hardware and software in the SABRE reservation system
NASA	Anthony J. Macina	Development, verification, and validation of software
NASA	Robert Castle, Jr.	Real time mission control
AT&T*	Douglas Dowden Nicholas Osifchin	The 5-ESS switch

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* Because of scheduling conflicts, the AT&T 3-hour presentation was made on December 22, 1987.

PROGRAM OF THE INNOVATIVE SCIENCE AND TECHNOLOGY (IST) WORKSHOP ON SDI BM/C^3

November 23-24, 1987

Monday - November 23, 1987

8:30 a.m.	Welcome and administrative details	Bohdan Balko, IDA
	Potential role of IST in BM/C^3 research	Dwight Duston, Deputy Director, IST
	Program of workshop	David D. Sworder, UCSD, Chairman

SESSION I - D.D. Sworder, Chairman

9:00 a.m.	Fundamental issues in the solution to the SDI BM/C^3 problem	Danny Cohen, ISI/USC
10:00 a.m.	A proposed solution to the SDI BM/C^3 problem	John J. Farrell, TRW
11:00 a.m.	Aspects of selected military systems that may have a bearing on the SDI BM/C^3 problem	Bruce Brown, BDM
12:00 noon	Lunch	

SESSION II - S.S. Penner, Chairman

12:30 p.m.	Aspects of selected civilian systems that may have a bearing on the SDI BM/C^3 problem	Frank Albini, IDA Consultant
1:30 p.m.	Elements of the IST program which may impact the SDI BM/C^3 problem	Dwight Duston, SDIO
2:30 p.m.	The human factor of man in the loop	David D. Sworder, UCSD

3:30 p.m.	Game theory, measures of effectiveness	Nils Sandel, Jr., Alphatech
4:30 p.m.	Communications links	Albert Bartels, STI
5:30 p.m.-6:00 p.m.	Discussion	
6:30 p.m.-8:30 p.m.	Reception and dinner	

Tuesday - November 24, 1987

SESSION III - D.D. Sworder, Chairman

9:00 a.m.	Algorithm development and the challenge of tracking the SDI dense threat	Oliver Drummond, Hughes Aircraft
10:00 a.m.	Robotics, artificial intelligence, and expert systems	Harold Sorenson, USAF
11:00 a.m.	Neural networks	C. Lee Giles, AFOSR
12:00 noon	Lunch	

SESSION IV - D.D. Sworder and A. Perrella, Jr., Co-Chairmen

12:30 p.m.-3:00 p.m.	Open discussion on SDI BM/C^3 research problems
3:00 p.m. -3:30 p.m.	Windup

APPENDIX B

MEMORANDUM FROM FRANK A. ALBINI ON INNOVATIVE SCIENCE AND TECHNOLOGY SUPPORT FOR BM/C^3 FUNCTIONS

This memo is a result of a study requested by IDA in preparation for the BM/C^3 workshop.

IDA
STD

Memorandum

TO	Dr. Bohdan Balko	*DATE*	7/19/87
FROM	Frank A. Albini, Consultant		
SUBJECT	Innovative Science and Technology Support for BM/C^{3}I Functions		

I. INTRODUCTION

As part of a continuing effort in support of the Innovative Science and Technology (IST) Office of the Strategic Defense Initiative Organization (SDIO), the Institute was requested to undertake a brief examination of the Battle Management, Command, Control, Communications, and Intelligence (BM/C^{3}I) functions of potential SDI systems to help identify promising areas of research and development pertinent to these functions. The IDA investigation, performed under IDA task order T-R2-316, took several approaches simultaneously.

This memorandum documents the findings of one of these approaches. It represents the views of the author alone. It should be understood that these views were developed mostly in deliberate isolation from (but not in total ignorance of) the extensive efforts currently and previously prosecuted as part of the SDIO program of research and system development. The motivations for this "in vacuo" mode of operation are several. Some of the more compelling are: 1) To become thoroughly familiar with the latest developments in this dynamic field of study would be to delay any findings substantially. 2) Any survey in depth of relevant work would necessitate extensive review and critique for the sake of completeness and balance, leading to the quest for consensus views on currently contentious issues (e.g., "Is it necessary to maintain a 'track file' on every object detected?") which could deflect the effort from its intended purpose. 3) The effect was intended to be suggestive rather than encyclopedic -- exploratory rather than definitive. Proceeding in the manner described assured that the results would not be misinterpreted in this regard.

II. ANALYSIS

A. Assumptions

The following analysis is organized according to a functional breakdown of the operation of a ballistic missile defense system which consists of space-based elements and terrestrial elements. No specific architecture is envisioned other than this generic structure, although principal components that have already been identified and that are generally understood to be a part of any first-generation system are presumed to be incorporated (e.g., a Boost

B-3

Surveillance and Tracking System (BSTS), a constellation of space-based kinetic weapon platforms, terminal defense interceptors with associated radar and optical sensors, etc.). It is understood that a first-generation system would not include interactive means of midcourse discrimination, and would have minimal capability to conduct midcourse battle against a threat making extensive use of decoys in midcourse phase.

Other assumptions were made which have far-reaching implications, at least in the view of the author. While some may seem trivial or self-evident, they are listed here to focus attention upon them and to clarify their implications as they impinge upon the analysis outlined in this section:

     1.   The system will be in place for a long time, and it is intended that the space-based elements not require maintenance or inspection by manned space missions.

     2.   The system should be capable of growth by addition of elements as technological progress yields up new capabilities.

     3.   The system should be robust in operation against a responsive and imaginative threat, to include defense-suppression tactics, interference with communications links, false signal injection, etc.

     4.   Constraints of design or disposition which would inhibit flexibility of operation are to be avoided without compelling motivation.

     5.   It should be possible to test individual elements in place, and to modify system connectivity to accommodate faults detected.

