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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD CONFERENCE PROCEEDINGS 580

Space Systems as Contributors to the NATO Defence Mission

(les Systèmes spatiaux contribuant à la stratégie de défense de l'OTAN)

Papers presented at the Mission Systems Panel 5th Symposium held in Cannes, France, 3-6 June 1996.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
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Space Systems as Contributors to the NATO Defence Mission

(AGARD CP-580)

Executive Summary

Space can provide vital support to the NATO Command, Control and Information System.

Satellite communications already form a significant component of such systems, but the burgeoning space capabilities now being developed outside NATO and in the commercial sector offer benefits to potential adversaries as well as NATO. While the military user is already aware of the benefits of other, exotic, space systems and of the potential benefit from smaller, cheaper tactical satellites (Tacsats), he needs to take account of the issues raised by these capabilities.

The overall objective of this symposium was to demonstrate the utility and feasibility for NATO of a wider range of space applications, and provide a cross fertilisation between military minds and the technical/scientific minds that work in the defence community. The papers presented addressed a wide range of technical capabilities, although a larger contribution from the military side of the defence community would have improved the balance of the proceedings.

The symposium was structured to open with presentations of military perspectives providing focus to subsequent sessions, which addressed various aspects of technical capability ranging through the following:

- Civil/commercial systems;
- Communications;
- Surveillance;
- Meteorology;
- Data fusion;
- Information extraction.

The symposium concluded with a panel and audience discussion, during which participants reinforced the importance of the role that space can play for NATO and proposed that NATO should form a “Space Programme Office” to establish a policy covering:

- space systems utilisation;
- space systems applications to warfighting;
- co-ordination of space systems policy with other warfighting (and training) elements of NATO forces.

Overall, the papers presented covered a wide area in considerable depth, stimulating some animated discussion and identifying concerns. The programme committee feels that the symposium achieved its objective and, in addition, provided recommendations of some initial steps for NATO to extend its utilisation and awareness of space systems beyond the present status.

C D Hall
Programme Committee Chairman

Les systèmes spatiaux en tant que contribution à la mission de défense de l'OTAN

(AGARD CP-580)

Synthèse

Les systèmes spatiaux peuvent fournir un soutien capital au dispositif OTAN de commandement, contrôle et information.

Les communications par satellite constituent déjà un élément non négligeable de l'architecture de tels systèmes, mais les nouveaux moyens spatiaux en développement en dehors de l'OTAN et dans le secteur commercial offrent des avantages aussi bien à l'OTAN qu'à ses adversaires potentiels. Bien que l'utilisateur militaire soit conscient des avantages offerts par d'autres systèmes spatiaux plus exotiques, ainsi que par les satellites tactiques TACSATS à dimensions réduites et à moindre coût, il doit tenir compte des questions soulevées par la mise en œuvre de ces moyens.

L'objectif principal de ce symposium a été de démontrer l'utilité et la faisabilité pour l'OTAN de disposer d'une large gamme d'applications spatiales, en facilitant des échanges réciproques entre les militaires et les scientifiques de la communauté de défense. Les communications présentées ont couvert un éventail considérable de possibilités techniques, mais une contribution plus importante de la part de la communauté militaire aurait permis de mieux équilibrer le programme.

Le symposium a débuté par des présentations sur les perspectives militaires qui ont donné l'orientation de la séance pour les différentes sessions. Les divers aspects des possibilités techniques ont pu être présentés et particulièrement:

- les systèmes civils/commerciaux;
- les communications;
- la surveillance;
- la météorologie;
- le fusionnement des données;
- l'extraction des informations.

Le symposium s'est terminé par une table ronde à l'occasion de laquelle les participants ont souligné l'importance du rôle que peuvent jouer les systèmes spatiaux pour l'OTAN. Ils ont aussi proposé la création d'un bureau des programmes spatiaux de l'OTAN qui aurait pour mandat d'établir une politique concernant:

- l'utilisation des systèmes spatiaux;
- les applications de combat des systèmes spatiaux;
- la coordination entre la politique adoptée en matière de systèmes spatiaux et les autres éléments opérationnels (et d'entraînement) des forces de l'OTAN.

Globalement, les communications présentées ont couvert en profondeur un large domaine. Elles ont donné lieu à des discussions animées et ont permis d'identifier certaines préoccupations actuelles. Le comité du programme estime que le symposium a atteint son objectif. De plus, il a fourni des recommandations concernant une démarche initiale possible pour l'OTAN, ce qui lui permettrait d'étendre son champ d'utilisation et d'élargir ses connaissances actuelles en matière de systèmes spatiaux.

C D Hall
Président du comité du programme

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* Published in Classified Supplement
† Not available at time of printing

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Chairman: Dr. T. Cunningham (US)

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Chaiman: Mr. D. Hall (UK)

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* Published in Classified Supplement
† Not available at time of printing

Theme

The fine technical capability of current military space assets has led to a keen appreciation of their military value and a growing demand for the services that they can provide. However, the large cost of providing this capability to every potential user is a driver towards effective and affordable, rather than **ultimate**, systems. Working Group (WG 16) of the disbanded Avionics Panel has recently addressed the military capabilities that can be provided by smaller, cheaper satellites — Tacsats. This Symposium covers different ground.

Therefore, the overall objective of this Symposium is to demonstrate the utility and feasibility of wider range space applications of NATO. The Symposium is structured with the following major areas, and aims to show the derivation of system solutions to mission requirements:

- possible future requirements for NATO space applications;
- examples of current and proposed space systems;
- discussion of current and future mission requirements;
- application-specific technology sessions to show what future mission possibilities will exist for the military user as new space technology becomes available;
- discussion session to link current and evolving space technologies with future mission possibilities.

The rationale for selection of these topics is the desire to encourage a cross fertilisation between ideas and desires for mission capabilities as expressed by military minds, and concepts for the realisation of technical capabilities as expressed by technical/scientific minds.

Thème

La grande capacité technique des moyens militaires spatiaux modernes a suscité une évaluation attentive de leur valeur militaire, ainsi qu'une demande croissante en ce qui concerne les services qu'ils sont en mesure de fournir. Cependant, le coût considérable de la mise à disposition de ces moyens à tous les intéressés possibles milite en faveur de systèmes efficaces et abordables plutôt que de solutions ultimes. Le groupe de travail No. 16 de l'ancien Panel AGARD d'avionique a récemment examiné le potentiel militaire d'une catégorie de satellites de taille et de coût réduits, c'est-à-dire, les TACSATS. Ce symposium couvrira d'autres sujets.

L'objectif principal de ce symposium est donc de démontrer l'intérêt et la faisabilité pour l'OTAN de la mise en pratique d'opérations spatiales de plus grande envergure. Le symposium est organisé autour des principaux domaines suivants et présente l'application des solutions systèmes aux besoins opérationnels :

- les besoins prévisibles pour les applications avec missions de l'OTAN dans le domaine de l'espace;
- des exemples de systèmes spatiaux actuels et proposés;
- l'examen des besoins opérationnels actuels et futurs;
- des sessions technologiques spécifiques à certaines applications servant à démontrer les possibilités opérationnelles qui seront offertes à l'utilisateur militaire au fur et à mesure de la mise à disposition des nouvelles technologies spatiales;
- séance-débat sur les liens qui sont à créer entre les technologies spatiales évolutives et les possibilités opérationnelles futures.

Le choix des sujets s'explique par le souhait de promouvoir un enrichissement mutuel entre les idées et les souhaits des militaires dans le domaine de la capacité opérationnelle et les concepts permettant de concrétiser les possibilités techniques tels qu'exprimés par les scientifiques.

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TECHNICAL EVALUATION REPORT

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INTRODUCTION

The 5th AGARD Mission Systems Panel Symposium was held in Cannes, France, from 3rd to the 6th of June 1996. Under the title "Space Systems as Contributors to the NATO Defence Mission", the symposium programme covered the principal space based applications for supporting NATO missions including Satellite Communication, Reconnaissance, Meteorology, Navigation, and Early Warning together with Information Extraction and Space Vehicle Management. The programme, under the overall Chairmanship of Mr David Hall from UK, was divided into six sessions containing a total of 25 presented papers and concluded with a final panel session.

The symposium attracted some 160 participants representing almost all of the Alliance nations. Drawn from the military community, government agencies, industry and academia, they encompassed a particularly diverse range of interests and specialisations.

SUMMARY

The intentionally broad coverage was designed to stimulate greater awareness of the expanding range of Space capabilities, applications and inter-relationships and of their relevance to NATO. The choice of presentation topics was necessarily highly selective and the level of treatment and technical content was very varied. Nevertheless, a well balanced combination of review, concepts, applications and technical papers successfully provided the context for discussion of a good representative cross-section of key technical, organisational and operational issues affecting the current and future use of Space within NATO.

By bringing the various aspects of space based support together, the symposium highlighted the military importance of the Space environment and provided a forum for interchange across disciplines and, in particular, between Space technologists and operational specialists and users. In this respect, more pro-active participation by operational end users would have been beneficial. Since its primary function was to be informative no major new revelations or break-throughs were expected, nor were they forthcoming. However, substantial benefits can be confidently expected to come from the stimulation of interest and cross-fertilisation of ideas and from a more informed level of debate.

General themes running through the symposium included:

a. Emphasis on exploiting space based assets and developing applications for direct, timely support for operational purposes.

b. The search for cost effective ways of securing access to space based capabilities, notably, through developing technology, international collaboration, dual military/use and use of burgeoning commercial capabilities.

c. Concern that potential adversaries will increasingly benefit from proliferating space capabilities and pose a threats to those of the Alliance.

RECOMMENDATIONS

It is suggested that:

- Whilst the broad scope of this first MSP symposium dedicated to space was appropriate, the scope of future meetings on Space should be focused on specific NATO mission oriented themes,

- Greater participation by operational planners and users should be encouraged,

- Relevant aspects of Space be positively included in the content of all future Panel meetings.

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[1] The views expressed by the author are his alone and do not necessarily represent those of any other body or organisation.

TECHNICAL CONTENT

This critique follows the sequence of the Symposium programme.

Welcoming the participants, the French National Delegate, Mr Marec, highlighted the remarkable expansion of the Space based applications and their particular and increasing importance to the evolving NATO missions. He emphasised the need to minimise costs by such means as developing new technology and smaller satellites, dual civil/military use and international collaboration. These remained recurrent themes throughout the symposium. In his opening remarks, Dr Wild, AGARD Director, noted that, although many Space topics had been addressed individually, AGARD had not been sufficiently pro-active in taking a coherent overall approach. This needed to be rectified and this symposium provided a valuable contribution.

Keynote Address

The opening address was given by L'Ingenieur General de l'Armement Daniel Estournet, the Chef du Service Technique des Systemes Strategiques et Spatiaux de le Direction des Missiles et de l'Espace a la Delegation Generale pour l'Armement(DGA). Taking a high level perspective, he robustly expressed his view that the use of the Space environment, hopefully not as a battlespace but in support of strategic and military operations, was of greater overarching significance than even the major developments in land, sea and air warfare during World War II. This stemmed from: the inherent attributes of Space, the stimulus that Space activities give to international collaboration and civil/military cooperation and, most importantly, from the crucial role of Space in the information revolution which is critical for political, commercial, industrial and, above all, national strategic and military operational purposes. This alone provided strong justification for holding regular meetings, such as this symposium, on the application of Space in NATO.

Noting the political and operational dimensions at NATO level and reminding the meeting that the AGARD mandate was focused on R&D, General Estournet made the following points:

a. Space offers alternatives for meeting current needs which may be cheaper, give better performance or increase redundancy but it also offers innovative options for meeting requirements which were formerly considered unacheivable or simply not envisaged. All the possibilities and the means of implementing them must be considered.

b. Although the Gulf war was a significant milestone in the dependence of modern armies on the intensive use of Space, the circumstances were unique and considerable improvisation had been necessary. If forces are to be fully supported in future, greater provision must be made in advance to conceive, develop and supply space based capabilities. Above all, these must be integrated within the user's operational environment. In focusing on R&D the operational user's requirements, perspective and involvement must not be forgotten.

c. Space expands the battlespace by virtue of communications, navigation and deep surveillance offering unprecedented C4I capabilities. This calls for far reaching structural changes in the armed forces and warfighting which cannot be achieved by simple adaptation.

d. He believed that the political and technical means exist to develop balanced and affordable Space capabilities. The challenge as he saw it was to devise and implement each required capability such that costs could be shared whilst at the same time preserving the right of the individual sovereign nations of the Alliance to have an autonomous appreciation of the whole situation before committing themselves to a particular course of action. Difficult technical problems would need to be overcome but this appeared to him to be a viable area for AGARD to address.

Session I - Invited Papers

This session set the scene and provided the diverse audience with a common appreciation of some of the principal topics to be taken up in subsequent sessions. The invited presentations highlighted three areas of high, possibly critical, topical and enduring interest for NATO. Namely: the evolving NATO satellite communications (SATCOM), the possibilities and limitations of synthetic aperture radar (SAR) and the potential of commercial systems for military applications. Though very different in character, each contribution succeeded not only in providing background but also in raising thought provoking issues which were to recur throughout the symposium.

NATO SATCOM Experience

The first presentation traced the evolution of the NATO commitment to and experience of using satellite communication, and provided insight into the issues and problems which are currently being addressed and debated within NATO in the context of its evolving missions. These included:

- the need and options for making better use of existing SATCOM capabilities,

- the requirements and options for replacing the NATO IV capabilities at the end of its notional life in 2001-2003,

- the critical role of comparative costs and performance trade-offs in trying to decide how NATO should proceed in the SATCOM business.

The attention of the meeting was drawn to key conclusions and recommendations of the post-2000 SATCOM Study, sponsored by NACISC, whose report was currently being considered in the policy areas of the Alliance nations.

The author concluded by highlighting the function of SATCOM as a force multiplier, the prospect of a gap in NATO SATCOM capability in the 2001-2006 timeframe, the growing need to use the mobile bands whilst continuing to focus on SHF, and the undiminishing need for military protection features.

The discourse provided a prime example of the problems, noted in the keynote address, of how to harness new developments to the evolving NATO missions in a politically acceptable way and at an affordable cost.

Possibilities and Limitations of Spaceborne SAR

The characteristics of non-intrusive, day-night, all-weather global reach, give space based synthetic aperture radar (SAR) outstanding potential for application to the demands of modern advanced weapon systems and in the extended missions of NATO. The development of SAR technology is maturing and civil systems are being implemented, the subject is, therefore, a current focus of attention for space based reconnaissance.

Focusing on the inherent physical attributes of SAR, the author of the paper described the technical trade-offs and compromises necessary to meet the affordable military system requirements. The following points emerged from the paper and discussion:

- SAR and optical systems have complementary rather than competitive roles,

- Military SAR system requirements may differ substantially from civil ones; they are more technically demanding and no single specification can be optimised to meet all of them,

- Military requirements, which call for advanced sensor and multi-mode, multi-satellite constellations, will be expensive to fulfil,

- Space based SAR offers a wide range of military potential but development and experience of its application is relatively immature and there is a need for more research,

- Technical limitations remain in data processing and management, antenna technology and power efficiency. However, the author, considered major advances in these areas could be expected within next 5 years.

Use of Commercial Satellite Systems

The meeting received a comprehensive review of the potential use of emerging commercial satellite systems for military applications based on the recently completed AGARD Study AAS 42. This provided an appreciation of their relevance to NATO and highlighted the multiplicity of technical, political, economic, industrial considerations applicable to their use for military purposes. The presentation concentrated on space based communication, remote sensing and navigation in which dramatic developments are taking place which will have far reaching military impact:

- Global mobile communication and direct broadcast connectivity available world-wide by increasingly more capable commercial SATCOM systems,

- Massive growth of civil applications and dependence on global satellite positioning systems, with consequent civil domination of the receiver and services markets,

- Proliferation of commercial space based surveillance systems making high resolution imagery available to both Allied and potentially hostile nations.

The substantial differences between the main space based applications resulted in a multitude of specific conclusions and recommendations which are covered in the paper. Its overall conclusions were:

- commercial systems will dominate the market and will be able to offer competitive services; NATO should include consideration of these in developing their communications, surveillance and C4I architectures and infrastructure,

- NATO planning must anticipate the need and set in place the means for secure access to the necessary commercial space capabilities in advance,

- account must be taken of the measures needed to counter the threats to NATO access and to appropriately deny adversaries the military benefits of commercial systems. .

Discussion centred on the threats to commercial services and the possibilities for denial of access, particularly in relation to satellite navigation and positioning. A general concern was the extent to which NATO could afford to rely on commercial capabilities. Not surprisingly, no consensus was reached on this complex issue but it appeared to be generally held that access to a core of dedicated military systems would continue to be needed.

Session II - Military Applications of Civil Systems

Although a wide range of candidate topics could have been included, the focus, as with the invited papers, was on communications and SAR.

Commercial Satellite Communications.

The thesis was put forward that security and survivability were now less critical for a high proportion of the new NATO mission communication needs; consequently, greater advantage could be taken of the advanced commercial systems which would be available to meet the escalating demand for capacity, diversity of services and global coverage. Military control and assured priority access to assets remained critical requirements and dedicated, secure military SATCOM would remain a primary requirement for special and vital military purposes. Nevertheless, dual-use technology could be developed and used and commercial payloads and spacecraft platforms could be modified to meet military needs, such as encryption and hardening, without major redesign. Their use on military owned satellites appeared to the author to offer a cost effective option.

No dissent from these possibilities was offered at the meeting, however, as indicated in the invited paper, the challenge is to achieve the most cost effective combination without compromising military effectiveness and there are many interrelated conflicting factors to be considered - not least of these being the whole life cost.

Synthetic Aperture Radar

Three different aspects of space borne SAR provided practical illustrations of the possibilities, limitations and trade-offs discussed in the invited paper.

The outline of capabilities and operational flexibility of RADARSAT, the first commercial SAR satellite launched in November 1995, demonstrated the wide range of potential military applications. However, although the system is relatively advanced, its military limitations were also noted and operational experience in military application of spaceborne SAR is clearly in its infancy. Concerns at the meeting were with the area coverage, frequency of target revisits and the procedures and timescales involved in ordering imagery and receiving the end product. The latter were dependent on the priority afforded and the availability of ground stations, and raised the more general point that "exploitation" of such imagery is a process which requires a substantial ground infrastructure. Discussion of the possibilities for positive regional denial brought out in discussion the complex international dimensions of such systems.

The following paper, on experimental use of European Space Agency ERS SAR imagery to monitor successive NATO naval exercises off Northern Norway over the period 1991-1996, provided a welcome example of experience gained under operational conditions. The ERS system is primarily designed for environmental remote sensing. Despite limited spatial resolution and unfavourable incidence angles, the ability to detect major ships and to give some limited ship signature discrimination was demonstrated as was the requirement for an effective supporting ground exploitation and communication capability. The inherent conflict between sensor/system specifications for hard target detection and those for environmental phenomena, such as wakes, currents, sea surface states, as discussed in the invited SAR paper, were well illustrated.

Backscatter from the sea surface is a determining factor in the detection of maritime targets at an acceptable false alarm rate. Analysis of the backscatter statistics of multi-channel data from the Shuttleborne SIR-C/X-SAR over the NE Atlantic in comparison with empirical models, demonstrated the need for improved understanding of the complex inter-relationship between radar parameters such as incidence angle, frequency, polarisation, backscatter, and the environmental characteristics of the target.

Discussion concluded that the remaining uncertainties made it difficult to define optimum SAR specifications for military purposes. More research and experimentation were needed to develop the military application and to demonstrate the value of commercial SAR systems. Nevertheless, operational staffs should be made aware of the potential value to adversaries of the information derivable from space based SAR.

Session III - Communication(Systems and Technology).

This subject is under intense active consideration both in NATO and by Alliance nations and naturally attracted strong interest. Three perspectives on meeting NATO requirements were presented: a concept for meeting the potential capability gap from 2001, a concept for the post-2005 generation, and predictions for post-2015. Each made similar premises concerning the evolving NATO missions and the need for a dedicated communications capability with protection, low detectability, and assured access which could not be achieved by terrestrial means and commercial satellites alone.

The gap filler proposition considered possible UHF, SHF and EHF payload combinations for a satellite to take forward NATO capability from the notional life expiry of NATO IV in 2001. Whilst SHF/EHF and UHF/SHF options could provide some capability, only the combination of UHF/SHF/EHF could meet post-2000 NATO IERS, including backward compatibility and protected stressed requirements, derived from the post-2000 SATCOM study. It was suggested that, by utilising mostly existing COTS components and modular design to minimise cost, a medium size satellite, featuring a combination of UHF/SHF/EHF multiple beams, could be produced. This would be to fulfil those NATO requirements, not carried by terrestrial links or commercial satellites, provide for expanded traffic and act as a precursor for future development.

In discussion, concerns were expressed about the assumed levels of availability and performance, the concept of using of medium data rate EHF, and suggested common standards and terminal compatibility.

For a post-2005 generation of SATCOM, a logical process for studying system requirements was reviewed using a "strawman" specification as an example. Several nations and companies were known to be conducting studies along similar lines for new modular telecom systems which could meet demanding new operational requirements and services and satisfy the need for greater protection. It was suggested that there was considerable commonality of purpose and, therefore, scope for cooperation and cost saving.

A necessarily more speculative review of the factors affecting the development of post-2015 SATCOMS included the changing role of NATO, economic drivers, communications requirements, threats, technology, commercial cross fertilisation. The author concluded that:

> a. NATO communications requirements will expand; survivability, efficiency, economy, flexibility must be key factors in seeking solutions.
>
> b. Terrestrial and commercial satellite systems will not be able to fully meet future military needs. The aim must therefore be for an optimum mix of capabilities balancing affordability with both peace and wartime operational requirements.

The author saw prospects for unprecedented capacity, responsiveness and security without resort to costly excessively complicated technology driven solutions. There was no dissent from the broad conclusions but concerns were expressed about:

> a. The degree of complementarity between EHF and SHF.
>
> b. The achievement of common standards and interoperability with different commercial systems, between Allies and between different terminals and networks,
>
> c. The ability of long life systems to respond to changes in standards, new functional requirements, and new technology.

The final session paper, on the potential benefits and limitations of EHF, provided a timely reminder that over-simplification and possible misconceptions could only be avoided if the design, procurement, and operational decisions were based on a whole system approach and on a clear understanding of the technological trade-offs. In the case of EHF, atmospheric attenuation, ground antenna size/link budget efficiency, bandwidth efficiencies, and ECCM performance (LPI, jamming efficiency) needed to be considered. The author concluded that EHF could provide an appropriate solution for specialised military SATCOM traffic requiring high levels of ECCM but at the expense of lower bandwidth efficiency and more stringent propagation constraints. Discussion centred on the price which must be paid for LPI and the need to assume harsh attenuation models, and questioned the need to change to EHF in the case of transparent transmissions.

The communications technology sub-session was confined to consideration of the requirement for accurate anti-jamming modelling; a critical factor in the justification for dedicated military systems. Successive papers described the development of a demonstrator to provide data on the anti-jam performance of active multi-beam antennas and associated sidelobe suppression. Tests were on-going using stressed and non-stressed conditions and would include real-time operation later in the year.

Session IV Surveillance - Reconnaissance, Meteorology, Early Warning

A broad view of surveillance was taken which recognised the increasing technological and operational synergy between these three related, but distinct, information gathering functions and areas of application.

Surveillance (Reconnaissance)

This sub-session focused on the feasibility of using small satellites to meet the theatre requirements for daily area coverage albeit at lower spatial resolution. Based on specifications for a small(500kg) satellite with an optical payload, the proposition was put forward that it could be produced at minimum cost and development timescale by using advanced but existing technology, combining existing spacecraft/launcher designs, capitalising on series production for other military/civil applications and by using modernised management techniques. Questions raised in the discussion concerned the stability of the proposed platform, attitude control and pointing accuracy, the ability to acquire multiple targets, resistance to jamming and international standards for interoperability. A more fuller treatment of the merits and limitations of small surveillance satellites is to be found in AGARD Conference Proceedings 522, dated February 1993.

Meteorology

Timely, accurate weather information in a useable form is becoming increasingly important to enhance effectiveness across a whole spectrum of military operations such as long range aircraft deployment, advanced line of sight weapon delivery and precision air drops. Two contributions described:

a. Techniques for improving the speed and accuracy of interpretation of data, derived from the DMSP microwave sensors, by generating imagery form for "visual algorithms" and by comparing in situ measurements with predictions calculated from the numerical models.

b. The design features and feasibility for small geosynchronous satellite systems to provide continuous day/night cloud imagery to support operations in regional conflicts. Payload options considered were daytime optical, optical/medium wave infrared(MWIR), day/night optical sensors. Near real time dissemination via a Global Broadcasting System could cost effectively complement the six hourly forecasts from the large multi-purpose systems. It was envisaged that the data would be distributed through NOAA.

Discussion centred on the technical aspects of the proposal including pointing accuracy, stability of the platform, choice of attitude seeker, the uncertainties of launching small satellites to geostationary orbits. Responding to questions, the author considered that, whilst the horizontal sample intervals were currently adequate, improvement in the vertical was needed.

Early Warning(EW)

Two presentations put forward contrasting concepts for space based early warning for Theatre Ballistic Missile Defence. The first proposed a simple short term affordable architecture combining space based Early Warning with Point Defense systems. The proposition was that, whilst EW was required to alert point defence weapon systems, early cuing and accurate tracking and prediction were unnecessary. In which case EW system specifications could be relaxed and only one, or possibly two satellites, would be necessary. The point defence system could combine EW with prior knowledge of probable missile types, origins, potential targets etc.

In contrast, the second proposal advocated two geostationary infra-red satellites for boost-phase detection and accurate tracking and prediction with high resolution short frame times but with a field of regard limited to theatre areas only. These could provide accurate cueing, thereby reducing search windows, for both intermediate fixed ground EW radars and weapon system radars and thus improve their operational effectiveness and duty cycles. A number of questions relevant to the wider TMD debate were raised in discussion: could handover between the various systems be made quickly enough? is the accuracy from two EW satellites sufficient? could revisit times cope with manoeuvring missiles? would the extension of the point defence weapon system range reduce need for intermediates?

The third paper shifted attention to the problems of modelling for accurate assessment of design trade-offs and performance. The particular problem in the case of SBIR was to quantify the impact of spatially structured background clutter (cloud scenes) on theatre missile detection performance. The paper outlined a methodology for combining sensor payload, constellation, and target parameters to arrive at system level performance assessment. A Theatre Missile Warning mission example was used to illustrate the use of an integrated electro-optical simulation system to demonstrate the impact of cloud background on payload design. In discussion, the author said the most stressing background was high cirrus edges and broken cloud. Uncertainty remained in the model which was to be further validated with data from MSX and MISTY(SWIR and MWIR) missions. A debate was still taking place concerning the value of multi-spectral imagers.

Session V - Information Extraction

This session was dedicated to the important topic of extracting and processing space derived data and, critically, presenting it in a usable form and timescale to the end user.

Attention was first drawn to the increased complexity of the imagery intelligence process created by the proliferation of sensors and sources and the diversity of means of exploiting them. This has created a need rethink the interpretation process to include task analysis and collection management more positively and to adapt the interpretation methodology to take account of multi-sensor environment. Discussion concerned the differences between the radar and optical cases, the resolution of ambiguities between different sensors, the differences between tactical and strategic applications and the options and international constraints on collaboration at the exploitation stage.

Integrated Air Deployed Strike Surveillance(IADSS).

Similar perceptions were discernable at quite a different level in the presentation on the IADSS. Although focused on UAV platforms, this provided a timely reminder that space based capabilities must be considered in conjunction with alternative or, more likely, complementary means of achieving NATO mission objectives. It also illustrated advanced concepts and technology development relevant to the analogous Space applications and the complementary use of Space communications.

This US Office of Naval Research project aims to define and demonstrate the feasibility of autonomous management of a multi-sensor (SIGINT, EO/IR/SAR) suite for integration and operation in the next generation of tactical surveillance UAV platforms and to advance the development of the required technologies. The ultimate objective is to develop a full system capable of near real time on-board processing, data fusion and reporting to supply the strike mission warfighter with fused SIGINT/IMINT for near real time battlespace surveillance, precision targeting, friendly and neutral force ID and battle damage assessment.

The five year project is expected to be completed in 2002 and will, in its final phase, demonstrate capabilities for a range of operational tasks including mission planning, reactive tasking, target search and recognition, on board image generation and annotation, and report distribution. It involves substantial development of advanced technology, contribute to the NATO tactical wide area surveillance mission and offers scope for international collaboration. Discussion centred on clarification of concepts of operation and on critical areas of technology such as hyperspectral analysis, data transmission and the complexity of product generation.

Bandwidth compression.

The final session presentation on bandwidth compression, neatly followed up on one of the areas of concern related to the previous presentation, by illustrating the complexity of issues specific to imagery transmission. The growth in volume and variety of imagery to be processed, the variety of encoders and machine exploitation techniques and the demand for real time tactical support increase the need for robust compression and decompression (codec) systems. These must now be optimised using criteria from both visual and machine automated processes. To date, military interests have been focused on photo-interpretation and the Joint Photographic Experts Group(JPEG) codec has become a de facto standard. Other techniques, in this example Modulation Lapped Transformation(MLT), have been shown to be advantageous for both military and civil applications. Civil interests are beginning to drive standards, which calls to question the extent to which common cause can be made with them and the degree to which special military requirements must be safeguarded.

Session VI - Vehicle Management

This session contained the only paper dedicated to space based global positioning, however, it provided a valuable example of the diversity of development of GPS applications and their impact on operational concepts, weapon design and operational effectiveness.

The performance of a Fire Support Team Vehicle (FIST) fitted with a brassboard Global Positioning Guidance Package (GGP), comprising a miniature GPS receiver closely coupled with a Miniature Inertial Measurement Unit (MIMU), was compared, under operational field trial conditions, with that of one fitted with the existing North Seeking Gyroscope system. The GGP gave significant improvements in the speed and accuracy of own site and target location and overall engagement time. The consequential operational benefits included improved unit life expectancy, minimised engagement time, location whilst on the move and lower unit and life cycle costs. Further development of the GGP unit and more rigourous FIST trials were being continued and other applications were envisaged including the US Navy F18 and possibly TACMS.

In a contrasting interpretation of the session title, the remaining papers addressed the critical subject of inexpensive physical access to Space. The first provided a wide ranging review of the current capabilities and likely world-wide developments in Space launchers in the context of the expanding NATO missions which will demand more functionality and greater use of space based assets. A key driver is the shift of emphasis from national level applications to meeting the time critical and diverse demands of the warfighter. The author's main conclusions were that:

a. The evolving NATO missions will increasingly rely on Space support which will demand improved capability to deliver, maintain and possibly recover payloads post-2000. Reliable low cost assured access to Space will be essential.

b. The military requirement for mainline expendable launch capabilities will continue and will be met by a widening choice of improved launchers.

c. Proliferation of commercial spaceports and small launchers will provide a widening choice of launch sites particularly for the small satellites.

d. Air launch systems could provide greater survivability through dispersed launch locations and new functionality such as greater freedom of choice of launch azimuth.

e. A Trans-Atmospheric Vehicle (TAV) system could fulfil many critical mission functions on demand. The interdependence of the Alliance members would logically suggest international collaborative development.

The final presented paper described a USAF initiative to explore the possibility of establishing a standard interface definition for payload integration activities for a medium launch vehicle. Spacecraft designed to this definition would then have a multiple choice of launch options and transfer from one vehicle to another could be achieved with reduced cost and delays. Definitions for structural interfaces, launch vehicle environment and ground system vehicle and payload handling were found to be feasible but large differences in approach were found to preclude the adoption of common load dynamics analysis.

Session VII - Future Systems Panel Discussion

The objective of this session was to involve the audience in open discussion of the principal issues which had emerged from the previous sessions. The Chairman, Mr Hall, initiated the proceedings by giving his own observations on a selection of high level topics including: the need at all NATO levels to appreciate the potential and impact of Space based systems, the realisation that adversaries will also benefit and measures must be taken to counter them, ownership of Space assets requires long term commitment and infra-structure investment, the critical role of Space based assets for operational C4I, options for NATO to secure access to necessary space based assets.

Much of the discussion focused on the options for NATO to gain access to space based capabilities - should it rely on the national means of member nations, lease or buy services from commercial sources or purchase its own systems? Although most of the arguments have been well rehearsed in other NATO fora a valuable exchange of views took place. A number of noteworthy appreciations emerged:

a. The issues and circumstances differ significantly in each of the main space areas - SATCOM, Surveillance, Meteorology, Global Navigation. They must be argued case by case but full account must also be taken of the technical and operational synergies between them.

b. Whatever route it may take to obtain access, NATO must be committed to ensuring that the infra-structure and agreed procedures are in place to exploit the products cost effectively. This includes measures to ensure interoperability and to train and to exercise their use in operational contexts.

c. There was some sympathy for the view that Space matters policy need to be given greater top down exposure and that consideration should be given to establishing an entity dedicated to Space within AGARD.

Allocution d'ouverture du Symposium AGARD/MSP (Cannes, 3-6 juin 1996) sur "les systèmes spatiaux contribuant à la stratégie de défense de l'OTAN"

par l'Ingénieur Général Jean-Pierre MAREC[1], Délégué National AGARD

Lorsqu'il m'a été proposé d'ouvrir ce Symposium sur "les systèmes spatiaux contribuant à la stratégie de défense de l'OTAN" organisé par la Commission MSP de l'AGARD, j'ai accepté très volontiers.

En effet, bien que mon activité à l'ONERA soit orientée depuis quelques années vers le secteur aéronautique, je garde pour l'Espace un très vif intérêt -en particulier, bien sûr, pour l'Espace Militaire, en ma qualité d'Ingénieur de l'Armement-car c'est dans ce secteur, et plus précisément en Astrodynamique, que j'ai effectué mes premiers travaux à l'Office. Plus tard, déjà tourné vers l'Aéronautique et membre de la Commission de Mécanique du Vol (FMP) de l'AGARD -devenue maintenant FVP- j'ai trouvé en Jack Levine de la NASA un partenaire de choix pour essayer de promouvoir l'Espace au sein de cette Commission.

C'est vous dire toute l'importance que j'attache à l'Espace, à l'Espace Militaire, au rôle de l' AGARD dans ce secteur vital pour l'OTAN, et donc au présent Symposium.

Depuis 1957, année du lancement du premier Spoutnik, l'Espace a connu un essor considérable.

Au début, des véhicules non habités -satellites et sondes- ont été utilisés pour des études scientifique et l'exploration spatiale. Plus tard, l'accent a été mis sur les applications : communications, observation de la Terre, météorologie, navigation,...

Les vols habités ont offert de nouvelles possibilités pour l'exploration (mission Apollo) et l'expérimentation (microgravité, recherche biologique), mais ont également permis non seulement le placement de satellites en orbite, mais encore leur réparation et même leur récupération. Des efforts sont faits à présent pour que l'homme puisse séjourner en orbite pour des périodes encore plus importantes, en utilisant des stations spatiales de grandes dimensions. De nouveaux véhicules, comme les véhicules transatmosphériques (TAV), à décollage et atterrissage horizontaux, pourraient encore accélérer l'utilisation de l'Espace.

Sur le plan de la Défense, l'Espace a tout d'abord été, pour les pays qui avaient la capacité d'y accéder, une façon d'affirmer -fût-ce à travers des applications civiles- leur suprématie technologique et, en particulier, la crédibilité de leur armement balistique stratégique. D'où la "course à l'Espace" à laquelle se sont livrés les Etats-Unis et l'URSS pendant plusieurs années.

Cependant, les possibilités d'applications spécifiquement militaires de l'Espace sont nombreuses : communications, renseignement (surveillance, reconnaissance, écoute, alerte précoce,...), météorologie, navigation, armes spatiales,... Le concept

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Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.

d'Espace Militaire s'est progressivement imposé et a reçu une consécration éclatante à l'occasion de la Guerre du Golfe. Les principales puissances spatiales se sont dotées de systèmes militaires dans les domaines des communications, du renseignement ou de la navigation, à l'exclusion -pour l'instant et espérons-le également pour l'avenir- des armes spatiales, après l'effort intense, mais de relativement de courte durée, des Etats-Unis dans le domaine de l'IDS. Par exemple, la France a développé les systèmes Syracuse 1 et 2 pour les communications et Hélios 1 pour l'observation.

L'Espace a la réputation d'être cher (coûts de développement, de production, de lancement, coûts opérationnels). Afin de diminuer les coûts des systèmes spatiaux militaires plusieurs solutions peuvent être envisagées, comme :

- l'utilisation de la synergie civil/militaire. Par exemple, la composante spatiale de Syracuse 2 est embarquée sur Télécom 2 aux côtés de la charge utile civile ; le satellite Hélios 1 utilise la même plate-forme que le satellite civil Spot 4 ; développement, production, lancement, opérations s'appuient en grande partie sur des moyens civils.
- l'emploi de concepts "rustiques", comme les mini-satellites, lorsque cela est possible.
- la coopération internationale.

Cette dernière a été longtemps freinée par la nature "stratégique" de l'Espace signalée plus haut, mais elle a tendance à se développer à la fois pour les raisons économiques qui viennent d'être mentionnées et pour des raisons politiques entre pays ayant des intérêts de défense communs (alliances, voire défense intégrée) comme c'est le cas, par exemple, pour les pays européens. Déjà Hélios 1 est le fruit de la collaboration entre la France, l'Italie et l'Espagne. Hélios 2 (pour le visible) et Horus (pour le radar) sont également envisagés en collaboration européenne, avec vraisemblablement cette fois la participation de l'Allemagne.

Nous arrivons tout naturellement au sujet du présent Symposium, c'est-à-dire ce que représente -et surtout représentera- l'Espace Militaire pour l'OTAN. Je n'insisterai pas sur ce point, car je pense qu'il sera abordé par l'Ingénieur Général Estournet dans son allocution et il sera amplement traité au cours du Symposium.

Je rappellerai seulement que l'OTAN dispose déjà dans le domaine des communications de moyens qui lui sont propres : ce sont les satellites NATO 4 dont le premier a été lancé en 1991 et qui sont des copies des satellites britanniques Skynet.

Je dirai en revanche quelques mots sur un sujet qui me tient particulièrement à coeur : l'Espace et l'AGARD.

Les succès remportés jusqu'à présent dans le domaine spatial, et qui ont été rappelés plus haut, ne signifient pas que tous les problèmes techniques soient résolus. Les problèmes restant à résoudre -et ceux qui ne manqueront pas d'être rencontrés à l'avenir- peuvent bénéficier de la compétence et des efforts de la communauté AGARD.

Il s'agit d'apporter une aide au développement non seulement des systèmes spatiaux de l'OTAN mais encore des systèmes spatiaux nationaux en se limitant, dans ce second cas, à des actions suffisamment amont pour que la confidentialité ne soit pas un obstacle.

Or, malgré le développement rapide de l'Espace, puis de l'Espace Militaire, rappelé précédemment, l'AGARD a été long à s'impliquer dans le secteur. Outre l'aspect confidentialité évoqué plus haut, il faut reconnaître que, historiquement, l'AGARD s'est affirmé dans le domaine aéronautique puis dans le domaine des missiles et que ses

Commissions sont essentiellement constituées d'experts de ces secteurs. La "compétence spatiale" de l'AGARD reste faible pour l'instant et c'est un élément dont il faudra tenir compte lors des renouvellements des membres des Commissions.

Sauf erreur de ma part, il a fallu attendre 1984 pour que soit tenu le premier Symposium à caractère spatial de l'AGARD, celui de l'AMP à Istanbul sur les "résultats des expériences spatiales en médecine et biologie".

Depuis, plusieurs autres Symposiums ont été organisés, encore trop rares à mon point de vue. Par exemple -en me limitant à une Commission que je connais bien, le FMP/FVP- deux Symposiums ont eu lieu :

- l'un en 1989, à Luxembourg, sur la "mécanique du vol des véhicules spatiaux",
- l'autre en 1994, à Cannes (déjà !) sur "les essais dans la conception et le développement de systèmes spatiaux". Je profite de cette occasion pour remercier encore l'Aérospatiale pour l'aide qu'elle nous a apportée dans l'organisation de ce Symposium très réussi.

Le programme AGARD 1996 prévoit, outre le présent Symposium du MSP,

- un Cycle de Conférences (LS207), également du MSP, sur "les applications nouvelles offertes par la navigation par satellite et leur incidence au niveau des systèmes",
- et un Cours Spécial (SC2) du FDP à l'IVK sur "l'aérothermodynamique et l'intégration de la propulsion pour les véhicules hypersoniques".

Comment promouvoir l'Espace au sein de l'AGARD ?

Il est possible de se contenter de l'évolution lente constatée ces dernières années. L'Espace est "naturellement" inclus dans les activités de l'AGARD, Advisory Group for Aero<u>space</u> Research and Development.

Cela paraît si évident aux Commissions de l'AGARD organisées par disciplines scientifiques et techniques génériques, qu'elles mentionnent rarement l'Espace, de façon spécifique, dans leurs Mandats (Terms of Reference) et leurs Listes de Sujets (Topics Lists).

L'AASC, concerné par des études de systèmes multidisciplinaires, fournit la liste des sujets déjà traités et, en effet, une étude AAS-42 sur "les applications militaires des systèmes de satellites commerciaux" a été consacrée à l'Espace. Les principaux résultats seront d'ailleurs rappelés à l'occasion de ce Symposium.

Chaque Commission peut donc introduire l'Espace au coup par coup, à l'occasion de l'organisation des diverses activités de l'AGARD.

Cela ne nous a pas paru suffisant au FMP/FVP. Pour promouvoir l'Espace de façon plus rapide, il nous a semblé qu'il fallait -au moins pendant quelques années de transition- une action plus volontariste et continue. D'où la création d'un Sous-Comité Espace au sein de la Commission, disposant de son propre Mandat et de sa propre Liste de Sujets. C'est une suggestion que je fais à l'adresse des autres Commissions, si elles n'ont pas encore adopté ce genre d'organisation.

En revanche, je ne pense pas qu'il faille créer une Commission Espace séparée. L'Espace bénéficie trop des acquis scientifiques et techniques de l'Aéronautique et des Missiles pour ne pas pleinement profiter de cette synergie, particulièrement évidente dans le cas des problèmes "aérospatiaux" comme ceux concernant les lanceurs, les véhicules de rentrée et les véhicules transatmosphériques (TAV).

Tout ceci est évidemment à revoir dans la perspective de la restructuration en cours de l'ensemble Recherche et Technologie de l'OTAN, et en particulier de la fusion AGARD-DRG. L'Espace, qui a déjà éprouvé quelques difficultés à se développer dans le cadre pourtant aéro<u>spatial</u> de l'AGARD devra trouver la place qui lui est due dans le cadre élargi de la nouvelle entité de Recherche et Technologie de Défense, quel que soit son nom.

L'Espace est en effet une priorité pour l'AGARD, ancienne ou nouvelle formule. De récentes études prospectives soulignent son importance.

Dans l'étude "New World Vistas : Air and Space Power for the 21st Century" de l'US Air Force, le chapitre 6 est consacré aux opérations spatiales qui sont déclarées "d'importance croissante pour le succès de l'accomplissement de la plupart des missions du 21ème siècle". Les thèmes des satellites distribués, de l'accès à l'espace, du contrôle de l'espace et de la projection de force depuis l'espace sont successivement développés. S'il est reconnu que les opérations spatiales contribuent déjà largement à l'"observation globale" et à la "connaissance globale de la situation", le contrôle de l'espace -voire l'armement spatial- devraient prendre une importance accrue compte tenu du nombre croissant de pays susceptibles d'avoir accès à l'espace.

Rappelons également que dans l'étude prospective Aerospace 2020 lancée par l'AGARD, les "véhicules spatiaux" sont l'un des sujets sélectionnés.

L'Espace est particulièrement important pour la Commission MSP des Systèmes et Missions car toute mission spatiale met en jeu un système complexe comprenant non seulement un segment spatial mais encore un très important segment sol, lui-même subdivisé en sous-segments : contrôle opérationnel et exploitation.

Le programme du présent Symposium du MSP me semble assurer un harmonieux équilibre entre l'aspect "top-down" de l'analyse des missions militaires de l'OTAN et "bottom-up" des technologies spatiales émergentes susceptibles d'aider à l'accomplissement de ces missions : c'est le domaine de compétence privilégié de l'AGARD. Le programme couvre les aspects synergie civil/militaire, communications, surveillance (reconnaissance, météorologie, alerte précoce), extraction et fusion d'information, technologies véhicule et systèmes futurs, c'est-à-dire la plupart des aspects intéressant l'Espace Militaire. Les points non traités pourront l'être à l'occasion d'activités futures du MSP. Déjà l'aspect navigation sera couvert dans le Cycle de Conférences LS207. Le thème de la surveillance de l'espace depuis le sol paraît également devoir être abordé.

Je suis convaincu de l'importance de l'Espace Militaire, en particulier en relation avec les activités de l'AGARD. Je regrette de ne pas pouvoir assister à la totalité de ce Symposium, mais j'aurai au moins le plaisir d'y participer cet après-midi et d'abord d'écouter avec intérêt l'allocution de l'Ingénieur Général Estournet.

Je déclare donc ouvert le Symposium.

Note dominante de la Conférence du symposium AGARD sur les systèmes spatiaux contribuant à la stratégie de défense de l'OTAN

par l'Ingénieur général de l'armement Daniel Estournet
Chef du Service technique des systèmes stratégiques et spatiaux
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Monsieur le Président,
Mesdames, Messieurs,

Je suis particulièrement heureux d'être ici parmi vous, et cela, pour une nouvelle fois puisque j'ai eu l'honneur de prononcer une allocution lors de l'ouverture du symposium AGARD sur *«les essais dans la conception et le développement des systèmes spatiaux»*, ici-même à Cannes, il y a de cela exactement 19 mois. C'est, en effet, avec une satisfaction non dissimulée que je constate l'intérêt renouvelé que vous témoignez à l'espace au travers de la tenue maintenant régulière de réunions sur le sujet.