     6.   Human oversight of system operation in real time must exist.

The implications of these assumptions are further explored in the following subsections, but some inferences are immediate if these tenets are accepted. The requirements for longevity, adaptability to changing technology, and operational flexibility combine to indicate the need for greatly disparate computer hardware to communicate. Further, it is unlikely that a fixed software protocol for data interchange could be maintained as secure over a long period of time. Thus, the tentative requirement for a programmable message-processing interface module can be identified. While even small personal computers now support interface software of broad capability, a militarized, space-qualified module capable of handling very large data packages is not available off the shelf. Such a module "on a chip," packaged for physical hardness against nuclear particle and electromagnetic disruption can be identified as a promising area for technological emphasis. Similarly, while special-purpose computers will be required or desirable in many instances, the need to accommodate changes in capability with new and additional components argues forcefully for the development of flexible, general-purpose, space-qualified computers as components of all space-based assets. Indeed the prosecution of technology for such "items without a mission" is the motivation for an IST effort in the SDIO.

B. Command, Control, and Intelligence

The functions of command and control enforce human management of the operation of the system and provide for the implementation of same. Provision for these functions requires that simple "control switches" be made available to the human operators, to allow them to select modes of system operation, such as "element a go to standby mode," "test element

x," "downlink sensor surveillance of geographical region y," "engage booster targets in geographical region z if trajectories threaten region w," etc. In other words, parameters which control the operation of the computer programs monitoring and controlling the various remote elements must be alterable at human command.

This requirement establishes the need for feedback from the system to the human overseers by which system response can be monitored and evaluated. The most natural means by which such information can be conveyed to people in real time is visual, so one can anticipate video display screens before which sit people monitoring system functions and issuing instructions controlling system operation.

Given the likely scenarios just described, it is to be anticipated that the managers overseeing system operation will require that sensor data be displayed before them so they may witness what the system sensors are experiencing. Furthermore, they will wish to capture sequences of this data stream for future study and evaluation, and to verify system responses to commands. The capture and study of sensor imagery is generally regarded as intelligence gathering, and the usual requirement for safeguarding such information is foreseen. These considerations and the need for immunity to jamming and spoofing lead to a clear requirement for secure channels of data transmission, including data encryption and a means of message validation. Thus, the pacing requirement on data transmission may well arise from the human requirement for video input and the need to encrypt and "errorproof" the data. Research on low-overhead methods of data encryption and error checking are seen as appropriate IST efforts.

The need to replicate on the ground every element of an operational system was recognized, if not emphasized, by the Eastport Study Group. If this is to be done, and there are many reasons for doing so, continual testing and evaluation can be undertaken in both "off-line" and "on-line" modes so that changes in command and control structures can be explored, new configurations evaluated, and faults isolated with confidence. Such a replica would offer a testbed for validating methods of managing the communications network as well. Thus, if an "adequate" technique can be put in place, it can be "perfected" in an evolutionary way. Perhaps an IST initiative in developing a prototype of the terrestrial replica could serve as a means of standardizing the testing and validation of promising components such as the programmable message-processing module identified above.

C. Battle Management

Battle management as a function entails the allocation of defense resources to the tasks of defense, in real time. This is not to say that battle management should be equated with the generation of guidance signals for an interceptor, the assignment of interceptors to targets, or the interpretation of sensor outputs. These specialized functions are best left to dedicated processors that perform only these unique tasks.

By taking the approach outlined by the Eastport Study Group--divide the overall problem into separate, easily understood tasks, develop adequate solutions to each, and integrate the components into a system by a flexible C^3 structure--the distinction between battle management functions and the details of engagement orchestration become clear. It is also clear under this distinction that, without a significant midcourse defense component, not much battle management is required.

1. Boost phase

In boost phase, the principal battle-management functions will be threat assessment, authorization of weapons release, assignment of interceptor platforms to areas of responsibility, and assessment of battle outcome. If a collection of sensor platforms and interceptor platforms is treated as a unit (e.g., a "battle group" or "maneuver unit" in tactical terms), then management of its engagements can be the assigned responsibility of the unit. Individual interceptor assignments, guidance, and kill assessments can be carried out by the unit, independent of all others. It is the feature of independence that renders the overall problem far more tractable than when viewed in the aggregate. Battle management then would consist in creating units, assigning platforms to them, monitoring the status of the units, assigning areas of responsibility, assessing the threat, authorizing the release of weapons (by unit), and monitoring the outcomes of engagements as reported by the units.

The kinematics of a boost-phase engagement fix the time during which a launch platform could release an interceptor with the possibility that it would close on a given booster. There exists a three-dimensional surface enclosing a launch platform, whose outer boundary grows with time, to some limit, representing the possible locations of an interceptor launched from that platform after the passage of that time. If the projected location of a booster lies within this surface when extrapolated on a common time basis, then that platform could launch a successful intercept. Clearly, there exists a "window" in time during which a successful intercept could be initiated from a given launch platform. Selection of an appropriate launch platform to conduct any given engagement is a mathematical problem with solution expressable in a form of essentially universal applicability. Development of such algorithms can proceed as an activity independent of virtually all other aspects of the defense system. It represents an example of the approach of building independent "blocks" of battle management logic that can be integrated in a hierarchical structure to synthesize a workable system. In a similar vein, the constructions of tracking and guidance algorithms, sensor control algorithms, engagement assessment techniques, etc., are all isolatable, independent problems. They can be embodied in "adequate" algorithms that can be tested, validated, and integrated into an engagement-management package. The package can be programmed and realized aboard some or all launch platforms and/or ancillary sensor platforms and form the basis for controlling battle groups or engagement units of flexible composition. As improvements are identified in applicable algorithms or logical structures, it should be possible--i.e., the system hardware and software should not make it impossible--to incorporate them into the operational system. This observation represents an arguable deduction that the controlling computer hardware should not be specialized to the extent that it would inhibit this capability to grow and improve. The broader implications of this design philosophy should be explored by SDIO studies before constraints on system flexibility are allowed by component "optimization." The degree to which such a philosophy constrains system performance, as an abstract mathematical problem, might be an appropriate IST study topic.