Les débuts de l'utilisation à des fins de défense ou de sécurité nationale de l'espace remontent à plus de 35 ans. Humainement, c'est plus d'une génération ; mais historiquement, ce qu'on appelle – peut-être un peu caricaturalement – l'espace militaire (disons plutôt : l'espace pour la défense) constitue un domaine relativement neuf pour la plupart de nos pays. L'existence de satellites de défense non expérimentaux en orbite autour de notre planète n'est déjà pas si ancienne ; l'utilisation effective de ces satellites a été naturellement progressive au début, et destinée aux plus hautes autorités ; si cette utilisation est aujourd'hui devenue constante et incontournable, les hautes autorités, plus politiques que militaires, en constituent toujours une clientèle de prédilection, et de poids ; quant aux exemples plus purement militaires d'utilisation intense, systématique et à applications multiples et conjointes en opérations de satellites de toutes sortes, ils n'ont été mis en évidence qu'encore plus récemment – je pense bien sûr au conflit du Golfe Persique, dans lequel l'espace a été une des clefs de la réussite des opérations alliées.

Il me semble que cet exemple d'emploi des moyens spatiaux doit avoir pour nous une valeur historique aussi marquée que celles de l'emploi de l'avion de chasse durant la bataille d'Angleterre, du char d'assaut sur les deux fronts d'Europe, ou du porte-avions durant la guerre du Pacifique. Elle est même, à mon avis, d'un ordre supérieur, et cela, bien que les moyens spatiaux militaires dont nos pays disposent ou disposeront ne consistent pas en armes à proprement parler, comme le sont un avion de combat, un blindé ou une unité navale ; bien qu'également la guerre du Golfe ait été un événement d'une ampleur bien moindre que la guerre mondiale – Dieu merci. Pourquoi donc l'apparition des moyens spatiaux dans nos stratégies et nos systèmes de défense représente-t-elle pour moi une nouveauté d'un poids plus fort que bien d'autres révolutions ? Pour plusieurs raisons, qu'il me semble utile d'évoquer ici.

Tout d'abord, lorsqu'on parle de l'espace, on parle certes d'un milieu, mais d'un milieu utilisé essentiellement comme intermédiaire, comme moyen technique, et non comme champ de bataille opposant des hommes, à l'instar de la surface terrestre, de la mer ou de l'air – du moins pour l'instant, et j'espère pour longtemps. Les civils ont sans doute une approche différente dans la mesure où ils connaissent des applications spatiales dont l'espace est la dernière finalité, je veux parler de la recherche spatiale ou de l'exploration de l'univers. Mais, pour longtemps je le répète, les missions des moyens spatiaux pour la défense ne peuvent que se rapporter à des actions qui ont lieu sur notre planète : l'espace militaire n'est pas un but en soi, a-t-on pu dire, ce qui entraîne d'ailleurs le désintérêt de certains. En contrepartie, et c'est là que je voulais en venir, loin de la terre, loin de la mer, loin de l'atmosphère, mais en réalité proches de tous et de la même façon, les moyens spatiaux, d'une part, présentent un profond caractère interarmées, d'autre part balayent la terre entière et dominent les théâtres d'opérations sans vraiment en faire partie, enfin apportent des solutions radicales, comme magiques, à des problèmes variés ; tout cela confère originalité et importance au domaine spatial militaire.

Si l'on passe du point de vue de la défense d'un pays à un point de vue multinational, ce même caractère planétaire fait que les moyens spatiaux constituent une nouveauté en matière de coopération internationale. Cela peut être rapidement analysé, par exemple selon les trois points suivants.

Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.

Premièrement, à moyens planétaires, stratégie planétaire : on voit mal comment l'usage même de tels moyens par un pays donné pourrait laisser indifférents ses alliés, aux plans successifs, d'abord, de la stratégie de chacun, ensuite de la compatibilité et de l'interopérabilité, enfin de la stratégie d'ensemble de leur alliance ; en effet, les affaires qui concernent la planète tout entière intéressent chacun de ses locataires... Deuxièmement, pour ainsi dire colocalisés, en des lieux élevés qui appartiennent à tous, il est presque géométriquement évident que les systèmes spatiaux devraient constituer, cette fois d'un point de vue purement technique, de bons sujets de coopération. Troisièmement, les satellites étant des éléments coûteux en général peu nombreux pour une mission donnée, ils peuvent fournir l'occasion d'une coopération non seulement pour leur réalisation mais aussi pour leur utilisation ; ce dernier type de coopération est véritablement nouveau car jusqu'à un passé récent, la coopération militaire entre pays s'en est tenue soit à réaliser en commun des matériels dont chacun se dote ensuite des quantités qui lui conviennent – c'est la classique coopération d'armement, qui se situe au niveau des spécifications et de la réalisation industrielle des matériels –, soit à constituer des forces alliées ou multinationales – c'est la classique coopération d'alliance en opération, qui se situe au niveau du commandement et des hommes ; or le partage de l'emploi d'un satellite, qui n'est ni l'un ni l'autre, qui est nouveau, curieux même, se révèle tout à fait possible, riche d'enseignements, et prometteur au plan coopératif : je ne citerai que deux exemples desquels je suis assez proche, celui du partage d'un satellite de télécommunication entre civils et militaires en France (Télécom/Syracuse), et celui du partage d'un satellite d'observation militaire entre la France, l'Italie et l'Espagne (Hélios).

L'exemple du système Syracuse me conduit à évoquer la troisième raison qui fait que la révolution spatiale revêt une importance particulière pour la défense : les moyens spatiaux sont parmi ceux pour lesquels la dualité civil/militaire est la plus forte, avec du reste une frontière mouvante entre le civil et le militaire. Cette dualité est due à la haute technicité du secteur, aussi bien pour les civils que pour les militaires – au point que, dans certains pays, on a pu constater la mainmise des autorités militaires sur le spatial civil. On a pu également assister à l'utilisation progressive de moyens militaires par les civils (GPS). Par ailleurs, très rapidement, des techniques initialement militaires sont progressivement utilisées par le civil, comme cela se passe en aéronautique par exemple, mais dans l'espace de façon à mon avis beaucoup plus marquée ; de plus, on constate également un phénomène inverse, selon lequel les militaires utilisent ou projettent d'utiliser, essentiellement par raison d'économie, des techniques ou des moyens spatiaux civils qui existent déjà grâce à certains programmes civils de recherches ou tout simplement grâce au marché (utilisation militaire d'INMARSAT ou de SPOT, dualité SPOT/Hélios, projet GBS, etc.).

Une quatrième raison enfin – mais peut-être est-ce la plus forte et aurais-je pu commencer par elle – que je vois à l'importance de l'avènement de l'espace pour la défense de chacun et de tous, consiste en ce que les systèmes spatiaux de défense sont, essentiellement, de très puissants systèmes d'information. En effet, si l'on s'essaie à un exercice de typologie, on voit qu'il s'agit soit de capteurs d'information (observation optique ou radar, écoute électromagnétique, alerte précoce), soit de synthétiseurs d'information (navigation), soit de relais de transmission d'information (télécommunication). Or, de plus en plus, et c'est là, dans l'histoire de l'homme, sans doute une révolution de portée supérieure à celle de la révolution industrielle du siècle dernier, les fonctions d'information prennent dans le monde un rôle de premier plan, ainsi que le prévoient d'ailleurs les savants, physiciens, biologistes, économistes, de plus en plus nombreux à considérer l'information comme un phénomène strictement fondamental. Ce rôle de l'information qui est fondamental pour l'action politique, pour le commerce, pour l'industrie, l'est en particulier dans la stratégie des états et dans les opérations militaires. L'importance du système spatial d'information est donc de nature particulièrement stratégique, j'oserais dire un peu à la manière de celle du missile nucléaire : les deux sont des instruments de souveraineté, les deux sont des sujets de grande sensibilité, les deux sont des éléments de dissuasion et, je crois, de stabilisation. J'arrête ici l'analogie, qui a ses limites comme toutes les autres, ne serait-ce que parce que le système spatial est, lui, matériellement utilisé en temps de paix comme en temps de crise.

*
* *

Ce que je viens de rappeler constitue donc, d'une part, un ensemble de très fortes raisons de nous réunir à présent régulièrement à propos des applications spatiales de défense pour l'OTAN, mais d'autre part également un cadre, une ambiance, et d'une certaine manière, des orientations à nos études.

Le champ des applications est vaste, ai-je dit. On ajoute souvent que ce champ, dans la plupart des cas, couvre la satisfaction de besoins déjà existants, parce qu'il fournit des solutions à meilleur marché, voire plus performantes, ou parce qu'il permet une redondance favorable ; même si elle n'est pas fausse, surtout les premières années, cette vision un peu méfiante et conservatrice à l'égard du champ des applications spatiales ne doit pas cacher que ces applications couvrent également la satisfaction de besoins auparavant jugés utopiques ou même tout simplement ignorés. Tout cela doit être pris en compte dans les réunions du genre de celle-ci où nous devons échanger des idées sur toutes possibilités offertes et les moyens de les mettre en œuvre.

Mais ce devoir de libre créativité technique n'est pas le plus important à mes yeux.

Ainsi que je l'ai laissé entendre, je perçois deux niveaux d'utilisation de l'espace pour une organisation comme l'OTAN : le niveau opérationnel et le niveau politique. En effet, l'OTAN est issue d'un traité d'alliance entre des pays souverains. Mais entendons-nous : l'AGARD est une institution qui traite de recherche et développement, son point de vue doit être technique ; je suis moi-même ingénieur, j'ai pratiqué la conduite d'études et celle de programmes, actuellement je dirige un service de programmes ; en conséquence, les connotations politiques ou opérationnelles contenues dans le titre du présent symposium *«les systèmes spatiaux contribuant à la stratégie de défense de l'OTAN»* ne sauraient être considérées autrement que comme un cadrage, un guide, et non comme le sujet même de vos communications ; vous l'avez d'ailleurs bien compris. Quant à moi, si j'ai la délicate mission d'élargir le débat le temps de cette introduction, j'essaie de le faire en toute modestie en m'en tenant au bon sens et en évitant d'empiéter sur des spécialités qui ne sont pas les miennes.

Pour ce qui concerne l'opérationnel, l'expérience de la guerre du Golfe est là pour nous donner une idée de l'intensité avec laquelle seront utilisés les moyens spatiaux par les armées les plus modernes, dans des circonstances analogues. Depuis cette opération, plus rien ne pourra être comme avant. Mais cet exemple est assez unique, et il convient de prendre un peu de recul à son égard, et même d'autant plus de recul que sa nouveauté a été plus remarquable : l'enthousiasme ne doit pas empêcher la lucidité.

Qu'il s'agisse des communications, de la cartographie, du renseignement militaire, de la navigation, de la localisation, de la météorologie, de la protection contre les missiles balistiques, tous ces domaines ont connu leur première démonstration opérationnelle militaire en grandeur nature lors de ce conflit, alors même que les systèmes correspondants n'avaient pas tous, loin s'en faut, été conçus pour cela. On peut certes prévoir, sans trop risquer de se tromper, que les futurs conflits d'une certaine ampleur verront un usage plus intensif encore de ces systèmes ; une telle prévision est évidente ; mais ce qui doit retenir plus spécialement notre attention est que cela ne pourra plus être improvisé. C'est pour cette raison-là qu'il importe, si nous voulons donner toutes leurs chances à nos forces armées, non seulement que les industriels étudient et optimisent à l'avance, puis réalisent et leur fournissent ces moyens spatiaux, mais encore et surtout que les forces armées les intègrent complètement dans leurs modes opératoires. Je considère même que la réalisation d'un système, au sens complet des termes "réalisation" et "système", comprend d'une part les travaux d'étude et de construction matérielle, et d'autre part ces travaux d'intégration par les utilisateurs ; les uns et les autres sont indissociables et les travaux d'accueil et d'intégration par l'utilisateur ne peuvent, comme les travaux de réalisation, avoir lieu qu'à l'avance, en temps de paix, et en leur consacrant le soin, donc le temps nécessaires. Cela ne doit jamais être perdu de vue lorsqu'on se préoccupe de recherche et développement.

J'insiste sur ce point car l'utilisation de l'espace pour des opérations militaires sera peut-être à l'origine de la plus grande discontinuité des relations entre la distance et le temps depuis la Blitzkrieg du début de la seconde guerre mondiale. En effet, l'espace permet un élargissement du champ de bataille grâce aux télécommunications, ainsi qu'une profondeur d'action sans précédent grâce aux systèmes de renseignement, de télécommunications et de navigation entre autres. En résumé, l'espace peut fournir les moyens C4&I d'une bataille sans précédent, permettre d'aller ainsi bien au-delà d'une simple amélioration des doctrines actuelles, et finalement, pourquoi pas, engendrer certains changements structurels dans les forces armées.

Le problème, car problème il y a, est que le coût de ces systèmes est une lourde contrainte, surtout lorsque les budgets d'équipement de nos forces sont en baisse... C'est ici qu'intervient de façon cruciale la solidarité entre nos pays alliés, qu'il s'agisse d'opérer en commun des systèmes spatiaux ou de permettre l'utilisation par d'autres de nos systèmes propres. Les exemples actuels respectifs des communications, avec les satellites OTAN, et de la navigation et de la localisation, avec le GPS, montrent que l'Organisation est dans la bonne voie.

Une autre source d'optimisation budgétaire est évidemment la synergie avec les systèmes civils, que j'ai citée parmi les éléments essentiels de la révolution spatiale. Là encore, qu'il s'agisse de développements technologiques coordonnés entre le civil et le militaire ou de l'utilisation militaire de systèmes civils, nos pays ne sont pas en reste. J'ai cité plusieurs exemples actuels, mais je pense que nous pouvons aller encore plus loin, comme le montreront certainement demain les discussions de la seconde session.

Je voudrais enfin évoquer, même en l'effleurant avec précautions, l'autre niveau d'utilisation des moyens spatiaux de défense, le niveau politique. Car vous avez bien compris que nous ne pouvons pas échapper au fait que c'est le niveau principal. Notre Alliance réunit des pays souverains ; ils doivent donc avoir une appréciation sûre et autonome de toute situation pour pouvoir s'engager dans le cadre de l'OTAN (puisque c'est de cette organisation que nous parlons), d'autant plus que le traité d'alliance en question est très fort et que son application peut avoir des conséquences extrêmement importantes sur nos populations. Cela n'implique pas que chacun de nos pays, pris individuellement, doive avoir systématiquement ses propres moyens ; cela serait inconcevable aussi bien financièrement que techniquement.

Mais il y a des solutions, politiques et techniques, pour construire quelque chose d'équilibré et d'accessible. C'est ainsi qu'il apparaît essentiel que l'Europe, dans son ensemble, dispose de systèmes spatiaux de défense, et cela pour le bien même de l'Alliance. C'est le sens de la coopération entre la France, l'Italie et l'Espagne, qui a débuté dans la seconde moitié des années 80 pour aboutir au lancement du satellite Hélios IA en juillet 1995 et à son utilisation opérationnelle partagée, dans le respect de la souveraineté de chacun. C'est le sens aussi de l'accord, signé solennellement par les trois pays Hélios I et par le secrétaire général de l'UEO en avril 1993, qui lie ces pays à l'UEO, véritable pilier européen de l'Alliance, pour la fourniture d'images provenant de ce satellite à fin de traitement exclusivement dans son centre satellitaire de Torrejon. Et pour l'avenir, c'est le sens de la déclaration franco-allemande de Baden-Baden du 7 décembre 1995, qui permet de continuer résolument dans cette voie en en élargissant les ambitions.

Il faut donc concilier l'impératif incontournable de la souveraineté de chaque état dans l'utilisation des systèmes satellitaires et les contraintes dues au poids de la réalisation de ceux-ci. Cela peut sans doute être décliné pour chaque type de système spatial, et une telle analyse est de nature à faire émerger de véritables – et difficiles – problèmes techniques. C'est ici que nous intervenons, que vous intervenez : comment concevoir telle ou telle application de sorte que son coût puisse être partagé tout en garantissant la souveraineté de chacun ? Voilà une excellente question. Je pense qu'un tel axe de recherche doit être prioritaire pour l'AGARD.

The Evolving NATO Satellite Experience

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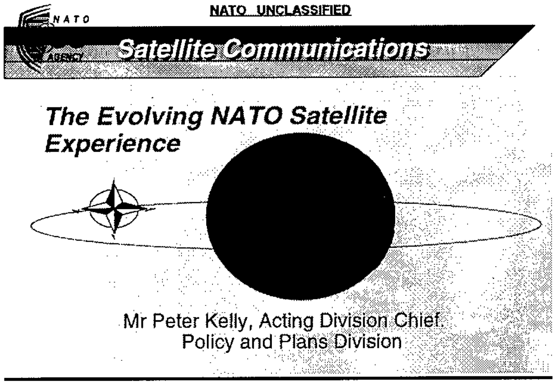
Biography

Air Commodore Peter Kelly entered the Royal Air Force in October 1956 and qualified as an Electrical Engineer in 1960 and is a Chartered Engineer. He obtained his Pilots wings in 1960 followed by an operational flying appointment flying Victor Mk1 & 1As. He then returned to engineering duties.

Then followed a number of tours, both at home and abroad, mainly in the communications engineering field before, in May 1977 being posted to Cyprus as the SO Eng at AHQ where he had overall responsibility for all RAF engineering on the Island and in Malta, including Nimrods, Phantoms and helicopters as well as various signals units. He then became OC 5 Maintenance Unit and Station Commander RAF Kemble. During this time he had responsibilities for the overhaul and deep repair of aircraft. He became DD Sigs 2(Air) on promotion in July 1983 and was head of UK NALLA. In 1986 he was selected for the post of Deputy Division Chief of the long term planning Division at NACISA in Brussels. The major task was a strategic rethink of CIS to cover the period up to 2008 and the digitalisation of NATO facilities. He returned to the Ministry of Defence on promotion to be the Director of CIS in the central staffs, with particular responsibility for all Strategic C2 facilities including C2IS. He took early retirement to take up an appointment as Chief of the C3 Architecture and Plans Branch and became the Division Technical Adviser to the renamed Architecture and Plans Division.



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Satellite Communications

The Evolving NATO Satellite Experience

Mr Peter Kelly, Acting Division Chief
Policy and Plans Division

The Evolving NATO Satellite Experience

I am very pleased to have been asked to give the scene setting presentation on the NATO use or projected use of space. NATO has been in the satellite business since the mid 1960s.

At this point however, I believe it would help if I was to stress that NATO's primary interest lies in the use of satellites for communications (SATCOM), although we have given consideration to the possible use of satellites for surveillance. Many of you may be aware of one of our latest requirements for battlefield intelligence information which will most probably be met through a new programme entitled Alliance Ground Surveillance(AGS). Current feasibility studies indicate that this may well be met by a mixture of fixed wing and rotary aircraft and not spacecraft.

Thus my presentation today concentrates exclusively on the use of satellites for communications (SATCOM).

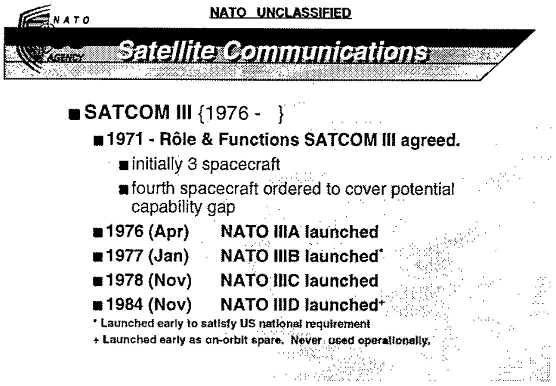
My aim in this briefing is to give you a rundown on the historical background of our involvement, what the NATO satellite system looks like today, go into some of the cost factors that will condition our thinking, outline some of the results of a recent study into SATCOM after 2000 and finally what our thoughts are for the future.

Our first venture in to SATCOM took the form of an evaluation programme on 1996 which provided a simple link between SHAPE at Casteau in Belgium and AFSOUTH at Naples in Italy. It comprised one voice and two 50 Baud telegraph channels. At the same time SATCOM II was in gestation and a firm decision to proceed was made in 1968 to provide SATCOM for consultation between the capitals of the NATO countries.

This led to the launch of NATO IIA in March 1970, which incidentally failed within a year, and the launch of IIB in February 1971. NATO II was based on UK SKYNET 1 (22 MHZ/16.3 dBW). The system consisted of 12 static ground terminals, and the IOC in 1972 gave 57 voice and 100 telegraph point to point circuits. By 1974 the services carried had tripled.

Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.

Even whilst this was going on NATO had already committed itself to SATCOM III as follows.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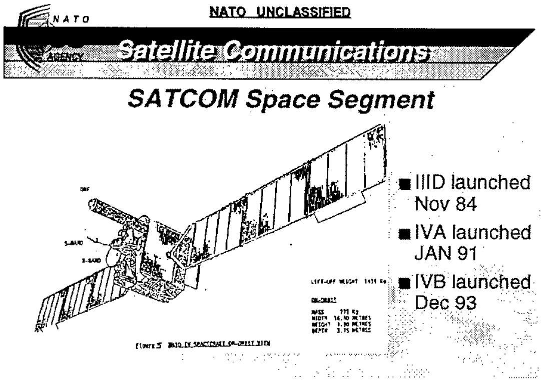
- **SATCOM III** {1976 - }
  - **1971 - Rôle & Functions SATCOM III agreed.**
    - initially 3 spacecraft
    - fourth spacecraft ordered to cover potential capability gap
  - **1976 (Apr) NATO IIIA launched**
  - **1977 (Jan) NATO IIIB launched***
  - **1978 (Nov) NATO IIIC launched**
  - **1984 (Nov) NATO IIID launched+**

* Launched early to satisfy US national requirement

\+ Launched early as on-orbit spare. Never used operationally.

The key points to note are that the satellites were designed for a seven year life and NATO decided to launch an additional spacecraft, IIID in 1984 to prolong the operational lifecycle of the constellation. The driving force behind the decision was the use by the US of NATO IIIB for two years in the Pacific and hence doubts existed as to its probable life. It is ironic that IIID has never been used and is still in a parking orbit.

On the ground segment side however, there was a major policy shift with the decision to provide electromagnetic pulse protection(EMPP) and also some transportable capability. Thus we introduced 9 new EMP protected SGTs, 1 large transportable, 2 landrover transportable terminals and a training facility at LATINA. In addition we modified 12 Phase II terminals. This leads me into our present system based on NATO SATCOM IV comprising the space, ground and control segments.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SATCOM Space Segment

- IIID launched Nov 84
- IVA launched JAN 91
- IVB launched Dec 93

The NATO SATCOM IV space segment provides a major improvement on its predecessors. It is three axis stabilised, provides for services in both the SHF where we have four channels and UHF bands where we have two fixed channels. The satellites themselves are ECCM and EMPP hardened and have antennae giving both earth coverage and spot beam coverage in the European area. They were designed for use with moderate size SHF ground terminals and small terminals at UHF.

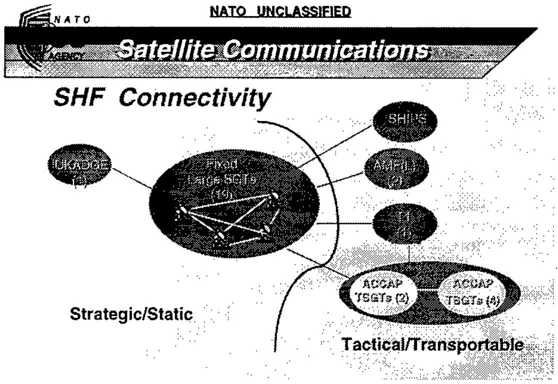
The locations of Nato's approved orbital slots are at 17.8 degrees West, 18 degrees west and 60 degrees west. We are currently using a US slot at 21 degrees for NATO IIID and a UK slot at 6 degrees east for NATO IVB.

The SATCOM ground segment comprises 19 network sites and a variety of transportable facilities as follows:

a. 19 static
b. 1 static dedicated user site
c. 1 T1 transportable (6.8m dish)
d. 6 ACCAP Transportable Terminals
e. 2 AMF(L) transportables (1.9m dish)
f. 1 COTS Terminal
g. 200+ UHF transportables

We planned for terminals in all the countries except FR and LU. Recently the number of SHF SGTs has been increased and we have also just purchased in excess of 200 UHF mobile terminals as well as a dozen SHF man portables.

The use made of the SHF connectivity is as as follows: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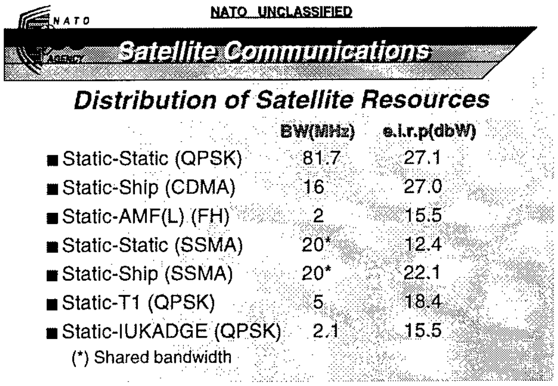
SHF Connectivity

The UHF was procured to support maritime operations but is now heavily used in support of operations in the former republic of Yugoslavia.(FRY) where we are running in excess of 30 nets using loaned capacity in addition to our own.

The SATCOM control segment consists of a technical control which for NATO III is provided by the 5th Space Operations Squadron USAF at Sunnyvale, California and for NATO IV at the Royal Air Force's 1001 Signals Unit at Oakhanger in England. Network and Operational control is exercised from the main control centre (MCC) at Kester(F1) in Belgium whilst the alternate control is at the NATO ground terminal(F4), situated also at Oakhanger. Monitoring control of UHF is also done from the MCC at Kester.

The satellite resources are distributed as shown:



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Distribution of Satellite Resources

	BW(MHz)	e.i.r.p(dbW)
Static-Static (QPSK)	81.7	27.1
Static-Ship (CDMA)	16	27.0
Static-AMF(L) (FH)	2	15.5
Static-Static (SSMA)	20*	12.4
Static-Ship (SSMA)	20*	22.1
Static-T1 (QPSK)	5	18.4
Static-IUKADGE (QPSK)	2.1	15.5

(*) Shared bandwidth

However we are not using our present capability to best advantage, in particular we are not making use of the bandwidth available to us, using approx. 150 MHz out of a nominal 500MHz available in the space segment as our existing SGTs have limited bandwidth High Powered Amplifiers(HPAs). Other limitations of our existing system is that we have a single fixed spot beam with limited EIRP and the interface is analogue, thus high-speed data transmission is not yet possible. Even more surprising is that we have some additional 20% equipped but idle capacity, but that is more a feature of our financial procedures.

We do have a short to medium term programme comprising funded and planned enhancements and have recently carried out an examination based on current operational initiatives in concert with the NATO military authorities.

Short to Medium Term Programme

In the short to medium term we have funded enhancements, planned enhancements and some ongoing operational initiatives.

Amongst the funded enhancements are broadbanding of the satellite ground terminals, improvements to the reliability of Electromechanical equipment, purchase of additional transportable SHF terminals, providing EPM for our TSGTs as well as encryption, an S-band terminal for Spacecraft control and provision of Digital Through-connection via SATCOM.

Amongst the planned enhancements are improving access to our static network for afloat commanders, extended EPM protection of SATCOM links utilising the Universal Modem when it becomes available, improvements to the reliability of the antenna drive systems and HPAs in the SGTs and upgrading the (CM & D) computers. We are also in the process of planning the provision of an alternate satellite control and examine the provision of User premises SGTs as a trade off against current access and maintenance costs.

As part of the ongoing operational initiatives we have reviewed our requirements for the static ground terminals as a result of which we have recently closed F8 at CARP in Canada. We now intend to have only 4 fixed ground terminals for UHF instead of 11 but as I have already mentioned we have now over 200 UHF mobile terminals in use which were not foreseen.

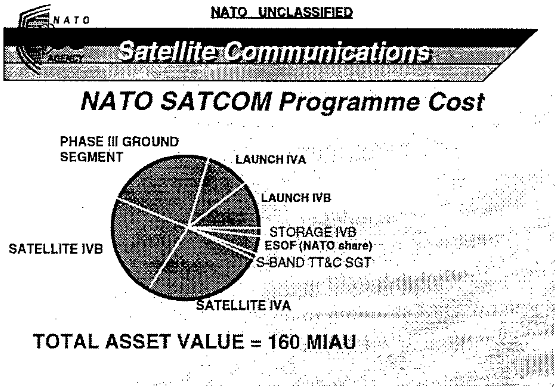
What next? Well as you are all aware since the demise of the Berlin wall and the new political scenario in the world, NATO's attention has turned away from purely Article V operations to what not surprisingly is termed Non-Article V ones. The major impact of which is the probable need for NATO to operate outside the envelope of its static infrastructure. The concept of Reaction Forces both Immediate and follow on has placed a new emphasis on the provision of facilities to deployed Headquarters such as a Combined Joint Task Force HQ with Land, Air and Maritime elements, which would operate outside NATO's normal area of operations. Not unnaturally we are looking to SATCOM to help us meet this requirement of stretching our static network into the theatre of operations. A further change is the involvement down into what was previously a totally national responsibility, that of the tactical area. In looking at the information exchange requirements e.g.. for Reaction Forces Air we have identified a heavy load which we believe can only be met by the use of SATCOM. Similarly in the Land Force concept of Framework nations epitomised by the Ace Rapid Reaction Corps (ARRC), SATCOM is required for links between the Corps and its Multi-national Divisions. This part of the concept is currently being proven in the IFOR in FRY. There is however only one problem and that is money! NATO like all the nations is currently embarked on a major down sizing and review of its financial and manpower commitments. As many of you will be aware NATO IV has a forecast life out to 2001 and possibly to 2003. There is however a strong lobby against NATO continuing to have its own satellite constellation and even continuing to use SATCOM except perhaps through leased commercial facilities i.e. service provision.

Costs

Before dealing with a major study into NATO Post-2000, I would first like to briefly run through the cost comparisons associated with the use of SATCOM.

There are three areas I will touch on, firstly the programme costs, based on NATO IV, secondly the day to day operating and maintenance costs to set a baseline and then finally I will show some comparisons for costing purposes for provision of SATCOM services. I realise this last element may be somewhat contentious but that can only be to the good if it helps to further clarify what is a difficult problem.

So first the costs associated with NATO IV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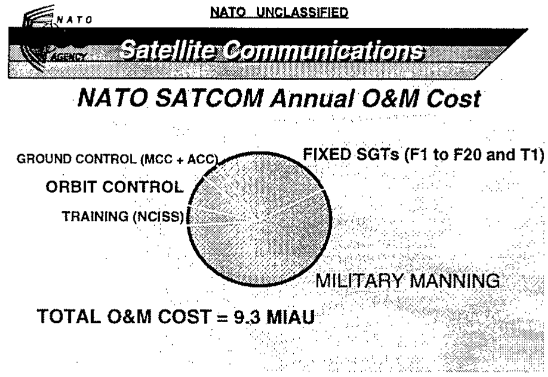
NATO SATCOM Programme Cost

TOTAL ASSET VALUE = 160 MIAU

The pie chart outlines what are effectively our sunk costs. Not surprisingly the major element is the cost of the satellites and their launch. However the total cost equates to about 750MUSD. This is about twice the cost of the previous programme. I would also emphasise at this point that NATO has its own accounting system and therefore some of what follows may be questionable given that starting point.

For ease of understanding 1 IAU equates to 4.633 USD in capital infrastructure costings but a little less in operating costs. NATO has two different standards between its financial committees!

Now to O & M costs.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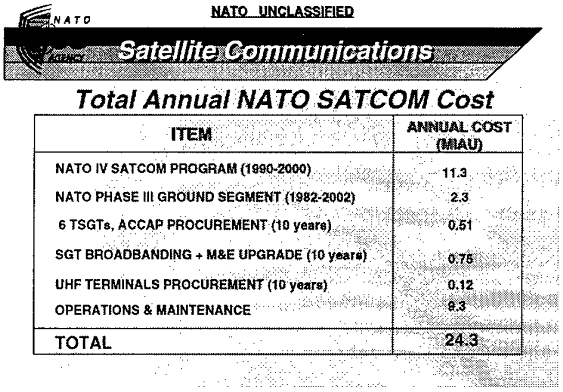
NATO SATCOM Annual O&M Cost

TOTAL O&M COST = 9.3 MIAU

These are estimated to be in the order of 9.3MIAU.

When I combine these as shown in my next table we are talking of an annual cost to NATO for SATCOM services of 24.3MIAU.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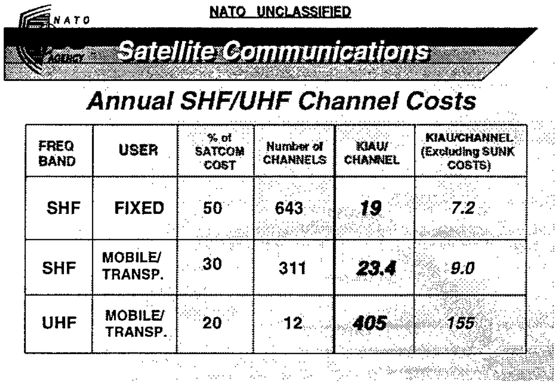
Satellite Communications

Total Annual NATO SATCOM Cost

ITEM	ANNUAL COST (MIAU)
NATO IV SATCOM PROGRAM (1990-2000)	11.3
NATO PHASE III GROUND SEGMENT (1982-2002)	2.3
6 TSGTs, ACCAP PROCUREMENT (10 years)	0.51
SGT BROADBANDING + M&E UPGRADE (10 years)	0.75
UHF TERMINALS PROCUREMENT (10 years)	0.12
OPERATIONS & MAINTENANCE	9.3
TOTAL	24.3

The only significant deviation is that the ground segment stations are amortised over 20 years rather than ten. Then applying shared costs and number of channels in use we have annual cost to NATO for different SHF/UHF fixed and mobile services as follows;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Satellite Communications

Annual SHF/UHF Channel Costs

FREQ BAND	USER	% of SATCOM COST	Number of CHANNELS	KIAU/ CHANNEL	KIAU/CHANNEL (Excluding SUNK COSTS)
SHF	FIXED	50	643	19	7.2
SHF	MOBILE/ TRANSP.	30	311	23.4	9.0
UHF	MOBILE/ TRANSP.	20	12	405	155

If we ignore the last column we have costs per channel of 19 KIAU, for fixed services, 23.4 KIAU for SHF mobile and an enormous 405 KIAU for mobile UHF but to put this last figure more into perspective each UHF channel is usually timeshared across 10 to 15 users bringing per customer costs down considerably. How do these compare?


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Satellite Communications

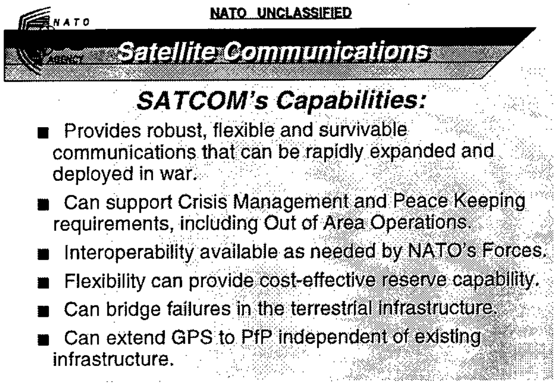
SATCOM's Capabilities:

- Provides robust, flexible and survivable communications that can be rapidly expanded and deployed in war.
- Can support Crisis Management and Peace Keeping requirements, including Out of Area Operations.
- Interoperability available as needed by NATO's Forces.
- Flexibility can provide cost-effective reserve capability.
- Can bridge failures in the terrestrial infrastructure.
- Can extend GPS to PfP independent of existing infrastructure.

First the fixed service provision is compared against leased line costs. As you can see there is not much to choose between them, and one could be convincing for either case.

In recent associated studies into replacement of the other major service systems, the IVSN for voice and the TARE for telegraph, we have also taken into account all our dedicated point to point connectivity with the aim of optimising into a rationalised service provision. Use of our SATCOM assets does make a considerable impact in reducing our overall costs.

However once we enter the mobile field things do change significantly.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NATO's costs are as derived and my comparison is based on how many days service I could buy for the same amount. It is a rough and ready comparison but in essence if you are in the military mobile business you do need a cost effective satellite capability. The main reason I have exposed you to this is to put into perspective the climate in which we are trying to decide where does NATO go next in the SATCOM business.

At the behest of the CIS policy committee the NACISC a study called the Post -2000 SATCOM Study has recently been completed and follow on work has now commenced in the Agency which will involve the use of Consultants/Contractors to determine the costed options for the way ahead.

NATO SATCOM Post-2000

The way ahead for NATO SATCOM Post-2000 depends on where NATO is going, who will be the future customers and the recommendations of the NATO SATCOM Post-2000 WP Report.

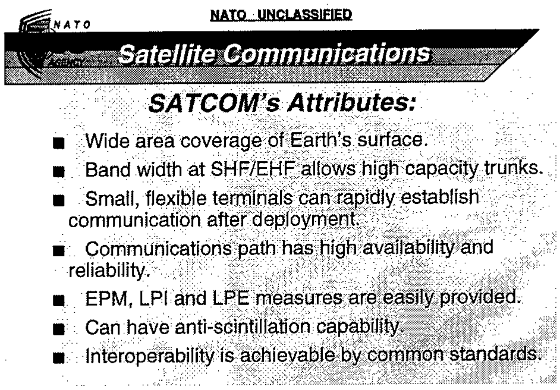
What we know today is that the geopolitical threat will continue to evolve but it will probably be at the edges of Europe. Financial pressures will most probably get worse and we face new challenges from enlargement and the involvement of the Partner for Peace nations and the North Atlantic co-operation council presently consisting of 38 nations. However NATO's objectives are to retain

a capability based alliance and,
a strong transatlantic link.

Why do we continue to need SATCOM?

To serve NATO HQs for political Consultation and Peace support in terms of emergency planning. To provide extended Command and Control facilities to NATO's military commanders, SACEUR and SACLANT and within the tactical arena to provide the links between multi -national divisions.

What does SATCOM give us?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Satellite Communications

SATCOM's Attributes:

- Wide area coverage of Earth's surface.
- Band width at SHF/EHF allows high capacity trunks.
- Small, flexible terminals can rapidly establish communication after deployment.
- Communications path has high availability and reliability.
- EPM, LPI and LPE measures are easily provided.
- Can have anti-scintillation capability.
- Interoperability is achievable by common standards.

The main attributes of SATCOM is its wide geographical coverage combined with the high capacity trunks its bandwidth allows. Added to this the various military features of EPM, LPI and LPE and the speed with which connectivity can be set up and you have a powerful instrument for military use. Incidentally we are always competing with the world's media for any spare commercial capacity in times of crisis.

SATCOM has become a victim of its own success. Its capabilities have been well demonstrated to the operational staff and, perhaps worse from our perspective as communications engineers, the commercial market has demonstrated capability beyond that available in the military field.

Live pictures from downtown Baghdad during Desert Storm proved more than just the remarkable accuracy of Cruise Missiles.

Desert Storm was though the first time the world saw the capabilities of the Allies demonstrated. The key element that allowed the exercise of effective command and control of such a large, multinational fighting force was communications and SATCOM was pivotal in their provision.

In terms of its capabilities it:

a. Provides robust, flexible and survivable communications that can be rapidly expanded and deployed in war.

b. Can support Crisis Management and Peacekeeping requirements, including Out of Area Operations.

c. Interoperability available as needed by NATO's Forces.

d. Flexibility can provide cost-effective reserve capability.

e. Can bridge failures in the terrestrial infrastructure.

f. Can extend GPS to PfP independent of existing infrastructure.

Thus it allows us independence from the national infrastructure out of area, provides a bridge to land systems on failure and has the potential to provide connectivity to our other allies.

SATCOM now has a proven track record in delivering these capabilities to both the politician and the commander.

Throughout the Cold War SATCOM formed a core element in our hardened communications infrastructure and in providing communications to the Fleet. However, our use of this capability had not been developed.

Elsewhere in France, the UK and the US national involvement in overseas operations has seen a radical change in attitude to the employment of SATCOM.

The working party considered all aspects of operating future SATCOM both military and commercial. All aspects were considered both commercial and military, what orbit should we go for, the shape of the future ground segment and how the capability should be controlled. In addition it looked into the various financial options for continuing to operate a military owned SATCOM system. In particular it looked at the consequences of trying to join one of the several consortia currently looking into the provision of new satellites in the early p art of the next century. These were all compared with the use of commercial solutions either terrestrial or satellite and finally they evaluated their conclusions.
Amongst the conclusions reached were the following:

a. NATO has a continuing requirement for a Military Satellite Communications.

b. The required assurance levels, when balanced against the threat, justify a military satellite.

c. The traditional Euro-Centric Coverage, provided by NATO IV, is inadequate to meet NATO's future needs.

d. From the financial analysis military SATCOM is cost effective for some fixed communications and all mobile communications.

The major conclusion reached was that NATO has a continuing requirement for a military satellite capability as the required service assurance levels when balanced against the forecast threat were considered to justify the military features. The coverage needs to be improved to take account of the changed political situation and from a financial viewpoint the equation in the case of fixed services is finely balanced.

The detailed report is in the policy areas of all the nations and goes into far more detail than I can cover today. I would like to highlight one particular aspect, no matter how it is finally provided SATCOM has proved itself to be a force multiplier. Amongst the other conclusions were that:

a. Overall a mix of commercial SATCOM and a shared military constellation provides the least cost solution.

b. Current national space segments will require replacement in the 2003-2008 timeframe.

c. NATO's long term requirements are closely aligned with those of the International Military Consortia.

d. NATO is faced with a capability shortfall in the period 2001 through 2005.

In summary, a mixed system would provide the least cost option, NATO's future is probably allied to one of the consortia and finally an interim capability to meet the shortfall in the period 2001 to 2005 will be needed.

The working party's report made the following recommendations to its Policy Committee the NACISC that it:

a. Agrees that SATCOM is essential in extending communications to deployed and mobile forces.

b. Agrees that, whilst commercial SATCOM has a role, it does not provide the necessary EPM and EMPP.

c. Invites the MNCs to produce their Post 2000 IERs (this task is now completed).

d. Notes that NATO will continue to require a military SATCOM Capability Post 2000.

e. Notes that, from a planning perspective, the NATO IV constellation requires replacement in 2001.

Thus, the key issues are that:

a. essential in extending the GPS to deployed and mobile forces of the Alliance and in the provision of SPS;

b. although commercial SATCOM can meet some of NATO's information exchange requirements, it cannot provide the necessary ECM and EMP countermeasures;

However the report highlighted the fact that the international military consortia were unlikely to provide a facility before 2004 at the earliest and NATO needed to plan what it should do in the meantime to fill the gap in the 2001 t0 2006 timeframe.

I have not strayed into the realms of what technology can do. E.g.. the use of SATCOM broadcast at 24MB/s or tactical switched ATM services but have concentrated on defining why SATCOM will continue to dominate military planning. We leave it to the scientific community to define the art of the possible whilst we live in the arena of the affordable.

CONCLUSION

There are serious shortcomings in our present system, not all of the capacity is in use. The ITU frequency allocations preclude NATO's use of much of the mobile band. The satellite Antenna beam patterns and channelisation still reflect our cold war needs. We have continuously failed to ensure all aspects of the system are procured simultaneously and we do not manage it as an integrated sub-system of our communications architecture. We are about to lose the capability at the turn of the century.

Post 2000 we will continue to focus on the SHF band for cost reasons and we will need to make much greater use of the mobile bands.

We will continue to place heavy reliance on military protection features; particularly the space segment will need to be hardened against limited threats e.g.. EMPP and we would seek diversified control under military management. We believe encrypted TT & C to be essential. Above all else if we are to stay in business we must continue to reduce costs wherever possible.

Possibilities and Limitations of Spaceborne SAR with Respect to Military Reconnaissance

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Summary

SAR systems for military applications have to be considered with respect to the requirements resulting from specific scenarios which are estimated by the objects to be observed. The most important requirements for military reconnaissance satellites are the geometrical resolution, the dimension of the covered area as well as timelining and the coverage repetition. The latter is strictly dependent on the satellites orbit, which leads to power requirements.

Synthetic aperture radar systems have potential resolution capabilities nearly comparable with optical systems. The image resolution as well as its contrast is indepent on weather conditions and optical vision. Foliage penetration, principally, is possible and lower frequencies allow to some extent surface penetration also.

Main restrictions of SAR are related to data processing, data handling and power requirements. Automatic real time image analysis as well as image interpretation is not yet possible at all.

However, special modes like Scan-SAR, Interferometry, Look Steering and Spot Light, as well as multi mode and multi satellite concepts seem to be able to overcome many limitations and to increase the efficiency of SAR systems for military purposes drastically.

1. Introduction

Synthetic Aperture Radar (SAR) is excellently suited for spaceborne surveillance and reconnaissance systems. SAR, principally, combines the advantages of microwave systems like weather independence, day/night capability, penetration capability etc. with wavelength and distance independent high resolution capability. Principally, SAR can detect, identify and classify man made and natural point targets as well as area and volume targets. SAR also has 3 dimensional mapping capability and MTI possibility as well. The state of the art as well as the development of techniques and technologies needed and possible to apply with present and future requirements will be shown shortly in order to point out the principal limitations as well as the possibilities for military use.