As a general observation, the geographical isolation and brief temporal window of opportunity for boost-phase engagements serve to isolate this phase of defense from dynamic interaction with terminal-phase battles in any but the most idealized sense. In other words, the capabilities and limitations of terminal defense components should not impinge upon any decisions affecting boost-phase engagements. Whether the boost-phase capability is richly or sparsely endowed with sensors and interceptors, it should be used aggressively to eliminate as much of the threat as possible. In the instance that there are few units available for assignment to battle and there are many targets to engage, the scarce resources should be used to maximum effect--i.e., the targets chosen for engagement

should be those most likely to be destroyed. This is so because the ultimate destinations of the warheads aboard the upper stages cannot be determined (at the time the assignments must be made) with sufficient precision to affect the terminal-phase engagements that would ensue.

2. Midcourse phase

The "modular" approach to system synthesis can be readily extended to midcourse phase defense. Whether interceptors are launched from space-based platforms or from terrestrial bases makes little difference to the logic of target assignment or the implementation of guidance. The details of how engagement units could be configured and managed need not be explored here, as the concept is simply an extension of that discussed for boost phase. The logic under which scarce resources are assigned must be more thoroughly developed, however, since the ultimate destinations of threat swarms should be clearly discernable less than halfway through their total flight times. At this stage of the encounter, the stress to which the terminal defense elements will be subjected and the remaining target values at risk (assuming some damage already has been done by the attack) should be considered in establishing the priorities for engagement in midcourse.

Here battle management must grapple with the problems of a developing attack structure, incompletely known, and perhaps partial information concerning the status of defended targets. This is a rich field of investigation for theorists dealing with time-constrained resource allocation, game theory, and strategy selection with partial information. It is an excellent example of the sort of situation in which the quest for a "best" solution could impede the recognition of an "adequate" solution. Clearly, the class of problems which arise here meritS attention, and research in these areas should be supported. But it is probably prudent at the same time to support one or more efforts to develop heuristic algorithms of structural simplicity and transparency that can be used as benchmarks in simulation studies of system performance. In this way, practical solutions which should at least evolve toward "adequacy" are assured, and the integration of midcourse defense capability into system architecture would not hinge upon theoretical developments which might prove intractable in implementation.

Midcourse defense, however implemented, must come to grips with the problem of dilution through proliferation of false targets. The implementation of schemes to discriminate false from real targets in midcourse flight has been a major topic of investigation since the inception of the SDIO and need not be elaborated here. The only observation pertinent to the present topic is that management of discrimination resources and their integration into systems evolving from a first-generation capability should be considered when weighing the merits of alternative schemes. A highly desirable development would be a subsystem embodying the capability to perform discrimination and also to engage and destroy targets in midcourse. A hypothetical example might be a neutral particle-beam subsystem which could interrogate many targets rapidly under low beam power and step up to a lethal power level whenever a target was identified as probably carrying a weapon. The integration of such a subsystem into any existing architecture and command and control structure would be vastly simpler than the integration of a competing subsystem which only classifies interrogated objects.

3. Terminal phase

From the perspective of systemwide battle management, the operation of the terminal defense elements represents yet another example of a unit which can engage targets within

its purview. Because the terminal defense batteries would be in fixed locations during the course of any attack structure foreseen, the chore of managing these units is intrinsically simpler than the management of boost-phase units.

The management of terminal defense resources (sensors, interceptors, communications assets, and allocatable computing power) has been investigated extensively in the past and is continuing at present. The state of development of such capability is high and probably already satisfactory. In the past, elaborate and carefully structured attack scenarios were used to stress battle management capabilities of postulated terminal defense systems. The enrichment of terminal defense capabilities by the addition of space-based sensors that can provide information about the directions of approach, trajectories, times of arrival, and intensities of threats can only strengthen these elements. At the same time, boost-phase intercepts (and possibly midcourse intercepts) will lessen the capability of the offense to structure attacks in time so as to overwhelm terminal defenses.

The primary connection between overall system battle management functions and terminal defense batteries resides in the passing of information of the nature described from the space-based components to the terminal defense components. The elements of a package of such information might include a classification of the booster which generated a specific threat swarm, the direction from which the swarm will approach the terminally defended area, when it will arrive, a rough estimate of the number of individual items within the swarm, its geometrical extent, etc. The terminal defense battery's sensors could then be left to sort out the reentry vehicles from the accompanying decoys, debris, and chaff. If some of the reentry vehicles in the swarm have been identified, such additional data could be handed over with considerable precision, allowing the terminal battery to conduct an early engagement using "precommitted" interceptors. But if such information is not available, the battery could rely on its own resources to effect reentry discrimination and engage the targets classified as reentry vehicles.

This approach would make it unnecessary for the system to maintain a "track" on every item which its sensors could detect. Assuming, for the moment, that midcourse discrimination and engagement actions do not impose such a requirement on the system, a great simplification of the bookkeeping aspects of battle management envisioned in early feasibility studies of SDI systems is possible. This particular point seems to merit specific study because of the impact it has on the data processing and communications capabilities required. In the view of this author, no compelling basis for the requirement to maintain a separate track on each item has emerged from an analysis of the functions of battle management from a system perspective. This is particularly the case if a modular approach to system synthesis is embraced.

D. Communications

It is clear that a large amount of information must be passed between elements of a widely dispersed network if a system of the type envisioned is to be realized. For efficiency, message packets may involve information for more than one recipient or for several simultaneously. Message packets would have to be received, checked for error, confirmed, stored, and forwarded from node to node. But the information content of a typical message packet must be considered in designing the communications network necessary to support system operation.

The fact that nodes in the network would be widely separated in space imposes a significant signal transit time, thereby complicating the problem of network management, the selection

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of appropriate protocols, and the assurance of link integrity against interference. The tradeoff between data transfer capability (bandwidth) and error rate -- the probability that a message must be repeated -- forces a compromise to assure maximal throughput or minimal delay in message delivery. The information content of a message packet is proportional to the product of the bandwidth of the channel and the length of the packet in time. And the average time required for the information to be transferred from one node to another includes the time required to process the message packet through error checking and decryption and to send and receive an acknowledgment of its transfer as well as the transit time.

As an example of the information content of a typical message packet, consider a fractional frame of sensor output equivalent to a video screen of high-resolution graphical data. Such a packet could consist of (say) 1000 × 1000 pixels in three "colors," each with perhaps sixteen "shades," or about 50 megabits. If the bandwidth of a communication link is assumed to be 100 MHz, the packet could be transmitted in one-half second. Ignoring, for simplicity, the possibility that data compression techniques might be possible that could reduce the information requirement by perhaps a factor of two, a 0.5 s message length might be taken as typical or slightly longer than average. For the present purpose, we can also ignore the overhead for encryption and error checking. Such a message packet length is large but not incommensurate with the time delay to be anticipated in moving the information from one node to another.

A minimal constellation of communication nodes would consist of four satellites with orbit radii of about 4-5 earth radii. The distance between nodes would be 6-8 earth radii, giving a one-way signal transit time of 0.13-0.16 s. So a one-way transit time of 0.15 s is perhaps representative, implying a node-to-node transfer time, including acknowedgment, of about 0.8 s. If a total of three node-to-node transfers is required to relay information from the most remote element to the command center, a total delay of approximately 2.5 s is implied. This should be taken as an upper limit, to be contrasted with the one-way transit time over the same distance of a very brief message that would be 0.4-0.6 s. An increase in communication link bandwidth to 1 GHz would reduce the message packet length to 0.05 s and the total delay to about 1.0 s. If the environment were degraded substantially, several repetitions of the message might be required to transfer it between nodes. This consideration alone implies a need for network redundancy so that a message can be relayed simultaneously over at least two paths. In the face of enemy action to deliberately degrade or disable nodes in the network, this desirable feature can be elevated to a requirement.

The need for flexibility and fault tolerance implies the capability to reconfigure the communications network in real time. Provision of such capability could be facilitated by having aboard many platforms with various other responsibilities a subsystem or module to perform the communications interface duties to allow them to serve as communication network nodes. The internal design of such a module could evolve over time, but it would have to conform to some minimal rigid specifications to assure its compatibility with other nodes in the network extant or planned when it is activiated. Research on the design features of, and development work to realize, prototypes of such minimal-constraint modules would be appropriate IST support activities.

If node-to-node dedicated communication links are postulated, a relay of a message packet from one node to another can be accomplished in a minimum of two one-way signal travel times plus the temporal length of the message packet. The additional one-way transit time is required for an error-checking confirmation that the message has been received as

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transmitted. If communication links are not dedicated, then either an effectively synchronous discipline must be followed or the availability of a clear channel must be established by a handshake protocol. Both methods impose additional delay in passing a message packet from one node to another. In the former case, a message can be inserted into a communication link when a prearranged time slot is determined to be available for it; the time slot can "rotate" around a constellation of communication nodes in true time synchrony or in a pseudosynchronous orderly fashion marked by a "token" identifying an empty time slot. In the latter case, the sending node must query the receiving node and obtain a "ready" reply before passing on the message packet. Such a protocol would be quite flexible but would require at least four one-way transit times plus the length of the message packet.

Because of the many possible ways of configuring data transmission networks and the many factors affecting their performance, exhaustive analysis of the options is perhaps impossible. So, while mindful of the admonition of the Eastport Study Group not to foresake adequacy in the pursuit of perfection, the author is compelled to suggest that fundamental research on the mathematical techniques for such assessment may have substantial payoff.

III. SUMMARY

This cursory analysis indicates several areas of research and development activity which are candidates for support. Some--or all--may already be supported by elements of the SDIO, and some--or all--may fall outside the area of responsibility of the IST office. Assessment of the appropriate level of support and the decision regarding which office of SDIO should oversee the investigations must be made by SDIO managers. The items offered below are intended to serve as a menu from which IST might select for the purpose of supporting the implementation of BM/C^{3}I activities of SDIO if deemed appropriate:

1. Development of a programmable, message-processing interface module that is physically hard against nuclear weapons effects, space-qualified, and capable of handling very large data packages.

2. Development of flexible, general-purpose, space-qualified computers.

3. Research on low-overhead methods of data encryption and error checking.

4. An IST initiative in developing a prototype of a terrestrial replica of the C^3 network to serve as a means of standardizing the testing and validation of candidate components.

5. Mathematical research on the question of the degree to which a modular design philosophy constrains system performance.

6. Mathematical research addressing the problem of selecting optimal strategies of defense resource allocation in the face of an attack whose structure is revealed sequentially, information about which is incomplete, and with incomplete information about the current status of the defended target set.

7. Development of heuristic algorithms addressing the problem outlined in 6, including simulations within which they can be tested.

8.   A study or several studies directed to answering the specific question, "Is it necessary to maintain a 'track' on every item detectable by the sensors of the system?"

9.   Fundamental research on mathematical techniques for the design of, and for the assessment of strategies of management of, a space-based network for data transmission.

APPENDIX C

MEMORANDUM FROM FRANK A. ALBINI ON THE WORKSHOP DEALING WITH INFORMATION FLOWS IN SELECTED CIVILIAN SYSTEMS

A summary of the many discussions that were held concerning the common features of the various C^3 systems we have investigated over the past few months. Copies of the visual aids used at the November 22-23, 1987, IST workshop on SDI BM/C^3 to summarize these findings are appended.

Memorandum

TO	Dr. Bohdan Balko, Asst. Dir. Science and Technology Division Institute for Defense Analyses Alexandria, VA 22311	*DATE*	January 21, 1988
FROM	Frank A. Albini, Consultant		
SUBJECT	A synopsis and analyses of the presentations on civilian systems and their data handling, information flow capabilities		

As part of the investigation of areas of appropriate interest to the SDIO IST office, IDA undertook to explore a sample of large-scale data management, communications, and complex system control implementations in commercial, military, and nonmilitary use in the United States. The sample was not exhaustive, and not all of the information gathered was felt to be pertinent, but some valuable insights were gained by examining these large systems. The development and operation of these large systems offer a wealth of experience which showed us things that must be done to assure that the systems do work, they showed us good ways to do things, and--perhaps most importantly--they showed us that things can be done which were unthinkable only a generation or so ago. To capitalize on this accumulated experience, we must be willing to accept the lessons learned in their development and operation.