2. SAR Basics and Specialities

SAR systems are mainly characterized by electrical parameters and observation geometry parameters as well. Very important electrical parameters for a radar are: frequency, antenna size with respective beamwidth and polarization and the transmitter power as well as the pulse repetition frequency. Main characteristics with respect to observation geometry are for spaceborne radars orbit altitude and inclination as well as swath width and geometrical ground resolution.

A synthetic aperture radar (SAR) is basically a real aperture radar with very high sophisticated data evaluation and image processing. Basic of SAR is the construction of a very long antenna along the flight path (here assumed as strongly linear) by means of data processing. Along the flight path are the measuring points for amplitude, phase and frequency of the backscattered signal. This is principally a normal array. However, in a conventional array all signals arrive at the same time and will be added at the receiver input simultaneously. The synthetic aperture may exist of one single element receiving the signals one after the other at the respective positions and store them correctly with respect to amplitude, phase and position. In such a way the real SAR antenna becomes the single element of a large (synthetic) array antenna. The stored echos can be added by a complicated data processing and in the image processor the SAR image can be produced.

The most important equations which combine different SAR parameters are given in Table 1 [1, 2]. Some specialities of SAR become evident. The azimuth resolution of a SAR is independent of wavelength and distance and a better resolution can be reached with smaller real antennas and not with larger antennas. This is opposite to real aperture radars and other optical systems. For SAR the theoretical limit of azimuth ground resolution is given by the half antenna length in flight direction. The range independency of the resolution is a reason for the possibility to extent principally SAR results gained with airborne systems on spaceborne systems also.

These equations also establish principal technological limits for the development and applications of spaceborne SAR.

Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.

1	Point Target S/N	$\frac{S}{N} = \frac{P_{ave} A^2 \sigma}{(4\pi)\lambda^2 R^3 (kT_o F) 2v\delta_{az}}$
2	PRF	$2v/D \leq (PRF) \leq c/2R_{max}$
3	Slant Res. (δ_{rg})	$\delta_{rg} = c/2B = c\tau_p/2$
4	Opt. Az. Res. (δ_{az})	$\delta_{az} = D/2$
5	Swath S	$S = c\, D/4v$
6	Synth. Ap. Length (L)	$L = \lambda\, R/D$
7	Az. Pixel Nr. (N_{az})	$N_{az} = R\lambda/2\ \delta_{az} = L/\delta_{az}$
8	Rg. Pixel (N_{rg})	$N_{rg} = S/\delta_{rg}$
9	Data Rate (DR)	$DR = N_{rg}\ PFR$
10	Pixel Rate (Q)	$Q = nvS/\delta_{az}\ \delta_{rg}$

A = Antenna Area, B = Bandwidth, c = Light Velocity, D = Antenna Length, kT_oF = Noise Characteristic, n = Number of Looks, P_{ave} = Mean Power, R_{max} = Maximum Distance SAR-Pixel, v = Platform Velocity, λ = Wavelength, σ = Radar Cross Section, τ_p = Pulse Length

Table 1 Important Relations for Strip Map SAR.

Radar measurements will be used for special target detection, classification and identification, surface roughness and structure estimation, and measurements of the dielectric properties like permittivity and conductivity; the echopower and ist fluctuations estimate the tone and the texture of an radar-image that means the image quality and the brightness. The measurements of the frequency spectrum and its variations enable the estimation of target velocities and also of wave directions of seawave spectra, and current velocities. Phase measurements allow mapping and change detection with extremely high accuracies as well.

3. Military User Requirements

The specification and development of SAR, principally, is based on the requirements deriving from the use and application of such a system. Mainly, military user require special parameters on specific objects to be observed, identified, and classified, like resolution, observation swath, type of targets as well as its special characteristics and behaviour (velocity, etc.), the grade of sensing (detection, recognition, identification, and description) as well as special accuracies, repetition rates, and timelining etc. These requirements lead to specifications for special electrical and geometrical SAR system parameters like frequencies, polarizations, orbits etc.

Military user, mainly, require

- high geometrical and radiometrical resolution,
- wide area coverage,
- extremely high observation repetition rates up to continuous observation,
- real time information capability,
- MTI capability.

Fig. 1, exemplarically, explaines these interconnections. However, in many cases the user requirements lead to specifications, which cannot be fullfilled with the state of the art of technology.

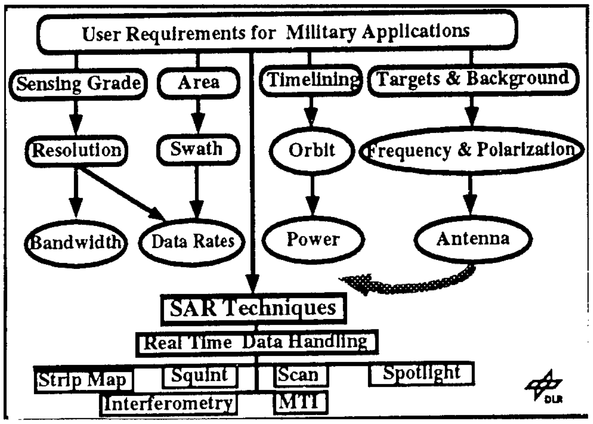

Fig. 1 Principal interconnections between user requirements and system specifications.

4. Limitations and Possibilities with Respect to Special Parameter

4.1 Resolution

Resolution in a wide sense is defined as the discrimination capability of a sensor considering two targets with equal properties (geometric properties, colours, velocities, frequencies etc.). The term has an inprecise meaning and there are a multitude of different definitions; resolution depends on many facts and system elements [3]. For reconnaissance purposes mainly angular resolution is under discussion. Angular resolution of a remote sensing system, principally, is defined as the minimum angular separation between two items which can be distinguished by the system.

In Table 2 requirements for different sensing grades (detection, recognition, identification, description) of special objects are listed [4]. Resolution requirements, however, entail requirements for the bandwidth of a SAR system

Object	Detection		Recognition		Identification		Description	
	Res (m)	BW (MHz)	Res (m)	BW (MHz)	Res (m)	BW (MHz)	Res (m)	BW (MHz)
Bridges	6	25	4.5	33	1.5	100	0.90	170
Radar	3	50	0.9	170	0.3	500	0.15	1000
Radiocommunications	3	50	1.5	100	0.3	500	0.15	1000
Material Depots	1.5	100	0.6	250	0.3	500	0.25	600
Troop Units or Bivouacs	6	25	2.1	71	1.2	125	0.30	500
Air Base Equipment	6	25	4.5	33	3	50	0.30	500
Artillery and Rockets	0.9	170	0.6	250	0.15	1000	0.05	3000
Aircraft	4.5	33	1.50	100	0.9	170	0.15	1000
Headquarters	3	50	1.5	100	0.9	170	0.15	1000
Ground-to-Ground Missile + Anti Aircraft sites	3	50	1.5	100	0.6	250	0.30	500
Medium Surface Vessels	7.5	20	4.5	33	0.6	250	0.30	500
Vehicles	1.5	100	0.6	250	0.3	500	0.05	3000
Land Mine Fields	9	17	6	25	0.9	170	0.025	6000
Ports	30	5	15	10	6	25	3	50
Coasts + Land beaches	30	5	4.5	33	3	50	1.5	100
Marshalling Yards and Railways Shops	30	5	15	10	6	25	1.5	100
Roads	9	17	6	25	1.8	83	0.6	250
Urban Areas	60	25	30	5	3	50	3	50
Military Airfields	-	-	1.7	90	4.5	33	1.5	100
Submarines on Surface	30	5	6	25	1.5	100	0.9	170

Table 2 Resolutions (Res) required for different sensing grades for special objects [4] togehter with the resulting bandwidths (BW) using the simple pulse length-bandwidth relation (3) in Table 1.

and the bandwidth is a technological key parameter for SAR realization. For detection, recognition, and identification of land mine fields, for example, resolutions between 9 m and 0.9 m are required, corresponding to bandwidths between 17 MHz and 170 MHz respectively which are realizable. For description, however, a resolution of 2.5 cm is required which entails a requirement for 6000 MHz bandwidth, a rather extreme enterprize especially for spaceborne SAR which is presently not realizable. Especially, for imaging systems like SAR the angular resolution is strictly connected to the radiometric resolution. The radiometric resolution is the minimum colour contrast necessary for the discrimination of 2 targets. The radiometric resolution in SAR images is dependent on the image statistic, the speckle. Therefore, by increasing the integration time (i.e. the observation time of a certain area represented through the number of looks on it) the specklewill decrease, the radiometric resolution increases (the image becomes sharper) but the angular resolution decreases.

In Fig. 2, 3 and 4 this tradeoff between geometric and radiometric resolution as well as the influence of the speckle is shown exemplarically [5]. These images from the DLR-Dornier airport at Oberpfaffenhofen have been taken by the airborne SAR of the DLR at 5 cm wavelength. Fig. 3 shows an 8 look image with low speckle and high contrasts; with its many details it is comparable to a photography. Fig. 4 shows enlarged a part of Fig. 3. This one look image has an azimuth resolution of 0,5 m and a range resolution of 2 m. (The resolution in range here can principally not be improved due to the limited bandwidth of the system). The increase of the speckle against the 8 look image in Fig. 3 is evident. The high resolution becomes clear by looking at the large black platform in the upper left corner. There an aircraft clearly can be seen. This aircraft together with ist background shows enlarged the Fig. 5 with the same resolution. The differences in range and azimuth can be seen evidently. This very image has been used for the estimation of the dimension of the aircraft. A comparison with the dimensions of a DO 228 aircraft leads to the conclusion, that the image shows with a high degree of probability a DO 228. The estimated dimensions (with the real values of a DO 228 in paranthesis) are: Total length 14,3 m (15,04 m), total wingspread 16,3 m (16,97 m), wingspread of the elevator unit 7,7 m (6,45 m). This is an excellent example for the applicability of SAR for reconnaissance purposes.

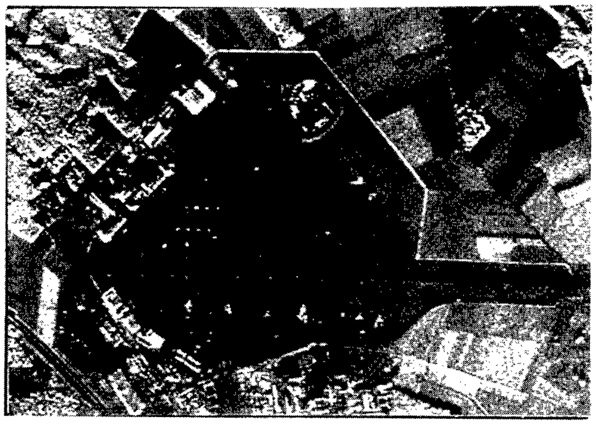

Fig. 2 SAR image of DLR-Research Center and airfield in Oberpfaffenhofen taken at 5 cm wavelengths from an aircraft at 914 m altitude. Scene dimension 1903 m x 2700 m [5].

4.2 Choice of Frequency and Polarization

The choice of frequency for systems depends on many factors. Atmosphere and ionosphere produce attenuation and frequency dependent distortions and errors as well. These effects set an upper limit due to attenuation for spaceborne radar at about 15 GHz and a lower limit for spaceborne SAR due to ionospheric granularity at about 1 GHz. Interferences with Earth bound communication links and surveillance radars set also a lower bound to about 1 GHz. Signal to noise ratio as well as ambiguity considerations seem to prefer the X-band for military purposes. The available frequency bands are also limited due to international contracts. The reflection behaviour of radar targets is strongly frequency dependent also, and, therefore, multifrequency systems are required in order to increase the information content of the respective observations.

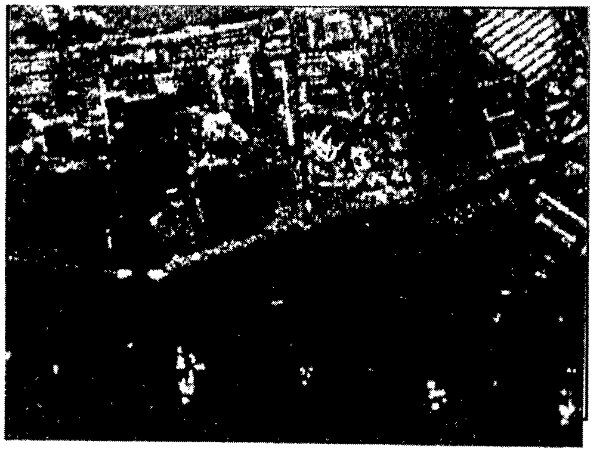

Fig. 3 Section of the image in Fig. 2 Scene dimension is 599 m x 828 m, ground resolution 0,5 m x 2 m (azimuth x range), 1 look. The aircraft on the large platform in the upper left corner is shown enlarged in Fig. 4 (Moreira, DLR).

Fig. 4 Enlargement of the aircraft on the dark platform in the upper left corner of Fig. 3. Scene dimension 34.5 m x 33 m, ground resolution 0.5 m x 2 m (azimuth x range). The lack of symmetry in the resolution pixels caused by the unsymmetrical ground resolution can be seen clearly. The different reflection typical for radar imaging as well as the speckle can be seen clearly.

The polarization behaviour of radar targets is mainly estimated through its dielectricity constant and its shape as well. In principle a complete description of a radar target

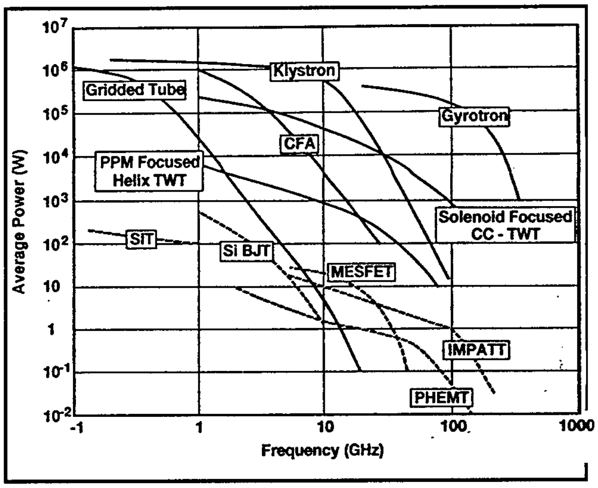

Fig. 5 Peak transmit power for RF sources vs frequency, circa 1993 [6], ___ vakuum devices, --- solid state devices.

can be given only if all copolar and crosspolar amplitudes and the respective phases of the radar signal are known. Such a "complete radar" gives all information on a target possible within the relative small bandwidth of the radar carrier frequency, it should be equipped with more than 1 channel in order to register the likepolar amplitudes the crosspolar amplitudes as well as the respective phases. This implies not only a tremendous expense but also large technical difficulties which arise at any time if exact phase measurements shall be conducted within extremely short time and with high accuracy. The data rates increase temendously.

4.3 Power Considerations

The transmitter power is a key element for radar design also. The mean transmitter power estimates and limits to some extent the distance from which a radar observation to a certain target can be successfully made and, therefore, the orbit altitude of a reconnaissance system is power limited. Principally, the power required increases with the 3rd power of the radar distance (Table 1). Otherwise, a large antenna beams more power to a required area (expressed through the so called antenna gain) than a small one, and, therefore, a large antenna seems to be favourable. But the ground resolution of a SAR is as better as smaller the real antenna is. These considerations lead to a tradeoff, which must be made carefully in order to fullfill a users requirements. In any case the transmitter power is a limiting element for the design of a SAR as well as the antenna. Todays state of the art are a few hundrets watt mean power (Fig. 5) and a few kilowatt's peak power. This entails requirements for the total power supply of a satellite. State of the art is here an amount of 6 kW to 10 kW as a maximum. These requirements can be fullfilled with solar power generators and atomic generators as well.

4.4 Antenna Limitations

The antenna is a key element also which estimates the capability of SAR-systems. In nearly all basic SAR equations the antenna dimensions occur. The antenna defines and influences respectively

- the receivers S/N by its area (gain),
- the along track resolution by its length,
- the swath width by its length,
- the across track resolution by its bandwidth,
- the ambiguity suppression by its sidelobes,
- the required onboard power,
- the polarimetric performance by its polarization,
- the data take opportunity in scan SAR and spotlight SAR by its beam steering,
- the surveillance capability by its length.

The antenna dimensions for spaceborne SAR have at present values of about 15 m x 1 m for microstrip array antennas (Radarsat). Mirror antennas for space applications can be larger.

The antenna also limits the SAR surveillance capacity fundamentally. Fundamental restrictions of the area coverage rate $\dot{A}$ can be deduced from equation (2) and (5) in Table 1. Therefrom results

$$\dot{A} = \frac{dA}{dt} = R_{max} \cdot v < c \cdot \frac{D}{4} .$$

For an antenna of 10 m length, used in SIR-C/X-SAR for instance results a maximum area covering rate of

$$\dot{A} < 750 \, km^2 \, s^{-1} .$$

A velocity of 7.5 km s^{-1} (corresponding to an altitude of about 300 km) leads to a maximum swath of about 100 km which can be observed with a 10 m antenna. This rough estimation is in good agreement with the facts in SIR-C/X-SAR experiments.

4.5 Mission Requirements

For military reconnaissance and target recognition, principally, a permanent coverage of certain scenes is required. This can be principally reached with a system contenting more than one satellite and with defined inclinations. Exemplarically, 20 satellites on 3 different orbit planes in an altitude of about 1800 km would allow a continous global coverage. However, this would lead to extremely high power requirements as well as to extreme cost. A daily repetition of the same swath will be reached at an altitude of 416 km and 97.6° inclination. SIR-C/X-SAR had repetition rates of 24 hrs at altitudes of 225 km and an inclination of 57°. However, for the observation of northern hemisphere regions an inclination of about 64° is necessary [7].

Military user also require a minimum time difference between data take and information delivery. This details the requirements for real time data handling as near real time processing and data evaluation as well.

4.6 Data Rates and Processing Requirements

SAR systems produce a tremendous amount of data. Requirements for high resolution and large swath widths make the data rates higher as far as the resolution becomes finer and the swath width becomes wider. All requirements for extensions of SAR to multifrequency, multipolarization ore multiincidence capability additionaly entail a multiplication of the data rates and this would exceed the present limitations of data handling. This seems to be a key problem in all SAR considerations. Therefore, different requirements have to be fullfilled in order to handle or reduce the data stream of future systems either by means of onboard processing or with development of new SAR Systems like stretch SAR etc. The capacity of data links must be increased. (First goal are 200 Mbit s^{-1}.) New data transmission systems with splitted data links to data relay satellites or ground stations respectively are under preparation. The carrier frequencies of these data links must be increased up to a maximum value in order to obtain large bandwidths.

Data storage capability has to be increased also. At present recorders with capabilities exceeding 100 Mbit s^{-1} are able for use in space. The present state is, however, to use more than one recorder, i.e. one recorder for each channel in multipolarization and multifrequency SAR.

State of the art for data handling (transmission and storage) are at the moment bitrates of about 100 Mbit s^{-1}, for 1998 the handling possibilities will increase to 200 Mbit s^{-1} up to 400 Mbit s^{-1} and for 2000 handling possibilities for bitrates of more than 500 Mbits s^{-1} are expected.

Real time SAR processing requirements lead to extreme requirements for the computer processor power (M flops) as well as to requirements for the respective computer memory (MB).

Conventionally the so-called data rate DR is adressed which is defined in (9) from Table 1. However, for the processor sizing the total computation load has to be considered, which takes into account the different operations to be done with each sample (range compression, corner turn, azimuth compression etc.). Therefore, the processor size required, principally, is proportional to the pixel rate Q (10 in Table 1) multiplied with the number k of operations per pixel. The latter is a so-called algorithm constant, a realistic value is about 500 operations per pixel per look [8, 9]. These considerations lead to the following expression for the processing rate PR:

$$PR = kn \frac{v \cdot S}{\delta_{az} \cdot \delta_{rg}} .$$

The Processor memory necessary, (MR), depends directly on the pixel number within the processing frame. The latter is proportional to the product of number of pixels in azimuth N_{az} times number of pixels in range N_{rg}. For MR holds [8]

$$MR \approx 10\ n^2 \cdot N_{az} \cdot N_{rg} =$$

$$= 10\ n^2 \frac{S}{\delta_{rg}} \times \frac{L}{\delta_{az}} = 40\ n^2 \frac{S \cdot R \cdot \lambda}{\delta_{rg}\ \delta_{az}^2} .$$

Remarkable is the inverse proportionality to the cube of resolution and the proportionality to both radar wavelength and image range.

For Radarsat, ERS-1 and SIR-C/X-SAR the resulting processor loads and processor memory requirements are given in Tab. 3.

An increase of resolution with respect to some requirements in Tab. 2 would entail a dramatic increase of processor and memory requirements. Computational requirements of this magnitude currently cannot be met neigther by a single processor nor by a processor network. Therefore, real time processing for these purposes at the moment is not possible in spaceborne SAR.The capability limits of microprocessor chips today available for real time processing are: Processing power ≈ 150 Mflops, Memory ≈ 4.000 MB [8].

5. Principal Penetration Capability of Microwaves

An advantage of microwaves over electromagnetic waves in optical regions is their penetration capability. Fig. 6 shows the variation of penetration with frequency of different surfaces [10]. A reasonable penetration depth into seawater cannot be reached with microwaves at all. However, in the frequency range between about 100 MHz and 200 MHz a reasonable penetration depth into dry and wet land seems to be possible (between 1 m for wet ground and several 10 m for very dry ground) whilst for fresh water ice penetration depths of 1 m and more depending on ice temperatures can be reached with frequencies up to 20 GHz. Penetrations of more than 4 km have been reached. Vegetation has a lower density than soil and that enables principally a better penetration into rough vegetation like foliage, bushes and crop than into solid landsurfaces.

6. Special SAR Modes and Techniques

A conventional SAR with a strictly sideward looking antenna and constant incidence angle over a long stripe, as it is described in capter 2 is called a SAR with strip map mode. However, the requirements for high resolution and

	X-SAR	SIR-C/L	SIR-C/C	ERS-1/2	RADAR-SAT
Looks (n)	4	4	4	4	1
Swath (S)/km	45	70	70	80	50
Range (R)/km	436	436	436	844	1227
Veloc. km/s	7.7	7.7	7.7	7.5	7.5
W.Length m	0.03	0.23	0.06	0.06	0.06
Res.Az m	30	30	30	20	9
Res.Rg. m	10	13	13	10	9
PR Gflops	**2.3**	**2.8**	**2.8**	**6.0**	**2.3**
MR GB	**3.0**	**3.2**	**0.8**	**2.5**	**1.5**

Table 3 Processor load (PR) an memory (MR) requirements resulting from specifications for SIR-C/X-SAR, ERS-1/2, Radarsat.

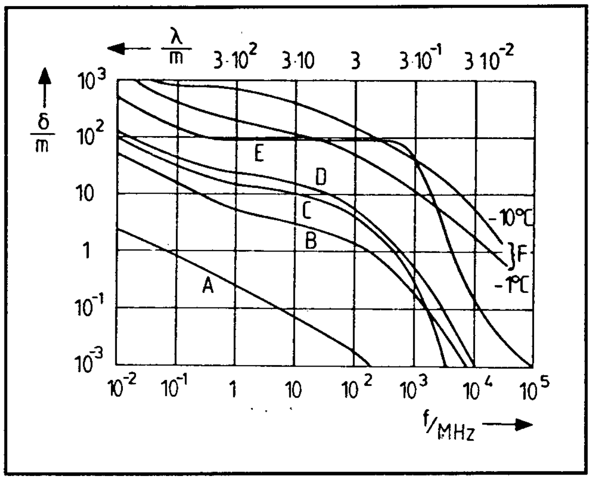

Fig. 6 Penetration depth δ as a function of frequency (lower scale) and wavelength λ (upper scale) for different surface qualities. A: sea water, B: wet ground, C: fresh water, D: medium dry ground, E: very dry ground, F: ice (fresh water) [10].

wide swath with large scenes as well are principally in conflict with the realiable data handling capabilities and due to power reasons with requirements for a large antenna which consequently follow. Therefore, new SAR techniques have to be introduced and developed which allow on the basis of phased array technology with electronically steered beams and distributed power a large scale and a small scale observation with small or large resolution respectively. For this purpose, mainly, the so-called Spot Light Mode and Scan Mode respectively are under consideration. The tradeoff between radiometric and geometric resolution is very often in conflict with military user requirements which need both high geometric as well as radiometric resolution. For this purpose the so-called Look Steering Mode is under consideration. In Fig. 7 the principals of these modes are scetched in comparison with each other.

For the required detection and tracking of moving targets special MTI-modes are under development. Especially for rapid and accurate collection of topographic data as well as for change detection and for the indication of targets which move directly in across track direction the Interferometry mode is applicable.

The combination of all modes allows variable resolution and swath widths as well; the tradeoff between resolution, swath width, power etc. leads to optimised configurations.

6.1 Spot Light Mode

Principally, the length of a synthetic antenna corresponds to the section of the flight path from which one target stays within the antenna beam and this fact leads to the requirement for wide beams and, therefore, small antennas for high resolution systems. The same effect, however, can be reached if a small antenna beam can be continuously pointed at the target. This allows also a longer synthetic array and, therefore, a finer azimuth resolution (Fig. 7b). However, the gain of azimuth resolution entails a loss off coverage due to the fact that during the continuous spotlight illumination of one part only the sensor passes other parts of the swath which will not be illuminated. Therefore, the spotlight mode can be used for the enlargement of a sector of the observed swath similar to the zooming with an optical camera.

The azimuth resolution for spotlight mode for small scan angles is approximately given by

$$\delta_{az} = \frac{\lambda}{2\phi_{scan}} .$$

ϕ_{scan} = scan or aspect angle respectively covered during illumination time. However, limitations are given here by the lack of coherence for wide angles and by the change of imaging geometry. This leads to special requirements for the PRF, for the antenna beam as well as for the steering capability of the antenna. Main disadvantage, however, is extremely small size of the area imaged, which, principally, is less than the real antenna footprint.

6.2 ScanSAR Mode

The ScanSAR Mode (Fig. 7c) can be used for an extension of the swath in radial direction using more than one

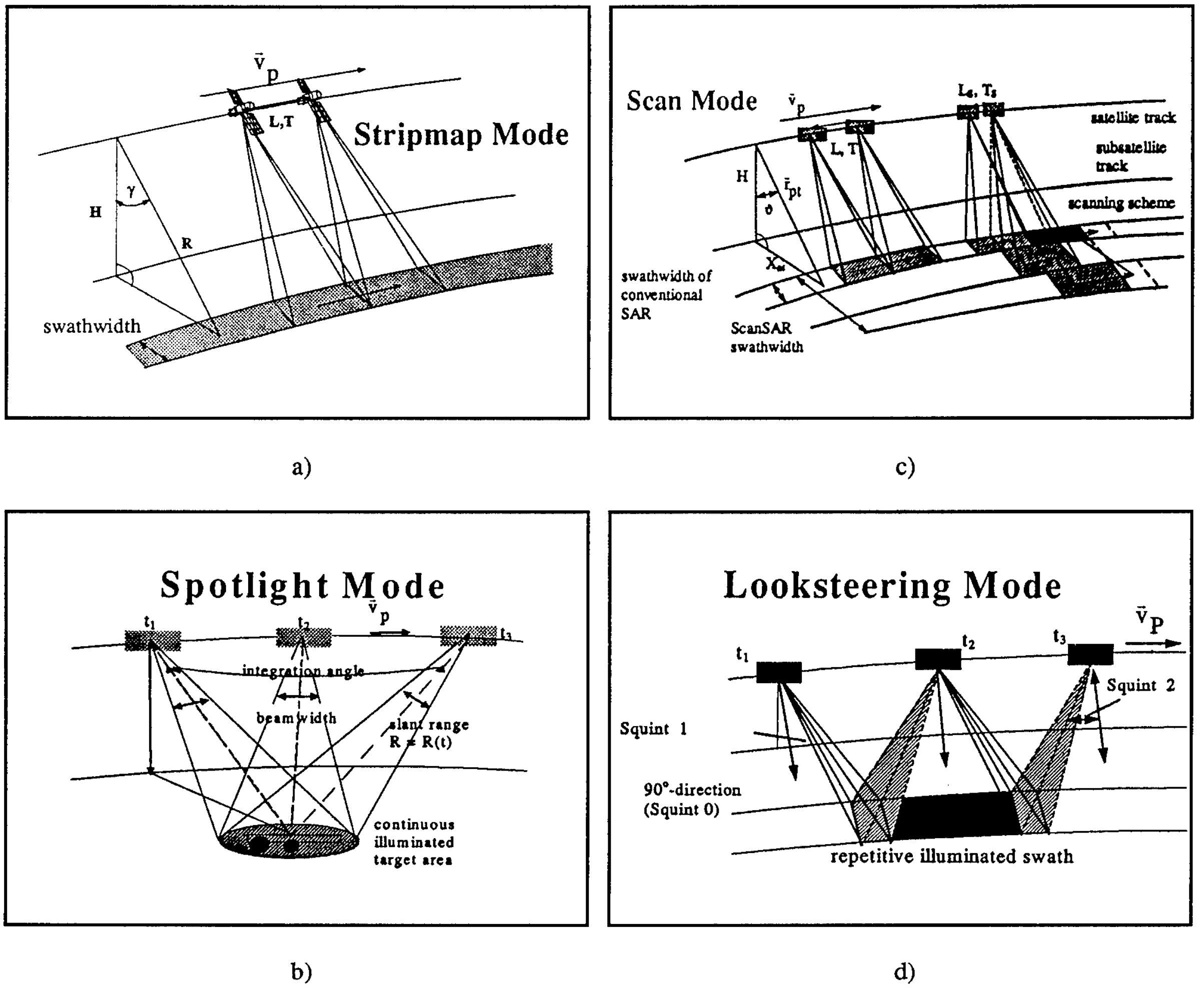

Fig. 7 Schematic and principal representations of different SAR-Modes.

beam generated in a time shared manner. This method increases the swath and reduces the geometric azimuth resolution. RADARSAT and SIR-C have ScanSAR modes.

While the sensor is moving the antenna beam is steered in discrete angular steps in a cross flight direction (elevation). After a certain illumination time the antenna is pointed at the next subswath and so on and after a certain number of scanning steps the beam is steered back to the starting subswath and the scanning cycle starts again. The advantages of the ScanSAR mode against the strip map mode are: the mapping area is increased drastically whereas the mapping time is reduced and, therefore, the repetition time for certain areas of interest can be reduced also. Additionally, the signal to noise ratio remaines nearly constant over the whole swath (exept the 3 dB change caused by the antenna diagramme within a subswath).

However, the reduction of integration time per point reduces the geometric resolution (which also becomes range dependent). The SAR system becomes more complicated due to special requirements for PRF which changes over the subswath's and antenna fast beam scanning capability. Especially, the probability of azimuth ambiguities increases with increasing PRF and, therefore, special scanning schemes have to be developed.

6.3 Look Steering Mode

The Look Steering Mode (Fig. 7d) increases the radiometric resolution without decrease of the geometric resolution within certain parts of the strip map swath. Principally, this will be obtained by steering the beam forward and backward respectively against the flight direction (similar to look steering). This method allows to image the same scene in repetition. The results are statistically independent images of the same scene which can be overlayed. This increases the radiometric resolution without reduction of geometric resolution.

The main disadvantage of look steering images is the lack of strip parts. A continous imaging of the whole strip in flight direction as in strip map mode is not possible. This is similar to the spot light mode. As in the spot light mode for look steering requirements result for the steering capability of the antenna. A sufficient switch angle range (± 10° for example) must be realised. The switch velocity must be high enough (1° s^{-1} for example) and the beam characteristic must be sufficiently independent from the switch angle over the whole range considered. Mostly critical, however, seems to be the scanning mechanism in connection with the bandwidth required.

6.4 SAR Interferometry

SAR interferometry, mainly, is a technique for rapid and accurate collection of topographic data, which is essential for establishing digital elevation models. However, coherence measurements which are principally essential for interferometry allow change detection as well and herewith special man made target detection. Normally, interferometry works with two antennas separated in cross velocity direction. The distance between the two antennas is the so-called baseline. Key of interferometry is the coherence of the signals received at both antenna positions. This enables the measurement of the phase difference of the both signals. This phase difference, principally, gives the altitude differences occuring in one pixel and herefrom a DEM can be evaluated. For spaceborne SAR, however, two pass interferometry is state of the art, where the geometrical conditions with two separate measurements at different times from the same satellite will be fullfilled (ERS-1, RADARSAT, SIR-C/X-SAR). ESA, presently, uses two satellites (ERS-1 and ERS-2) in a tandem mission. State of the art is an altitude accuracy of about 10 m. With differential interferometry, which uses more than 2 measurements, accuracies in the range $\le$ 1 cm have been obtained. The following formulas describe the principally possible altitude measurement accuracy, δ_z, which is reachable theoretically with a baseline B from a satellite in a distance R and a given phase accuracy δ_φ for a vertical across track antenna positions.

Normal interferometry: $\delta_z \approx \frac{\lambda \cdot R}{2\pi B} \delta_\varphi$.

Differential interferometry: $\delta_z \approx \frac{\lambda}{4\pi} \delta_\varphi$.

The latter formula points out the tremendous accuracy which can be reached. Technically feasable is $\delta_\varphi \geq 5°$ which leads to a theoretical accuracy of 0.007 λ. This points out why accuracies of better than 1 cm have been reached against point targets.

6.5 MTI Possibilities of Spaceborne SAR

SAR, principally, has the ability for moving target indication which is for military user very often both a strategic and tactical requirement. The Doppler coding of the received signals, which is produced by the movement of the carrier platform, is decisive for processing of SAR raw data. On principle a SAR processor with an azimuth bandwidth centered at 0 Hz images all targets of which the Doppler frequency seems to be 0 when the illumination direction of the radar is orthogonal to the flight direction. This is why fixed targets can be focused and positioned precisely.

However, targets which have a different relative speed to the airplane than the fixed targets, might not be indicated or focused, respectively. Depending on a different Doppler frequency, they will be displaced to different positions in the image. The tangential displacement compared to the original, real position is a direct measure for the radial velocity.

The following methods represent the state of the art of MTI with SAR: A radar with very high pulse repetition frequency and a narrow azimuth antenna beam is used. Moving targets can be perceived and their radial velocity determined. For slow moving objects a long antenna is necessary. The method, mainly, allows an accurate measurement of radial moving targets [12]. In addition the use of a radar system with two or more antennae displaced in the along track direction is proposed in [13, 14]. These methods alow high accurate moving target localization, velocity determination and subclutter visibility. This is very similar to along track interferometry. The method is very precise but needs high efforts.

In [15], a multilook method is proposed in which the positions of moving targets are determined by observing several images taken in a time series (multilook). In [16], the use of a Wigner Ville Distribution for detecting and focusing moving objects is proposed. The computer effort in [15] and [16], however, is very high.

The method proposed in [17] uses the reflection displacement method for analysis of the spectrum to detect, localize and determine the tangential as well as the radial velocity of moving objects.

7. Conclusions

SAR is an indispensable tool for military purposes. Its advantages are mainly weather independence, subsurface penetration capability and day and night capability. The resolution requirements for many reconnaissance purposes generally can be fullfilled with the present state of the arts technology. The present main limitations due to technological restrictions with respect to data handling and power alignment will be repressed within the next decade to levels which will allow high resolution observations with multipolarization and multifrequency systems over a wide swath. However, at present the resolution obtainable with optical spaceborne systems is an order better than that obtained with SAR and this fact seems to remain, even if the SAR capability increased. Therefore, SAR will be one component only in military systems as a valuable and necessary tool beside optical instruments.

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NATO Naval Exercises As Observed From Civilian Radar Satellites

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SUMMARY

Near real–time use of the radar satellite ERS–1 has been demonstrated during several NATO naval exercises in Norwegian waters. In several cases low resolution SAR images have been satisfactory for detection of ships, while full resolution images have provided some additional information about the ships. Oceanographic features of interest for operation of acoustic sensors have also been observed. The steep incidence angle of ERS–1 is a very limiting factor for detection of smaller ships. The upcoming satellites RADARSAT and ENVISAT will improve on this.

1. INTRODUCTION

The radar satellite ERS–1 was launched by European Space Agency in July 1991, and is still active by the time of writing. It was followed by the Japanese radar satellite JERS–1 in February 1992, and ERS–2 in April 1995. In November 1995, the Canadian RADARSAT–1 was launched. All of these are civilian satellites equipped with synthetic aperture radar (SAR), which gives a certain detection capability over ocean, both versus hard targets (ships) and soft targets (currents, waves, oil slicks, wakes).

To test and demonstrate the ship detection capabilities of such satellites, Norwegian Defence Research Establishment (FFI) has made use of the ERS–1 satellite under five major NATO naval exercises:
- "North Star 1991"
- "TEAMWORK 1992"
- "Battle Griffin 1993"
- "Strong Resolve 1995"
- "Battle Griffin 1996"

During several of these exercises, ERS–1 SAR images were acquired, processed and analysed in near real time (< 2 hours), and information was sent to a maritime HQ in order to demonstrate the capabilities of satellite SAR. Some results from these demonstrations will be shown here. Also, we shall discuss the major limitations of existing and forthcoming civilian satellites, and stress where military systems should differ.

2. INFRASTRUCTURE

The ERS–1 satellite was launched in July 1991 equipped with a C–band (6 cm) vertically polarized synthetic aperture radar. The physical antenna size is 10m x 1m. ERS–1 SAR raw data for our ship detection tests were received at Tromsø Satellite Station (TSS), located at 69.5°N in Northern Norway, and processed with the CESAR SAR processor, a fast processor once developed at FFI and now manufactured by the Norwegian company Kongsberg Informasjonskontroll AS. TSS is capable of processing a 100km x 100km ERS–1 image in less than 8 minutes with CESAR. There are two types of fast delivery SAR images for ERS available from TSS: full resolution (30m) and low resolution (100m). For RADARSAT, the user can order any NxN average of the finest pixel size.

An experimental radar satellite data analysis centre was established at FFI outside Oslo (60°N), where SAR images were received digitally from TSS using ground data network (low res) or satellite link (full res). A software system, called DIMAS, for enhancing images, obtaining geoposition and studying backscatter signatures has been developed at FFI. Automatic detection methods have also been studied and demonstrated [4].

The same infrastructure used for ship detection has also been utilized during the Norwegian oil spill detection project [9],[11],[12],[17] and the NATO MILOC "Rocky Road" campaigns [14].

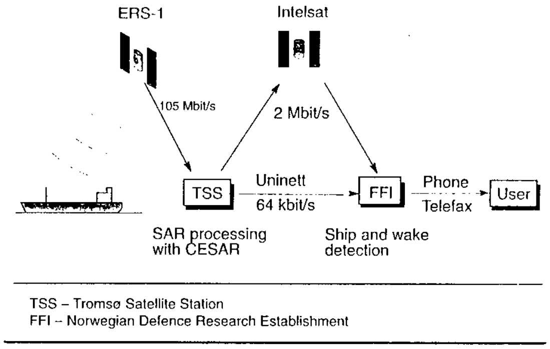

Figure 1. ERS–1 near real time demonstration chain.

3. SIGNATURES

The prime detection target is the ship itself. With 30 m resolution ERS–1 cannot give many details, but vessels longer than 100 m may show some characteristics related to the ship superstructure. An additional observation of the ship wake has high value, confirming the presence of a ship and giving information about the heading and (sometimes) the speed. SAR signatures of several identified NATO ships have been obtained and compared with ship images in JANE's [5].

Generally, the ship targets themselves were easier to detect than the wakes. For the naval exercises reported here, one needed not be

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concerned about icebergs, which further north can give ship–like signatures in radar satellite images [1].

It has been well documented in Norwegian waters that ERS–1 SAR images can reveal oceanographic information [3],[6],[7],[15],[18]. Therefore, signatures of current shears, eddies, and internal waves have also been registered during the exercises.

4. EXAMPLES

4.1 "North Star 1991"

This exercise took place shortly after the launch of ERS–1, and FFI was only able to do off–line analysis of the exercise. On 18 September several major naval vessels were imaged by ERS–1, both inside and outside Vestfjorden. In some cases there was a striking correspondence between the SAR signature of the vessel and its superstructure, in other cases the relation was not that obvious. The capability of ERS–1 for detecting ocean features of interest to naval applications was also well demonstrated. A clear current shear signature could be observed. It had been transected by one major ship 20 minutes before the image was taken, and another group of ships was just 15 minutes away from it. Figure 2 shows the current shear with a few vessels in its vicinity. Acoustic conditions in Vestfjorden are well known to be complex, and this is one of the reasons why the area was selected as the site of the 1993–1995 "Rocky Road" NATO MILOC campaign [13],[19].

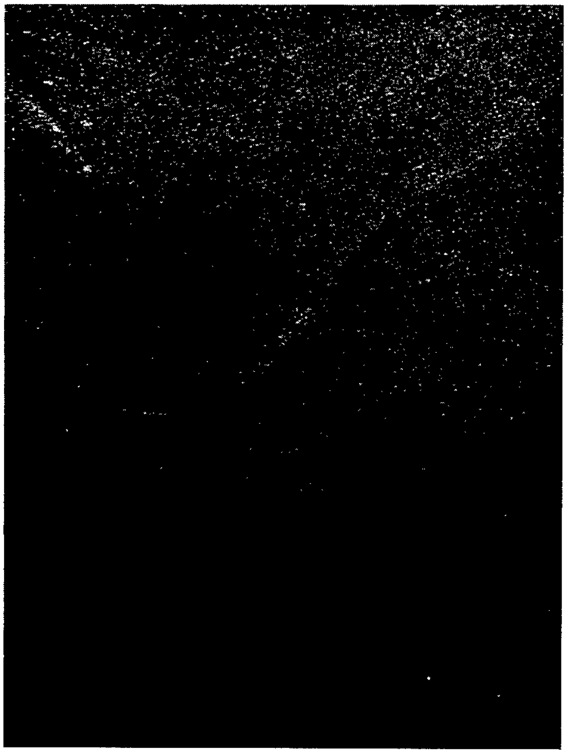

Figure 2. Current shear and naval vessels during "North Star". The current shear is 22 km long. (c) ESA/TSS.

4.2 "Teamwork 1992"

By March 1992 FFI was operating a 2 Mbit satellite link from TSS, which made it possible to receive even full resolution (20 m pixel size) images in near real time. ERS–1 was moving in a 3 day orbit at that time, and a total of 8 passes from the exercise area in Northern Norway were analyzed at FFI. Figure 3 shows the original (handwritten) message faxed from FFI to the HQ on 19 March, when a convoy moving north was detected. The two transport ships (Merchant Preposition Ships) showed a very typical SAR signature. Escorting frigates were just barely visible in the quite rough conditions. Ocean structures associated with the continental shelf break west of Lofoten were also visible in the SAR image. Figure 4 shows a SAR signature of one of the transport ships.

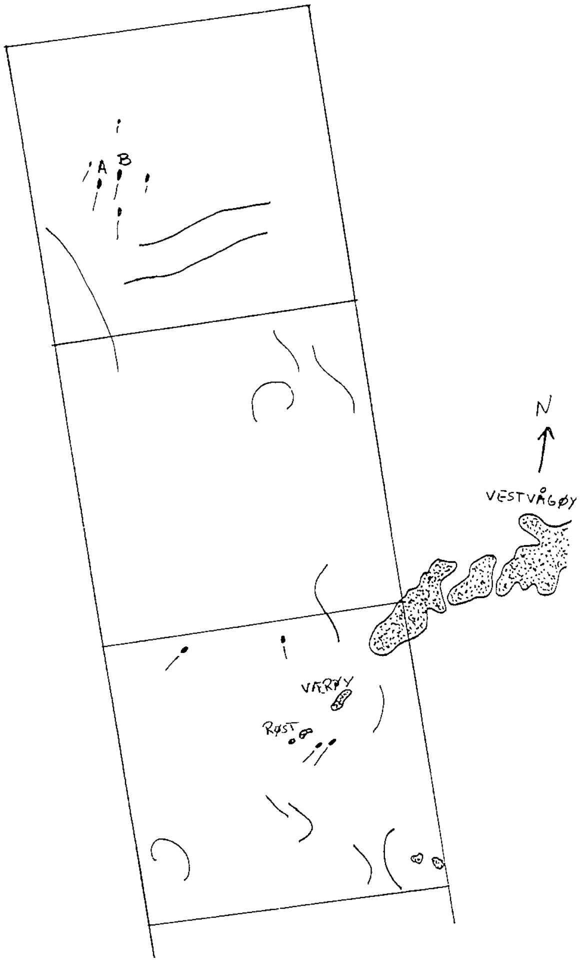

Figure 3. Original fax message showing analysis of ERS–1 pass during "Teamwork '92".

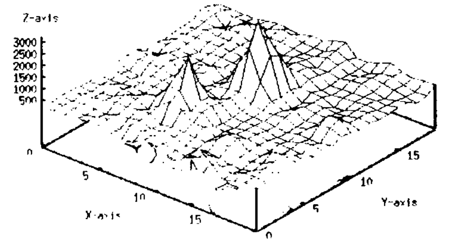

Figure 4. SAR signature of transport ship during "Teamwork '92", with radar backscatter values displayed on the z axis. Notice the two distinct peaks. Transport ships usually give such strong backscatter from bow and stern.

4.3 "Battle Griffin 1993"

An ERS–1 pass over Vestfjorden in March 1993 during the NATO exercise "Battle Griffin" showed that frigates and destroyers could be easily detected against the sea clutter even in low resolution (100 m) images during light wind conditions.

4.4 "Strong Resolve 1995"

During exercise "Strong Resolve" FFI failed to get good images of the participating vessels outside of Norwegian waters, but on 5 March 1995 ERS–1 showed NATO ships conducting landing operations in Norwegian fjords, see Figure 5. Figure 6 shows the signature of a typical military vessel participating in the exercise.