The systems which were investigated in some detail (NORAD's Command Center Support, NASA Mission Control Center Support, Shuttle Flight Control System, SABRE Airline Reservation and Dispatching Support System, and AT&T's 5ESS) share common features which, taken together, offer some practical guidance for the course of development of the SDI BM/C^3 software and hardware. Some, but surely not all, the common features evident are:

1) All of these systems have evolved since their inception, some for many years. Extensive changes in software are continuous.

2) Software maintenance is considered essential, often being the dominant maintenance cost of the system.

3) Human oversight of system operation is mandatory, and testing is done both to validate changes and to ensure nominal operation of hardware and software during "routine" operations.

While many features of these systems can be considered valid prototypes of some of the functions of an SDI BM/C^3 system, serving to reduce development time and cost for same, none of them can be considered to be "mature" in the sense that they are no longer undergoing change and development. The changes that are being introduced increase speed or capacity, reduce costs, enhance reliability, allow more rapid detection and correction of flaws, ease the burdens of oversight, and better support necessary human decision making.

It might be argued that these systems are evolutionary in nature because they represent only the current stages of development on ongoing human activities and are thus not representative of the kind of system that would be needed to support a space-based ballistic missile defense system. But it can be argued with equal validity that they represent capabilities that are many orders of magnitude beyond what any human-operated system could ever achieve and thus do serve as simulacra of a BM/C^3 system for SDI. A warehouse-sized room filled with clerks, each equipped with extension telephones, notepads, and binoculars with which to read distant chalkboards, was required to handle the New York City airline reservation traffic for American Airlines when the SABRE system development cycle was initiated in the late 1950s. Replacement of the current system with such a primitive model would be unthinkable. Similarly, while human operators once made plugboard connections to complete telephone circuits for long-distance calls, the current volume of U.S. long-distance telephone traffic could not be serviced if the entire U.S. population sat before telephone plugboards.

Thus, while management of a ballistic missile defense system may be beyond current human experience, so was management of any of these large systems inconceivable before they were developed. It can perhaps be taken as axiomatic that the BM/C^3 system will evolve as experience with its functioning is gained. Such an assumption offers not only guidance for system development, but a design philosophy and a set of operating principles that admit of continual improvement in performance. The major lessons offered by the collective experiences of these large systems can be distilled into the following paradigm for BM/C^3 system design:

- Space-based hardware must be flexible rather than rigid and probably should support modular connectivity. Changes in software must be accommodated with minimal disruption of nominal functioning. In this light, excess capacity or capability should not be seen as wasteful but as necessary to admit evolutionary growth. (The SABRE system offers one model for these features.)

- Fault tolerance must be a guiding principle of design for individual components, subsystems, and collections of elements that must work together. Testing features must be built in, and "work-around" capability must be accessible remotely. (The 5ESS approach offers a model for such capabilities, as does the NASA Mission Control System in a less sophisticated form.)

- Human oversight must not be "appliquéd" as an afterthought, but considered at every major design juncture. Monitoring the health and status of the components of the system is not enough. It must be possible to perform virtually continuous testing of various parts of the system and to exercise the system under a variety of simulated stresses and degraded conditions. Such testing must be undertaken both to gain experience with the capabilities and limitations of the system and to allow the evolution of corrective strategies and "fixes" that can be implemented in place. (The NORAD Control Center experience offers a particularly good model in this regard.)

It is perhaps the requirement for human oversight that poses the greatest challenge in developing the SDI BM/C^3 system. Because there is no current model from which to decide what data are to be brought before the human monitors (and in what form) and no clear functions which can be assigned the human monitors in an information-flow diagram, the system designer is left with little guidance in this regard. From this quandary one can infer the requirement for a series of terrestrial prototypes or developmental models based on simulations. Such prototypes could be exercised with a variety of levels and kinds of information displayed, while simulated failures, data losses, communication-link dropouts, etc., are imposed on the system. Through such simulations, necessary and sufficient levels of monitoring detail will emerge, as will the kinds of "work-arounds" and "fixes" needed to cope with expectable flaws and failures. Many such features can then be automated or called into play with minimal delay through development of the appropriate support software.

Through such exercises, the experience needed to monitor and control system operation can be gained, and the system can be expected to evolve toward a stable and reliable configuration. Only after such experience is gained can one be assured that the required command and control functions will be achieved and that the system will be viable when installed. To ignore the requirement for human oversight of system operation would be a serious error. But until experience is gained in this area, it is fruitless to speculate on the system implications of meeting this requirement. Thus, "simulated experience" can be both a learning tool and an aid to system development. Support of such activity may not be an

appropriate IST function, but it is arguably a necessary instrument for assessing the performance and acceptability of any BM/C^3 component hardware or software item.

Editor's Note: The following pages present copies of a set of Vugraphs summarizing information gleaned from these studies and used in the presentation by F. Albini at the IST workshop on SDI BM/C^3 on November 23, 1987.

THE SABRE SYSTEM

-- EVOLVED FROM THE ILL-FATED SAGE SYSTEM OF LATE 50'S

-- TULSA BASED. SUPPORTED BY ~ 300 MYE STAFF

-- SERVES ~ 20 US AIR CARRIERS AS RESERVATIONS DEPT.

-- INCLUDES DISPATCHING SUPPORT

-- EVOLVING FOR MORE THAN 25 YEARS

-- PROGRAMMER/CE CADRE ON DUTY AT ALL TIMES

-- 4 - 6 MILLION LINES OF ASSEMBLER CODE

-- SEVERAL BILLION DOLLARS CUMULATIVE COST TO DATE

-- SUBSTANTIAL GROWTH CAPACITY IN CURRENT STATE

USES SPECIALLY-MODIFIED IBM HARDWARE

USES ATT COMMERCIAL TELEPHONE NETWORK

SABRE SYSTEM RESERVATIONS MANAGEMENT

- ~ 4 MILLION LINES OF ASSEMBLER CODE

- MAINTAINS ~ 20 MILLION ACTIVE PASSENGER FILES

- FARE STRUCTURE EXPANDS THIS TO CA. 1 BILLION RECORDS

- FARES ARE CHANGED AT THE RATE OF 100,000 PER DAY

- 140 RECORDS PER PASSENGER ARE MAINTAINED

- PASSENGERS CHANGE ITINERARY 5 TIMES ON AVERAGE

- PASSENGER FILES ACTIVE FROM BOOKING TO RETURN PLUS 2 DAYS

- SYSTEM SERVES 100,000 VARIED TERMINALS VIA 2000 PORTS

- 16,000 MESSAGES PER SECOND IS PRESENT SERVICE CAPACITY

- INCOMING MESSAGES AVERAGE 15 - 20 CHARACTERS

- REPLIES (OTEN FILLING DISPLAY SCREEN) IN LESS THAN 3 SEC

* OPERATING SYSTEM IS NOT SECURE *

SABRE SYSTEM DISPATCHING SUPPORT

- MAINTAINS DATA BASES TO SUPPORT "WAR ROOM" IN DALLAS

- AIRCRAFT TRACKING -

  - OUT/OFF/ON/IN STATUS BY TELEMETRY

  - COULD DOWN - LINK FLIGHT RECORDER DATA

- AIRPORT FACILITIES, STAFF, STATUS, WX, ETC.

- CREW TRACKING -

  - BY NAME, QUALIFICATIONS, WORK SCHEDULE, ETC.

- AIRCRAFT STATUS, MAINTENANCE SCHEDULE

- PARTS INVENTORIES

- AIRPORT/LOCAL EMERGENCY FACILITIES INFORMATION

* ALTHOUGH MORE AUTOMATION OF DECISION-MAKING IS
BEING EXPLORED, THERE IS NO CURRENT EFFORT OR
CHANCE FORESEEN TO REPLACE MAN IN THE LOOP

SABRE SYSTEM FEATURES IN SDI CONTEXT

* IF PASSENGERS ARE THOUGHT OF AS RVS AND DECOYS

  - DATA RATE IS 1-2 ORDERS TOO LOW FOR SDI

  - BUT FILES ARE MUCH LARGER THAN SDI WOULD NEED

    (ASSUMING CENTRALIZED TRACKING OF EACH OBJECT NEEDED)

  - REPLACING DISKS WITH SOLID STATE MEMORY ... ?

* IF DISPATCHING IS THOUGHT OF AS BATTLE MANAGEMENT

  - NEED TIME SCALE COMPRESSION BY 10 X FOR DECISIONS

  - BUT NUMBER OF VARIABLES TO CONSIDER PERHAPS 10 X FEWER

  - NEED MORE AUTOMATION OF DECISION AIDS

  - AND WE LACK 40 YEARS OF EXPERIENCE IN THE TASKS

* MAKING THE SYSTEM SECURE WOULD INCREASE OVERHEAD

* SABRE SYSTEM IS BRITTLE. SDI MUST BE FAIL-SOFT

SHUTTLE FLIGHT CONTROL

- SOFTWARE DEVELOPMENT START 1973, DONE BY 1981

- SHUTTLE PROGRAMS TOTAL CA. 20 MILLION LINES OF ASSEMBLER CODE

- DEVELOPMENT COST REPORTED AS $300-400 MILLION

- 300-350 MYE FOR DEVELOPMENT AND CONTINUING SUPPORT

- MODIFICATIONS - 4K TO 12K LINES PER 4 TO 6 MO INCREMENTS

- "HAL" LANGUAGE DEVELOPED, BUT ACCOUNTS FOR 5% OF CODING

- USED OFF-THE-SHELF FLIGHT COMPUTER HARDWARE ONLY

- ONBOARD HARDWARE/SOFTWARE REPLICATED ON THE GROUND

- MAN-IN-THE-LOOP FEATURES

  - EXCLUDED DURING ASCENT AND DESCENT PHASES

  - REQUIRED DURING ORBITAL FLIGHT PHASE

- SYSTEM FAULT TOLERANCE REQUIREMENTS STRINGENT

* SHUTTLE = 20 MILLION LINES

* SDI BM/C3 = 100 MILLION LINES??

SHUTTLE FCS FAULT - TOLERANCE FEATURES

- REQUIREMENT FOR HARDWARE FAULT TOLERANCE

  - TWO-DEEP WITH NO PERFORMANCE LOSS

  - APPLIES TO SENSORS, PROCESSORS, AND ACTUATORS

- REQUIREMENTS FOR SOFTWARE FAULT TOLERANCE

  - ONE COMPUTER CANNOT DISABLE ANOTHER

  - SELECTABLE INDEPENDENT CONTROL CODE BACKUP

- APPROACH USED TO MEET REQUIREMENTS

  - TRIPLE REDUNDANCY FOR SENSOR INPUTS

  - INPUT CONSISTENCY AND VOTEDOWN LOGIC

  - TRIPLE REDUNDANCY FOR ACTUATORS

  - MANUAL SELECTION OF BACKUP COMPUTER (W/INDEPENDENT SOFTWARE)

* MOST FAILURES EXPERIENCED HAVE BEEN SOFTWARE

* EMI COULD DISRUPT COMMON INPUT DATA BUS

MISSION CONTROL FLIGHT SUPPORT

- MISSION CONTROL MONITORS SYSTEMS AND DIRECTS CREW ACTIVITIES

- MONITORING IS BY PEOPLE WATCHING CRTS AND EVENT LIGHTS

- CONTROL CAN BE EXERCISED REMOTELY BY DATA LINK

- CREW DIRECTION IS BY VOICE LINK FROM MISSION DIRECTOR

- FLIGHT SIMULATOR IS REPLICA OF ONBOARD HARDWARE, SOFTWARE

- ALL SYSTEMS ARE DOUBLY REDUNDANT FOR FAULT TOLERANCE

     (ONLY ONCE DID DUAL FAILURE OCCUR ... SOFTWARE)

- 10 SPECIALISTS MONITOR SYSTEM DISPLAYS

- EACH CONSOLE HAS 1-3 OTHERS IN "BACKROOM" SUPPORT

*AS WITH SABRE SYSTEM, MAN IN THE LOOP IS SEEN AS ESSENTIAL -
BUT ADDITIONAL AUTOMATED DECISIONS AIDS ARE DESIRED

SDI IMPLICATIONS OF SHUTTLE EXPERIENCE

* SOFTWARE DEVELOPMENT RATE ACCELERATING

* SOFTWARE SUPPORT MUST BE CONTINUAL

* SIMULATION EXERCISES REVEAL SOFTWARE FLAWS

* HARDWARE, SOFTWARE RELIABILITY OF LARGE SYSTEMS
  NOT YET DEMONSTRATED TO BE ADEQUATE FOR SDI MISSION?