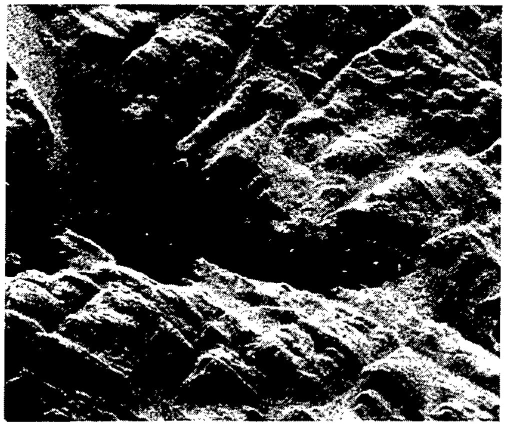

Figure 5. ERS–1 SAR image from a Norwegian fjord showing NATO vessels during the exercise "Strong Resolve", 5 March 1995. (c) ESA/TSS.

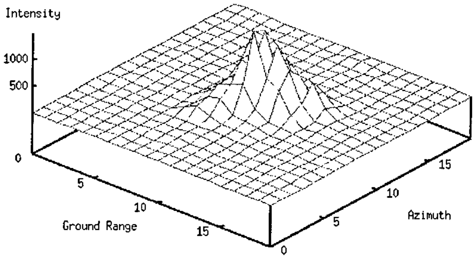

Figure 6. Typical SAR signature for a military vessel. The central part of the ship gives the strongest radar backscatter.

4.5 "Battle Griffin 1996"

Also the 1996 NATO exercise "Battle Griffin 1996" culminated in Northern Norway in the month of March. This was the first exercise with both ERS–1 and ERS–2 being utilized for demonstration purposes. For instance, NATO ships operating in the fjords of Troms were observed by ERS–1 on 10 March and by ERS–2 the day after. RADARSAT was flying at this time, but TSS was not ready for processing RADARSAT data yet. Once more, clear evidence of the large oceanographic variations in Vestfjorden was obtained, se Figure 7.

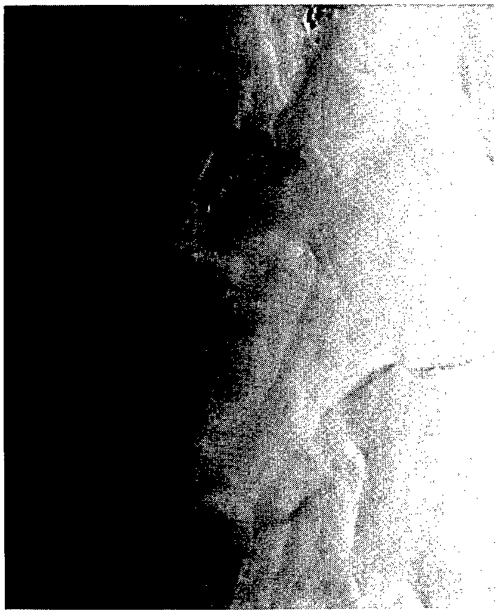

Figure 7. ERS–1 SAR image 3 March 1996, showing oceanographic structures, islands and ships in the Vestfjorden area during "Battle Griffin 1996". (c) ESA/TSS.

5. FUTURE CIVILIAN SATELLITES

The new generation of radar satellites is represented by:

- RADARSAT–1 (Nov 1995): C–band, horisontal polarization, steerable beam, scanSAR.
- ENVISAT (1999): C–band, several polarizations, steerable beam, scanSAR.

These satellites offer some increased capabilities, notably wide–area coverage by use of scanSAR, and the ability to point at incidence angles more favourable for ship detection. However, it must be emphasized that also these satellites move in polar orbits, and can only provide sporadic coverage of a given area [10],[16].

NATO should be aware that near real time use of civilian SAR satellites together with modern anti–ship missiles form a considerable threat from an opponent if a NATO fleet is operating within the range of such weapons [2]. Equipment for real time processing of SAR images will soon be commercially available. For instance, Kongsberg Informasjonskontroll AS has recently demonstrated ERS–1 full resolution processing in 1 min 45 sec with the new CESAR–5 processor.

6. TECHNICAL DEFICIENCIES OF CIVILIAN SATELLITES

The radar backscatter from the ocean surface depends strongly on parameters such as incidence angle, radar wavelength, and polarization. Generally, for civilian radar satellites, incidence angles have been chosen more for the purpose of environmental ocean studies than for hard target detection. This limits the detection capability against small targets. The 23° incidence angle of ERS–1 and ERS–2 makes these satellites capable of detecting large vessels only.

Although clearly technically inferior, the JERS–1 SAR (35°) has shown a much better detection capability versus ships. RADARSAT's "Fine Resolution" (10m x 10m) radar beams at approximately 40° incidence angle will have a detection capability of clear military relevance.

Civilian radar satellites will be vulnerable to jamming in the foreseeable future [8].

7. MILITARY SATELLITES?

The need for a detection and quantification capability against both hard targets (ships) and soft targets (wake, oil spill, currents) is putting strong demands on the SAR system. Because of the rapid incidence angle–related fall–off in radar backscatter from the ocean, a very wide dynamic range must be accomodated. Many civilian satellites are excellent for environmental use. It would simplify the design of military satellites if these could focus on hard target detection only. However, if both ship superstructure and ship wake information from the same satellite are considered essential, the SAR instrument clearly must be complex. A minimum configuration could be one cross–polarization channel for hard target detection and one equal polarization channel for the description of ocean features.

8. CONCLUSIONS

At high latitude civilian radar satellites can give some coverage of major naval exercises. During all of the NATO exercises "North Star 1991", Teamwork 1992", "Battle Griffin 1993", "Strong Resolve 1995" and "Battle Griffin 1996" ESA's ERS–1 satellite happened to detect the major participating naval vessels at least once during each exercise.

The typical civilian radar satellite spatial resolution of 30 m severely limits the possibility of classification of vessels, but it has been shown that large transport ships give quite different SAR signatures than dedicated military vessels. In many cases, a reasonable estimate of ship length can be made from ERS–1 SAR images.

Ship wakes have been frequently seen in ERS–1 images, revealing information about direction of motion. During several of the exercises, ocean features of possible relevance for sonar operations were observed in the same SAR image that showed the surface vessels. No oil spill has been detected from the vessels participating in the five NATO exercises reported here.

The hard target detection capability of the ERS satellites is strongly limited by the steep incidence angle of the SAR system. RADARSAT and ENVISAT wil provide more flexible instruments with modes better suited for ship detection.

Military satellite SAR systems should ideally have at least two polarizations, as a cross polarized channel is believed to be optimal for detection of vessels, while equal polarization will provide most information about the ship wake and oceanographic features of military interest.

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Radar Backscatter Statistics from the Sea Surface: Implications of SIR-C/X-SAR Observations for Maritime Surveillance

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SUMMARY

Multi-channel synthetic-aperture radar (SAR) observations from the SIR-C/X-SAR experiment in the N. E. Atlantic (April 1994) are analysed, to test models of both the mean and the distribution of radar backscatter from the sea surface. The data cover incidence angles from about 20° to 40°, and wind speeds from about 5 to 10 m s^{-1}. Empirical and theoretical models of the mean fit the data well at C band, to an accuracy of 1 - 2 dB. Discrepancies at L and X bands point to needs for better empirical models at these frequencies, and for modifications to existing descriptions of short-wave spectra in theoretical models. Single-look SIR-C/X-SAR data (spatial resolution ~ 7 - 10 m) fit well to a K distribution, but multi-look data (spatial resolution ~ 25 m) fit a lognormal distribution. The observed second moments can be explained by the modulations of resolved ocean-surface waves, but only if relatively large hydrodynamical modulations are assumed. Swell-wave modulations are sometimes significantly larger at X band than at C and L bands. The implications of these results for the false-alarm rates in marine-target detection are discussed.

1. INTRODUCTION

With the development of wide-swath techniques for the Canadian RADARSAT satellite and the European Space Agency's planned Envisat satellite, the potential of spaceborne synthetic-aperture radar (SAR) for routine maritime surveillance is of increasing interest. The ability to detect targets is influenced not only by the mean but also by the distribution of backscattered returns from the sea surface. The distribution determines the frequency of occurrence of 'false-alarm' detections.

The behaviour at grazing incidence is relatively well established. There, departures from Rayleigh amplitude-statistics, in the form of spiky, high-amplitude returns, become more prominent as the spatial resolution becomes finer. Hence the optimum solution for maritime surveillance at grazing incidence is not necessarily to make the spatial resolution as fine as possible. There have been much fewer studies at the moderate incidence angles (typically 20° to 50°) relevant for spaceborne SAR. Some studies with ground-based radars (e.g. Thompson & Gotwols 1994 [1]; Gotwols & Thompson 1994 [2]) show that departures from Rayleigh amplitude-statistics also occur at moderate incidence angles, but with a different distribution to the grazing-incidence case. Hence the preferred radar parameters for maritime surveillance from spaceborne SAR are not yet clear. In order to address this subject, we analyse data from the Shuttle Imaging Radar, SIR-C/X-SAR, mission in April 1994. This mission obtained an extensive set of data over the N. E. Atlantic, where the ocean was imaged simultaneously at different radar frequencies and polarisations. Supporting in-situ measurements were also made to characterise the environmental conditions. In this paper we show how the analysis of this data-set can test and improve our understanding of the behaviour of both the mean backscatter and the backscatter distribution, and hence lead to an appropriate selection of image-threshold parameters for maritime surveillance using spaceborne SAR.

Section 2 describes the observed behaviour of the mean radar backscatter in the SIR-C/X-SAR data-set, and its interpretation in terms of models of the scattering from the sea surface. Section 3 then considers the observed characteristics and modelling of the distribution of radar backscatter. The implications for maritime target detection are then discussed in Section 4, and the conclusions of this paper are summarised in Section 5.

2. MEAN RADAR BACKSCATTER

The SIR-C/X-SAR data-set analysed here has the following key features:

(i) It covers an extensive range of SAR parameters, namely:
- simultaneous observations in L, C and X bands
- dual polarisation (HH and VV) at L and C bands, and VV polarisation at X band
- incidence angles covering the range from about 20° to 40°.

(HH signifies horizontal polarisation transmitted and received; similarly VV signifies vertical polarisation.) Spatial resolutions are about 25 m for the multi-look data, and about 7 - 10 m for the single-look data which are also available in some cases.

(ii) The SAR data have been calibrated as a result of efforts throughout the mission, thus allowing predictions of

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absolute backscatter cross-sections to be tested. The absolute calibration of SIR-C/X-SAR is often better than 1 - 2 dB, and the relative calibration between the simultaneous frequencies or polarisations can be better than a fraction of a dB (Freeman et al. 1995a [3] & b [4]; Zink 1995 [5]). However, calibration uncertainties which are greater than this occur towards the edges of some swaths.

(iii) In-situ measurements of wind and wave properties were made at the same times and positions as the SAR data-takes, thus allowing dependences of the observed backscatter on environmental conditions to be established. Wind speeds varied from about 5 to 10 m s^{-1} over the nine-day period when the SIR-C/X-SAR data were obtained.

2.1 Observed Behaviour

Figure 1 shows examples of the dependences of the mean backscatter cross-section, σ_0, on incidence angle which are found in the SIR-C/X-SAR data. The data from different days lie within a few dB of an overall trend, which is that σ_0 in VV polarisation falls by a factor of about 20 from 20° to 40° incidence. Some more significant departures are apparent at the edges of some swaths, where the variation in the antenna gain has not been removed completely. A steeper dependence on incidence angle is found in HH polarisation, and hence the ratio of σ_0 in VV to that in HH polarisation increases with increasing incidence angle (Figure 2). HH and VV complex amplitudes are highly correlated, with a typical correlation coefficient of about 0.9.

The data also show a dependence of σ_0 on radar frequency. Figure 3 shows that the mean cross-section at X band is about half that at C band, irrespective of the incidence angle. Similarly, the mean cross-section at L band is also about half that at C band, and hence the observations here imply that σ_0 reaches a maximum around C band.

The data do not show any strong dependences of mean cross-section on wind speed or direction, or on the sea state as characterised by the significant wave height obtained from the buoy measurements. There is a weak tendency for σ_0 to increase with increasing wind speed, but it is not statistically significant here.

2.2 Interpretation

The observed behaviour here may be compared against the predictions of empirical and theoretical models of the mean backscatter cross-section. The empirical ones are model functions which have been developed to retrieve wind speeds and directions from radar-scatterometer measurements. They therefore give expressions for σ_0 at a given frequency, polarisation and incidence angle as a function of the wind speed and direction only. Hence they neglect the influence of other potentially important factors such as the air-sea temperature difference, and the presence of swell waves and surface films. The empirical models tested here are the model functions CMOD-3 (Long 1995 [6]) and CMOD-4 (Stoffelen & Anderson 1993 [7]), developed for the ERS-1 wind scatterometer at C band, VV polarisation, and the multi-frequency model developed by Snoeij et al. (1992) [8], which is tested here in both VV and HH polarisations at L and C bands.

The theoretical models apply a rough-surface scattering theory to an assumed description of the surface wave-height spectrum. (Volume scattering is considered negligible because microwave radiation does not penetrate the sea surface to any significant degree. The scattering from foam and spray is expected to be negligible at the wind speeds studied here.) The scattering models tested here are the composite-surface or two-scale model (Valenzuela 1978 [9]) and the model developed by Holliday et al. (1986) [10]. The latter is based on the Kirchhoff approximation, and therefore does not predict any difference between the backscatter in HH and VV polarisations. Our interest in it here is in determining the range of conditions (in particular, the range of incidence angles) for which it gives reliable predictions of the mean backscatter cross-section of the sea surface. The models of the wave-height energy spectrum which we consider are those developed by Donelan & Pierson (DP, 1987) [11] and by Donelan, Banner & Jähne (DBJ) as given by Apel (1994) [12].

Figure 4 illustrates the results obtained at C band, VV polarisation. Note that we only show model predictions in Figures 4 and 5 for the highest wind speed encountered, 10 m s^{-1} upwind, which therefore gives the largest predicted cross-sections here. However, our conclusions are based on the comparison of each data-take with predictions using the wind speed and direction at the time of imaging. The model functions CMOD-4 and CMOD-3 (the latter is not shown) both agree with the observations to within a fraction of a dB. The theoretical cross-section is overestimated with the DP spectrum, but good fits are obtained with the DBJ spectrum, with both the composite-surface scattering model and that of Holliday et al. (1986) [10].

Figure 5 illustrates the results obtained at L band, HH polarisation. This time, the empirical model (Snoeij et al. 1992 [8]) predicts values which are too high relative to the data at the lower incidence angles. The theoretical cross-section is again overestimated with the DP spectrum. Here the DBJ spectrum does not fit well with the model of Holliday et al. (1986) [10], and it shows a systematic misfit with incidence angle with the composite-surface model. The theoretical models also show disagreements with the observations at X band, VV polarisation. There, the discrepancy between the observed and predicted cross-sections is correlated with wind speed.

These results have the following implications. Firstly, the predicted mean cross-section is obtainable to an accuracy, defined as the standard deviation in a single reading, in the range 1 to 2 dB. This is consistent with the uncertainty in the SIR-C/X-SAR calibration and the anticipated errors in the in-situ measurements of the environmental conditions. Empirical models only agree with the observations to this accuracy at C band. This points to a requirement to develop better empirical models at other radar frequencies, for the range of incidence angles and environmental conditions available for testing here. Secondly, the disagreements with the theoretical models at L and X bands indicate a need for more accurate descriptions of short-wave spectra. For example, the disagreement at X band implies that the wind-speed dependence in short-wave spectra is not as severe as in the DBJ model.

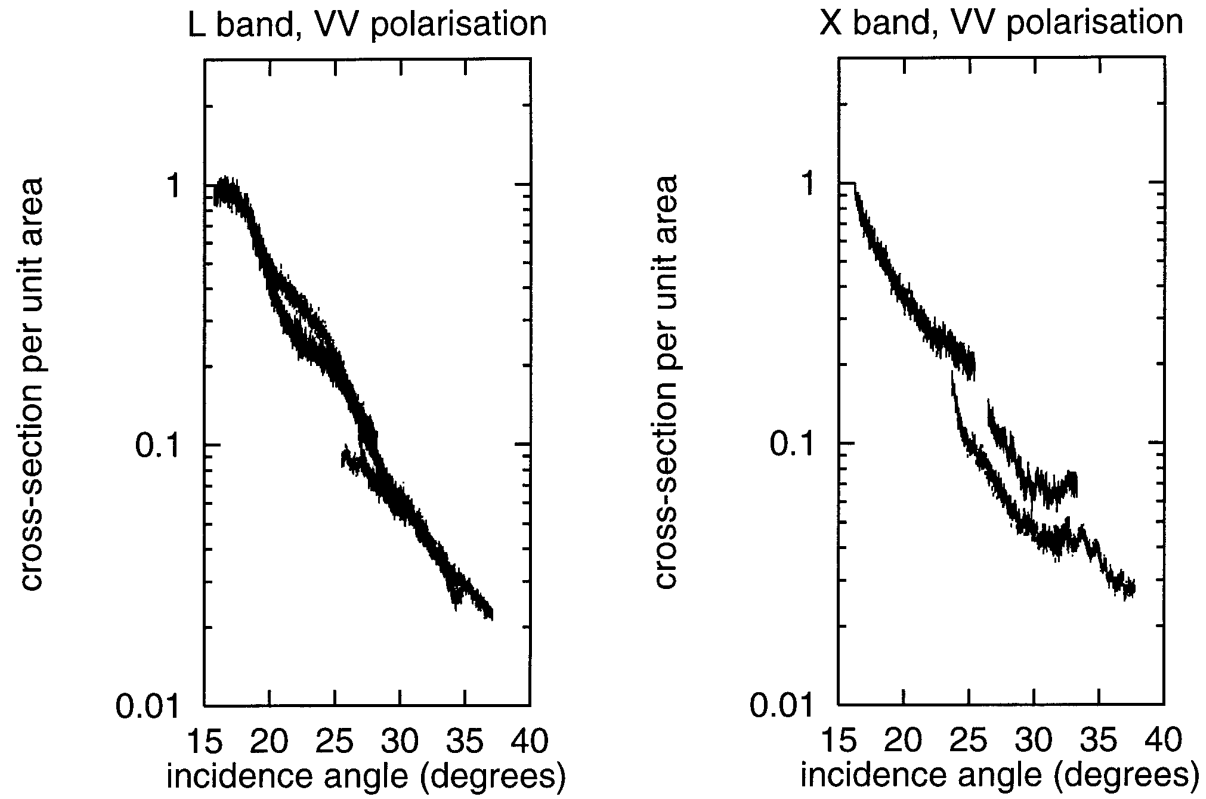

Figure 1. Mean cross-sections in SIR-C/X-SAR data plotted against incidence angle. Left: L band, VV polarisation. Right: X band, VV polarisation. (Note that the data plotted in Figures 1 - 5 are from the same data-takes.)

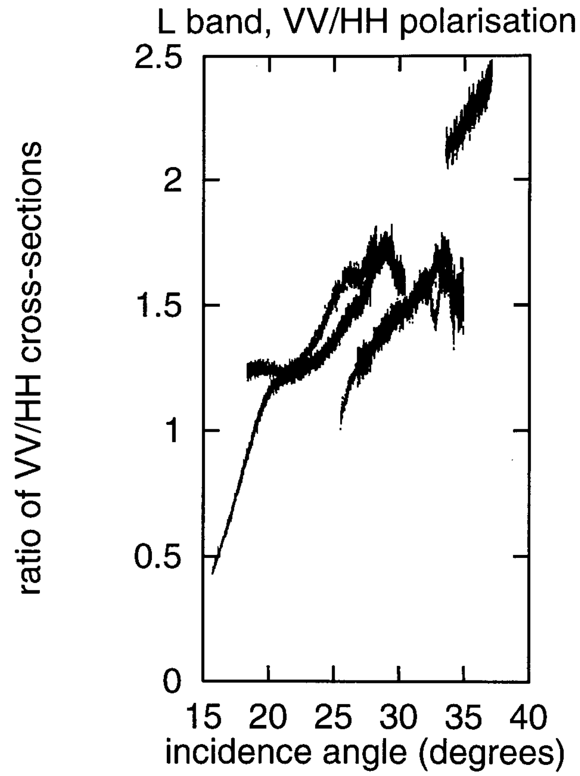

Figure 2. Ratio of cross-sections in VV to HH polarisation at L band for SIR-C/X-SAR, plotted against incidence angle.

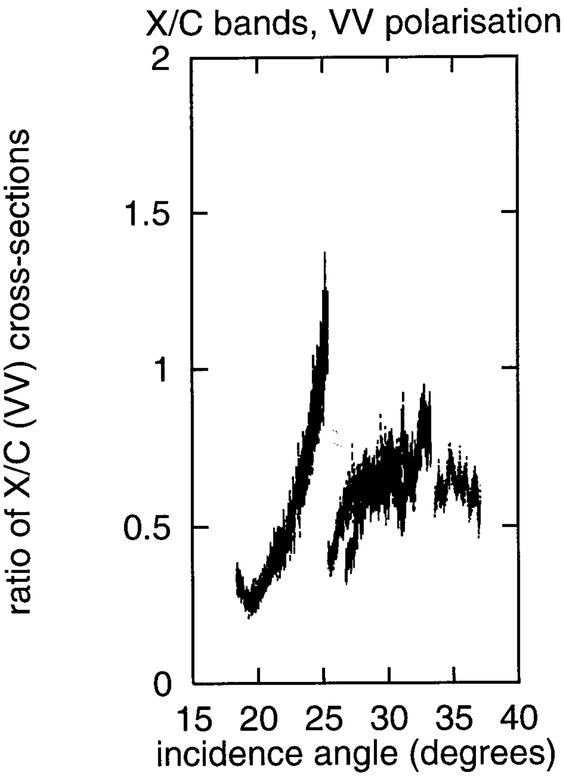

Figure 3. Ratio of cross-sections at X band to C band in VV polarisation for SIR-C/X-SAR, plotted against incidence angle.

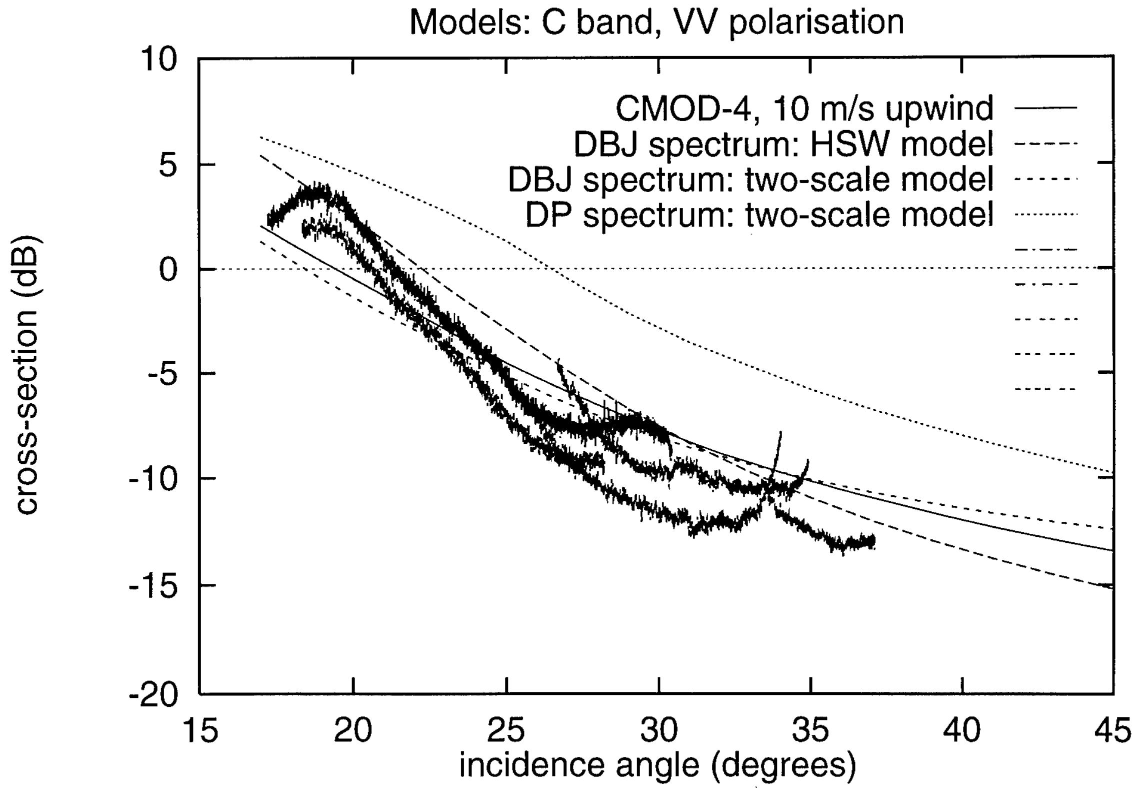

Figure 4. Comparison of empirical and theoretical models of the mean cross-section at C band, VV polarisation, with selected SIR-C/X-SAR data. The models are plotted for the case 10 m s^{-1} upwind.

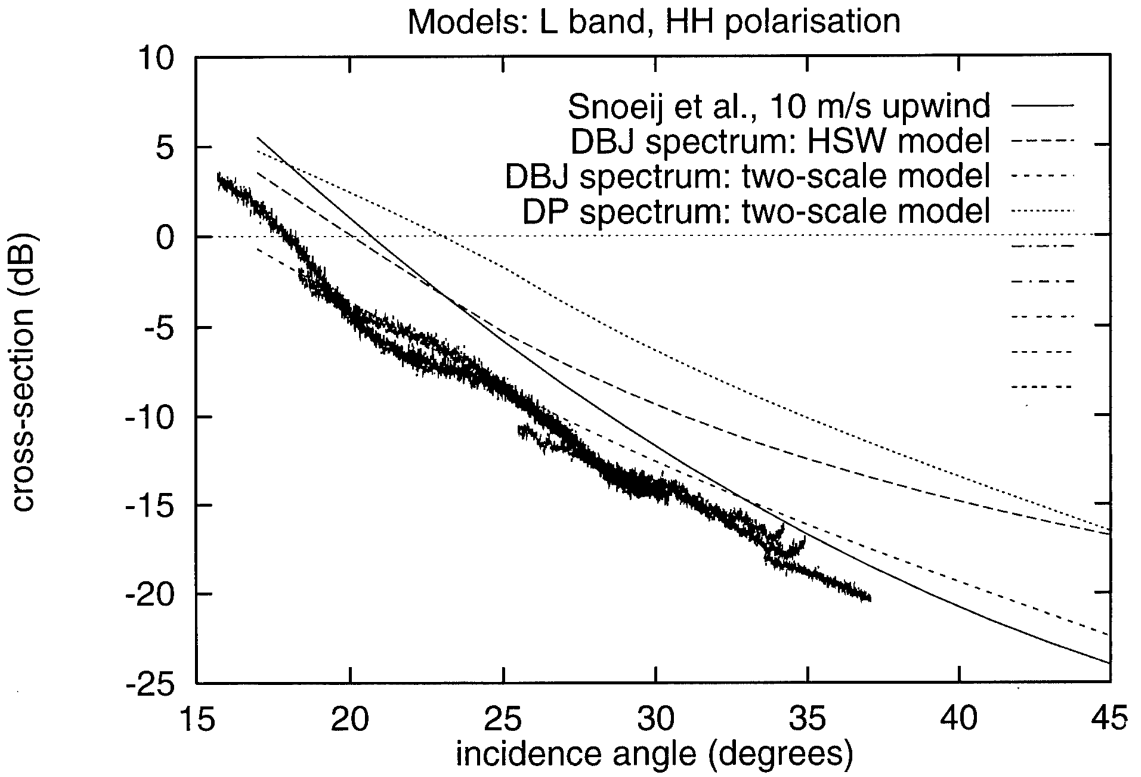

Figure 5. Comparison of empirical and theoretical models of the mean cross-section at L band, HH polarisation, with selected SIR-C/X-SAR data. The models are plotted for the case 10 m s^{-1} upwind.

3. BACKSCATTER DISTRIBUTION

3.1 Observed Behaviour

A key question is whether the distribution of backscattered intensities departs significantly from the gamma distribution (multi-look images) or the exponential distribution (single-look images) expected from the influence of speckle statistics alone. To answer this, we analyse the normalised moments of the image intensity I. The normalised moment of order n, f_n is defined as the ratio $\langle I^n\rangle/\langle I\rangle^n$, where the angular brackets denote averages over the area chosen (about 4 km in range by 6 km in azimuth here). Thus f_2 should take the value $1 + 1/L$, where L is the number of looks, if speckle noise is the only important factor influencing the observed distribution of image intensities.

We find that the observed values of f_2 are generally greater than $1 + 1/L$ in the SIR-C/X-SAR data. Greater values of f_2 are obtained in HH than in VV polarisation, and with increasing radar frequency at fixed polarisation. The single-look images show a greater percentage increase above $1 + 1/L$ than the multi-look images do; values of

$$Y = f_2\, L/(L+1) \qquad (1)$$

are typically around 1.2 for the single-look images and 1.1 for the multi-look images.

The distribution which fits the observations may be determined by plotting f_n as a function of n. Figures 6 and 7 compare the results for single-look and multi-look images of the same data-take at L band, HH polarisation. We always find that the single-look data fit closely to a K distribution, whereas the multi-look data fit closely to a lognormal distribution. At present it is not clear whether this difference in behaviour is caused by the difference in spatial resolution, or the difference in SAR processing.

In an attempt to address this issue, we analysed the moments of multi-look airborne-SAR images at C band, VV polarisation, taken over Loch Linnhe, Scotland, in 1989. These had a spatial resolution of about 10 m, similar to that of the single-look SIR-C/X-SAR data. The Loch Linnhe data fitted a K distribution, suggesting that the better fit of the lognormal distribution on the multi-look SIR-C/X-SAR data is the result of a dependence on spatial resolution. However, we cannot rule out the possibility that there is actually a more complex behaviour involving other factors such as sea state.

3.2 Interpretation

We interpret the observed values of the normalised second moment f_2 in terms of the influence of the modulations from ocean-surface waves. There are expected to be too many scatterers per resolution cell for waves on unresolved scales here to have a significant influence on the observed values of f_2. Hence we consider the influence of resolved waves. Our modelling applies wave-imaging theory to the buoy measurements of ocean-wave spectra, made at the times and locations of the SIR-C/X-SAR data takes, in order to predict values of f_2. This modelling incorporates:

(i) the finite spatial resolution of SIR-C/X-SAR, approximated as a gaussian point-spread function;

(ii) a linear wave-imaging transfer function, combining the effects of tilting, hydrodynamical modulations and the 'velocity bunching' imaging mechanism which describes linear aspects of the influence of wave motions on SAR images (Alpers et al. 1981 [13]); and,

(iii) the loss of azimuthal resolution ('azimuth smearing', Alpers et al. 1986 [14]), assumed to arise from the orbital motions of ocean waves on all scales.

The 'azimuth smearing' in (iii) is calculated from the available buoy data. Some uncertainty in this factor arises because the buoy data have to be extrapolated to determine the contribution from surface wavelengths shorter than about 20 m. However, the dominant source of uncertainty is that the hydrodynamical modulations in (ii) are poorly understood. Theoretical predictions based on wave-action balance give values of m_h, the dimensionless hydrodynamical transfer function, which are about 4.5 or less (Alpers & Hasselmann 1978 [15]). Experimental measurements of m_h, however, are up to 2 - 3 times greater than this (e.g. . Wright et al. 1980 [16]; Plant et al. 1983 [17]; Schröter et al. 1986 [18]). Also, m_h often has a non-zero phase, implying that the maximum short-wave modulations are displaced from the crests of the long waves. We therefore take the hydrodynamical contribution to (ii) to be an empirically adjustable factor.

Our results show that we can obtain agreement with the observed values of f_2 using this model. Some cases are consistent with $m_h = 4.5$ or lower; these tend to be cases with either no swell or swell propagating closer to the azimuth than the range direction. The majority of cases require higher values of m_h, in the range 6 - 24. The fitted values of m_h generally increase with increasing radar frequency. Their phases are often poorly determined; only in a few cases can we say whether they are positive or negative, and there is no systematic change in the phases with radar frequency. The fitted values of m_h here are sometimes greater than those inferred from tower-radar data. A possible reason for this is that we have assumed a dependence of m_h on wave direction which is too severe; we used a sine-squared dependence here.

Finally, while we can account for the observed values of f_2, we note that our modelling invariably leads to a K distribution, approximately, for the backscattered intensities. We do not yet have a model which can account for the lognormal distributions observed with multi-look data.

4. IMPLICATIONS FOR TARGET DETECTION

We now examine the implications of these results for marine-target detection on SAR images. We consider detection based on thresholding. Typically, a threshold-to-mean (T/m) ratio is chosen to give a false-alarm rate of 10^{-8} per pixel. A typical value $T/m \sim 15$ is required for C band, VV polarisation, with the lognormal distribution fitted to the multi-look data here. A K distribution with the same

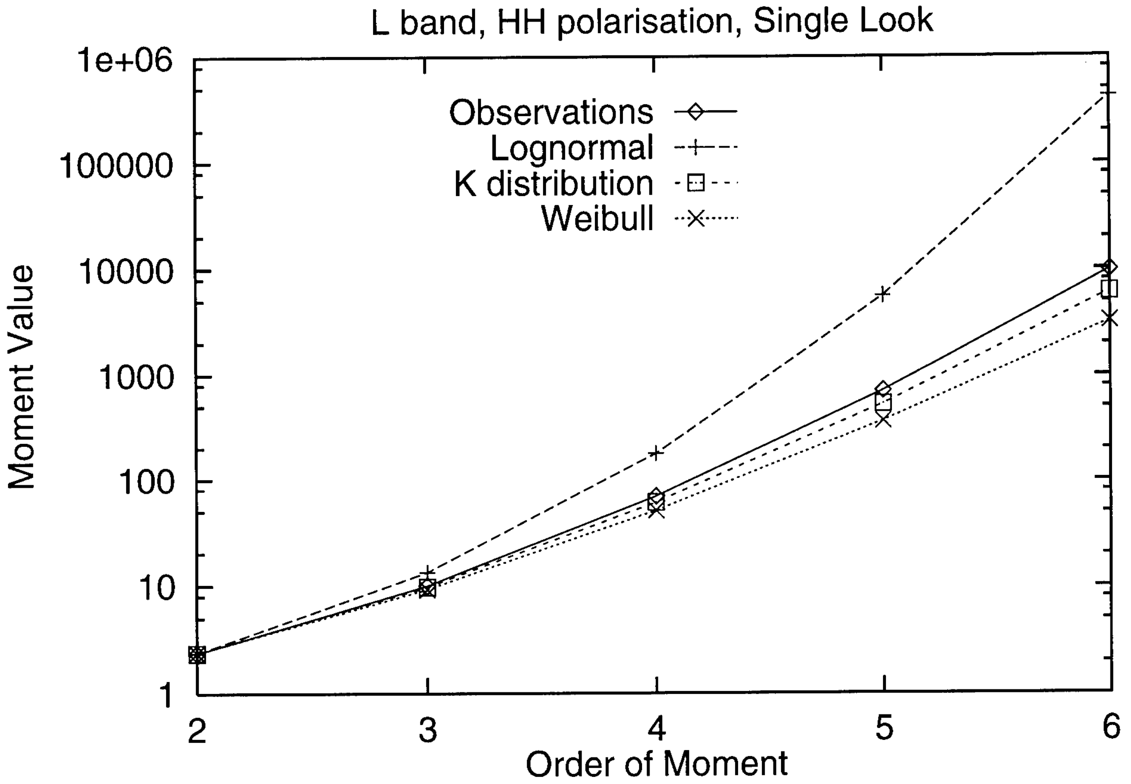

Figure 6. Comparison of the normalised moments of order $n = 2$ to 6 observed on a single-look SIR-C image with the predicted dependences of lognormal, K and Weibull distributions which match the observed $n = 2$ moment.

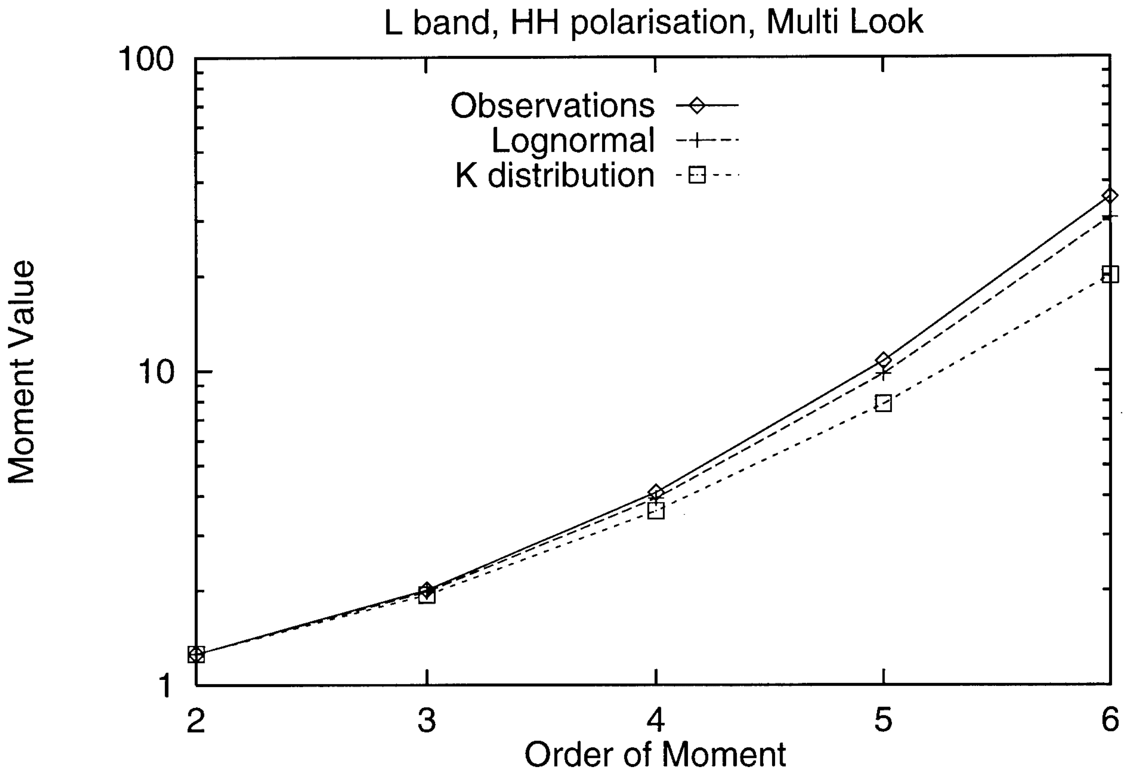

Figure 7. Comparison of the normalised moments of order $n = 2$ to 6 observed on a multi-look SIR-C image (the same case as in Figure 6) with the predicted dependences of lognormal and K distributions which match the observed $n = 2$ moment.

normalised second moment f_2 (that is, the same mean and variance) would require $T/m \sim 10$ for the same false-alarm rate. Using $T/m = 10$ on the lognormal distribution would increase the false-alarm rate by a factor of about 70. The difference between the lognormal and K distributions therefore has a significant impact on the false-alarm rates occurring in maritime surveillance using SAR images.

The value of T/m required for a given false-alarm rate generally increases with increasing radar frequency. Typically $T/m \sim 20$ for the multi-look data at X band, VV polarisation, for a false-alarm rate of 10^{-8} per pixel. The reason for this is the larger value of f_2, arising from larger image modulations from ocean waves. In some cases the modulations caused by the dominant swell waves are much greater at X band than at C and L bands. This can be seen from profiles of the image power spectra (Figure 8). Some (but not the majority) of this difference arises because the direction of the imaged swell-wave peak changes slightly with radar frequency, implying that the directional dependence of the wave-imaging transfer function changes with radar frequency. However, computer simulations are required to evaluate the likelihood of an individual wave crest being mistaken for a target.

Lower values of T/m can be used if different SAR frequencies or polarisations are combined. A particularly interesting case is the polarisation ratio VV/HH, because of the strong correlation between these channels noted in Section 2.1. However, speckle noise is very severe on ratio images, and so it is necessary to form multi-look images before taking their ratio. Here we find that $T/m \sim 3$ for a false-alarm rate of 10^{-8} per pixel on the ratio VV/HH of the multi-look images at C band. The usefulness of the ratio image for target detection depends on the difference between the values of VV/HH for the target and the ocean background.

5. CONCLUSIONS

Models of both the mean and the distribution of radar backscatter from the sea surface have been tested, using multi-channel SAR observations from the SIR-C/X-SAR experiment in the N. E. Atlantic in April 1994. Empirical and theoretical models of the mean fit the data well at C band, to an accuracy of 1 - 2 dB, over the range of incidence angles (about 20° to 40°) and wind speeds (about 5 to 10 m s^{-1}) available for testing. However, there is a need for better empirical models at L and X bands, and for modifications to the short-wave spectra assumed in theoretical models of the mean backscatter at these radar frequencies.

Single-look SIR-C/X-SAR data fit well to a K distribution, but multi-look data fit a lognormal distribution. It is not clear whether this behaviour is a consequence of the different spatial resolution or the different SAR processing. Analysis of ERS-1 SAR data would help to clarify this uncertainty.

The observed second moments can be explained through the modulations of resolved ocean waves, but only if relatively large hydrodynamical modulations are assumed. Swell-wave modulations are sometimes significantly larger at X band than at C and L bands. The lognormal distributions which fit the multi-look data require significantly greater thresholds for target detection than K distributions with the same mean and variance, for a given false-alarm rate. Thresholds or false-alarm rates may be reduced by combining simultaneously obtained radar frequencies or polarisations. The ratio of VV to HH polarisations at a given frequency is a potentially appropriate combination, because of the strong correlation in the ocean backscatter in these two radar channels.

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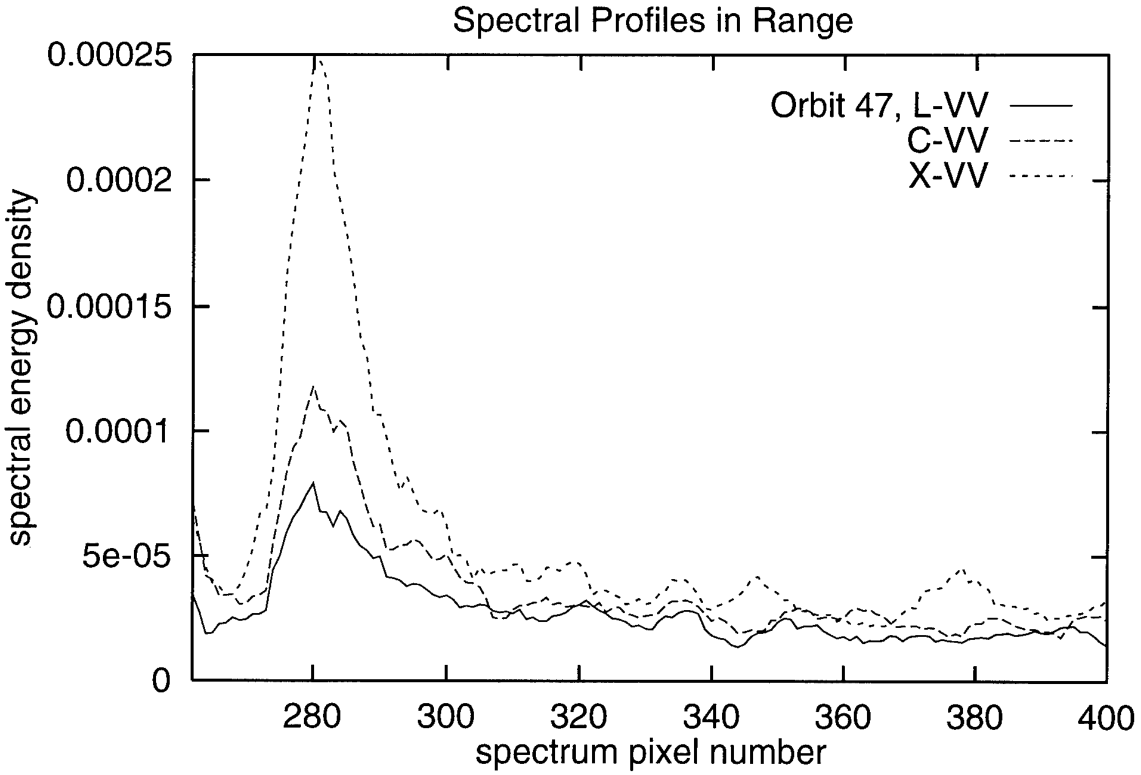

Figure 8. Profiles of spectra of fractional image modulations in VV polarisation at L, C and X bands in the range direction for a SIR-C/X-SAR data-take. The d.c. component (zero wavenumber) in the spectrum occurs at pixel number 256, outside the range of the plot.

Possible Features of NATO Communications Satellite Gap Filler

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1. Introduction.

NATO strategy is changed and emphasis is now on Multinational Groups, Mobile and Rapid Reaction Forces which are easily deployable in the crisis area and capable of rapid responses. In the new political scenarios, satellites are the only assets which can provide the timely and reliable communications required to exercise the command and control of deployed forces. It is also clear that space is the fourth component of a military operation and the role of communication satellites is of crucial importance for peace keeping, peace making operations and for the conduct of conflicts in areas where ground communications facilities can not be easily set up or are not any longer available. NATO communications satellites are expected to terminate their operational life around 2002/2003 and a decision is to be made on how to procure the communications capacity required to support NATO operations after that period. Based on the above consideration, we will examine a range of solutions to overcome the possible lack of NATO MILSATCOM assets in the next few years.. In addition the possible solutions will be based on the criteria of using entire units and packages available off the shelf as many as possible for the construction of the NATO Gap Filler Satellite.