* CONSIDERABLE FAULT TOLERANCE HAS BEEN DEMONSTRATED
  BUT NOT GRACEFUL DEGRADATION WITH CUMULATIVE FAULTS

* EXPERT SYSTEMS (AI) EXPECTED TO BE OF GREAT BENEFIT
  BUT DIRECT EVIDENCE OF THIS IS YET TO BE DEMONSTRATED

SOME ASSUMPTIONS ABOUT SDI

1. THE SYSTEM WILL BE IN PLACE FOR A LONG TIME, AND IT IS INTENDED THAT THE SPACE BASED ELEMENTS WILL NOT REQUIRE INSPECTION OR MAINTENANCE BY MANNED SPACE MISSIONS.

2. THE SYSTEM SHOULD BE CAPABLE OF GROWTH BY ADDITION OF ELEMENTS AS TECHNOLOGY AFFORDS NEW CAPABILITIES.

3. THE SYSTEM SHOULD BE ROBUST IN OPERATION AGAINST A RESPONSIVE AND IMAGINATIVE THREAT, TO INCLUDE DEFENSE-SUPPRESSION TACTICS, INTERFERENCE WITH COMMUNICATIONS, FALSE SIGNAL INJECTION, ENVIRONMENT DEGRADATION, ETC.

MORE ASSUMPTIONS ABOUT SDI

4. CONSTRAINTS ON DESIGN OR DISPOSITION WHICH WOULD INHIBIT FLEXIBILITY OF OPERATION ARE TO BE AVOIDED WITHOUT COMPELLING MOTIVATION.

5. IT SHOULD BE POSSIBLE TO TEST INDIVIDUAL ELEMENTS IN PLACE, AND TO MODIFY SYSTEM CONNECTIVITY TO ACCOMMODATE ANY FAULTS DETECTED.

6. HUMAN OVERSIGHT OF SYSTEM OPERATION IN REAL TIME - AT LEAST UP TO THE POINT OF WEAPON RELEASE - MUST EXIST.

APPENDIX D

COMMENTS ON SATELLITE LASER COMMUNICATIONS FOR SDI

Robert F. Botta

APPENDIX D

COMMENTS ON SATELLITE LASER
COMMUNICATIONS FOR SDI

A major point of interest during the IST workshop on SDI BM/C^3 held at IDA on November 22-23, 1987 and in subsequent discussions was the role of laser links in communications. The following comments were prepared to provide a background for the subsequent discussion of possible SDI BM/C^3 systems.

Obtaining quantitative estimates of such values as weight and power is difficult because of the many possible configurations for laser satellite communication. Classifications of systems can be made in terms of the type of laser used and the detection technique (Refs. 1-3).

The main contenders for lasers are Nd:YAG solid state and GaAlAs semiconductor. Each has its proponents: McDonnell Douglas likes Nd:YAG, while TRW and NASA favor GaAlAs.

Detection methods are either direct or coherent. Direct detection uses a "photon bucket," while in coherent detection a local laser at the receiver is mixed with the incoming transmitted beam. A comparison, developed from the McDonnell Douglas report (Ref. 1), is shown in Table D-1. Among the technology advances required for coherent detection are

- A receiver capable of frequency acquisition and tracking
- A diffraction-limited receiver
- Improvements in spatial tracking.

A comparison of some features of Nd:YAG and GaAlAs lasers is shown in Table D-2. Note that for operation with direct detection, power-combining techniques can be used to obtain necessary output power levels using low-power, high-reliability GaAlAs diodes.

Table D-1. Comparison of Detection Systems*

	Direct Detection	Coherent Detection
Technology	Mature	Immature
Receiver	Does not require diffraction-limited optics	Diffraction-limited optics required
Spatial tracking	Not stressing	Stringent at receiver as well as transmitter
Frequency tracking	Not needed	Required
Relative received power	–	Theoretically 10-13 dB better
Required background	Additional power needed to overcome background noise	Can operate with sun in FOV
Spectral purity		Single-frequency laser required
Jamming	–	More resistant to jamming (narrow-filter bandware)
Scintillation	–	More susceptible since phase information is needed for detection

*From McDonnell Douglas report (Ref. 2).

Table D-2. Comparison of Laser Features

Characteristics	Nd:YAG	GaAlAs
Technology maturity	Mature	Rapidly evolving
Efficiency	<1%	10-20%
Laser pumping	Required	Not needed
Modulation	External, additional equipment needed	Internal, vary injection current
Cooling	Necessary	Minimal
Beam collimation	High	Some spreading
Tuning	Single frequency	Tunable
Lifetime	~5 yr	100,000-200,000 hr (~10-20 yr) for 10-25 mW; 2000-4000 hr for 50-100 mW

Planned Experiments

McDonnell Douglas has a Nd:YAG system scheduled for testing on DSP. It has the following characteristics:

- 150 mW output at 0.53 μ
- 20 cm optics
- Direct detection
- 1.5 Mb/s at 10^{-7} BER
- Input power 235-250 W
- Transmitter weight 250-300 lb.

Lincoln Laboratory and NASA plan an experiment for the ACTS satellite that will examine both direct and coherent detection using GaAlAs semiconductor lasers. Characteristics include:

- 30 mW output at 0.86 μ
- 20 cm optics
- Direct and heterodyne detection
- 220 Mb/s
- Input power 200 W
- Total weight 240 lb.

The estimated launch date is late 1990.

Application and Advantage of Laser links

McDonnell Douglas recommends using Nd:YAG lasers with coherent detection for high-data-rate links (see p. 4-38 of Ref. 2 for reasons) and GaAlAs diodes for lower data-rate links (reasons on p. 4-40). Other factors that affect the applicability of lasers for various types of links include:

- **Tracking**--More difficult for links with high dynamics such as SSTS-CV. Easier to maintain track using direct detection.

- **Jamming**--Lasercom is inherently robust with heterodyne detection having an advantage. Jammer must be virtually in line of sight.

- **Scintillation**--Direct detection more robust in scintillated environment since phase information not needed by receiver.

- **Duplex operation**--By slightly offsetting the frequency, GaAlAs lasers can be used for simultaneous transmitting and receiving. Nd:YAG is not tunable so transmitting and receiving must take place in separate time intervals.

- **Atmospheric absorption**--Laser links are considered primarily useful for space-space links. By using airborne platforms at high altitudes, they could also be employed for space-air links. Also, through spatial diversity achieved by having several alternative earth stations, a space-ground link can be maintained with high probability.

Analyses

Studies for TDAS carried out by Ball Aerospace Corporation indicate that GaAlAs lasers can achieve a data rate of 2 Gb/s at 10^{-6} BER at a range of 84,000 km, using 40 cm optics. Such results must be interpreted cautiously, however, since different studies often reach very different conclusions. For example, the TRW study claims that existing and projected near-term state-of-the-art pointing for lasercom is not adequate for SDI BM/C^3, while the McDonnell Douglas study finds that current pointing mechanisms are sufficient for SDI needs. GaAlAs lasers have not yet, to my knowledge, been space qualified. The McDonnell Douglas Nd:YAG system has been space qualified. However, since such items as pointing, acquisition, and tracking subsystems and power supplies are similar for both types of laser systems, there should be no obstacles in getting them space qualified for the semiconductor laser systems.

REFERENCES, APPENDIX D

1. TRW, Inc., *Laser Communication Experiment II (U)*, RADC-TR-87-26, March 1987, (SECRET).*

2. McDonnell Douglas Corporation, *Laser Communication Experiment I*, RADC-TR-86-156, Vol. 1, November 1986.

3. Eastman Kodak Company, *Laser Communication Experiment Definition Study*, RADC-TR-87-31, April 1987.

* No classified material from Ref. 1 appears in this document.

APPENDIX E

A COMMUNICATIONS FLOW CHART FOR
SPACE-SEGMENT SDI BM/C^3

Figure adapted from R.D. Turner, D.M. Yanni, and H. Freitag, *Functional Analysis of SDI BM Processes (Space Segment) (U)*, Institute for Defense Analyses, IDA Paper P-1928, in publication (SECRET).[*]

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[*] No classified material from IDA Paper P-1928 appears in this document.
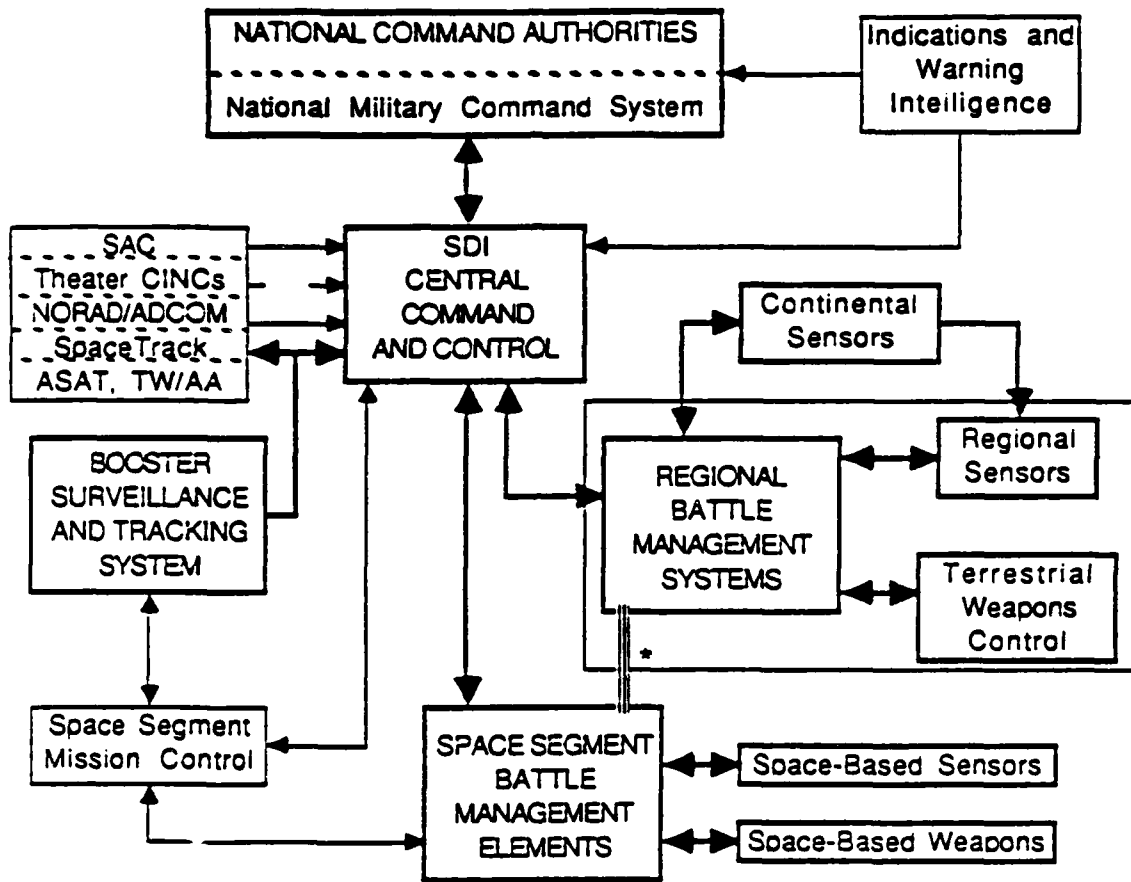
* (U) Regional Battle Management Systems, Regional Sensors, and Terrestrial Weapon Control units are assumed to be collocated on a region-by-region basis

(U) Denotes possible communications support of regional defenses by space segment battle management elements

Figure E-1. SDI Communications Interfaces.