2. NATO Information Exchange Requirements.(IERs)

The NATO Command, Control and Communications Architecture is divided into the Special Purpose and the General Purpose Segments. They can be defined as follows:

- Special Purpose Segment: a specialized communications component, which meet the requirement for highly survivable communications.
- General Purpose Segment : a mixture of NATO, national and commercial assets supporting mobile and static communications .

NATO IV A and B Communications Satellites provide their contribution to both components. The NATO SATCOM Post 2000 working party identified as total satellite communications a IERs of about 130 Mbps soon after year 2000.

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Notwithstanding the lack of a full agreement by the nations, we can consider that figure realistic enough considering the expected implementation of new wideband services.That figure represents in fact an approximated increase of one order of magnitude of the satellite communication services loaded on the NATO IV A and B in 1993 .

The document indicates moreover that under stressed conditions around 10 Mbps are the Special Purpose Segment IERs on Communication Satellites. If dramatic changes take place in the satellite communications capacity procurement philosophy, changes however unlikely to occur as they will bring the total reliance on some major NATO nations or the total dependance on commercial satellites, the immediate consequence will be the unfulfillment of at least of a portion of the NATO communications requirements. However as rule of thumb, we can suppose that half of the traffic, roughly the traffic generated by static terminals, could be accomodated on Commercial Satellites or routed via terrestrial networks.To clear the remaining portion of traffic, which includes the stressed traffic and traffic generated by mobile users, a Military Satcom System is needed.

NATO can not therefore renounce to a military communications satellite which could be moreover designed to provide:

- multiple beams, which ensure a flexible coverage and permit the use of disavantaged terminals.
- direct connections of small terminals ,which allow the timely set up of tactical nets
- resistance to up links jamming : a typical requirement of deployed forces.
- communications protection from the effects of nuclear explosions.

3. Description of the possible NATO Gap Filler Satellite.

A. General.

The NATO Gap Filler Communication satellite should provide coverage of Europe, North and Central Africa, Middle East and Western Asia to cope with NATO's new roles represented by " out of area " operations. The frequency bands of operation should be selected among the UHF, SHF and EHF . The UHF and SHF bands provide the benefit of ensuring backwards compatibility with existing ground terminals.The SHF band has, in addition, the capability of routing a portion of the stressed SPS traffic. Finally the EHF processed band could be used for the transmission of the stressed traffic, while a transparent portion of it, for transmissions at high data rates. As the EHF terminals will be largely introduced into service by mobile forces, the EHF band could be used for their direct connections. NATO Gap Filler Satellite should in fact be designed to provide support to mobile operations which require primarily the use of manportable and other small terminals . For that purpose adequate EIRP should be radiated at UHF and on all beams generated at SHF and EHF .

Four possible configurations of the NATO Gap Filler Satellite will be considered.

(1) UHF, SHF and EHF configuration

(a) Introduction

A NATO Satellite Gap Filler based on a UHF, SHF and EHF payload will be able to route all NATO traffic in the coverage area provided that a relevant portion of the traffic of the Special Purpose Segment would be cleared through the EHF payload.

(b) Payload description:

To be able to clear all NATO traffic the payload should be featured as follows:

((1)) UHF Payload

The UHF package will be basically applied to continue the use of the large amount of small UHF terminals presently in the NATO inventory (around 200 terminals), most of them assigned to Rapid Reaction Forces. 20 UHF channels each with a 25 KHz bandwidth will be required to establish all possible connections. To increase the number of partecipants to the networks, TDMA/DAMA access could be used on selected nets. Global coverage within the field of view of the satellite will provide every terminal, wherever deployed, with the possibility of communicating. Multicarrier linearized solid state power amplifiers, rated at 60 w linear power, will amplify the transmit carriers. Using TDMA/DAMA systems, the UHF package will be able to carry between 0,25 to 0.5 Mbps, meeting the majority of tactical communications requirements.

((2)) SHF Payload

The SHF payload will meet the backwards compatibility and mobile users connectivity requirements. A payload configured in 4 transparent channels, each driving a solid state power amplifier (SSPA)will be sufficient to cope with the expected traffic on that band. In fact a first repeater will be required to route traffic for mobile forces, a second repeater will be dedicated to the transmission of TRANSEC protected traffic, while the two remaining repeaters will be used to meet other communications requirements. All the repeaters will be connected to multibeam and to earth coverage antennas and to a SHF/EHF mechanical spot antenna.To keep at minimum the modifications of the existing TTC control stations, the TTC uplink could be operated at SHF . All the communication services will be provided through transparent satellite channels.

As the up link TTC Signals will be encrypted and spread, one channel on board processed will be required to provide highly protected commands to the satellite.The 4 transparent repeaters, through a switching matrix, will have the possibility of connecting traffic received from all beams and the mechanical spot antenna to a global coverage and viceversa.The 4 SHF repeaters are supposed to be capable of carrying at least 20 Mbps (5 Mbps on the repeater for Marittime Forces, 0.5 Mbps on the repeater dedicated to TRANSEC traffic and the remaing 14.5 Mbps on the two left repeaters).

((3)) EHF PAYLOAD

The use of regenerative EHF channels will offer the possibility of transmitting data rates from 2.4 Kbps up to 2 Mbps with an adequate level of robustness against exploitation and jamming, implementing the waveforms of STANAG 4522 "Digital Interoperability between Medium Data Rate (MDR) EHF SATCOM terminals".

The EHF antennas will support global, multibeam and spot coverage.

The output of the global coverage, the spot and multibeam antennas will be connected to 10 MDR channels each of 62.5 MHz bandwidth .

The output of those channels will be dehopped and down converted to an intermediate frequency..The signals received will be,then, demodulated by the Signal Processor and routed to destination via a Message Processor . Through the on board Access Control Messages system, the field units may request the Control Station the implementation of some communications services such as moving the spot beam to an appropriate area, establishing a new network, joining an existing net and making a point to point call. The above mentioned communication services will be performed in near real time which is one of the basic communication requirements of modern mobile forces. To the left portion of the EHF band, 4 transparent channels of 62.5 Mhz bandwidth will be applied. The 4 transparent channels, which could be cross strapped to the SHF payload,will be able to carry traffic at data rates higher than the 2 Mbps allowed on the regenerative EHF MDR channels. A Master Clock Generator will be applied to the satellite to provide time reference to all digital equipment. In addition, the Master Clock Generator will provide time reference to the Ground Network, using beacon emissions at EHF and SHF. The time transmitted will constitute the reference on which all ground terminals will be synchronized.

(c) Satellite Antennas

The antennas suite will be composed of antennas capable of ensuring the coverage with the generation of the spots required..

((1)) UHF Antennas.

One receive and one transmitting patch antenna with dimensions of 6.5 square meters each will ensure the earth coverage with the appropriate gain to allow communications from/to all UHF terminals.

((2)) SHF Antennas.

The SHF multibeam and the mechanical steerable spot up link antenna will be associated to the nulling system designed for jammer location and nulls generation . The reconfiguration of the antennas, with the steering in the required directions of the multibeam and of the mechanical spot antenna will happen after a few seconds that ground commands have been received.
The multibeam antenna diameter will be of 1.2 mt.,which is a dimension suitable to generate at the earth surface multiple beams of 1500 km. of diameter. The composite beams can therefore ensure a wide coverage area, the SHF down link antenna with diameter of 1 mt. will generate a corrisponding wide area of larger dimension. A 0.8 mt. diameter mechanical steerable spot beam antenna will also provide up/down link coverage in both the SHF and EHF bands for communications and the jammer location and nulls generation service. Two earth coverage horn antennas will complete the SHF antenna suite, one will be used for the up link signal reception while the second for the down link transmission.

((3)) EHF Antennas.

The EHF up/down link multibeam antenna of about 0.4 mt. diameter, with a receive beam of about 800 Km. of diameter at the earth surface, will have nulling and reconfiguration capability over the Central Europe, Middle East and Western Asia Area. The nulling system and the antenna configuration will be controlled from the ground, as in the case of the SHF antenna. The mentioned SHF/EHF mechanical steerable spot antenna and two global coverage horns will complete the EHF antenna suite.

(d) Satellite Payload mass and power budget.

The payload mass estimate is around 400 Kg. for a total satellite dry mass of about 1200 Kg. The launch mass is in the range of 2500 Kg. for a mission life of about 10 years with full orbital control . The total power requirement is in the range of 2200 to 2500 W.

The satellite main characteristics are :

° Orbit : Geosyncronous
° Stabilization: 3 axis
° Attitute Control: Sun and Earth Sensor
° Comms.Payload : UHF,SHF and EHF bands
° Payload mass : 400 Kg.
° Satellite dry mass : 1200 Kg.
° Launch mass : 2500 Kg.
° Power : 2200-2500 W
° Propulsion : Liquid bipropellant
° TTC : SHF band. EHF could be used also
° Operational life : 10 years.

A Satellite possible layout is at fig. 1, while its simplified payload block diagram is at fig.2

(e) Considerations.

The introduction of wideband communication services will bring a growth of the data rates to be transmitted. . Such medium size multifrequency satellite would be able to meet all NATO IERs and future traffic expansion.It will constitute probably the precursor or the first in orbit of a new generation of a constellation of satellites.

(2) SHF + UHF Configuration

In case the EHF payload is not selected for the Satcom Gap Filler architecture, the satellite configuration will be changed in a way that mass and power comsumption will not be reduced.
In fact the number of SHF repeaters would be increased from 4 to 6 together with the application of an additional European Coverage Beam antenna. The mass would moreover increase as some repeater channels would require higher power achievable with the substitution of SSPAs with TWTAs to support mobile and disavantaged terminals.
As a matter of fact we assume that this solution would not be considered as it appears unsuitable to meet NATO IERs particularly under stressed conditions.
In addition, that solution will augment the need of using commercial satellites to route static terminals traffic.

(3) SHF + EHF Configuration

This solution seems very attractive because the elimination of the UHF payload permits a large reduction of satellite mass and power comsumption, also facilitating the thermal control aspects . With that architecture the satellite dry mass would be as low as about 900 Kg and the overall power requirement about 1700 w. The disavantage of that architecture is that NATO UHF backwards requirements are to be met with high cost leased UHF channels on which no or limited control could be exercised. The SHF + EHF configuration appears, however, suitable to route all NATO IERs.

(4) SHF only Configuration

From the mass and power requirements point of view this solution is equivalent to the SHF + EHF architecture .Different simplified solutions could be made available. As an example the "SHF only solution "may be conceived provided with a SHF multibeam, a mechanical steerable spot antenna and global horns plus SSPAs to reduce the payload dry mass. This type of satellite, alone or better in constellation of two, would have the advantage of minimum cost although with the probable limitation of being unable to route all stressed traffic. It should be considered only if the requirement to keep as low as possible the financial cost of the Gap Filler Satellite is prevailing on achieving the capability to clear all NATO IERs.

4. Conclusions.

Military Communication Satellites are the unique, strategic assets able to provide the necessary communications capability for exercising the Command and Control of mobile and deployed forces and for ensuring the special purpose segment communications during peacetime operation and in times of crisis. According to our view, NATO can not renounce to military Satellites and preference should be given to the UHF, SHF and EHF configuration. That configuration could be used as a bridghead towards the future, as during its operational life it will be able to meet the identified IERs and , at the same time, to cope with possible further traffic expansion.
In fact:
- the use of the UHF band, presently made primarily by ships, submarines and manpack terminals, will be in the next few years increased, as new airborne terminals will become operational on the Alliance aircraft.

- the SHF band will be more extensively used by transportable and mobile terminals now entering into service. When the satellite SHF capacity will be completely filled, a portion of the traffic could be allocated on commercial satellites, on terrestrial networks or moved, in some instances, to the satellite EHF transparent band.
- The EHF regenerative band could be used to carry, through the applied MDR package, all Special Purpose Segment traffic or a relevant portion of it, being complemented by the SHF band

The EHF trasparent band could be used to accomodate traffic moved from the other bands. In addition, the trasparent portion of the EHF payload is particulary suitable to establish :

* high capacity links between all type of users.
* switch board extensions to Land Forces deployed H.Q. and Air Force detached Units.
* high data rate links between NATO Static Terminals, saving the money to go commercial.

Finally, due to the satellite mechanical steerable spot beams antenna, all that could be achieved in full compliance with the Forces deployment requirements which are normally:

* for Army troops and Air Force detached units: coverage of geographic areas of reduced dimensions .
* for Navies: global with reiterated coverage of some selected areas.

NATO would put at risk its military credibility if it does not replace NATO IV Satellites with a system suitable to route its IERs. The illustrated UHF, SHF and EHF Satellite could be timely constructed, as the majority of the required units have been already developed.

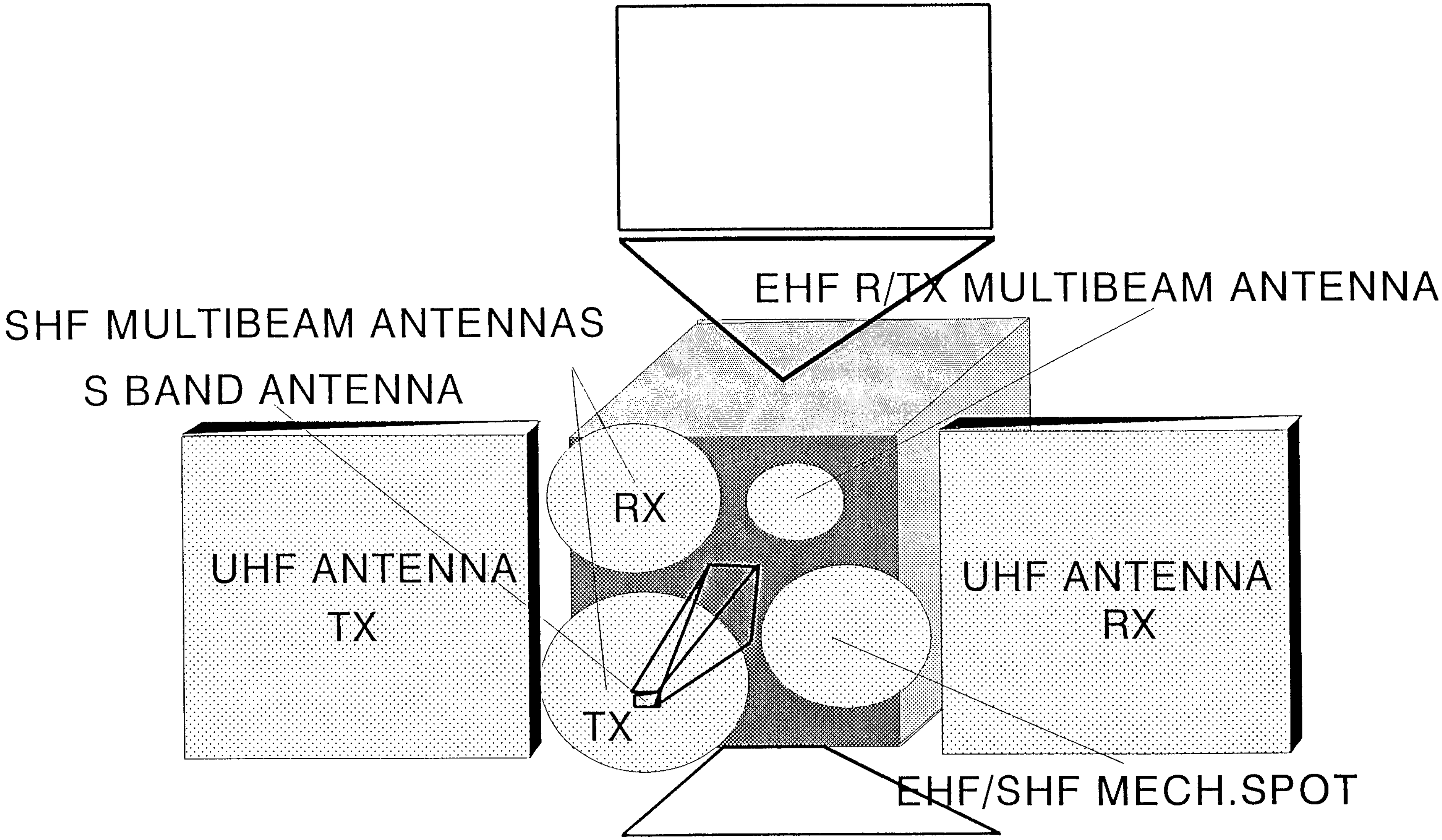

FIG.1: POSSIBLE SATELLITE LAYOUT (ONLY MAIN ANTENNAS ARE SHOWN)

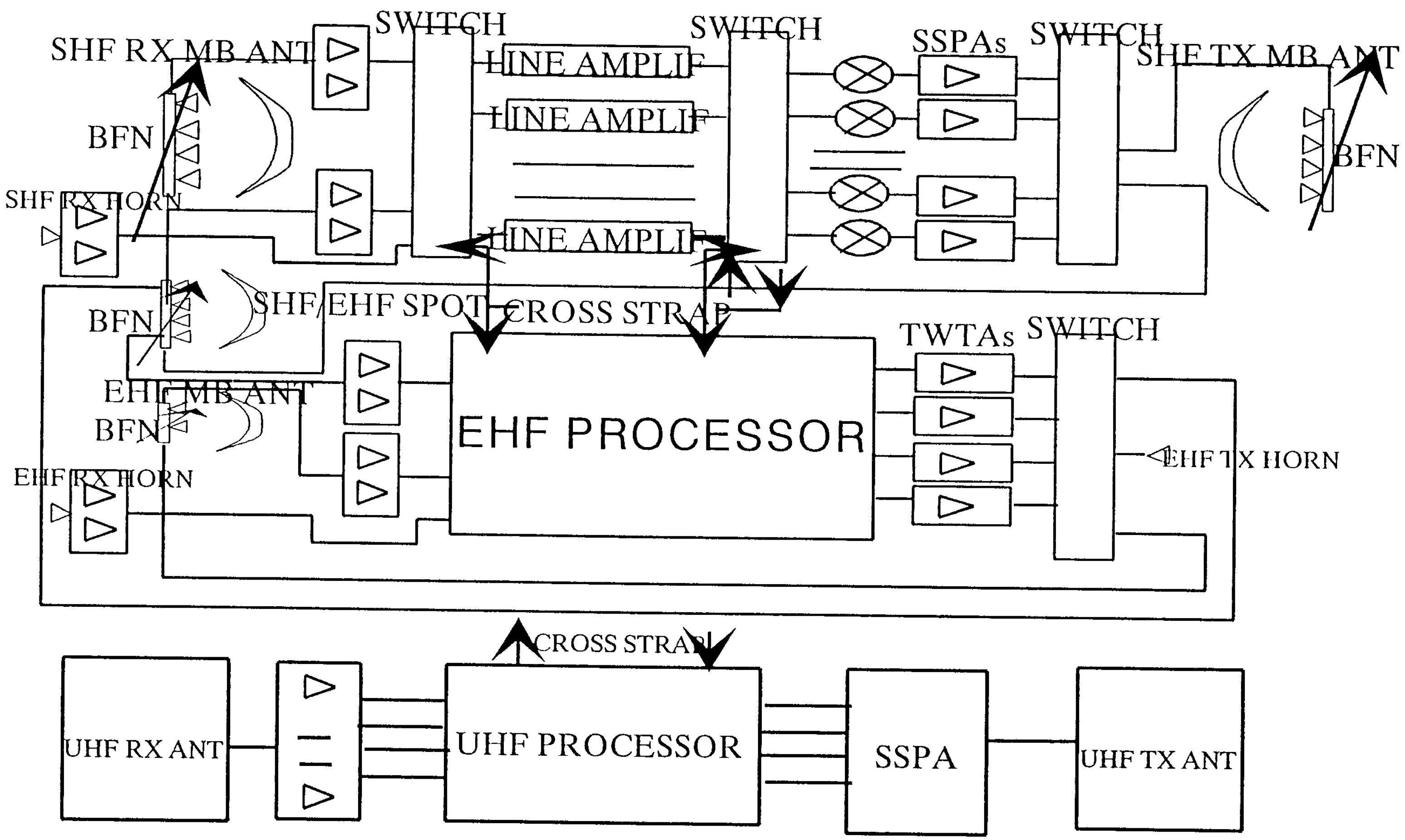

FIG.2: SIMPLIFIED PAYLOAD BLOCK DIAGRAM

RESULTATS EXPERIMENTAUX D'ANTIBROUILLAGE D'UNE ANTENNE EMBARQUEE DE TELECOMMUNICATION PAR SATELLITE

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SOMMAIRE

LISTE DES SYMBOLES

FAFR : Feed Array Focal Reflector
DRA : Direct Radiating Array
OLS : Opposition dans les Lobes Secondaires
CAN : Convertisseur Analogique/Numérique
RFP : Réseau Formateur de Pinceaux
CDMA : Code Division Multiple Access
FH : Frequency Hopping
Conops : Concept of operations

Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.

I - Introduction

La prochaine génération de satellites de télécommunications militaires doit permettre une meilleure satisfaction des besoins opérationnels en assurant la desserte de davantage de théâtres d'opérations simultanés et un surcroît de protection contre le brouillage électromagnétique (réf. 1).

Sous l'égide de la Délégation Générale de l'Armement Alcatel Espace et THOMSON-CSF ont étudié et réalisé un démonstrateur d'antenne antibrouillée pour la réception SHF à bord d'un satellite.

Cette antenne multifaisceaux active est associée à un antibrouillage autoadaptatif utilisant une technique dite « d'opposition dans les lobes secondaires » (OLS). L'analyse et la simulation de plusieurs solutions ont conduit au choix d'une antenne à réflecteur munie d'une rétine active, associée à un traitement OLS. L'OLS élimine le brouillage des voies principales par la sommation pondérée, en analogique, de celles-ci avec des voies auxiliaires destinées à capter les brouilleurs. Le calcul de la pondération adéquate s'effectue en numérique.

L'antenne antibrouillée est donc constituée de deux fonctions principales : la fonction réception et la fonction annulation de brouilleurs.

La fonction de réception comprend :

- la réception des signaux par un ensemble réflecteur plus réseau de sources actives,
- l'amplification faible bruit des signaux reçus,
- la formation des faisceaux voies principales et voies auxiliaires par sélection et sommation pondérée (phase et amplitude) des signaux captés sur chacune des sources.

L'annulation de brouilleurs comprend :

- la transposition en bande de base des voies de réception,

- la numérisation des signaux et leur stockage,

- la configuration des voies auxiliaires en fonction de la direction d'arrivée des brouilleurs,

- le calcul des coefficients d'opposition et la mise en opposition analogique des voies auxiliaires sur les voies principales.

Le démonstrateur d'antenne antibrouillée a été réalisé et testé fin 95. Les mesures en champ lointain se poursuivent aujourd'hui afin de caractériser les performances d'ensemble face à une variété de scénaris opérationnels : brouilleurs découpés, brouilleurs lointains (en dehors du lobe principal de l'antenne) et brouilleurs proches (dans le lobe principal).

Le démonstrateur actuel effectue les calculs d'auto-adaptation des coefficients d'antibrouillage en temps différé. Un calculateur temps réel sera associé au démonstrateur fin 96, afin de valider, courant 97, les performances dynamiques du système d'antibrouillage avec des cadencements identiques à ceux de l'antenne opérationnelle.

II - Hypothèses de travail

Les principales hypothèses prises en compte pour l'étude sont les suivantes :

- Bande de fréquence SHF : liaison montante à antibrouiller 7.9 à 8.4 Ghz,
- Antenne de réception opérationnelle comportant 4 faisceaux directifs orientables avec la capacité d'antibrouiller simultanément l'ensem ble des faisceaux face à des brouilleurs multiples,
- Pour assurer la continuité de service des systèmes existants de la composante sol actuelle, l'antenne doit être compatible avec les signaux de type SYRACUSE 1 et 2 : CDMA, SS-FDMA et FDMA «civil »
- Pour répondre aux futurs besoins, elle devra être compatible avec les signaux de type nouveau qui pourront être introduits, notamment du saut de fréquence de type STANAG 4376,
- Brouilleurs de tous types : à bruit, à raies (monoraie ou multiraies), continus ou découpés...

III - Objectifs du démonstrateur

Du point de vue de l'antibrouillage, les points durs essentiels sont :

- la largeur de bande 7,9 - 8,4 Ghz sur laquelle l'antibrouillage doit être effectif,
- la dynamique importante des signaux à traiter (cas des brouilleurs forts et moyens),
- le pouvoir de résolution important nécessaire pour lutter contre les brouilleurs proches, en bord de couverture.

Le but des travaux réalisés sur le démonstrateur est :

- de démontrer la faisabilité d'une antenne antibrouillée répondant aux exigences de performance exprimées dans les Conops,
- de conforter les spécifications induites sur les sous-ensembles et les composants par les exigences d'ensemble,
- de valider et de mettre au point les algorithmies de mise en oeuvre de l'antibrouillage,
- de caractériser et de maîtriser l'ensemble des paramètres dimensionnants du sous-système,
- de vérifier les performances aux limites (brouilleurs se rapprochant du bord de couverture, brouilleurs en limite de dynamique des chaînes de réception...)

IV - Rappel du principe de l'OLS

On cherche par la méthode OLS à réduire au maximum la puissance de brouillage reçue par une antenne directive pointée dans une direction utile et attaquée par un ou plusieurs brouilleurs.

Pour cela, on utilise des voies auxiliaires, auxquelles sont connectés des récepteurs idéalement identiques à celui de la voie principale.

Traditionnellement, la méthode OLS est utilisée avec des voies auxiliaires formées à partir de capteurs peu directifs (voire globaux).
L'antibrouillage atteint alors sa performance maximale contre les brouilleurs pénétrant le diagramme d'antenne par ses lobes secondaires (d'où l'appellation OLS : opposition dans les lobes secondaires).

La même technique appliquée à des voies auxiliaires directives d'ouverture similaire à l'ouverture du faisceau principal permet d'obtenir des performacnes excellentes face à des brouilleurs situés à proximité du bord de couverture (scénario opérationnel le plus vraisemblable sur les théatres déportés et contre lequel des antennes non antibrouillées sont particulièrement vulnérables).

C'est donc par abus de langage que le nom de la technique « OLS » a été conservé bien qu'elle permette une opposition sur des brouilleurs bien plus proches que dans les lobes secondaires, dans les flancs du lobe principal, dès le bord de couverture.

Les signaux reçus sur les voies principales et auxiliaires étant constitués de combinaisons linéaires différentes des mêmes signaux (signal utile et brouilleurs), il est théoriquement possible de supprimer ceux issus des brouilleurs par adjonction au signal V_p de la voie principale d'une combinaison linéaire adéquate des signaux V_{ak} des voies auxiliaires, à la condition que le nombre de voies auxiliaires soit supérieur ou égal au nombre de brouilleurs.

Ainsi pour un OLS à n voies auxiliaires, le signal anti-brouillé de la voie principale $V_p'(t)$ est donnée par

$$V_p'(t) = V_p(t) - \sum_{k=1}^{n} w_k V_{ak}(t),$$

où $V_p(t)$ est le signal de la voie principale (non anti-brouillé), $V_{ak}(t)$ le signal de la voie auxiliaire k et w_k le k-ième coefficient du vecteur d'opposition $\underline{w}$ défini par

$$\underline{w} = \Gamma_a^{*-1} \underline{C}, \qquad \text{(formule de Wiener)}$$

où Γ_a est la matrice de covariance $n \times n$ des voies auxiliaires définie par

$$\Gamma_a = E[\underline{V}_a(t)\,\underline{V}_a(t)^H]$$

avec

$$\underline{V}_a(t) = [V_{a1}(t), V_{a2}(t), \ldots, V_{an}(t)]^T,$$

et où $\underline{C}$ est le vecteur d'inter-corrélation défini par

$$\underline{C} = E[V_p(t)\,\underline{V}_a(t)^*].$$

(L'étoile * désigne la conjugaison complexe et l'exposant^T désigne la transposition matricielle).

En effet , on démontre que la puissance moyenne résultante $E[V_p'(t)^2]$ due aux brouilleurs est minimale si l'on prend pour $\underline{w}$ la valeur $\underline{w} = \Gamma_a^{*-1} \underline{C}$,

V - Etude d'un FAFR + OLS mixte

1) Description du démonstrateur

Le démonstrateur d'antenne antibrouillée en SHF est constitué de deux sous-ensembles.

Sous-ensemble antenne

Il s'agit de l'aérien qui a été étudié et mis au point par ALCATEL ESPACE .

La partie rayonnante est constituée d'un réflecteur de 2,2 m de diamètre et d'un réseau de 100 sources positionnées sur une plaque support. Parmi ces

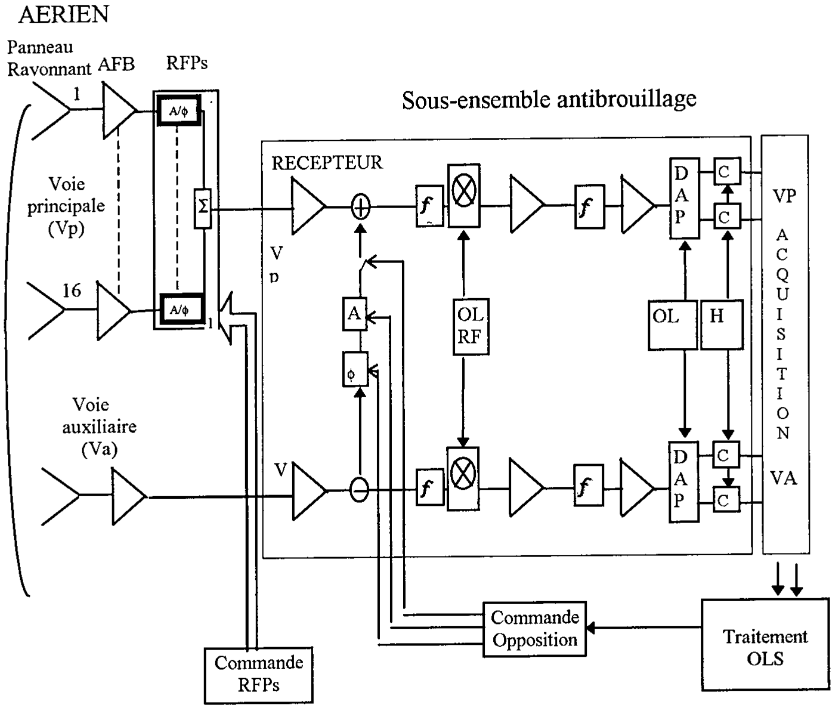
100 sources, 32 au plus sont actives, c'est-à-dire suivies d'un amplificateur faible bruit et connectées à un réseau formateur de pinceaux. Les autres, passives, servent à reproduire le même environnement pour toutes les sources actives.

Les 32 sources actives sont réparties en deux groupes de 16 sources, disjoints ou non.

Le déplacement des réseaux de formation de pinceaux ajouté à ses commandes (A,ϕ) permet de réaliser toutes les positions de faisceau principal (correspondant à la voie à antibrouiller). Quant à la voie auxiliaire (celle qui capte le signal de brouillage), elle est réalisée par sélection de la source qui reçoit le mieux le brouilleur.

Le pointage et la conformation des faisceaux sont commandés à partir du calculateur de commande des formateurs de faisceaux (RFPs).

Synoptique du démonstrateur



Sous-ensemble antibrouillage

Il s'agit du système regroupant la réception, l'opposition en analogique à 8 Ghz et le calculateur en temps différé qui permettent d'antibrouiller l'antenne. Ce sous-ensemble a été étudié et mis au point par THOMSON-CSF AIRSYS.

En sortie des réseaux formateurs de pinceaux, les signaux sont routés vers le dispositif d'antibrouillage. Ce dispositif comprend deux chaînes de transposition en FI et de numérisation, un module d'acquisition et de traitement, et un module d'opposition analogique.

L'opposition est débrayable par commutateur, ce qui permet d'obtenir la voie principale antibrouillée ou non en entrée du module de traitement.

Lorsque l'opposition est inhibée, le calculateur de traitement calcule le coefficient (amplitude et phase) d'opposition et peut appliquer ces coefficients aux signaux numérisés stockés dans sa mémoire (possibilité de faire de l'OLS en numérique).

Lorsque l'opposition est activée, les coefficients calculés précédemment sont appliqués à la voie auxiliaire et on peut observer directement la voie principale antibrouillée (OLS mixte).

Il existe également un dispositif de calibration permettant d'injecter un même signal en entrée des récepteurs des voies principales et auxiliaires et ainsi de mesurer leurs caractéristiques différentielles.

La partie acquisition, gestion, exploitation de l'antibrouillage est traitée par un calculateur en temps différé qui :

- réalise les calculs des coefficients d'opposition,
- permet l'exploitation des données avant et après traitement pour en extraire l'ensemble des informations permettant d'appréhender les performances d'antibrouillage.

2) Caractérisation des performances

Les performances issues des essais de ce démonstrateur permettent par extrapolation d'évaluer les performances de l'antenne opérationnelle.

Ces performances sont, en mode non contraint (hors brouillage) : le diagramme et le G/T de l'antenne et, en mode contraint : la réjection du brouillage et l'atténuation des signaux de communication. Elles sont exprimées en fonction de la position du brouilleur par rapport à la station émettrice, du type de brouilleur (à raies ou à bruit, continu ou découpé) et de sa PIRE, du type de communication et de la PIRE de station émettrice.

3) Déroulement des travaux

L'étude s'est déroulée en cinq étapes principales :

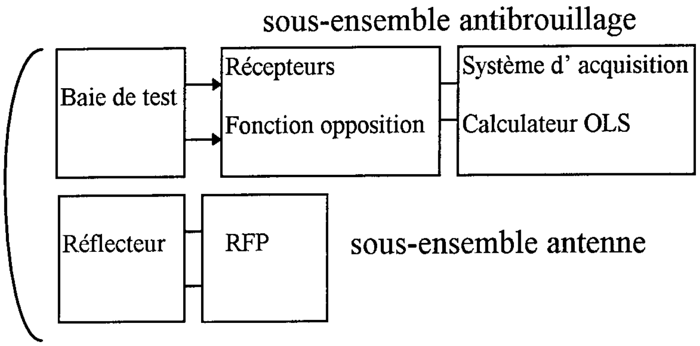
1) Définition du démonstrateur représentatif de l'antenne opérationnelle envisagée
2) Simulation et prévisions des performances de l'antenne antibrouillée
3) Réalisation des sous-enembles aérien et système de réception d'antibrouillage
4) Tests des sous-ensemble
5) Tests en champ lointain du démonstrateur

4) Méthodologie des tests

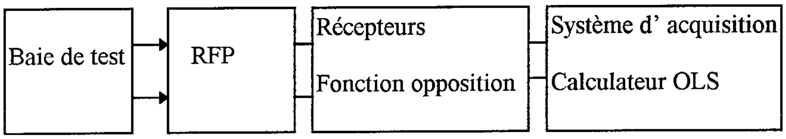
Le démonstrateur a été testé en trois phases successives qui correspondent à une complexité croissante du matériel et à une validation progressive en permettant d'analyser et de maîtriser les phénomènes physiques mis en jeu.

Ces trois phases sont schématisées dans la figure suivante :

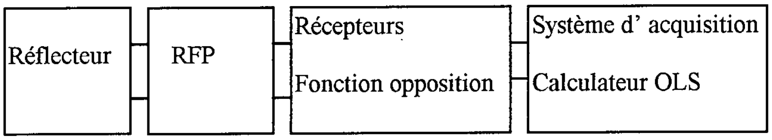
Première phase :



Deuxième phase :



Troisème phase :



Lors de la première phase, les différents sous-ensembles constituant le démonstrateur ont été testés séparément.

A l'issue de ces tests , on a pu définir les réglages des seuils pour les tests de mise en oeuvre de l'OLS, c'est à dire définir quand on doit considèrer que le signal est brouillé, sur quels échantillons il faut faire le calcul et si l'on doit appliquer le coefficient d'antibrouillage que l'on a calculé.

On a pu aussi observer l'effet du nombre de bits de commande des atténuateurs et déphaseurs sur la qualité de l'opposition et la robustesse algébrique du traitement vis à vis du rapport de signal utile/brouilleur.

Les récepteurs ont été appréciés du point de vue de la linéarité et du nombre de bits nécessaire pour atteindre les objectifs fixés.

Lors de la deuxième phase, on a montré que la partie active de l'aérien (hors phénomènes optiques dus au réflecteur), c'est à dire les éléments rayonnants avec leur amplificateur faible bruit et le système de formation de pinceaux, associée au sous-ensemble l'antibrouillage donne des résultats du même ordre de grandeur que ceux obtenus lors de la première phase.

La troisième phase permet de tester le démonstrateur complet en champ lointain et d'en apprécier ses performances en fonction de :

- la puissance de brouillage,
- du rapport de puissance utile/ brouilleur,
- de l'écart angulaire entre l'utile et le brouilleur,
- du type de menace (bruit,monoraie, biraies...)
- du type de forme d'onde utile (CDMA,FH...)
- de la découpe des brouilleurs.

5) Principaux résultats obtenus à ce jour

Les tests effectués à ce jour, permettent de démontrer que les performances sont conformes et en certains points supérieures aux objectifs qui avaient été fixés en début d'étude, et ceci quelque soit le type de menace considéré.

L'architecture retenue permet d'envisager un matériel opérationnel réalisable en technologie spatiale, à faible consommation et relativement simple de conception.

Les spécifications induites sur les sous-ensembles antenne, réception, opposition et sur les composants par les exigences d'ensemble ont été confortées. Les paramètres dimensionnants ont été caractérisés.

Dans toute technique d'opposition, il est impératif de maîtriser les imperfections différentielles des voies de réception de l'antenne antibrouillée des éléments rayonnants de l'aérien jusqu'au calculateur d'antibrouillage.

Le démonstrateur a permis de caractériser les imperfections différentielles de l'ensemble des voies de réception, de vérifier la faisabilité technologique des exigences exprimées et de valider l'algorithmie auto-adaptative de calcul des coefficients d'opposition.

La fonction opposition représentant le coeur de l'OLS mixte doit permettre d'appliquer au plus près le coefficient d'opposition issu du calculateur d'antibrouillage. Pour cela, compte-tenu de la non linéarité des composants, nous avons mis au point des techniques d'étalonnage des composants et des algorithmes de linéarisation qui permettent d'appliquer les coefficients d'antibrouillage avec une précision correspondant à un niveau de réjection meilleur de quelques dB que le niveau de réjection visé.

La calibration doit être rafraîchie pour chaque canal de travail (position de l'oscillateur local hyperfréquence de réception), à chaque nouveau réglage de l'amplification de tête et pour certains écarts de température à bord du satellite.

La fonction opposition analogique doit aussi présenter une fonction de transfert (en amplitude et en phase) la plus plate possible dans la bande hyperfréquence à traiter de façon à ne pas altérer les signaux issus des voies auxiliaires car cela correspondrait à une erreur d'annulation.

Le démonstrateur a permis de caractériser la fonction de transfert des fonctions opposition et de vérifier la faisabilité technologique des exigences exprimées.

Le démonstrateur fonctionne en temps différé et a permis de mettre au point l'algorithmie de traitement de l'OLS mixte associée à des modules annexes tels que la calibration qui sont indispensables pour un bon fonctionnement.

De cette analyse ont pu être dérivées les exigences fonctionnelles du calculateur opérationnel :

- fonctions réalisées,
- puissances de calcul nécessaires,
- débits associés,
- algorithmies et tests à mettre en oeuvre.

La faisabilité d'un calculateur temps réel réalisant l'ensemble de ces fonctions suffisamment rapidement pour éviter des pertes de liaison néfastes à la communication en présence des différents scénaris de menace a été établie.

Cette conclusion sera vérifiée expérimentalement par l'adjonction fin 96, d'un calculateur temps réel au démonstrateur.

VI - Evolution du démonstrateur en 1996 - 1997

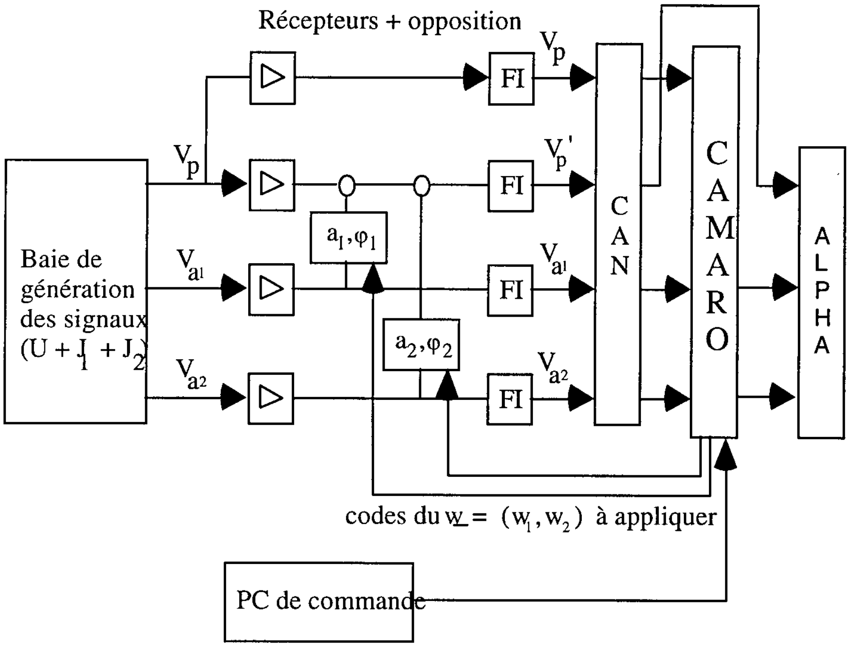
Le calcul en temps différé réalisé sur le démonstrateur actuel sera remplacé fin 96 par un calcul temps réel réalisé sur le calculateur d'antibrouillage CAMARO (réf. 2) développé par THOMSON-CSF.

Cette évolution permettra de valider expérimentalement les performances dynamiques spécifiées pour l'antenne opérationnelle dans des scénaris multi-brouilleurs.

Un schéma synoptique du démonstrateur est donné dans la figure ci-après.

Le calculateur d'antibrouillage CAMARO reçoit les paramètres de configuration par l'intermédiaire d'un PC de commande. Une station de travail DEC-ALPHA est connectée à l'ensemble afin d'effectuer des calculs de performances.

Synoptique du démonstrateur envisagé



Avec un cadencement identique à celui de l'antenne opérationnelle, le démonstrateur permettra d'apprécier les performances de réjection en présence de plusieurs brouilleurs découpés, et de qualifier les techniques de gestion des coefficients d'opposition.
Les performances dynamiques d'antibrouillage seront mesurées en termes de minimisation des pertes ou des réductions de service en présence de brouillage.

A l'issue de ces travaux,la totalité des sous-ensembles fonctionnels constitutifs de la fonction anti-brouillage auto-adaptatif (antenne, réception, opposition, corrélation numérique, calcul et gestion temps réel des coefficients d'opposition) ainsi que leur regroupement d'ensemble auront été validés.

VII - Références

(1) Présentation de la future génération de systèmes de communications militaires par satellite

5ème symposium AGARD-MSP Juin 96.

(2) Technologies numériques pour une charge utile antibrouillée de télécommunications par satellite

5ème symposium AGARD-MSP Juin 96.

Technologies Numériques pour une Charge Utile Anti-Brouillée de Télécommunications par Satellites

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Table des Matières

1 Préface

Les futures générations de systèmes de communication militaire par satellite nécessiteront un surcroît de protection contre le brouillage et une plus grande facilité d'interconnexions entre stations de différents types. La satisfaction de ces besoins requiert pour la fonction de transmission de disposer d'un calculateur d'antibrouillage.

Ce calculateur réalise, de façon numérique, différentes fonctions :

- L'acquisition numérique à haute fréquence d'échantillonnage de blocs de données en provenance du ou des canaux de transmission.

- Le traitement intensif d'antibrouillage nécessitant notamment la formation de matrices d'intercorrélation et la résolution de systèmes linéaires.

- Les traitements intelligents, effectués en parallèle de l'antibrouillage, de type calibration, localisation d'émission, synchronisation temporelle et spatiale , correction de linéarité des commandes d'atténuation et de rotation de phase de la consigne d'antibrouillage.

Sous l'égide de la Délégation Générale de l'Armement, Thomson-CSF a étudié, pour des dispositifs d'antibrouillage de type OLS mixte, un tel calculateur.

Les puissances de calcul de l'ordre de quelques centaines de Mégaopérations par seconde pour la partie répétitive et de quelques dizaines de Mégainstructions par seconde pour la partie intelligente se prêtent bien à une réalisation en deux sous-ensembles :

- Un système frontal, pour les traitements répétitifs très gourmands en puissance de calcul brute. Ce système est, pour l'essentiel, constitué d'un ASIC prenant en charge la formation des matrices d'intercorrélation entre voies.

- Une machine parallèle multinoeuds pour l'ensemble des traitements intelligents, résolution des systèmes linéaires compris.

Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.

Un noeud est une ressource numérique autonome dont l'architecture de base comprend un DSP, ses mémoires de programme, de travail associé et un ASIC de type Crossbar d'abonnement du noeud au réseau de communication internoeuds. Cette architecture multinoeuds est étroitement dérivée de la machine parallèle "Camaro" développée par Thomson-CSF AIRSYS pour ses besoins propres, notamment Radar.

Les différents noeuds de la machine sont standardisés et interchangeables.

Les Entrées/Sorties se font directement sur le réseau de communication.

De plus, les noeuds sont abonnés à un bus de servitude prenant en charge les fonctions de téléchargement, test et reconfiguration de la machine.

Le calculateur est ainsi reconfiguré en fonction:
- Du mode de fonctionnement et du type d'applicatif,
- Des caractéristiques des formes d'ondes de transmission et de synchronisation,
- Des différents besoins en puissance de calcul,
- Des besoins en redondance et en disponibilité.

Moyennant l'adjonction d'ASIC coprocesseur au DSP de chaque noeud et au renforcement du réseau de communication, cette même architecture s'adapte aux problèmes de la FFC adaptative et à l'OLS numérique d'une antenne multifaisceaux.

2 Antibrouillage par OLS Mixte

Dans un antibrouillage de type OLS mixte, à la différence d'un OLS tout numérique ou d'une Formation de Faisceau par le Calcul (FFC) adaptative, le canal antibrouillé reste analogique. Le filtrage optimal est réalisé sur porteuse, le plus souvent en fréquence intermédiaire. Cette approche non seulement simplifie de façon conséquente l'antibrouillage, mais garantit aussi la disponibilité du Canal en cas de panne éventuelle du calculateur d'antibrouillage. Les coefficients de filtrage optimal sont appliqués au canal via un ensemble atténuateur/déphaseur. Par contre l'ensemble des calculs de filtrage optimal se font en numérique, à partir d'une acquisition vidéo des différentes antennes concernées.
[voir figure 1 : Synoptique OLS Mixte]

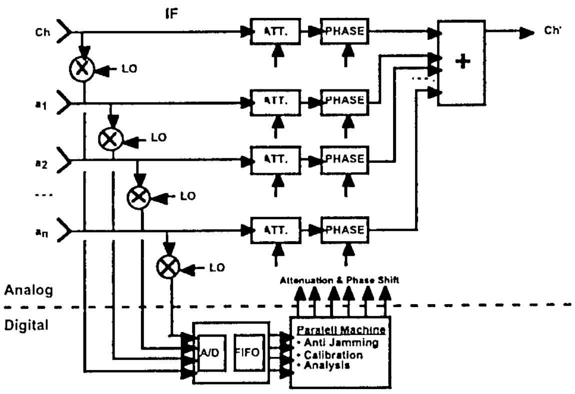

Fig. 1 : Synoptique OLS Mixte

Les fonctions principales du calculateur numérique sont les suivantes :

- Calcul des coefficients de filtrage optimaux. L'algorithme mis en oeuvre est proche du classique LMS (Least Mean Square). Le calcul est effectué en direct ou en récursif. L'algorithme comprend la formation de la matrice d'intercorrélation entre toutes les voies, la résolution du système linéaire, la conversion cartésienne/polaire.

- Calibration des atténuateurs/déphaseurs. Le calculateur mesure leurs fonctions de transfert et corrige leurs comportements non linéaires.

- Calibration des voies. Le calculateur permet de mesurer les défauts différentiels entre les voies afin de les corriger avec une action complémentaire sur les commandes de CAG pour rester dans la bonne plage de dynamique en fonction du niveau de brouillage.

3 Présentation de Camaro

L'architecture du calculateur d'antibrouillage Spatial est étroitement dérivée de celle de Camaro et son atelier logiciel est une version adaptée d'Octane.

Il est donc intéressant de décrire Camaro et Octane avant d'aborder le calculateur Spatial.

3.1. Introduction

Forte de son expérience dans le domaine Radar, où le traitement du signal temps réel nécessite des puissance de calcul et des débits de communication très élevés, associés à un contrôle temporel complexe, Thomson-CSF Airsys a développé l'ensemble Camaro/Octane. Camaro est une machine parallèle optimisée pour le traitement du signal temps réel intensif, systématique et/ou intelligent. La modularité de la machine est importante et permet de traiter des problèmes nécessitant de 10 à 2000 DSPs (Processeur de Traitement du Signal) flottant 32 bits tout en pouvant encapsuler des coprocesseurs ASICs pour certaines fonctions particulièrement intensives. Octane est l'atelier logiciel associé à la machine. L'atelier regroupe l'ensemble des fonctions logicielles nécessaires à toutes les étapes du développement d'un applicatif de traitement, de la phase initiale de description de la machine utilisée et de la description du parallélisme mis en place jusqu'à la phase d'exploitation de la machine munie de son applicatif, en passant par toutes les autres phases intermédiaires : compilation, simulation, téléchargement, mise au point, gestion du parallélisme, tests intégrés, ...

Cette machine s'adapte particulièrement bien à des traitements de type :

- Radar
- Sonar
- Télécommunication
- Guerre Electronique
- Traitement d'Image
- Accélérateur Hardware
- Simulateur
- Synthétiseur Numérique

A ce jour, sur le marché COTS ("Commercial Off The Shelf"), sont disponibles plusieurs machines temps réel adaptées au traitement de données (Classe 1) ou au traitement mixte de signal et données (Classe 2). Par contre Camaro est la seule machine disponible adaptée aux traitements du signal de types intelligent et systématique (Classe 3).
[voir figure 2 : Classes de machine]

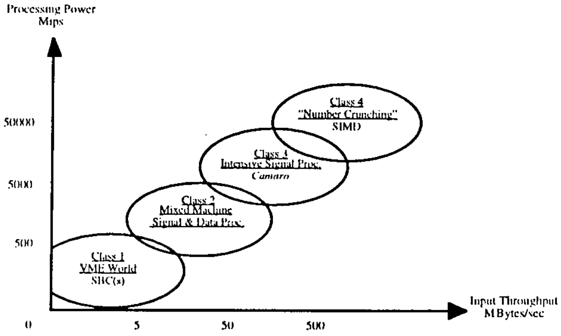

Fig. 2 : Classes de Machine

3.2. Architecture de Camaro

Les quatre classes de machines décrites précédemment se différencient par les choix de base de 3 paramètres fondamentaux que sont :

- Les Opérateurs de traitement
- L'"Operating System" (OS)
- Le principe du Réseau de Communication

[voir figure 3 : Principes Machines]

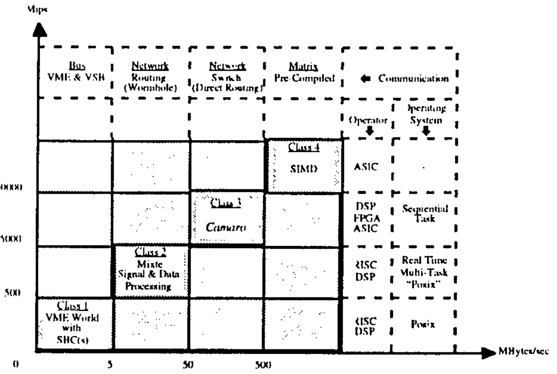

Fig. 3 : Principes Machines

Les choix de base de Camaro, que l'on retrouve intégralement sur le calculateur Spatial, sont les suivants :

- L'opérateur principal de traitement est de type DSP 32 Bits. Les DSPs 32 bits présentent un bon compromis puissance de calcul, intelligence. De plus ils disposent de bons compilateurs "C". A ces DSPs peuvent être associés des ASICs coprocesseurs pour les traitements les plus exigeants.

• L'"Operating System" n'a pas besoin d'être de type multitâches avec préemption. En traitement du signal intensif, les tâches se déroulent séquentiellement. Il faut par contre privilégier le temps réel, soit en l'occurrence le temps de commutation de tâches qui ne doit pas excéder quelques microsecondes.

• Le réseau de communication est de type "Direct Routing". Des canaux de communication sont ouverts entre les noeuds de traitements. Ces canaux ne sont pas partageables. On évite de la sorte tous les problèmes de conflits de communication existant sur les approches de type Bus ou routage dynamique (de type "Wormhole" ou non). Le fonctionnement de ce réseau garantit le déterminisme, la prédictabilité et la robustesse des communications, aspects essentiels dans les applications à fortes contraintes "Temps Réel".

La topologie "Hardware" du réseau de Camaro est bidimensionnelle (2D). Cette caractéristique 2D est importante pour l'implantation des applications à débit de communication élevé rencontrées dans certains traitement comme, par exemple, les Radars à "Formation de Faisceau par le Calcul".
[voir figure 4 : Architecture Général 2D]

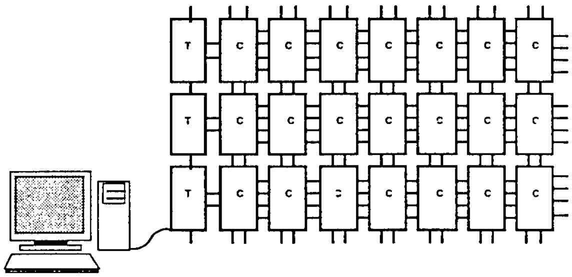

Fig. 4 : Architecture Générale 2D

Chaque carte de traitement, au format "Double Europe" 6U, comporte :

• Un Crossbar (Interface entre le Réseau le Noeud de traitement).

• Un noeud de traitement constitué d'un "Cluster" de 7 DSPs de la famille Analog Device "Sharc" (ADSP2106X). La puissance de calcul du noeud est supérieure à 560 Mflops.

• Des connecteurs pour des cartes mezzanines. Ces cartes autorisent différentes variations d'extension telles que ASIC coprocesseur, "I/O" haut débit ou un second "Cluster" de 7 Sharcs. Dans ce cas, la puissance totale de la carte dépasse le Gigaflops.
[voir fig. 5 : Synoptique Carte de Traitement]

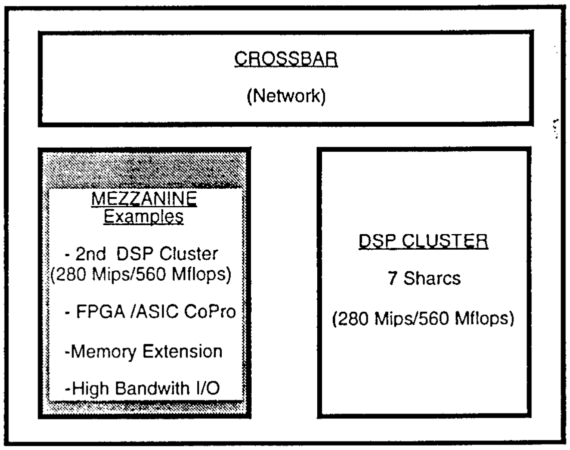

Fig. 5 : Synoptique Carte de Traitement

En plus de la carte principale de traitement existe, pour chaque panier, une carte de servitude regroupant les fonctions de distribution d'horloge, de téléchargement, de "Debug" et d'interface à la Station de Travail Hôte sur laquelle est basé l'atelier logiciel.

La machine est très modulaire. Un système minimum peut ne comporter qu'une paire de cartes, alors qu'un gros système peut être constitué de 5 paniers de 21 cartes et donc dépasser les 100 Gigaflops en technologie 1996.

Par ailleurs, les concepts de la machine suivent de très près l'approche du "Model Year Concept" tels que décrit dans RASSP. Cette particularité lui permet de s'adapter facilement à l'évolution rapide des technologies numériques, notamment celles des processeurs de traitement du signal.
[voir fig. 6 : Evolution Puissance & Débit par Carte]

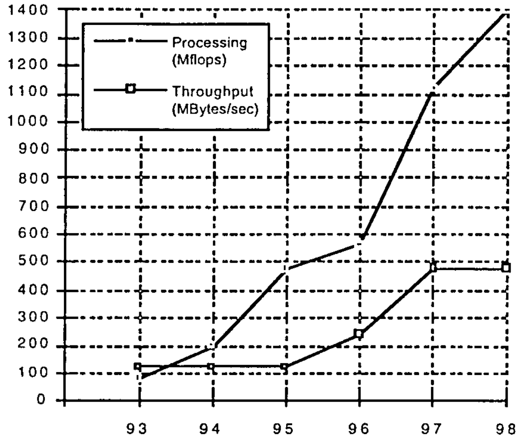

Fig. 6 : Evolution Puissance & Débit par Carte

La machine présente d'excellentes capacités de contrôle temporel. La machine permet tout à la fois le:

- Multi-fonction. Plusieurs traitements indépendants, couplés ou non, peuvent résider dans la même machine.

- Multi-burst. Les traitements s'effectuent sur un ensemble de données (Burst). La structure de ce "Burst" et les traitements associés peuvent complètement changer de "Burst" à "Burst" sans interrompre la machine.

- Multi-mode. Il est possible de changer la chaîne complète de traitement sans réinitialiser la machine.

4 Présentation de l'Atelier Octane

Deux points de focalisation principaux caractérisent l'approche retenue lors de la conception de cet atelier :

- Présenter une productivité maximale, notamment dans la gestion des nombreux processeurs présents.

- Assurer une excellente qualité logicielle, critère lui aussi essentiel lorsqu'un très grand nombre de processeurs fonctionne simultanément et de façon asynchrone. Critère encore plus fondamental dans une utilisation spatiale.

De plus l'atelier présente une interface utilisateur "User Friendly" et une bonne cohérence d'ensemble facilitant son apprentissage en un temps réduit.

L'atelier logiciel peut s'adapter à différentes familles de machines parallèles, à la condition que son modèle de programmation soit de type "Data Flow". Dans un tel modèle, la synchronisation des différents noeuds de traitement s'effectue par les données et conduit à une double encapsulation : celle des communications et celle du traitement.
[voir figure 7 : Encapsulation]

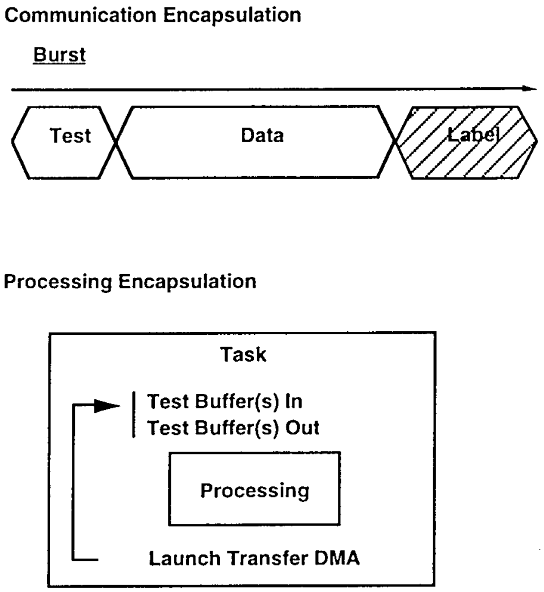

Fig. 7 : Encapsulation

Les six caractéristiques principales de l'atelier sont les suivantes :
[voir figure 8 : Fonctions de base de l'atelier]

- Génération Automatique du Code de Communication. Cette génération est rendue possible par l'encapsulation du traitement qui sépare les fonctions de communication et de traitement. La génération du code de communication joue un rôle majeur dans la productivité de l'atelier et dans la qualité du code.

- Simulateur sur Station de Travail. L'ensemble du code d'une application multi processeur, traitement et communication, peut être simulé et donc mis au point sur station de travail avant son chargement sur la machine parallèle.

• <u>Gestion de Configuration.</u> L'atelier gère le "Makefile" de tous les processeurs installés dans la machine. Travail qui deviendrait très fastidieux, voire impossible à effectuer manuellement.

• <u>Gestion du Parallélisme</u>. Même si une machine parallèle de traitement du signal peut comporter des centaines, voire des milliers de noeuds de calcul, il est rare que le nombre de programmes effectifs distincts soit très élevé. Octane n'effectue la compilation que de ces programmes distincts, autorisant ainsi un gain de temps énorme à la génération du code machine d'un applicatif.

• <u>Exploitation Machine</u>. Octane permet d'ouvrir une fenêtre de "Debug" sur chacun des processeurs installés dans la machine. Un mode trace est disponible en fonctionnement, facilitant la mise au point d'une application complète. La station de mise au point peut être déportée de la machine cible.

• <u>Logiciel de Test Intégré "On Line"</u>. L'atelier génère un code de test intégré au reste du code permettant, en fonctionnement opérationnel, de tester l'ensemble des ressources des noeuds de traitement ainsi que les canaux de communication. Les incidents détectés par ces tests sont automatiquement transférés au contrôleur centralisé externe.

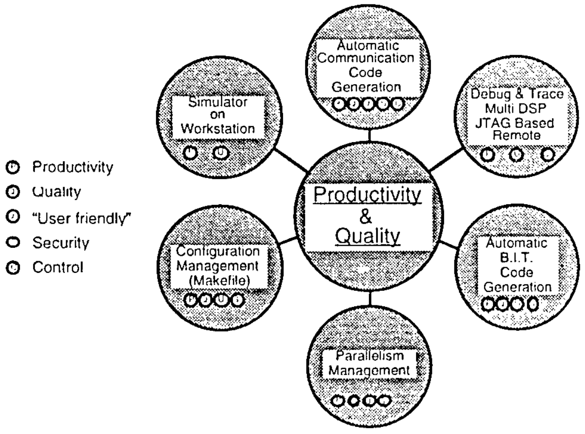

Fig. 8 : Fonctions de base de l'atelier

Pour réaliser l'implantation d'un traitement, l'utilisateur part de la chaîne de traitement. Sur cette chaîne, chaque fonction de traitement du signal est identifiée ainsi que les ressources de base nécessaires à sa réalisation (Principalement la puissance de calcul de la fonction et ses débits de communication avec les autres fonctions).
[voir fig. 9 : Exemple de Chaîne de Traitement]

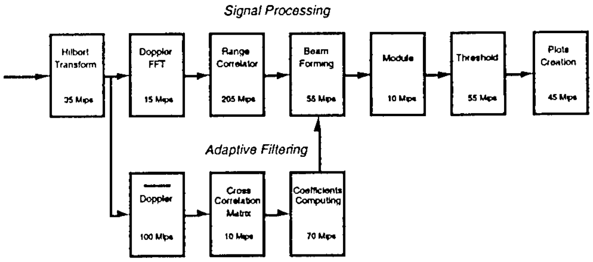

Fig. 9 : Exemple de Chaîne de Traitement

A partir de cette chaîne, l'utilisateur définit la découpe en "Macropipeline" de son traitement. Cette découpe va, le plus fréquemment, permettre de réduire le nombre de logiciels différents à développer en regroupant plusieurs fonctions dans le même noeud de traitement. Pour chaque étage de "Macropipeline" est aussi défini le nombre de processeurs en parallèle qui réaliseront l'étage ainsi que l'axe de découpe de cette parallélisation.
[voir fig. 10 : Décomposition en "Macropipeline"]

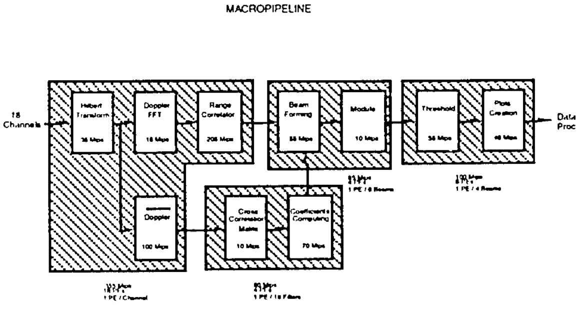

Fig. 10 : Décomposition en "Macropipeline"

La décomposition une fois faite, l'utilisateur rentre dans Octane pour, dans un premier temps, définir la machine cible. Pour cela, il dispose d'un éditeur graphique et d'une bibliothèque d'icônes des cartes de la machine.
[voir figure 11 : Saisie Graphique de la Machine]

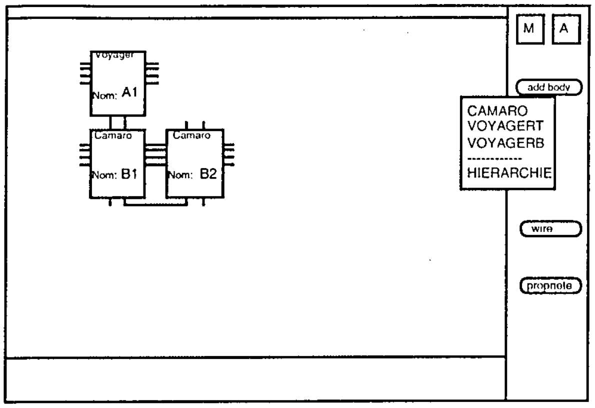

Fig. 11 : Saisie Graphique de la Machine

L'étape suivante consiste, sous le même éditeur graphique, à décrire le traitement sous forme d'un ensemble de processeurs et de leurs liens de communications. Cette description suit la découpe en "Macropipeline" préalablement établi. Pour cette description des échanges inter processeurs , l'on dispose de 3 primitives de communications de base :

- Le "Buffer". Il permet une liaison asynchrone entre 2 processeurs élémentaires.
- Le "Broadcast" . Il donne la capacité à un processeur de pouvoir envoyer ses données à un ensemble de processeurs.
- Le "Store & Forward" . Il assure le remultiplexage de données provenant de différents processeurs avant d'attaquer l'étage suivant.

[voir figure 12 : Saisie Graphique du Traitement]

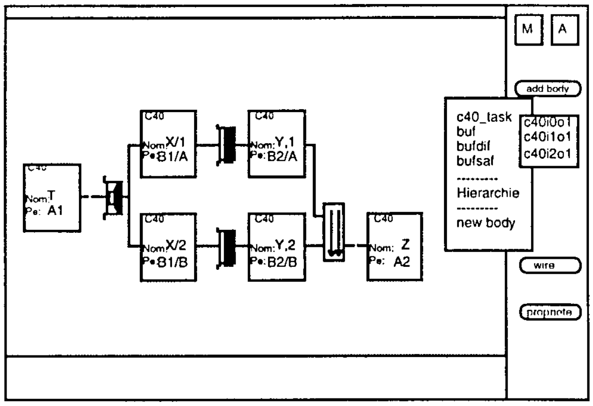

Fig. 12 : Saisie Graphique du Traitement

A ce jour, plus de soixante implantations de ce type sont réalisées avec succès et démontrent par là-même la bonne adéquation du jeu de primitives de base au problème du traitement du signal intensif.

A partir de cette double description graphique, la machine et le traitement, l'atelier Octane va automatiquement effectuer le routage de cette application. Le routage génère :

- Les paramètres de configuration des "Crossbar" du Réseau.
- Le code de communication pour l'ensemble des processeurs installés.

Ce routage automatique est l'un des fondements de l'atelier, notamment sous l'angle de la productivité. Cette productivité générale de l'atelier est corroborée par une analyse faite a posteriori. L'analyse portait sur l'ensemble du code existant dans une application, dont la part écrite manuellement. Il ressort que la part manuelle est inférieure à 10 % de la totalité du code généré.
[voir figure 13 : Répartition du Code Applicatif]

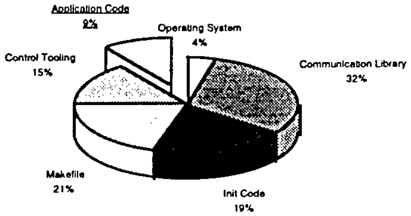

Fig. 13 : Répartition du Code Applicatif

5 Calculateur Spatial

Dans le cas de la réalisation du calculateur de l'OLS mixte, une fois réglé le problème de la matrice de covariance par un ASIC placé juste derrière les codeurs, l'ensemble des fonctions de traitement restant à implanter se prêtent très bien à la mise en oeuvre d'une machine parallèle.

Le choix d'utiliser une machine parallèle offre une solution élégante aux problèmes de redondance du spatial. En effet, le fait de disposer de noeuds banalisés interchangeables associés à un réseau de communication reconfigurable, permet l'implantation des ressources de redondance de façon plus économique qu'une approche câblée.

Par ailleurs, la machine peut être téléchargée et reconfigurée à partir du sol, autorisant une évolution du traitement après le lancement du satellite, en fonction de l'évolution de la menace.

Le fait qu'une machine parallèle soit naturellement modulaire, permet son utilisation dans différentes fonctions de traitement du satellite, tout en conservant un MCV correct (Masse Consommation Volume). C'est un avantage économique marquant, car l'on ne développe qu'un seul équipement.

Comme solution de départ, l'ensemble Camaro/Octane est un bon candidat, car il autorise un fonctionnement de base, du matériel et du logiciel, hautement sécurisé. Cette sécurité est apporté par :

- Les choix architecturaux. Notamment le réseau de communication de type "Direct Routing" évitant tout conflit.
- Le modèle de programmation de type "Dataflow" autorisant la double encapsulation du traitement et des communications.
- La génération automatique du code de communication effectuée par l'atelier logiciel.

Camaro/Octane forment donc une excellente base de départ pour un calculateur spatial. Néanmoins une adaptation importante doit être faite pour tenir compte des contraintes propres aux systèmes spatiaux.

La première adaptation concerne le DSP, car il doit être spatialisé. Pour le calculateur, le choix c'est porté sur l'ADSP 21020 d'Analog Device en cours de spatialisation chez MHS (Matra Harris Semiconductor). L'architecture retenue est cependant adaptée à l'utilisation de tout autre processeur. C'est l'une des richesses fondamentales de l'architecture qui lui confère robustesse, évolutivité et sécurité, trois critères essentiels pour une application spatiale.

Le noeud de traitement est construit autour du DSP. Le DSP étant de type "Harvard", il possède deux "Bus" afin d'améliorer les performances sur les algorithmes de type produit scalaire. Une RAM de type statique est disponible sur chacun des deux "Bus".
[voir figure 14 : Synoptique du Noeud Spatial]

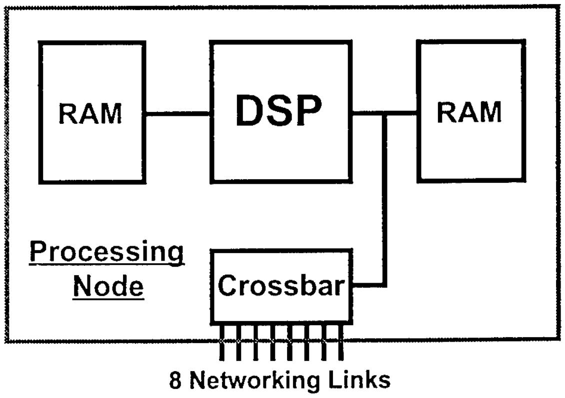

Fig. 14 : Synoptique du Noeud Spatial

Le "Crossbar" présente huit liens banalisés de communication. Il s'agit d'un Asic en technologie "Hard Rad". Ce point est très important, car la majorité de processeurs dont on peut disposer sont plutôt simplement "Rad Tolerant". En cas de défaillance du processeur, le fait de disposer d'un "Crossbar" de type "Hard rad" permet de conserver intacte la fonction de communication du noeud et facilite ainsi grandement la reconfiguration de la machine. L'isolation et la non propagation des pannes ont été des critères déterminants dans le choix de l'architecture de communications.
[voir fig. 15 : Noeuds de Base avec liens Externes]

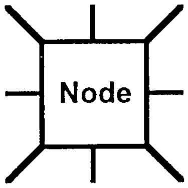

Fig. 15 : Noeud de Base avec Liens Externe

Une carte comprend quatre noeuds de ce type. Chaque noeud possède un lien de communication avec les trois autres noeuds. Les cinq liens restant de chaque noeud, soit vingt au total, sont ramenés au connecteur de la carte.

[voir figure 16 : Carte avec 4 Noeuds]

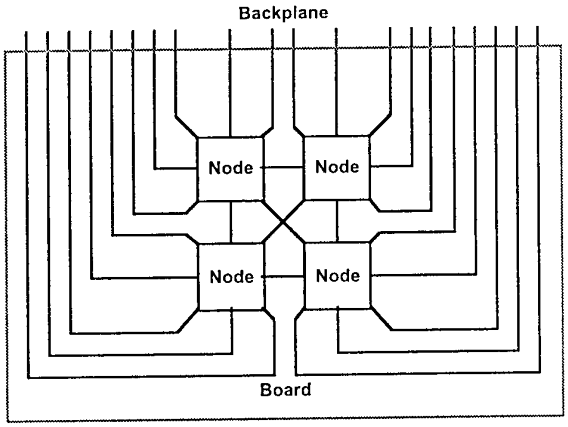

Fig. 16 : Carte avec 4 Noeuds

L'assemblage de la machine complète ce fait par association du nombre de cartes nécessaires pour le traitement, redondance incluse, sur une toile de fond imprimée.
[voir fig. 17 : Exemple de Machine à 16 Noeuds]

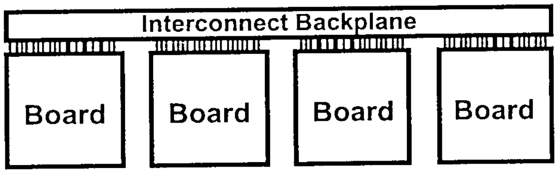

Fig. 17 : Exemple de Machine à 16 Noeuds

La topologie réelle de la machine est fonction de l'interconnexion des noeuds assurée par la toile de fond. Il est donc très facile d'adapter pour chaque calculateur la puissance de calcul installée et la topologie globale.

De la topologie retenue, dépend en bonne partie la capacité de reconfiguration de la machine en cas de défaillance d'un noeud.

De ce fait, on privilégiera des topologies ou les noeuds sont fortement couplés afin de disposer d'un grand nombre de chemins de déroutement en cas de reconfiguration.

La topologie "Nid d'Abeille" est sur ce plan tout à fait excellente.
[voir fig. 18 : Topologie Nid d'Abeille à 16 Noeuds]

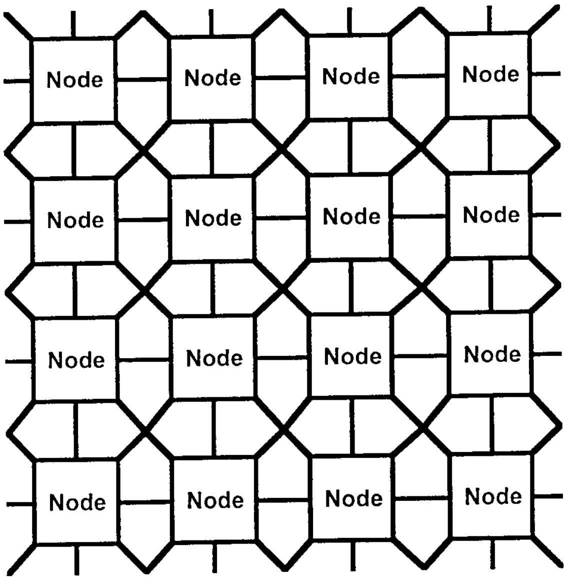

Fig. 18 : Topologie Nid d'Abeille à 16 Noeuds

Les liens non utilisés des noeuds périphériques peuvent servir aux entrées/sorties de la machine.

Bien d'autres topologies sont réalisables, par exemple, dans le cas d'une machine à six noeuds, la configuration en "Étoile" présente d'excellentes qualités de redondance.
[voir fig. 19 : Topologie en Étoile à 6 Noeuds]

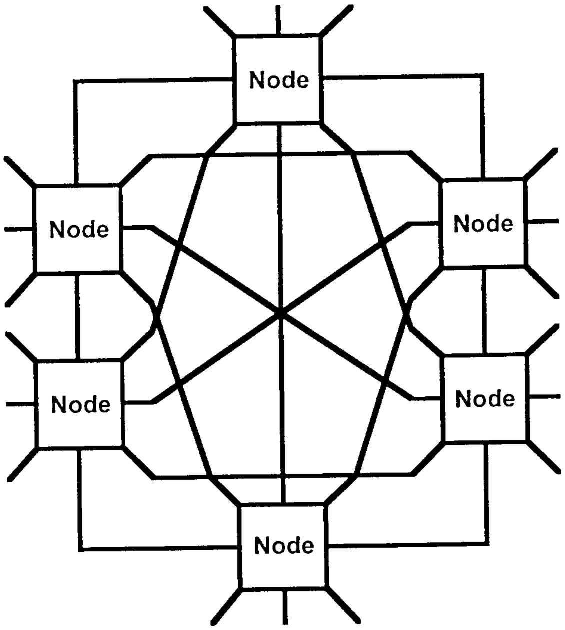

Fig. 19 : Topologie en Étoile à 6 Noeuds

6 Conclusions

L'approche retenue, pour le calculateur d'antibrouillage spatial, présente un excellent faisceau de qualités sur les plans de la sûreté de fonctionnement, de l'implantation de la redondance, de la résistance à l'évolution des spécifications des algorithmes et de la limitation des risques par la mise en oeuvre d'une technologie éprouvée bien adaptée au spatial.

L'obtention d'une très bonne sûreté de fonctionnement du calculateur, tant sur le plan matériel que logiciel, a été une préoccupation constante. Elle est obtenue par la reprise de concepts éprouvés au sol pour le traitement du signal intensif, l'ensemble Camaro/Octane, combinée avec des règles d'architecture et une technologie propre au spatial.

La gestion de la redondance de la machine parallèle s'avère plus économique en volume de matériel qu'une approche câblée classique. Les noeuds de traitement étant banalisés, il n'est pas nécessaire de doubler ou tripler chaque fonction à implanter comme dans une solution classique. Il suffit de disposer d'un ensemble de noeuds de réserve.

L'architecture du calculateur n'est pas dépendante des spécifications précises du traitement implanté. Cette orthogonalisation permet de résister aux évolutions des algorithmes dans la phase de définition du projet, et même après le lancement du satellite. Cette propriété permet aussi l'utilisation du calculateur pour d'autres fonctions que l'antibrouillage, sans développements spécifiques.

Les risque inhérents au développement du calculateur sont limités de par l'utilisation de technologies classiques et éprouvées en spatial associée à une indépendance de l'architecture vis à vis du processeur utilisé.

Tactical reconnaissance by a constellation of small satellites

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ABSTRACT

The need for tactical reconnaissance satellites has been well assessed in the recent few years. Many concepts have been explored and proposed, mainly based on small satellites. The present technology permits the implementation of good performance instruments suitable to withstand with the limited resources of the small satellites. Alenia Spazio has been studied the architecture of constellation of small satellites both for civil and military applications since four years and the scope of this paper is to present the status of the projects. Despite the proposed satellite configuration is tailored on military requirement, the dual use of technology and resources is of paramount importance in a world where investments must be returned and optimized. This aspect with its implications shall be discussed in relation to the system architecture.

The peculiar and most important requirements of tactical reconnaissance are surely the day/night, all weather capabilities and the high revisit time. The SAR (Synthetic Aperture Radar) is the only instrument able to operate in those environment especially when very high resolution is not the driving factor. Consequently it is used as satellite main payload . In addition to the microwave instrument, two other payloads and a function are embraced : an IR sensor, an ELINT package and a data storage and distribution function embedded in the normal data transmission subsystem.

The combination of the three payloads increase remarkably the detection capability of the system and in same case it is possible to recognize the targets. Smart utilization of data storage resources provide additional services like messaging , transport and distribution of remotely processed images and others.

The choice of the radar frequency depends on many factors like: detection capability, physical dimension of the electronics and antenna, power consumption due to the efficiency , processing complexity . Simulations and real data demonstrate that the detection depends on frequency in a very complex way. Despite the S-band was found generally better especially for metallic targets, in some situations (particular angles of view, etc.) or for particular kind of targets, where contrast between pixels is more important than signal to noise/ clutter ratio or natural targets , X-band presents some advantages . In a more ambitius context Ku and Ka bands are considered because the antenna size is very small and single pass interferometry can be implemented by placing two antennas on the same satellite.

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1. Introduction

The satellite system under consideration is an enhanced version of the COSMO system being proposed for civilian applications (see Ref. [1],[2]) which, with suitable modifications and additions to the payloads complement, is well suited to support tactical operations.

Tactical applications stress the importance of short revisit intervals over selected sites and the use of high resolution SAR instruments for the detection of surface targets independently from weather and sun illumination. This task is achieved implementing a constellation of small dedicated satellites carrying SAR instruments. The addition of infrared sensors, with high to moderate geometric resolution, say in the 20 m range, seems also an important addition for tactical uses when data fusion is considered. Electronic Intelligence, meant as a listening capability, was also considered in the preliminary mission design, since it may reveal an increase of electronic activity from radars, or ground-based communication equipment, possibly linked to the enemy's military activity. Again, the utilization of ELINT data must always be seen in a data fusion context. Both tasks require implementing a second dedicated constellation of small satellites, which is here proposed to be optionally added to the first one.
To insure real-time access to spacecraft assets, both in terms of commanding the operating modes, activation times and functions of the spaceborne instruments as well as near real-time retrieval of satellite gathered data, indipendently from the time-evolving satellites' orbital positions and Mission Control Center location, the satellite constellation is assisted by a Multi Satellite Data Relay System (MSDRS) which is proposed to be unconventionally made up by a further constellation of six small satellites in ICO (Intermediate Circular Orbit) interconnected via intersatellite links. The key elements of this system architecture, including both the tactical Surveillance constellation, the IR plus ELINT satellite constellation and the MSDRS complement are below discussed and reviewed.

2. The SAR satellite constellation

Previous studies have shown that, for a tactical scenario, a revisit interval of between twelve and six hours is necessary to support tactical operations. In addition a good geometric resolution, of the order of 1 m, is necessary to pinpoint targets of tactical interest whose general features and deployment or presence in the tactical scenario may be known from previous activity of strategic observation satellites, or ground intelligence. Day-night and all-weather operation is mandatory for tactical support, which rules out optical sensors in favour of radar instruments which, due to the resolution requirements, must be SARs. To meet the revisit intervals requirements at any latitude, a constellation of five small satellites injected in a 500 km sunsynchronous transverse orbit is proposed. Full accessibility to any point on Earth within the +- 85° latitude belt is insured by relying on both spacecraft roll steering and cross-track electronic beam steeering to be able to access, in sequence, target areas spaced apart by about 400 km within a fraction of a second. With this system configuration it is possible to have access to any site in the above latitude band with a maximum delay of 12 hours at the equator decreasing to 4-6 hours at middle latitudes. Adding a second ring of five satellites, this time in a near-noon plane, halves the mean revisit interval to six hours for sites at the equator down to 2-3 hours at middle latitudes.

The SAR instruments operates at X-band , in a Stripmap mode, and can provide a 1-look geometric resolution of the order of 1 m over a swath which, depending on the off-nadir angle, is in the 10 to 20 km range. The choice of the X-band ,over S-band, is motivated by comparable or better contrast ratios for certain surface targets. The SAR antenna dimensions are 2 m in the along-track direction by about 4 m in the cross-track direction. The peak pulse power is of the order of 3 kW with a duty of 5 to 10% depending on the off-nadir angle, for which a maximum value around 50° is projected. Since in a tactical scenario only few images per orbit are required, an instrument operating duty of 5 % of the orbit period was found more than adequate, with significant attendant savings in terms of the mean orbit energy requirements. To cope with the high data volumes generated, one takes advantage of temporary storage and near-lossless advanced data compression techniques. As an example, exploiting chaotic compression - a technique being developed in Italy by TER - raw SAR data can be compressed by a 20:1 factor without appreciable losses in image content, which also means target detection and, compatibly with the geometric resolution, target identification. Accordingly each SAR raw image is temporarily stored in a buffer, then subjected to compression and sent to ground via the above mentioned Data Relay satellite system at much lower speeds, thus exploiting the continuous visibility of the data relay satellites from the Surveillance satellite. Assuming 0.8 Gbyte per raw SAR uncompressed image, 40 Mbyte after compression and a transmission bit rate of 8 Mbit/sec only, the transfer time of each compressed image to the Mission Control Center will take 40 seconds: which can be considered a near- real time data transfer to all practical effects. A redundant mass memory of 8 Gbit will make up the necessary storage means to be able to process and store a second SAR image, taken at a short time interval from the previous one (this is an important requirement for a tactical scenario) while the latter is being transmitted to ground via the relay network.

The estimated SAR payload mass, taking advantage of the recent technology improvements, can be kept within 100 kg; the data compression and storage system will add another 20 kg for a total of 120 kg. The DC power consumption , at full operation, is around 800 W, including fast beam steering, data compression and storage. However, considering an operational orbital duty of 5 % - outside which the bulk of power consuming units is switched off - the mean orbit energy demand should not exceed 260 Whr, which can be easily met with a medium size solar power plant.

3. The IR / ELINT satellite constellation

Besides the SAR satellite constellation, a second constellation of small satellites has been conceived and preliminarly sized, to cope with the additional requirement of detecting traces of military-related activities which can manifest under the form of thermal or radiofrequency emissions.

3.1 The Infrared sensor

To make sense a thermal imager should have a geometric resolution better than 30 m, to be able to pick hot spots due to heat-generating artifacts, above the ground thermal emission. At this resolution, the size of an infrared imager is not such to be easily accommodated on the same small satellite that carries the SAR instrument, even if , in principle, the instrument could be flown in the same transverse sunsynchronous orbit where the SAR satellites will be conveniently injected. Taking into account both the desirability for an ELINT package (which would be accomodated along with the thermal imager on the same platform), a second small constellation of six satellites, flying at a lower altitude around 350 km, seems justified. Each spacecraft would carry three angularly squinted infrared telescopes with an aperture of 40 cm, a short focal lenght, and a viewing arc of 20° each, thus providing three contiguous coverage strips for a total viewing arc of 60° or 350 km on ground. At nadir, the projected resolution at midband is about 20 m. The focal plane of each telescope would carry an assembly of about 6000 detectors working in the full 8-12 micron band. The estimated mass of the complex of three telescopes and electronics is around 120 kg. The payload would generate a data volume around 50 Mbit/sec, which can be losslessly compressed by a factor of four becoming of the same order of magnitude of the compressed dataflow from the SAR payload, and can be thus relayed through the Data Relay network . The estimated DC power consumption is around 300 W; however taking into account the mean orbital duty - of the order of 15 % - and the units always on even in cruise mode, the mean orbit energy requirement is estimated to be around 80Whr.

The six satellites of the constellation are injected by triplets spaced by 120° , in two sunsunchronous orbital planes, angularly spaced by about +-45° with respect to the SAR constellation orbit plane laying, so that the infrared satellites overpass the sites during the morning and afternoon hours as well as during the late evening and during the night. The mean revisit interval is around six hours for sites at the equator, decresing to a few hours for sites at higher latitudes.

3.2 The ELINT package

The listening capability has been limited to the L, S and X bands for pinpointing hostile long and medium range surveillance and tracking radars. As a starting point we have considered the capability of locating these emitters within few km, sufficient to direct air-raids, and to discern their key characteristics such as operating frequency, PRF, modulation , to identify at least the emitter type.

For the intended purpose the ELINT coverage is an annular ring tangent to the Earth as seen from the satellite orbital altitude: in this way the radar emissions from the radar beam, usually directed towards the horizon, or from the close-in sidelobes, will have the greatest probability of entering the satellite antenna, thus maximizing the detection sensitivity. Preliminary link budgets show that a satellite antenna spotbeam of about 12 degrees with a boresight canted by about 57° with respect to the local nadir, would provide the necessary gain to detect a 100 kW pulsed radar, when looking at it through the radar antenna sidelobes, as well as a reasonable coverage. Implementing a mechanically spinning antenna, at 3 revolutions per minute, the resulting coverage will be in form of an annular ring with an outer diameter of about 2000 km and a depth of 1300 km. As the satellite moves in its orbit, the annular ring sweeps an area as wide as its projected diameter. Besides, during one antenna revolution (20 seconds) the annular footprint advances by about 150 km, on Earth, implying that, depending on the satellite-emitter geometry, the latter may remain within the annular ring for up to 8 revolutions and thus can be observed with different aspect angles, giving rise to a data sequence enhancing its detection and location.

To implement the required coverage, the ELINT antenna will be made by three 80 cm diameter reflectors operating at L, S and X band, mounted at 120° on the same spinning platform. A two-axis monopulse feed system will be used to improve the

location accuracy of the ground emitters. At the lower frequencies the predicted 'single measurement' location accuracy is around 15 km, at the coverage edge: this can be considerably improved by both observing the apparent emitter location as the satellite moves in its orbit and combining multiple data set obtained from subsequent satellite passes. The antenna overse at X_band even allows implementing multiple beams in the elevation plane, to further push the achievable location accuracy.
At 3 rev/min each potential target will remain in the rotating antenna 3 dB beamwidth for 660 msec, available for signal analysis hence emitter detection and identification. The receiver architecture and technology is a matter of technology trade-offs: a parallel channellized approach, using electro-optical technology , appears a good candidate for the assumed 0.5 GHz analysis bandwith at each of the three operating frequencies.
Assuming to perform on board all signal processing, the data rate generated by the ELINT package has been estimated to be around 30 kbit/sec., thus negligeable with respect to the data volume generated by the infrared payload. The estimated ELINT payload mass of 50 kg is due mainly to the spinning antenna platform, wherein lightweight techniques can be however adopted. The estimated DC power consumption is around 200 W, including processor and spinning table. Again, taking into account the mean orbital duty, the required orbit energy turns out to be around 80 Whr.

3. The Multi Satellite Data Relay System

The operation of a tactical constellation implies to command and control in real time the spacecraft operation from a Mission Control Center independently from the orbital position of the satellites, and the ability of receiving the satellite gathered data in near real time, to support the tactical operations. As an alternative to the conventional approach of using a pair of geostationary satellites, we considered solutions based on a constellation of ICO satellites interconnected by intersatellite links, to improve the coverage, operational flexibility and reduce costs. The full results of this study, fully in-house funded, will be reported in a future paper: here we will only give a summary of the most appropriate system configuration. The MSDRS (Multi Satellite Data Relay System) will consist of three satellites in a near polar orbit and three satellites in a near equatorial orbit , both with an orbit period of about six hours. Each triplet is interconnected via intersatellite links, and has means to communicate with ground terminals when in view of the satellites. as well as with the LEO satellites.

The intersatellite links are fundamental to guarantee a 100% connectivity between each LEO satellite and any ground station independently from the orbital position of either satellites. The MSDRS system allows managing the multiple data flows originated by, or destined to, the LEO satellites with rather simple payloads, also thanks to the reduced datarates owing to the advanced compression techniques adopted. The MSDRS configuration does also provide inherent redundancy in that multiple paths are available between each ground station and any LEO satellite of the constellation, enhancing the probability of being able to carry out a task (sending commands or receiving data) even in case of partial or total failures of one of the relay satellites.

The communication package will consist of:
- a dual antenna Intersatellite link section, with two opposite looking fixed mounted antennas of 60 cm diameter and two 5 W transmitters operating at 60 Ghz;
- an Interorbit link section, also operating at 60 Ghz, provided with two mechanically steerable antennas of 30 cm diameter to provide two simultaneous and independent

accesses from two LEO satellites transmitting 10Mbit/sec datastreams from LEO terminals equipped with 30 cm steerable antennas and 10 W transmitters;
- a ground-to-satellite link package, operating at 20/30 Ghz, which includes a 60 cm diameter dual frequency steerable antenna and a 5 W transmitter, supporting up to 3 simultaneous downlinks at 10 Mbit/sec, when operating in conjunction with a Mission Control Station equipped with a 3 m diameter antenna;
- an S-band dual transponder, able to: a) receive commands from ground and either to terminate them onboard or to retransmit them to the LEO satellite(s) in view, or to reroute them to the nearest data relay satellite; and b) transmit DRS generated housekeeping telemetries, or accepting and retransmitting to ground telemetry signals generated by the LEO satellite in view, or to send to ground telemetry signals originated by a non visible LEO satellite and routed via the nearest relay satellite.

All data channels are demodulated and regenerated on board to implement data rerouting; a switching matrix, operated under ground control, is used to establish the interconnection paths for the various links: single hop LEO to ground via the DRS and multiple hops LEO to ground via interorbit and intersatellite links, for both the high speed (10 Mbit/sec) data channels and the low speed CMDs and TLM data.

The communication package mass is estimated around 80 kg, with a Dc power consumption of 150 W ; nevertheless the projected operational orbital duty will, probably, not exceed a 30% value, this impacting positively the spacecraft energy balance. The practical implementation of the satellite for the MSDRS approach requires a small satellite of about 300 kg at launch , about 40% of which for LEO to ICO transfer, hence a net drymass of the order of 180 kg. The small size allows implementing the constellation with two launches of three satellites each in the two specified orbital planes.

The equipment installed on board each LEO satellite, consisting in a 60 Ghz 10 W modulator and transmitter, and a steerable 30 cm antenna will have an estimated mass around 15 kg with a DC power consumption of 80 W; for an operating orbital duty of 15 % (worst case), the orbital energy requirement is less than 15 Whr.

4. The satellite for the LEO constellations

Considering the envelope of the payloads requirements, respectively 135 Kg and 275 Whr mean orbital energy for the SAR satellites, and 185 kg and 175 Whr mean orbit energy for the IR/ELINT satellites, it turns out that the same basic platform can be adapted for both missions , by trading the larger payload mass of the IR/ELINT satellites with the reduced energy demand. Assuming a payload fraction around 0.5 of the drymass the spacecraft weight would be in the 350-400 kg range, to which a suitable propellant mass for orbit keeping will have to be added for a mission lifetime of at least 5 years. This may lead to a launch mass of the order of half a ton, which is compatible with the launch capability of nearly all small launchers being developed and also with multiple launches with larger vehicles. The main platform characteristics would not be dissimilar, except minor points, from those already described with reference to the proposed COSMO system for civil applications (see e.g. Ref. [3]).

5. Conclusions

A system architecture capable to satisfy high revist time and high spatial resolution images has been presented as derived from the civil COSMO project. The same platform could be adopted to complement the SAR payload with military application sensors.

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Interpretation of Passive Microwave Radiances for Tactical Applications: Current and Future Capabilities of the Defense Meteorological Satellite Program (DMSP)

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1. Introduction

The DMSP program is the Department of Defense polar satellite system chartered to provide high quality meteorological data to strategic planners at major military command centers such as Air Force Global Weather Central in Omaha, Nebraska, as well as to tactical forces in the field. DMSP has a long history of flying state-of-the-art microwave instruments that derive vertical temperature and water vapor profiles, and detailed surface and near-surface properties such as soil moisture, and ocean surface wind speed. These microwave sensors compliment the prime sensor, the Operational Linescan System (OLS). The OLS is a cross-track scanning cassegrain telescope that samples in the visible and infrared wavelengths, featuring near constant horizontal resolution across the scan. Figure 1 shows a Advanced Very High Resolution Radiometer (AVHRR) channel 1 at 0.4-0.6 microns (1.1 Km resolution at nadir only) . At the edge of scan, the AVHRR pixels become elongated, whereas the OLS remains nearly constant. The data from Figure 1 were taken at the Aerospace real-time groundstation with DMSP Flight 11 transiting at 1450Z on 26 April of 1995, and NOAA 12 at 1541Z on the same day. The coverage of these passes were virtually identical, but the difference in resolution between the two sensors is very apparent. The OLS has an additional capability of being able to image in the visible at night making use of reflected moonlight. Figure 2 is an example of the low light capability showing Japanese fishing fleets in the Pacific off the coast of Japan.

DMSP has recently flown the first operational water vapor profiler in the microwave regime (the Special Sensor Microwave Water Vapor Profiler SSM/T-2, hereafter referred to as T-2) to compliment the microwave temperature sounding capabilities of the Special Sensor Microwave Temperature Sounder or SSM/T-1 (hereafter referred to as T-1) as well as the microwave imager, the SSM/I (hereafter M/I). In the following sections, these sensors are discussed in terms of using the measured calibrated radiances as useful imager that can characterize background types, changes in surface emissivity, rain detectors, and as indicators of suspended ice. One "visual algorithm" is discussed, and a more complicated numerical weather prediction visual technique is outlined.

2. Brief Description of DMSP Microwave Instruments: Current Capability

The T-1 and T-2 are through nadir or equivalently, cross-track scanning (perpendicular to the velocity vector of the spacecraft) instruments having the property (like the AVHRR) that the pixel size grows as a function of scan angle. The T-1 was originally flown as an experiment in the early 1980's in order to demonstrate the capabilities of performing temperature profiling in the 50-60 Ghz regime. The T-1 has seven channels with very low noise characteristics, typically less than 0.4 Kelvin at all frequencies. The T-2 was added to the T-1 in the early 1990's again as an experiment to prove the capabilities of water vapor profiling using three channels on the wing of the very strong 183 Ghz water vapor resonance line, one window

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channel at 91.655 Ghz, and a mixed window, atmosphere channel at 150 Ghz. The noise characteristics of the T-2 are equivalent to the T-1. Vertical resolution in the atmosphere is achieved by sampling in frequency on the wings of a strong absorption features. The window channels provide surface characterization in order to correct atmosphere channels for any surface contamination. The M/I is a very different device in that the field-of-view is fixed with respect to nadir, and the instrument scans in a continuous circular fashion taking data approximately 50 degrees either side of the satellite sub-track, and calibrating during the remainder of the scan. M/I calibrated radiances are used today as "imagery" products. The M/I has four frequencies from 19-85 Ghz. The channels are all dual-polarized with the exception of the 22 Ghz. The first M/I flew on Flight 8 in 1987 and is now a key sensor for the Air Force and Navy forecasters. The T-1 and T-2 are used operationally as "profilers" and not as "imagers". The following section discussed the DMSP microwave sensor suite in terms of "imagery" data only.

3. Microwave Radiances As Imagery

In order to fully exploit all DMSP and NOAA microwave data (both cross-track and conical sensors) as imagery, there are adjustments to the radiances that are required merely due to the differences in viewing geometry. Ideally, quantitative correlation of data from the conical M/I, and the cross-track T-1 and T-2 is required. In order to compare data, the cross-track scanning radiances must be adjusted for polarization rotations. Figure 3 illustrates the magnitude of the adjustment. This scatterplot shows M/I 85 Ghz Horizontal polarization vs T-2 91.655 Ghz mixed polarization. The theoretical envelope in which the radiances fall is shown by the two heavy lines. Points falling outside this envelope are cloud contaminated pixels. Figures 4 and 5 illustrate M/I 85 and T-2 91.655 adjusted imagery.

Two techniques will be illustrated in order to provide insight into microwave radiance imagery interpretation. The first technique takes advantage of today's powerful workstations and 24 bit display devices. Our first "visual algorithm" is illustrated in Figure 6. This figure represents a 24 bit combination of T-2 data. In the red color gun is mapped the 183.31 ± 7 Ghz radiances, in the green color gun is mapped the 91.655 Ghz radiances, and in the blue color gun the 150 Ghz radiances. The 183 Ghz water absorption line is the strongest below 200 Ghz. The 150 Ghz channel is a partial surface, partial atmosphere channel subject to water vapor absorption, and the window channel at 91.655 Ghz completes the selection. The "visual algorithm" examines a complex scene that shows a very active frontal system to the west of Chile. The OLS infrared is shown in Figure 7 for reference. In this complex scene, the "visual algorithm" attempts to locate heavy rain. The 183 and the 150 Ghz channels will be scattered by the raindrops so low brightness temperatures are expected. The 91.655 Ghz surface channel should completely dominate in these conditions. Therefore, the expectation is to "see" very little red and blue in areas of heavy rain, but substantial green. This is precisely what the "visual algorithm" sees in this multispectral display. The analyst can interactively modify color lookup tables in order to maximize contrast for data interpretation. This is analogous to real-time optimization of multiple linear regression coefficients in statistical methods. Verification of these findings are done by calculating rainrate contamination by the accepted linear regression algorithm (Hollinger, 1989). This is an extremely efficient tool for the forecasters to evaluate storm intensity, rainbands in tropical storms, and for climatologists interested in the global distribution of rain. One particularly significant advantage of this algorithm is that it appears to detect rain over all backgrounds. Traditionally, the M/I rainrate algorithm is only applicable over the oceans.

The second technique of interest is more complex than the first visual technique. Numerical Weather Prediction analysis and forecasts are used as input to a microwave radiative transfer model. Conventional fields of atmospheric temperature and mixing ratio at 15 atmospheric levels are mapped to appropriate microwave brightness temperatures over the entire grid. These model predicted fields can now be intercompared to in-situ microwave radiances from DMSP sensors. Figure 8 illustrates measured T-1 brightness temperatures at 50.5 Ghz, an atmospheric window channel. The bottom left panel is the predicted brightness temperatures without modeling clouds. The final product is the lower right panel of predicted brightness temperatures including cloud effects. Typically, the forecaster uses numerical weather prediction model data only as guidance in order to begin a forecast. The microwave radiances have been included in the model data by virtue of being assimilated as a temperature and water vapor sounding. However, rain and cloud signatures in the microwave radiances translate into reduced accuracy atmospheric soundings that ultimately get assimilated into model analysis and forecasts. Comparing the numerical weather prediction data inverted to radiance space to the in-situ radiances can be a powerful tool to re-insert lost (or simply not correctly modeled) information such as the accurate location of water vapor, clouds, rain, and ice. Ideally, the in-situ radiances could be assimilated into the model radiances to provide new information back to the model. For now, a comparison of model "radiances" to in-situ radiances can be used to improve both strategic and tactical forecasts. This technique is still very new and will be worked on extensively in order to prototype an operational system for the future.

4. Future Microwave Sensors: DMSP and NOAA

DMSP will fly the SSMIS on the next generation Block 5D3 spacecraft. This sensor combines the T-1, T-2, and M/I in a single conical scan device . This will optimize data for "visual algorithms" since the viewing geometry (thus polarization) is constant, requiring no subsequent corrections. This sensor will provide very high resolution co-registered data at all frequencies. The SSMIS will also add significantly to the overall earth coverage due to the increase in active scanning area. Finally, the first mesospheric sounding capability will be a key feature of the SSMIS. Soundings to 70 Km will now be possible worldwide. In addition to the SSMIS, NOAA will be flying the AMSU A and B on NOAA K. These instruments are cross-track microwave sensors and will require polarization corrections in order to be intercompared to the SSMIS during the Calibration and Validation phase of the program. AMSU A and B are designed to retrieve temperature and water vapor at similar frequencies to the SSMIS.

5. Conclusion

The notion of microwave radiance as imagery is introduced as useful to a forecaster in much the same fashion as a visible or infrared image. A simple "visual algorithm" was presented whereby atmospheric intelligence is extracted without complex and computer intensive calculation. A more complex technique of comparing calculated radiances from numerical weather prediction models to in-situ measurements was also introduced. This technique of "radiance assimilation" is currently being actively worked by the numerical weather prediction communities. Their interest is also in using the data to improve model forecast skill. The focus that is intended from this work is to intercompare model "radiances" to in-situ radiances and visual algorithms to improve the skill of the real-time forecaster.

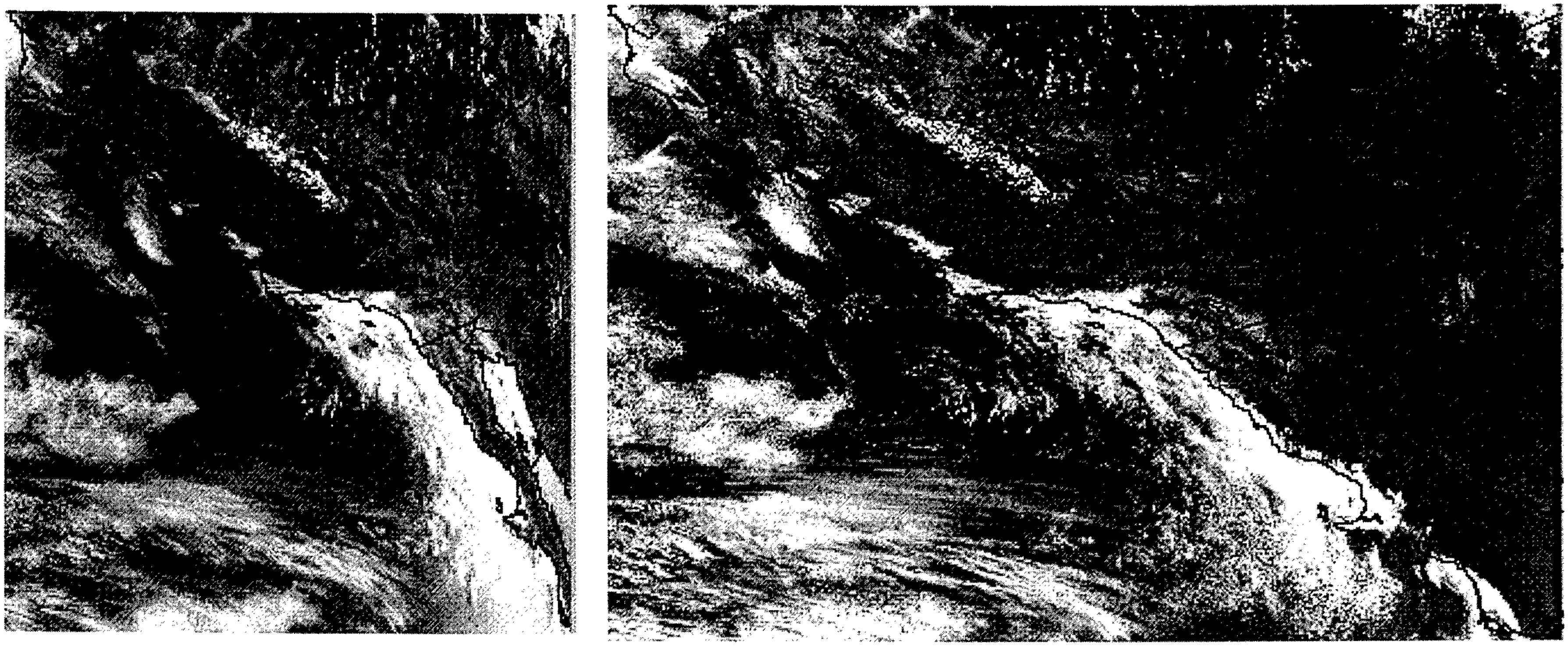
6. Acknowledgment

The authors would like to thank Dr. Carol Selvey of the Aerospace Corporation DMSP Environmental Applications Center for providing the microwave radiative transfer simulation and numerical weather prediction model system results.

7. References

[1] J. Hollinger, "DMSP Special Sensor Microwave/Imager Calibration/Validation , 20 May 1991.

NOAA AVHRR and DMSP OLS



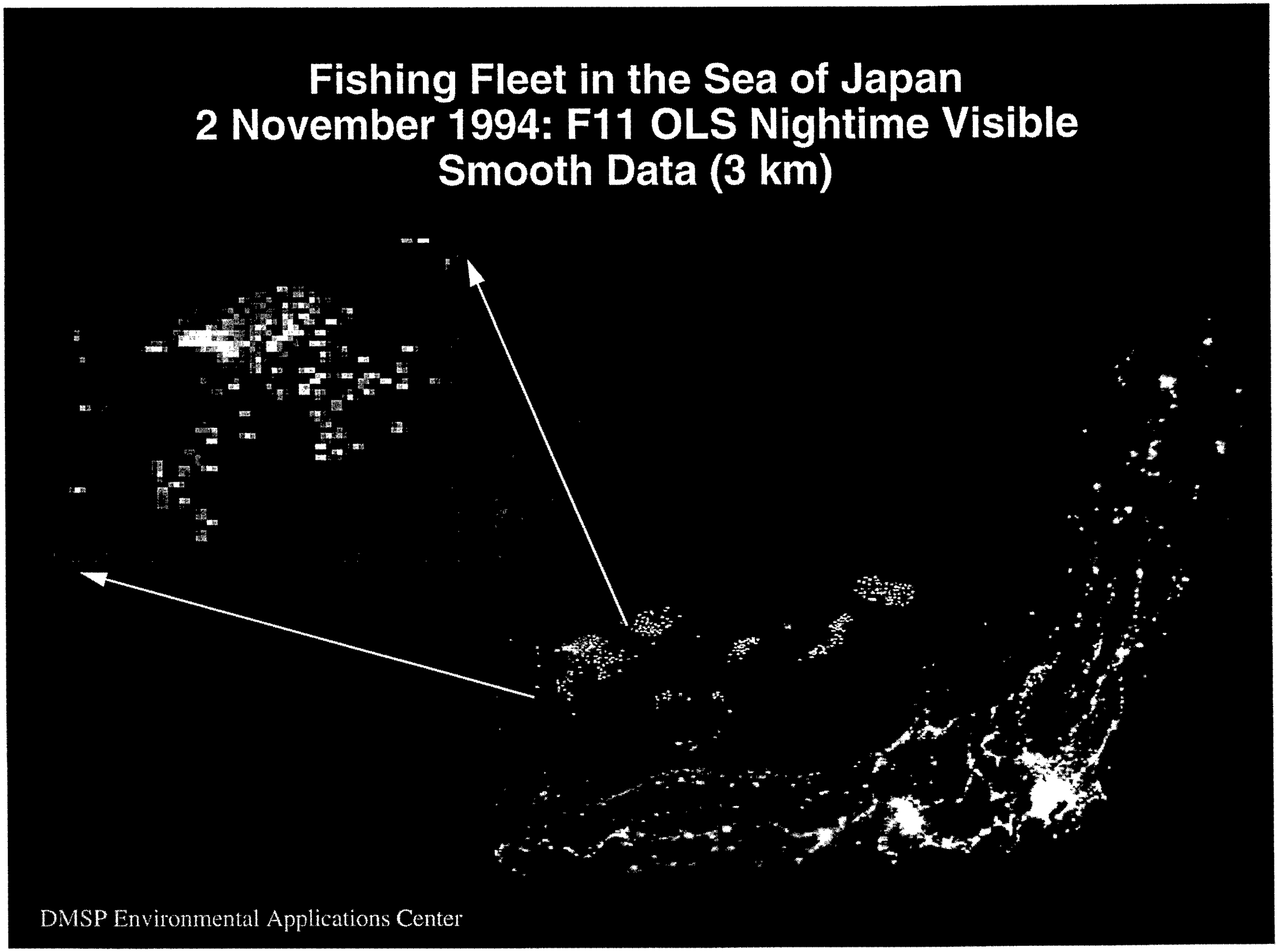
NOAA Channel 1 0.4-0.6 Microns

1.1 Km Resolution At Nadir

DMSP OLS Channel 1 0.4-1.1 Microns

~ Constant 0.5 Km Resolution

Figure 1



Fishing Fleet in the Sea of Japan
2 November 1994: F11 OLS Nightime Visible
Smooth Data (3 km)

DMSP Environmental Applications Center

Figure 2

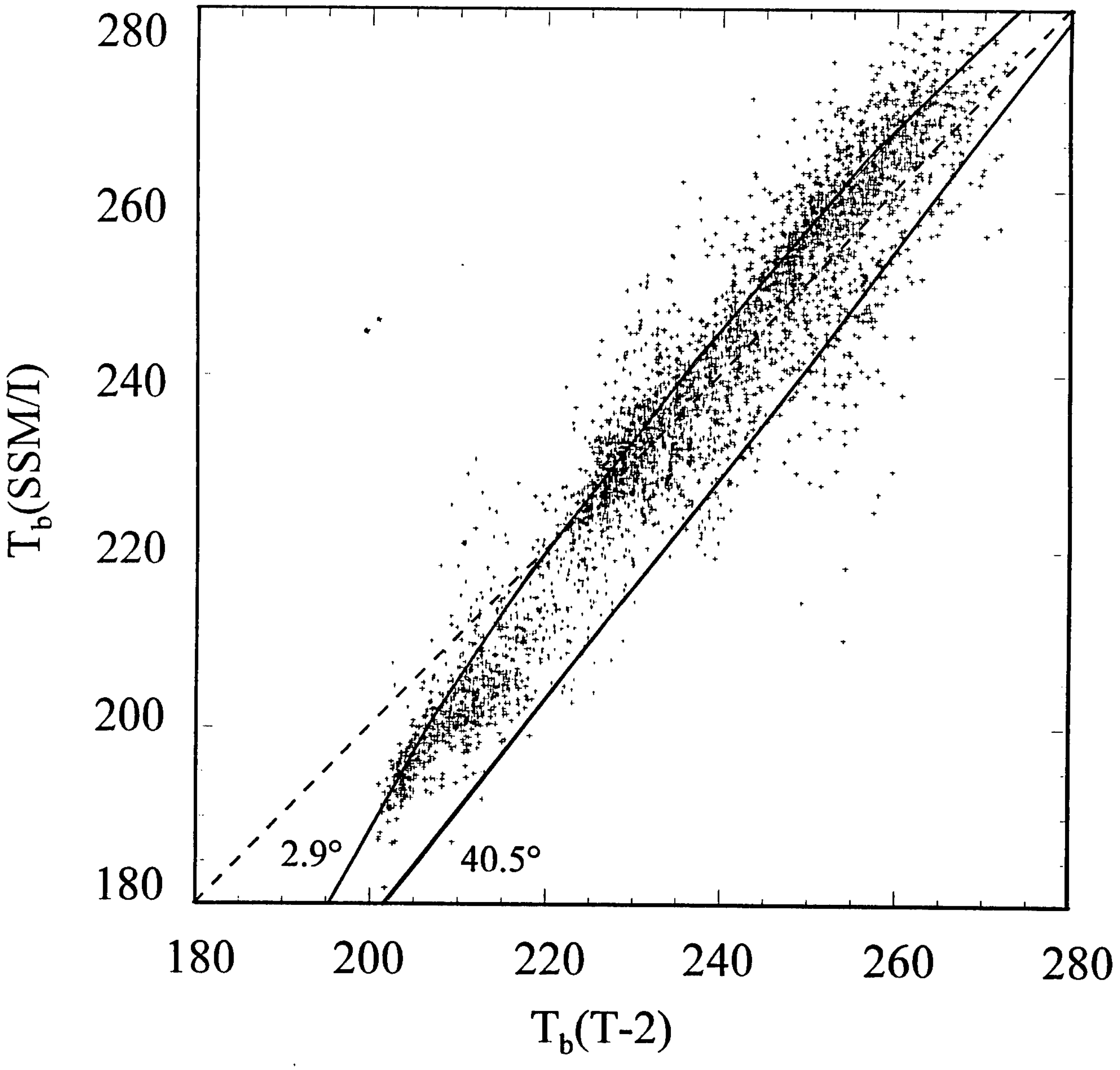

280
260
240
220
200
180
180
200
220
240
260
280
T_b(SSM/I)
T_b(T-2)
2.9°
40.5°

Figure 3

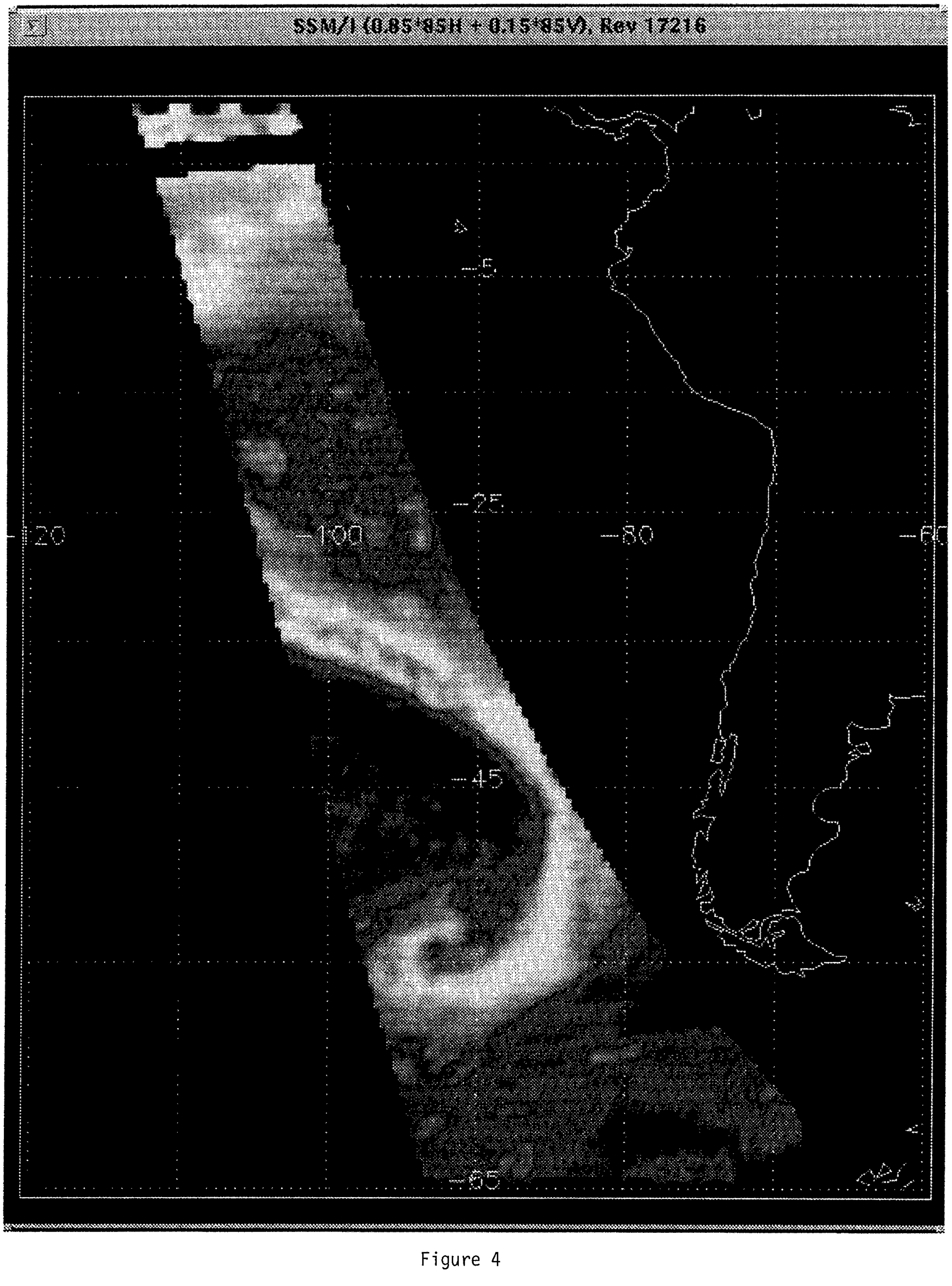


Figure 4

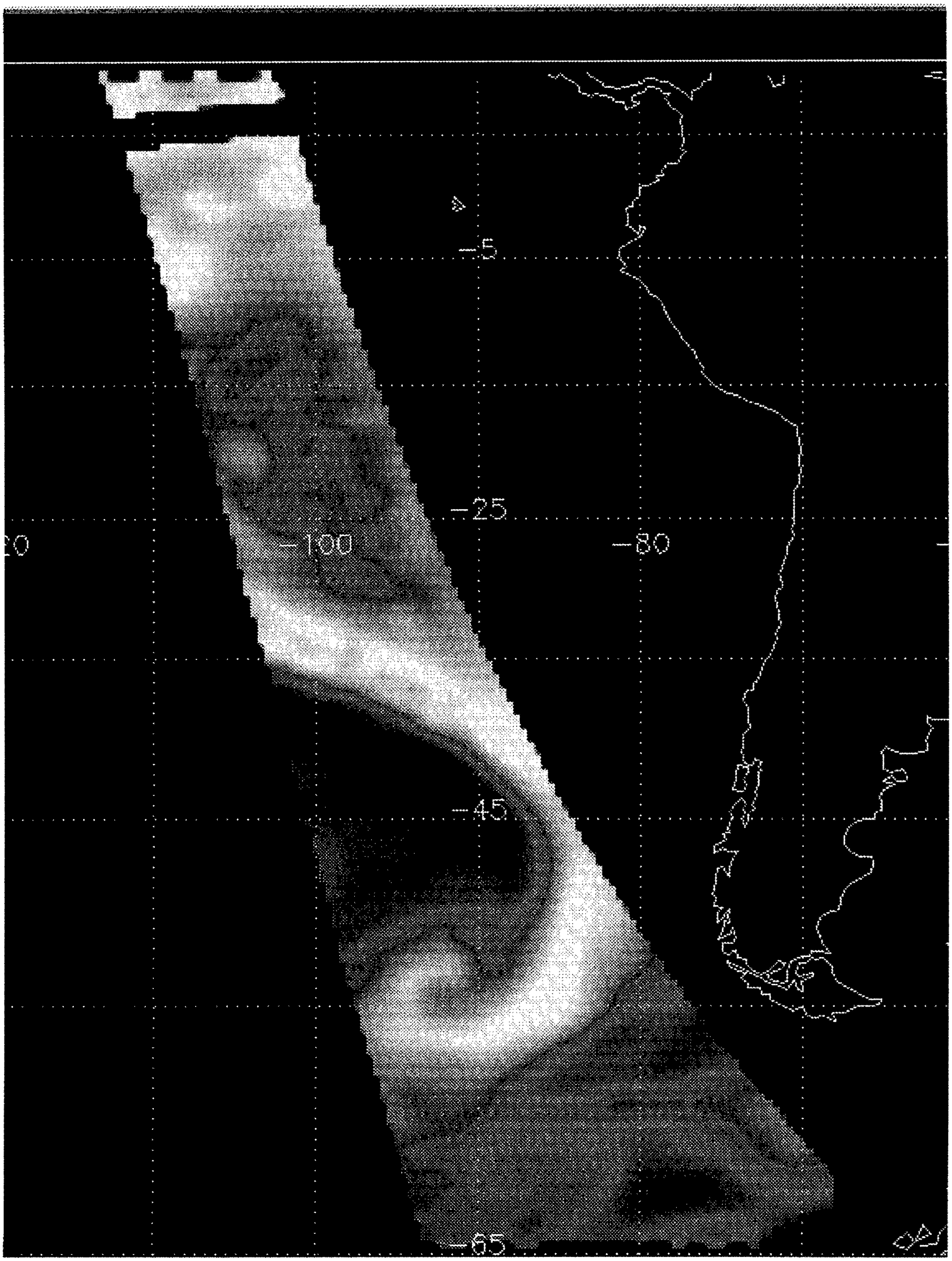


Figure 5

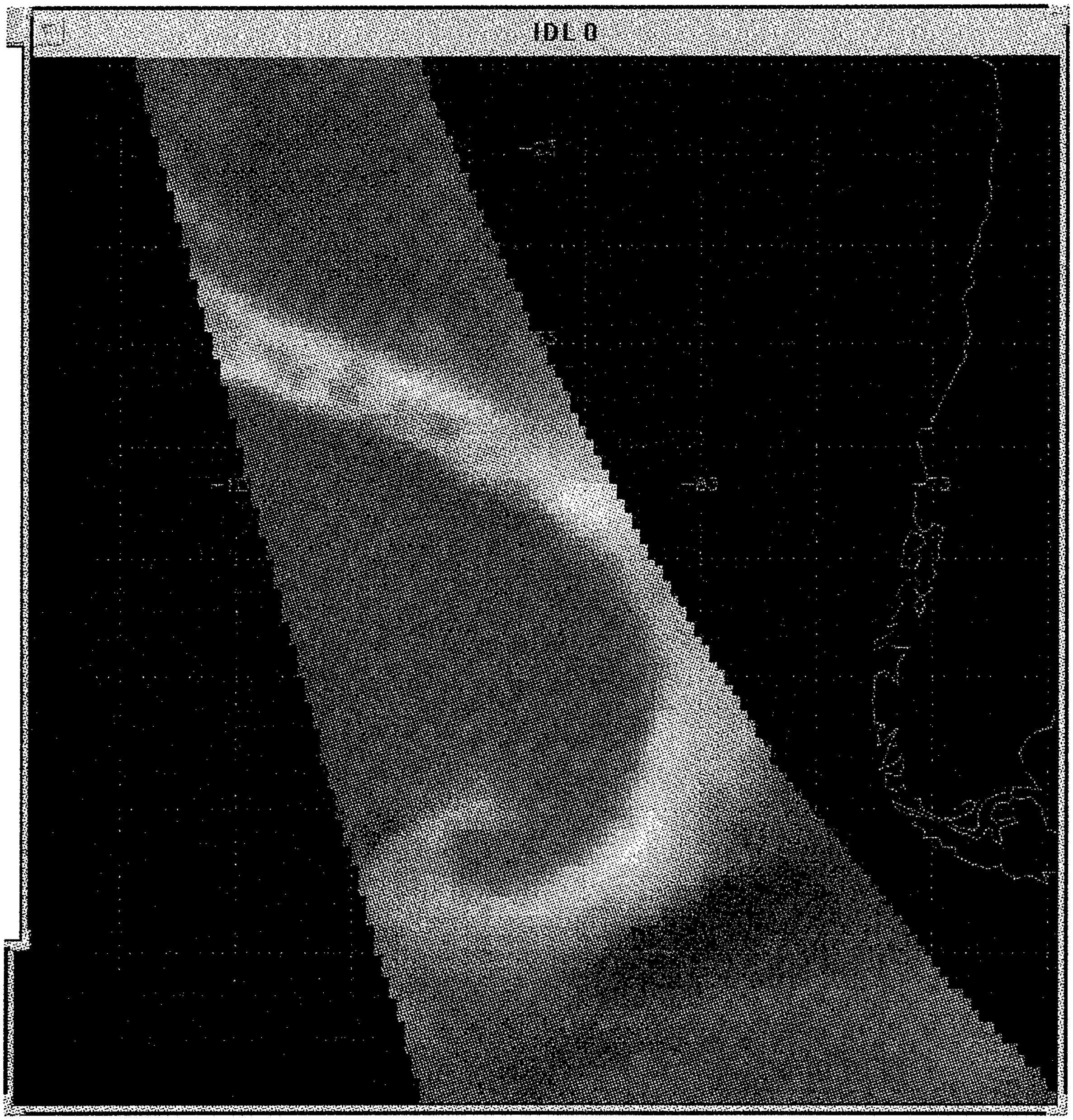
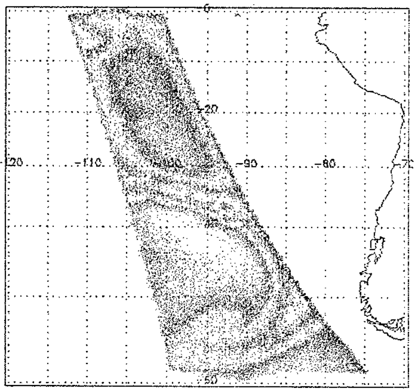


Figure 6


#1 (R:R (sgdb17216.gif),G:G (sgdb17216.gif),B:B (sgdb17216.gif)):{M1}
Functions
Cancel
IDL 15
02z-31mar95
-5
-25
-120
-100
-80
-60

Figure 7

Model Accuracy at 50.5 GHz-Cloud Contamination

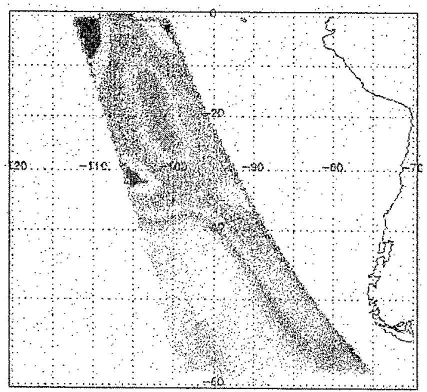


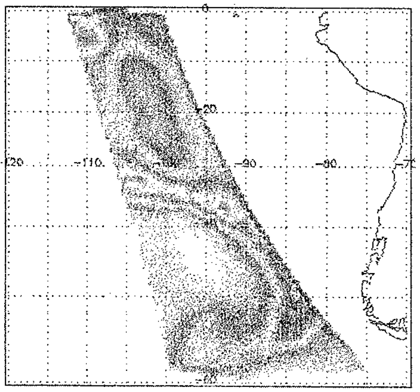
Measured
Brightness
Temperatures

White = 217 K
Red = 253 K

Predicted
Brightness
Temperatures; No
Simulated Clouds

White = 221 K
Red = 248 K





Predicted
Brightness
Temperatures;
Simulated Clouds

White = 222 K
Red = 257 K

- Introduction of the homogeneous rectangular cloud reduced the standard deviation between the measured and predicted brightness temperatures from 6.6 K to 4.0 K

Figure 8

SMALL METEOROLOGICAL SATELLITES FOR NATO MILITARY OPERATIONS

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ABSTRACT

The planning and effectiveness of military operations can often be greatly enhanced by timely meteorological information. This information is particularly important during rapidly changing weather conditions and can be critical to the success of military operations in a dynamic tactical environment. Due to the ever increasing pace of modern high technology warfare, the revisit time of low orbit meteorological satellites is inadequate to provide the war fighter with timely weather data.

Continuous and timely theater weather information can be obtained from sensors on geostationary satellites which are in a position to observe a particular theater of operations. Continuous monitoring also provides the capability to animate successive frames of data. This technique has been shown to be a powerful tool to interpret meteorological information. While this concept is not new, current meteorological satellites in geostationary orbit are not available to provide continuous coverage. In addition to improving the timeliness and accuracy of environmental information for operations planning, weather data could be provided in near-real-time to troops in the field and potentially to the aircraft cockpit.

This study focused on the concept of small geosynchronous satellites to meet the need for continuous cloud imagery including longitudinal movement to optimize coverage over given theaters of operations. Requirements for the satellite were investigated and the necessary sensor parameters identified. Based on these requirements, a number of sensors of varying capabilities were designed and conceptual designs for spacecraft compatible with these sensors were developed. Data communication to operational forces was also explored. Finally, applicable launch vehicles were identified and costs for the sensors, satellites, and launch vehicles, were estimated.

It was concluded that sensor and small satellite technology is sufficiently advanced to provide NATO military forces near-real-time cloud imagery at a relatively modest cost.

INTRODUCTION

Planning and effectiveness across the spectrum of military operations can be greatly enhanced by timely, usable, and accurate weather information.[1] One of the tools military meteorologists and oceanographers use to gather this information, especially from data-denied areas, is the weather satellite. The current constellation of weather satellites in low earth orbit, however, cannot continuously observe the battlespace environment, forcing military meteorologists and oceanographers to provide short term forecasts of up to six hours with no updated satellite information. While these forecasts are adequate for many applications, forecasting rapidly changing geophysical parameters continues to be a major challenge as illustrated in the following examples.

Cloud Fields: Many DoD smart weapons require line-of-sight visibility to target laser guided munitions. The attacking aircraft must continue to illuminate the target as the bomb homes in on the reflected laser energy. If unforecast clouds are in the target area, the smart weapon could lose lock-on and miss the target, perhaps causing unacceptable collateral damage. If up-to-date cloud information were available,

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the attacking formation would gain tremendous flexibility, choosing while enroute the best ingress corridor at the best altitude for the weapon load to avoid the clouds or moving to an alternate target much earlier in the strike mission. Operation Desert Storm is a case-in-point. Attack aircraft sorties often had to fly multiple hours to reach targets, sometimes finding the area obscured by unforecast weather, then proceeding to an alternate to find it also obscured, and then facing a decision to rendezvous with a tanker (if available) or return to base.

Low Level Winds: A coordinated strike on a series of targets which are closely spaced requires close attention to the wind direction and speed in the target complex. If the first target is upwind of the next in a series of attacks, smoke and dust from the first strike can obscure the next strike's targets. The capability of a continuous "bird's eye" view of the weather in the target complex once again adds tremendous flexibility to the attacking force allowing them to switch to alternate lay down strategies while enroute.

Diurnal Phenomena: Since low earth orbiting weather satellites visit the same spot of the earth at the same time every day, some diurnal phenomena which affect the battlespace may never be observed or forecast until the strike force encounters it. Fog in the littoral zone, for example, may not be discernible on an early morning low earth orbit pass, and can "burn off" before the late morning pass, forcing, at the very least, an abrupt change in tactics of an attacking force.

Hazardous Weather: Squall lines, severe convective weather, amount and type of precipitation, tropical cyclone movement and extent of damaging winds, are all significant weather phenomena which impact military operations and would benefit from continuous observation.

Continuous and timely theater weather information can be obtained from sensors on geosynchronous satellites which can observe a particular theater of operation between 60 degrees latitude north and south. An example of this type of satellite is the GOES which carries a number of instruments for meteorological observation. However, this type of satellite is large, costly, and is designed to provide data for global weather forecasts. The GOES, for example, can scan the earth disc approximately every 30 minutes (although the capability to rapidly scan a small area does exist).

A geosynchronous satellite dedicated to military operations could provide continuous high resolution weather monitoring for any theater of interest. This satellite, linked to a suitable military communication system, could provide near-real-time cloud images to military forces. In addition to improving the timeliness and availability of data for the planning function, this data could be available to support a variety of tactical scenarios, possibly including the transmission of cloud data directly in the cockpit. Continuous monitoring also provides the capability to provide qualitative data for animation, which is a powerful tool to quantitatively interpret meteorological information.

The objective of this study was to develop small geosynchronous satellite concepts which would provide continuous high resolution cloud imagery that could be downlinked in near-real-time to operational military forces. The study focused on small, relatively simple sensor concepts that would provide only cloud imagery for specific military theaters and would result in a satellite that is much lower in cost than current large, complex geosynchronous meteorological satellites. Optimized coverage for any given theater of operations would be provided through longitudinal movement of the satellite and other theaters on the observable earth disc would be covered through sequential operation of the sensor.

The paper describes a set of assumed requirements presenting three sensor options, including their corresponding design and performance, discusses communications with military forces, and describes the candidate small satellite designs. Finally, the paper presents the availability and type of launch vehicles required, and the resulting cost estimates for the satellites and launch vehicles.

ASSUMED REQUIREMENTS

The requirements for this study can be divided into those for the sensor, communications, spacecraft, and launch vehicle. The most critical requirements are described here.

There are six data and corresponding sensor requirements: 1) The imaged area should be comparable to that of a military theater of operation. The corresponding sensor requirement chosen was a field of view from

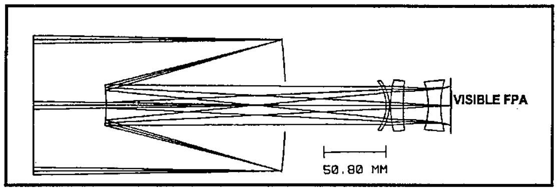
500 x 500 km to 1000 x 1000 km. 2) Daytime cloud imagery is required with nighttime operation highly desirable. Sensors were designed with a visible-only capability as well as an infrared-imaging capability. 3) A high resolution suitable to support tactical operations is required. The sensor design requirement chosen was a ground sample distance (GSD) of 0.5 km for visible images and 2 km for infrared images. 4) The refresh interval must be appropriate to weather front vertical and horizontal velocities. A revisit time of 1 min is adequate since weather fronts do not typically move more than 0.5 km in 1 min. 5) The ability to cover up to 4 theaters of operation sequentially is desirable. To maintain the 1 min revisit requirement for a given theater, the sensor is required to image a theater every 15 sec. 6) The imagery shall be of high quality. To avoid image smearing, the sensor integration time was restricted to 6 sec or less.

It was assumed that real-time or near-real-time communications are required to transmit imagery to tactical forces. The satellite is to have a nominal lifetime of 10 years, and to have sufficient propellant to make a number of longitude changes to cover various theaters of operation during its lifetime. Current technology was assumed for the sensor and spacecraft so that the satellite could be launched in 3 to 4 years if desired. The main launch vehicle requirement is that it be able to launch the spacecraft to geosynchronous orbit at a reasonable cost.

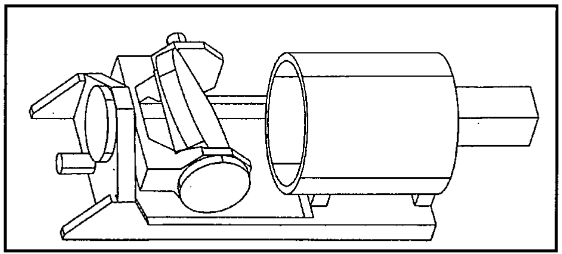
SENSORS

To perform the cloud imaging function, three sensor options were considered: 1) a small simple visible sensor for daytime imaging only, 2) a sensor that could provide both day and night cloud imagery, and 3) an intermediate capability sensor operating in the visible waveband that could provide some nighttime imaging under moonlight conditions. All of the designs were staring systems rather than scanning systems which results in a simpler lighter weight sensor with fewer moving parts and thus also potentially more reliable.

A daytime visible sensor was designed because it is the lightest weight sensor and results in the smallest, lowest cost satellite. The sensor is shown in Figure 1. It has a Ritchey-Chretien/Cassegranian optical system and utilizes a commercially available charged couple device (CCD) focal plane array (FPA). The focal plane is a 2048 x 2048 element array with 15 μm pixels and a nearly 100% fill factor. The integration time under typical lighting conditions is less than 1 msec. The sensor produces a GSD of 0.5 km.



Optical Design



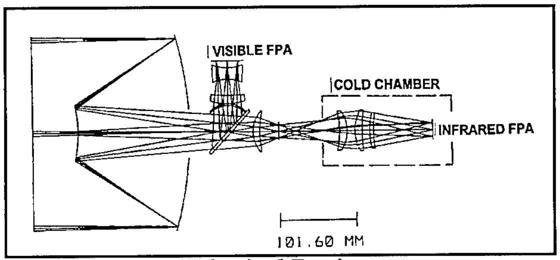
Sensor Assembly

Figure 1. Daytime visible 9 cm sensor

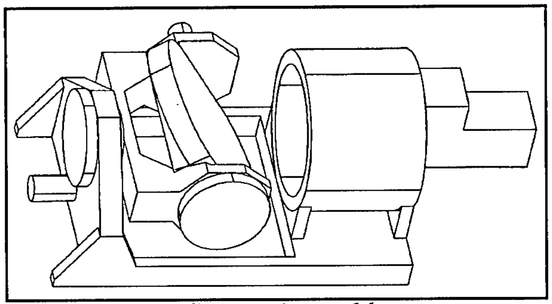
The sensor has a two-axis gimballed mirror to provide coverage of any theater within the geographic coverage of the sensor. The mirror motion plus settling time allows 1 image every 15 seconds. The total sensor weighs just under 21 kg including a 25% growth contingency. Total power input is estimated to be 12W for the gimbal drive and control and 2W for the focal plane array electronics.

A day and night cloud imaging sensor was designed with an infrared focal plane in addition to the visible focal plane. The sensor shown in Figure 2 is the same design as the visible-only system except that the aperture is 23 cm in diameter and an infrared focal plane is added. The sensor utilizes a reimaging optical design with a Lyot stop which enables the use of a cold chamber around the IR FPA to minimize thermal background. The visible focal plane is the same as for the daytime visible sensor. The IR focal plane selected is a 256 x 256 element HgCdTe array which for this application operates at a bandpass of 3.8-4.0 μm. This focal plane is well within the current state of the art (a 1024 x 1024 HgCdTe FPA has been developed).[2] The IR FPA uses 40 μm pixels and has a GSD of 2 km. The sensor assembly is very similar to the visible-only sensor except that it is larger. The total weight is about 66 kg including 25%

growth contingency. The gimbal drive and control requires 14W and the focal plane array electronics require 3W. A 1.1 m^2 radiator is required to cool the IR focal plane to 100 K. The integration time for the MWIR focal plane depends on the nighttime cloud temperature, but is still only 27 ms for cloud temperatures as low as 240 K.



Optical Design



Sensor Assembly

Figure 2. Visible/MWIR 23 cm aperture sensor.

The third sensor is a compromise design that is lighter and lower cost than the visible-MWIR sensor, but has the simplicity of the visible-only sensor. It provides some nighttime imaging under moonlight illumination with somewhat degraded performance. The sensor is virtually identical to the daytime visible sensor except that it has a 23 cm aperture which allows imagery under moonlight conditions. The sensor weighs just under 40 kg including a 25 percent growth contingency.

Imaging under moonlight illumination requires much longer integration times than for daylight. As stated in the Assumed Requirements section, it is desirable to limit the integration time to six seconds or less to prevent image smearing. This does not allow 0.5 km GSD to be obtained with moon illumination. However, by combining signals from adjacent pixels which decreases the GSD, and increases the signal-to-noise ratio, nighttime imagery can be obtained for about six days on either side of the full moon for 1 km GSD increasing to 10 nights on either side of the full moon for 4 km GSD. This sensor would thus allow imaging for about two-thirds of a month without the need for an IR FPA and the required 1.1 sqm radiator.

COMMUNICATIONS

The spacecraft communications system must be able to transmit the images produced in real time. The sensor gimballed mirror allows as many as four separate scenes per minute to be obtained. The visible CCD focal plane has 4.2 million pixels. Assuming 12 bits per pixel, the maximum data rate for a visible focal plane would be 3.36 Mbps. The IR focal plane adds only another 66,000 pixels; consequently, the maximum data rate for both the visible and IR focal planes, is 3.41 Mbps. The data rate can obviously be reduced by lowering the transmitted frame rate and/or by data compression. Currently available data compression algorithms allow data to be compressed by factors of as much as 10 to 1 with little or no loss of information content. For example, for an image transmission rate of one frame per minute and a 10 to 1 data compression ratio, the required transmitted data rate would be under 100 Kbps.

For the purposes of the system design, a 4 Mbps communication system which transmits 10W at 1.68 GHz was incorporated in the spacecraft design. The satellite would have its own dedicated ground terminal and an antenna diameter of 18 m would be required if there was no data compression. For a data compression ratio of 2 to 1, the required ground terminal antenna diameter would be 9 m and for a compression ratio of 10 to 1, the antenna diameter would be only 4 m.

The cloud imagery can be transmitted to military users utilizing the planned Global Broadcast System (GBS). The GBS is a high-power, high-capacity satellite system that can provide high data rates to small, lightweight, low cost user terminals. It is basically a military version of a commercial direct broadcast television system.

From the dedicated ground terminal, the cloud images are relayed either by terrestrial or satellite communication to the GBS broadcast management center where they are uplinked to the GBS satellite which then downlinks the data directly to military forces. Each GBS channel has a data capacity of tens of Mbps so that it can easily handle even uncompressed cloud images.

The cloud imagery is thus available to ground forces, naval units, or air bases. Eventually, the data could be received by command and control aircraft, such as the E-3 AWACS. The command and control aircraft could possibly relay the images to combat aircraft. Eventually, it may be possible to transmit the images directly from the GBS satellite to combat aircraft if they can be equipped with suitable antennas.

An interim GBS system with a GBS communications package hosted on UHF follow-on satellites is planned to be launched starting in early 1998. It will have two spot beams of about 900 km diameter and one broad area coverage beam. An objective dedicated GBS satellite system is planned to be launched by 2001.

SPACECRAFT DESIGN

Conceptual spacecraft designs were derived from SCDesign, a spacecraft design model, developed by The Aerospace Corporation. Starting with a description of the payload (weight and power), orbit parameters and various subsystem parameters, a spacecraft concept was developed. The solution methodology relies heavily on iterative techniques to solve the interdependent algorithms making up the system model. SCDesign uses various algorithms best suited to accurately size each subsystem. The structure subsystem is sized based upon empirical and parametric relationships. The thermal, processing, power and propulsion subsystems are sized by means of analytical algorithms based on physical relationships and technology parameters. Finally, the Telemetry, Tracking and Command (TT&C) and Attitude Determination and Control (ADAC) subsystems are sized based on actual off-the-shelf hardware weight and power requirements.

The baseline mission inputs to SCDesign included: Payload weight, power (operating power plus the 60 watts required for the 4 Mbps payload communication system) and pointing requirements (15 and 5 μrad accuracy and jitter accuracy, respectively), altitude (geosynchronous), inclination (0.5 deg), stationkeeping ($\pm$ 0.5 deg inclination tolerance, East-West plus momentum dumping totaling 50 m/s ΔV), mission duration (10 years), and repositioning requirements. Lightweight, low power telemetry subsystem hardware was identified from existing options. The ADAC hardware chosen included: Digital sun sensors, earth scanning sensors, torque rods, gyros, reaction wheels and processing capability. Battery (NiH_2) and solar array power densities (GaAs) and efficiencies were input, resulting in array, battery, array drive and power distribution sizes, weights and power requirements. The power requirements for the sensor payloads were doubled to include payload thermal control and to provide some growth contingency. The spacecraft thermal control subsystem was sized based upon End of Life (EOL) power requirements. The structure subsystem was sized based upon total desired mass fraction. Extensive use of composites was assumed to reduce structure weight. A bipropellant propulsion subsystem [Mono Methyl Hydrazine (MMH) and Nitrogen Tetroxide (N2O4)] was chosen for this study and was sized based upon final launch mass.

Using CAD software, a physical vehicle configuration was generated based upon the requirements generated from SCDesign (solar array and radiator sizes, equipment packaging). In addition, stowed configurations were studied to ensure that the spacecraft would fit inside the launch vehicle shroud.

The propulsion subsystem includes propellant required for orbit circularization (from geosynchronous transfer orbit to geosynchronous orbit), North-South stationkeeping, East-West stationkeeping, momentum unloading, and repositioning maneuvers. The propellant reserved for repositioning is sufficient for 10 longitude maneuvers of 1 deg/day and 4 longitude maneuvers of 6 deg/day. The latter maneuvers would be used when crisis warning times are not sufficient to allow slower repositioning or when large longitude changes are required. Obviously, other combinations of maneuvers are possible.

The resulting satellite designs are summarized in Table 1. The dry masses, which include a 15% spacecraft bus growth margin, range from 323 kg for the smallest spacecraft with the visible 10 cm sensor to 386 kg for the largest spacecraft with the visible/ IR 23 cm sensor. The corresponding launch masses range from 772 kg to 921 kg. Proposed launch vehicles, which have the capability to place these satellites in geosynchronous orbit, are also indicated. Figure 3 illustrates a possible configuration for the largest satellite.

LAUNCH VEHICLES

Small launch vehicles that are currently available or proposed are shown in Figure 4. Of these, only Pegasus and the basic Taurus have flown successfully to date. No small launch vehicle has launched a small satellite to geosynchronous orbit. However, many of the launch vehicles shown in Figure 4 potentially have the capability of launching a small payload to geosynchronous orbit with the addition of a suitable apogee kick motor.

Table 1. Small Satellite Designs

	Small Satellite with Visible 10 cm Sensor		Small Satellite with Visible 23 cm Sensor		Small Satellite with Visible/IR 23 cm Sensor	
	Mass (kg)	Power (W)	Mass (kg)	Power (W)	Mass (kg)	Power (W)
Payload						
Sensor	21	28	40	32	40	34
Communication	5	60	5	60	5	60
Payload Thermal					27	
Spacecraft						
Propulsion	50	5	52	5	54	5
ADACS	53	145	53	145	53	145
TT&C	10	54	10	54	10	54
Thermal (Spacecraft only)	21	35	21	36	22	36
Power	77	25	77	25	78	25
Structure	47		51		57	
Spacecraft Summary						
EOL Power		352		357		359
BOL Power		435		441		444
Bus Mass	258		265		273	
Dry Mass	284		310		345	
Growth Allowance	39		40		41	
Dry Mass with Margin	323		349		386	
Propellant and Pressurant	427		463		511	
Wet Mass	750		812		896	
Adapter	22		23		24	
Launch Mass	772		835		921	
Launch Vehicle	Taurus II-0		Taurus II-0		LLV3	
Performance to GTO	817		817		1075	
Launch Vehicle Weight Margin	45		-18		154	
Launch Vehicle Percent Margin	6%		-2%		14%	

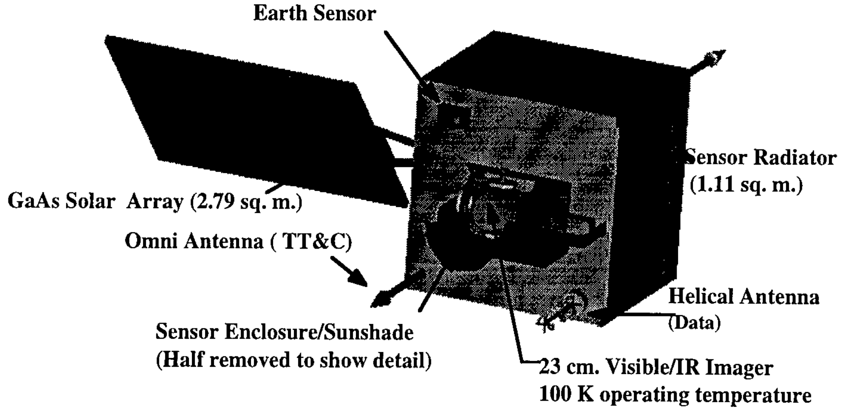
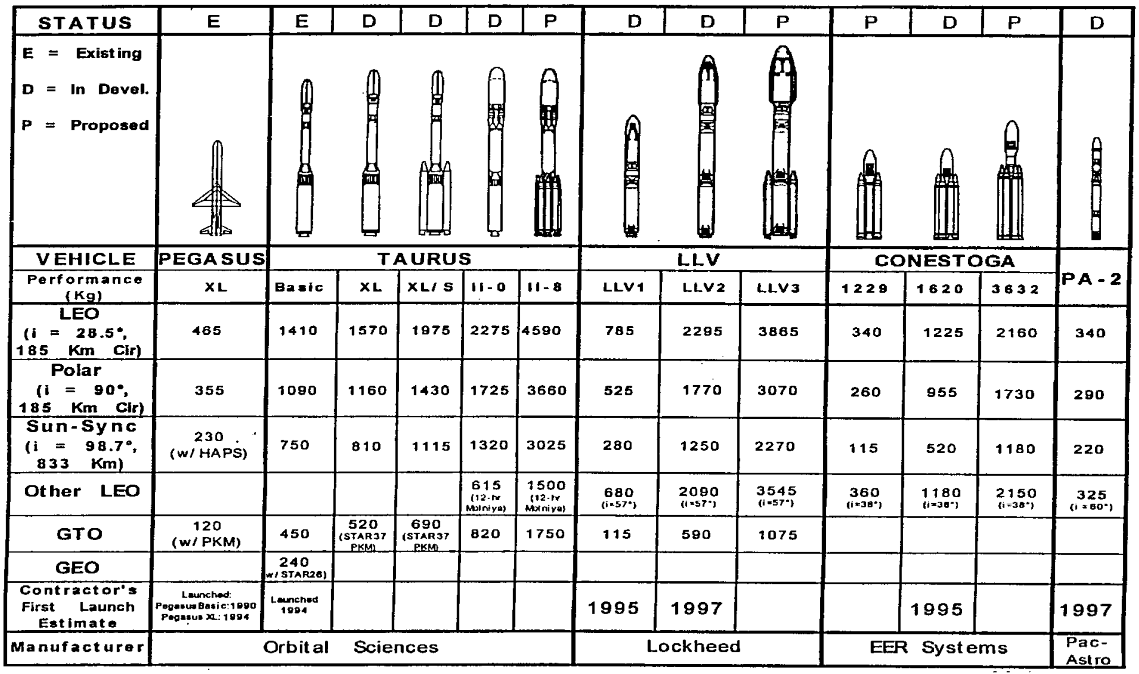


Figure 3. Small Meteorological Satellite



STATUS	E	E	D	D	D	P	D	D	P	P	D	P	D
E = Existing D = In Devel. P = Proposed													
VEHICLE	PEGASUS	TAURUS					LLV			CONESTOGA			PA-2
Performance (Kg)	XL	Basic	XL	XL/ S	II-0	II-8	LLV1	LLV2	LLV3	1229	1620	3632	
LEO (i = 28.5°, 185 Km Cir)	465	1410	1570	1975	2275	4590	785	2295	3865	340	1225	2160	340
Polar (i = 90°, 185 Km Cir)	355	1090	1160	1430	1725	3660	525	1770	3070	260	955	1730	290
Sun-Sync (i = 98.7°, 833 Km)	230 (w/ HAPS)	750	810	1115	1320	3025	280	1250	2270	115	520	1180	220
Other LEO					615 (12-hr Molniya)	1500 (12-hr Molniya)	680 (i=57°)	2090 (i=57°)	3545 (i=57°)	360 (i=38°)	1180 (i=38°)	2150 (i=38°)	325 (i =60°)
GTO	120 (w/ PKM)	450	520 (STAR37 PKM)	690 (STAR37 PKM)	820	1750	115	590	1075				
GEO		240 w/ STAR26)											
Contractor's First Launch Estimate	Launched: Pegasus Basic:1990 Pegasus XL: 1994	Launched 1994					1995	1997			1995		1997
Manufacturer	Orbital Sciences						Lockheed			EER Systems			Pac-Astro

Figure 4. U.S. Commercial Small-Class Expendable Launch Vehicles

As indicated in Table 1, the small satellite with the visible 10 cm sensor requires a Taurus II-0 launch vehicle, the satellite with a visible 23 cm sensor also requires a Taurus II-0 launch vehicle, and the satellite with the visible/IR 23 cm sensor would require an LLV-3 launch vehicle. None of these launch vehicle configurations currently exist. It is possible that they may exist after the turn of the century providing there are customers for these vehicles.

An alternative is to use a larger proven launch vehicle and launch two of these satellites at a time or share the launch. vehicle with another satellite. Figure 5 shows the performance of two launch vehicles which are suitable for this purpose. Delta II 7925 has just enough capacity to launch two small satellites with the visible/IR 23 cm sensor, and has substantial margin to launch the lower weight satellites. Ariane 40 can launch two of the small satellites with the visible/IR 23 cm sensor with about a 200 kg margin.

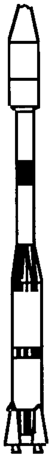
STATUS	Operational	Operational
		
VEHICLE Performance (Kg)	**Delta II 7925**	**Ariane 40**
LEO (i = 28.5°, 185 Km Cir)	5,090	4,900
Polar (i = 90°, 185 Km Cir)	3,820	3,900
Sun-Sync (i = 98.7°, 833 Km)	3,180	
Other Orbit	1,280 (Molniya)	
GTO	1,840	2,050
GEO	910 (w/ AKM)	Requires Kick Motor
First Launch	1990	1988

Figure 5. Delta II 7925 and Ariane 40 Performance

COST ESTIMATES

The sensor payload cost estimates were derived from the Air Force Passive Sensor Cost Model which is a parametric model that estimates the cost of developing and producing space qualified electro-optical sensors. The model is based on historical data from a wide range of USAF, BMDO, NOAA, and NASA sensor programs.

The spacecraft cost estimates were derived from The Aerospace Corporation's Satellite Cost Model. The model utilizes cost estimating relationships for the design, development, and production of 37 types of spacecraft components. The model is based on historical component level data from 15 satellite programs and adjusts estimates based on component design heritage and number of similar units previously produced.

The cost estimates for the three sensors are shown in Table 2. The production cost is the average unit cost based on the production of four flight sensors. In all cases the development cost is larger than the average production cost.

Table 2. Sensor Cost-Estimate Summary - FY95$M

	Visible 10 cm		Visible 23 cm		Visible/MWIR (23 cm)	
	Devel	Prod	Devel	Prod	Devel	Prod
Focal Plane(s)	-	0.1	-	0.1	0.3	1.0
Telescope	1.0	0.8	5.0	4.4	8.0	5.1
Gimbal	0.7	0.3	1.4	0.7	1.4	0.7
Structure	0.3	0.2	0.5	0.3	0.5	0.3
Integration Assembly & Test	0.6	0.3	1.3	0.5	1.5	0.6
Total (FY95$M)	2.6	1.7	8.2	6.0	11.7	7.7

The first unit and additional production small satellite cost estimates are given in Table 3. These estimates include the cost of the sensors from Table 2. The satellite cost estimates assume that the contractor will use an existing design for the spacecraft bus rather than develop an entirely new design.

Table 3. Small Satellite Cost Estimates - FY95$M

Sensor	First Unit Cost	Additional Production
Visible 10 cm	64	34
Visible 23 cm	71	35
Visible/MWIR (23 cm)	81	39

The estimated cost of a complete earth station, which includes telemetry, tracking, and command capabilities as well as mission data downlink reception, is about $1.85 million. This estimate assumes no data compression which would require an 18 m diameter antenna. With 2 to 1 compression, a 9 m antenna is required and the cost is $1.35 million, and with 10 to 1 data compression, a 4 m antenna is required and the cost drops to $1.05 million.

The cost of an extended capability Taurus or the Lockheed LLV-3 would probably be of the order of $30 million or more. This cost should be considered a very rough estimate since these vehicles exist only as preliminary designs. On the other hand, the cost of the Delta II 7925 or Ariane 40 launch vehicle is about $55 million. Since these vehicles can launch two satellites, the launch cost per satellite would probably be less than if the smaller launch vehicles were used.

SUMMARY/CONCLUSIONS

Electro-optical sensors and small satellite designs were developed to provide both day and night high resolution weather imagery from geosynchronous orbit. Real time dissemination of this imagery to military users is possible using the Global Broadcast System. The cost of the system is modest especially compared with the cost of large geosynchronous satellites.

Launch is a potential problem. No small launch vehicle has yet launched a small satellite to geosynchronous orbit, and it is not known if one will be available in the foreseeable future. However, two of the satellite designs from this study can be launched on a Delta II 7925, or an Ariane 40 launch vehicle or alternatively, the launch vehicle can be shared with another satellite.

Another possible option, not investigated in this study, is to place a sensor on a large geosynchronous satellite, such as a communications satellite. This may be a feasible option for the visible 9 cm sensor which weighs only 21 kg.

ACKNOWLEDGMENTS

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Electro-Optical Sensor Simulation for Theatre Missile Warning

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SUMMARY

An integrated Electro-Optical Sensor Simulation (EOSS) capability has been developed which can analyze the performance of space-based, surveillance systems at both the sensor and constellation levels. For sensors operating in an infrared-blocking band against an earth background, target detection is generally limited by sensor output variations known as clutter, which results from the interaction of the sensor with background scene structure such as clouds. EOSS uses a scene generation model to create the required cloud scenes and an end-to-end simulation of the imaging chain to evaluate the impact of these backgrounds on sensor performance. Results from these detailed simulations are combined within a constellation-level analysis tool to provide global sensor coverage and target detection statistics as a function of sensor design, background level, target parameters, and constellation size and type. This simulation capability has been used to determine theatre missile detection and report times for a representative space-based, infrared surveillance architecture. The trade between sensor performance and payload weight has also been explored, with uncertainties in the background clutter modeling playing a key role in driving the sensor designs in the direction of heavier and more expensive payloads.

INTRODUCTION

The ability to provide early warning against theatre missile attack has become a key mission area for NATO military planners. A space-based, infrared surveillance system can indeed provide such warning. However, enhancing the timeliness and utility of any future space-based, infrared surveillance system will depend greatly on an accurate appraisal of the phenomenology involved and its impact on sensor design and performance. System performance may be seriously compromised if non-optimum sensor designs or system architectures are deployed.

The Aerospace Corporation (Aerospace), which supplies general systems engineering and integration services to the U.S. Air Force's Space and Missile Systems Center, is often asked to provide quick-response assessments of a wide variety of space-based sensor concepts. Frequently, an analytical approach is deemed sufficient to meet the accuracy required for such assessments. Sometimes, however, highly detailed simulations are required, especially when the assumptions underlying the analytical approximations have been violated. For example, a key component in many sensor performance evaluations is the spatial structure of the background against which target detection must be accomplished. For analytical approximations, it is typically assumed that the background amplitude distribution is Gaussian, leading to a simple convolution of the background clutter with the noise distribution inherent to the sensor. However, many backgrounds do not have Gaussian amplitude distributions because of commonly occurring features such as cloud edges, land/sea interfaces, etc. Under such circumstances, detailed pixel-level focal plane simulations are required if an accurate assessment of the sensor's performance is to be made. On the other hand, when the emphasis is on the system performance of a constellation of sensors, such a level of detail has generally been viewed as too time consuming and costly to incorporate within a constellation-level simulation.

This paper describes a methodology for accurately quantifying the impact of spatially-structured backgrounds on the performance of space-based infrared sensors and, further, to couple these results with higher-order systems engineering trades and mission performance tools. In effect, high-fidelity sensor and phenomenology models are used to generate constraints and data bases for use within constellation-level simulations, thereby enhancing their overall accuracy. This integrated simulation capability has been used to support both sensor and systems trades for a number of space-based, infrared surveillance system studies, including those dealing with Theatre Missile Warning (TMW). In order to illustrate the models and analysis procedures, we evaluate a nominal space-based, infrared surveillance architecture against the TMW mission for two potential theatres of operation. System performance is derived for three generic IR scanning sensor designs, and parameterized against the potential variations and uncertainties in the background structure. We also examine the cost, as characterized by payload weight, of meeting the high levels of performance likely to be required by future theatre commanders.

SIMULATION TOOLS

For a space-based, infrared surveillance system, the simultaneous interplay between the sensor, target and background determines the capability for target detection. Thus, in order to accurately predict the ability of an EO sensor constellation to perform a given mission, it is necessary to incorporate all of the salient geometry, dynamics and phenomenology into a single tool. One of the main focuses of our effort to develop an integrated EO sensor simulation has been to incorporate the effects of realistic clutter phenomena (i.e. cloud edges, sun glints, etc.) within constellation-level, space surveillance simulations. Our mechanism for accomplishing this is to generate clutter

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statistics using a high-fidelity sensor simulation tool to process a range of background scenes which vary in cloud content, sensor viewing geometries and solar angles. The various simulation tools used are described below and a flow chart showing their interconnectivity is given in Figure 1.

SSGM (Synthetic Scene Generation Model[1]) is an industry tool which encapsulates many phenomenology codes under one architecture. SSGM was developed by Photon Research Associates Inc. (PRA) of San Diego, California, under a contract supervised by the U.S. Naval Research Laboratory for the Ballistic Missile Defense Organization. The primary use of SSGM in this analysis is to generate background scenes in the canonical short-wave infrared (SWIR) blocking band at 2.7 microns. This water absorption band is useful for the boost-phase detection of missiles because it provides a compromise between early detection and background clutter. The background structure in this band is dominated by solar scatter off the tops of clouds. Higher altitude clouds generally result in higher levels of clutter because the sunlight suffers less attenuation by the atmosphere. Cloud backgrounds are synthesized in the CLDSIM model within the SSGM from a pixel map of cloud type and altitude which have been derived from measured satellite imagery. PRA uses standard and established methods to estimate cloud height from long-wave infrared (LWIR) satellite imagery with an accuracy of about 1-2 kilometers. SSGM can be used to generate a set of scenes with a variety of viewing geometries in the desired spectral band and atmosphere with the specified pixel resolution. Figure 2 shows a flow chart of this process. For a given cloud data base within SSGM, a matrix of SWIR scenes which spans all possible sensor viewing geometries and solar angles is generated. The data base of cloud scenes has been enlarged as updated versions of the SSGM have become available, a process which is still on-going. The expected range of the modeling uncertainties within SSGM is incorporated directly into our analyses.

VISTAS (Visible and Infrared Sensor Trades, Analyses, and Simulations[2]), an ongoing development project at Aerospace for the past several years, combines classical image processing techniques with detailed sensor models in order to produce static and time dependent simulations of a variety of sensor systems including imaging, tracking, and point target detection scanners and starers. The imaging chain of an EO sensor, from background scene input to signal processor output, is modeled. The sensor system transfer function is applied to a high resolution input scene, such as those produced by SSGM. Real data of sufficient quality and resolution can also be used as input to VISTAS. The transfer function includes the effects of the optical point-spread-function; detector aperture; and, for a scanning system, the temporal aperture due to the scan motion during the integration time. Line-of-Sight (LOS) drift and jitter can be incorporated to produce a time sequence of two dimensional images. This is particularly important for staring sensors. The blurred scenes are re-sampled at the system resolution and any clutter rejection filters (analog/digital, spatial/temporal) are applied. The output is calibrated to account for the effect of target response. This process is described below. Finally, the output scenes are analyzed for figures of merit such as the standard deviation or the number of exceedances at any given threshold. These provide a statistical representation of clutter for the background scene and sensor design under consideration.

TRADIX is a constellation-level analysis tool which combines EO sensor models with accurate target and background phenomenology models in order to evaluate system-level performance against either orbiting or ballistic targets. TRADIX models space sensors operating in both the above-the-horizon (ATH) and below-the-horizon (BTH) modes, from the Visible to the LWIR. It contains a hard-body target signature model, ballistic missile intensity and trajectory profiles, and detailed background models, including zodiacal light, stray-light from non-rejected earthshine and sunshine, and the SSGM/VISTAS-generated clutter statistics along with atmospheric path radiance and transmission. These models are integrated with Aerospace's orbit propagation library, ASTROLIB, to provide a dynamic simulation tool for studying the constellation-wide performance of EO sensors. TRADIX provides sensor-constrained coverage and report time statistics as well as frequency-of-occurrence information for the relevant geometric and radiometric parameters which determine sensor design requirements. TRADIX may also be used to generate target detection constraints for tracking error analyses and other higher-level simulations.

Critical inputs to the above tools include: the focal plane pixel topology; the sensor's noise characteristics; details of the filters and signal processing; the optical design and its straylight rejection capability; platform drift and jitter; constellation orbits and phasing; target signatures and dynamics, and the CONcepts of OPeration (CONOPs) for the sensor payload (i.e., scan modes, revisit times etc.). These can all be obtained from various groups within Aerospace, or they may be supplied by an external organization whose design concepts have been submitted for independent review.

Frequency-of-occurrence information on meteorological conditions is another critical issue for the performance of a space-based, infrared surveillance system against earth backgrounds. For this, we rely on a global cloud statistical model[3] based on University of Wisconsin HIRS-2 (High - Resolution Infrared Sounder) data from NOAA (U.S. National Oceanographic & Atmospheric Administration) polar orbiters[4]. When completed, this cloud data base will be incorporated within the EOSS framework and will be used to predict background conditions and target obscuration for regions of interest. With this data base, we already have a statistical basis for assessing system performance against clouds of various altitudes for a given time of year at a given geographical location.

The EOSS integrated set of sensor analysis tools has been applied to a wide variety of EO sensor system optimization and analysis problems, including: sensor design; filter optimization and clutter rejection studies; sensitivity to background assumptions and statistics; system level performance evaluation, and comparison/selection among alternative deployments (numbers of satellites and/or orbital parameters). EOSS clutter statistics have also been incorporated within other Aerospace system-level simulations which deal with tracking error analysis and sensor resource scheduling.

SCENE-BASED CLUTTER ANALYSIS

The performance of an IR sensor operating in the SWIR

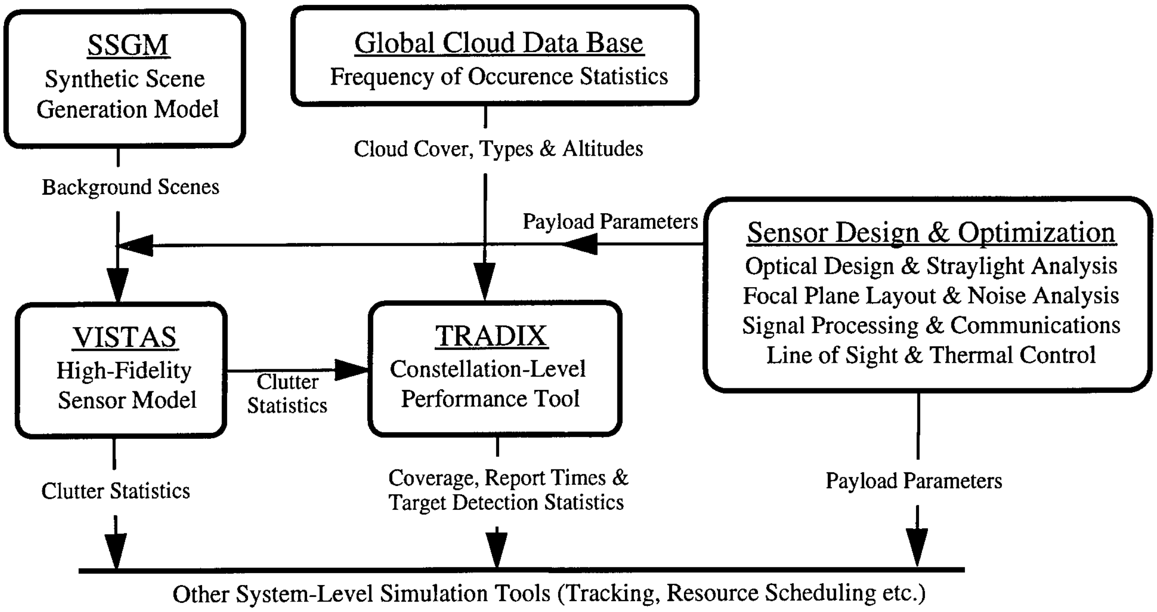


Figure 1. Flowchart of Integrated Electro-Optical Sensor Design and Simulation Capability

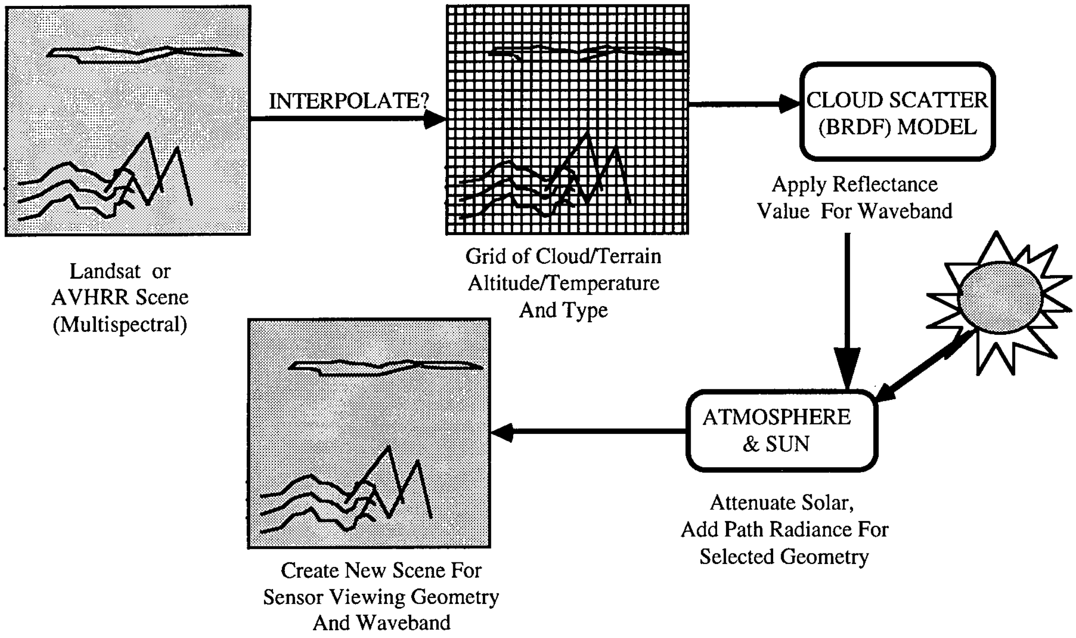
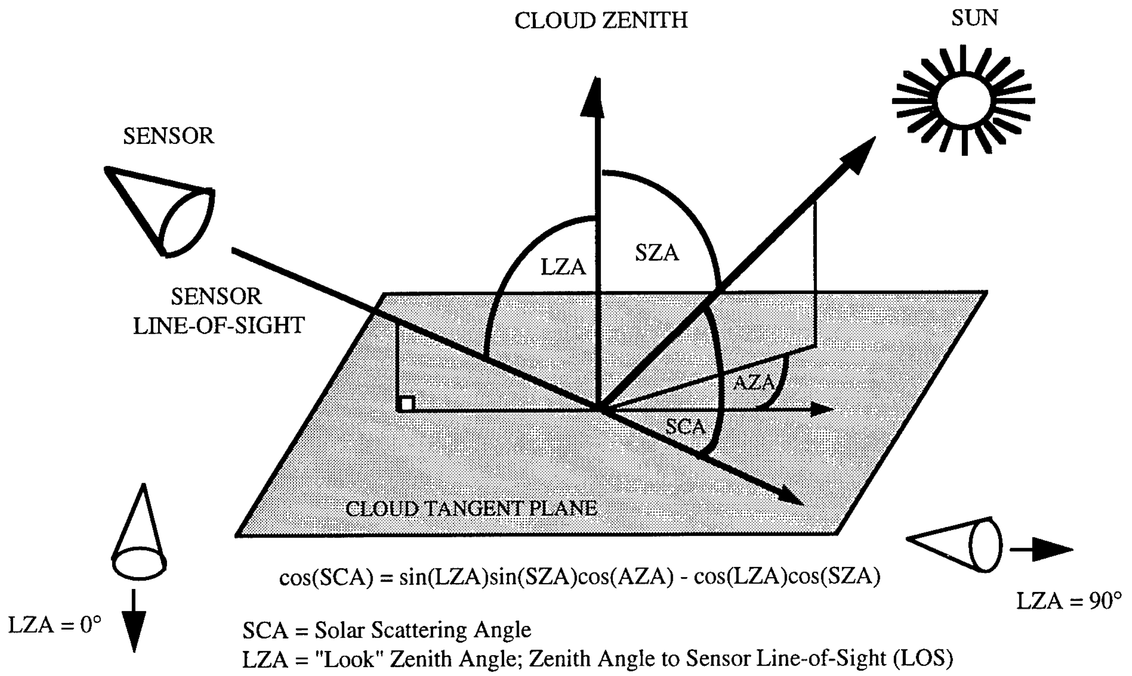


Figure 2. Flowchart of Synthetic Scene Generation Model (SSGM)



$$\cos(SCA) = \sin(LZA)\sin(SZA)\cos(AZA) - \cos(LZA)\cos(SZA)$$

SCA = Solar Scattering Angle
LZA = "Look" Zenith Angle; Zenith Angle to Sensor Line-of-Sight (LOS)
SZA = Solar Zenith Angle
AZA = Relative Azimuth Between Sun and Sensor LOS Vectors

Figure 3. Solar Scatter Coordinate System

Table 1. Cloud Statistics for Nominal and Stressing data bases

Name	Size (km)	Scale (m)	Cloud Coverage		Altitude (km)	
			Type	%	Mean	Min - Max
Nominal	512 x 1170	200	Water Water/ Ice Ice	37.2 17.5 0	2.5 4.5	0.5 - 6.0 2.0 - 8.4
Stressing	512 x 1170	200	Water Water/ Ice Ice	17.8 22.0 21.0	3..5 6.7 9.1	0.5 - 7.8 1.4 - 9.2 8.0 - 9.9

blocking band against an earth background is dominated by the structure in the background scene and by the sensor-target-sun viewing geometry [5,6]. This geometry is well represented by two angles: the Look Zenith Angle (LZA) and the solar SCAtter angle (SCA), both of which are defined in Figure 3. The SCA is the dominant angle which determines the level of solar scatter off the cloud tops; the smaller the SCA, the more closely the conditions correspond to the forward scattering case. Previous work utilizing SSGM scenes has indicated that the effects of solar azimuthal variations on the observed clutter level are of secondary importance. When viewing nadir (LZA = 0°), the minimum possible SCA is 90°, whereas at the limb (LZA = 90°), the sun can be directly in the sensor LOS, i.e. the SCA can be 0°. In addition to defining the projection of the SSGM cloud data base onto the sensor LOS, the LZA is directly related to the range to the target and to the path length through the atmosphere for a target at a given altitude, and thus to its apparent irradiance for a given time after launch. Thus low altitude targets viewed close to the limb may suffer from the worst case combination of range, atmospheric transmission loss and solar scatter-induced clutter. Unfortunately, most of the surface area covered by a given space sensor viewing the Earth lies at the larger LZAs. The overlapping coverage provided by a constellation of many sensors mitigates this problem.

The SSGM scenes used as the inputs to the VISTAS simulation should ideally have at least 3 to 5 times better resolution than the sensor being modeled in order to avoid the effects of aliasing. Several data bases exist in SSGM with sufficient resolution and spatial extent for the sensors under consideration. Two were chosen for this study : a "nominal" data base, which contains low- to mid-altitude clouds; and a "stressing" data base, which comprises mid- to high-altitude clouds. Each of these is approximately 512 km x 1170 km at nadir with a 200 m resolution. The cloud types and altitudes for these data bases are given in Table 1. We refer to these data bases as being nominal and stressing because of the clutter levels which typically result when they are passed through a sensor simulation. In addition, the lower-altitude clouds in the nominal scenes occur more frequently than the higher-altitude ice clouds in the stressing ones. Representative images of the two data bases, as seen through a midlatitude summer atmosphere at LZA = 60° and SCA = 90°, are shown in Figures 4 and 5, respectively. Note the projection effect at an LZA of 60° shortens the apparent size of these scenes to 510 km x 570 km (still at 200 m projected resolution). The brighter clouds in these images are actually at higher altitudes where there is less attenuation of the sunlight both before and after it scatters off the cloud tops.

The most significant caveat on this analysis is that it is utilizes the CLDSIM model contained within SSGM. A number of uncertainties are inherent in this model, one of those being the bi-directional reflectivity distribution function (BRDF) model of solar scattering from the clouds. PRA estimates that the final uncertainty in the apparent cloud brightness distribution is less than a factor of 3. The impact of this modeling uncertainty is addressed by scaling the intensity of each scene with a linear scale factor. Factors of 1/3, 1/2 and 1 are typically applied to the nominal scenes, while factors of 1, 2, and 3, are applied to the stressing scenes. In this way, the effect on system performance of varying the cloud types and altitudes and the additional impact of the SSGM modeling uncertainties can be quantified.

For a scanner, each background input scene results in a single simulated static output scene. Figure 6 shows the results of scanning the stressing scene of Figure 5 with two different IR scanning sensors in geostationary orbit. The salient difference between the two scanning designs is their respective projected ground footprints, namely 1.8 km and 3.6 km at nadir. A 9-tap, ac-coupled transversal filter has been applied to the sampled output scenes line-by-line, in the scan direction, which is considered to be perpendicular to the limb (which is out of the field of view and toward the top in Figures 4, 5 and 6). This spatial filter essentially performs a local background subtraction so that the output scene has a mean of zero. The intensity of a target relative to the surrounding background is the principal method for detection. The output scenes are referenced to apparent intensities at the aperture via the scanner target response as described in the next section. In Figure 6, grey represents the mean level of zero, while white and black represent positive and negative exceedances, respectively. The cloud edges seen in Figure 5 are clearly delineated by the exceedances of Figure 6.

The simulation outputs are examined for clutter content by creating a probability of false exceedance (PFE) distribution as a function of threshold intensity in kW/sr. This function is formed by counting the number of pixels in the output scene that have a value greater than or equal to each threshold and dividing by the total number of output pixels. Examples of the PFE as a function of threshold for the two IR scanner outputs of Figure 6 are shown in Figure 7. Note that these plots do not include sensor electronics noise, photon noise, etc., but do include the effect of target response, which is discussed in the next section.

In order to set a threshold, an acceptable false exceedance rate for each sensor design must be determined. For architectures where the mission data processing is done on the ground, this involves knowing the number of focal plane detectors, the sampling rate, the number of bytes per sample and the down-link size in Megabits per second. This information may also be coupled with some knowledge of the target detection algorithms to be used, for example 3 out of 4 (or 3/4) consecutive monocular hits for first report issuance, or 3/4 + 3/4 hits from two independent sensors for stereo detection and tracking. One must also limit the number of false exceedances from the sensor to some practical value so as not to issue large numbers of spurious alarms. In Figure 7, we show a threshold of ~6 kW/sr for the 1.8 km scanner design corresponding to a typical PFE value of 1.E-04. It can be seen from Figure 7 that when that same threshold is applied to the 3.6 km footprint design, the PFE is approximately 3 orders of magnitude higher, whereas the reduction in the number of detector channels is only a factor of 4. Looked at another way, the same PFE value results in 4 times higher thresholds for the 3.6 km scanner, which is the footprint ratio squared. The ground footprint of an IR scanner is a key design parameter in determining sensor performance against structured backgrounds.

Up to this point, we have considered only the background clutter noise. In order to properly account for the other

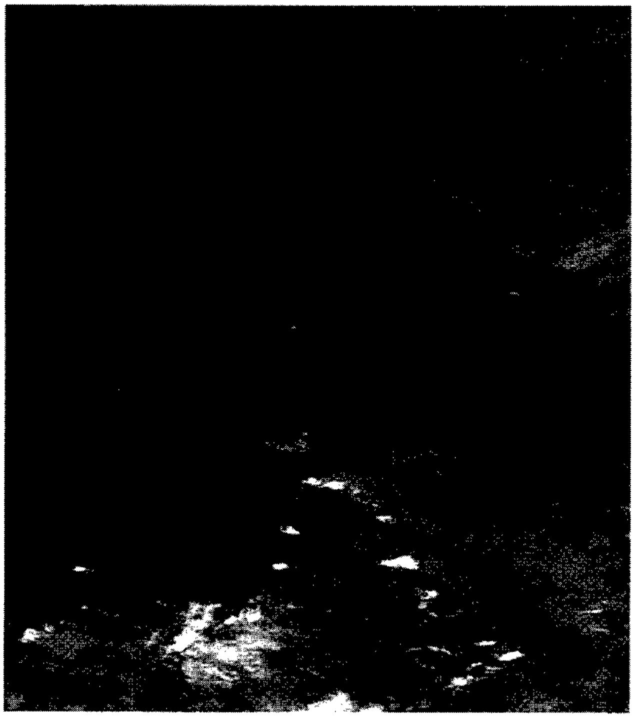


Figure 4. "Nominal" scene used for clutter performance analysis: 2 - 8 km altitude water & water/ice clouds; 200 m resolution; mid-latitude summer atmosphere

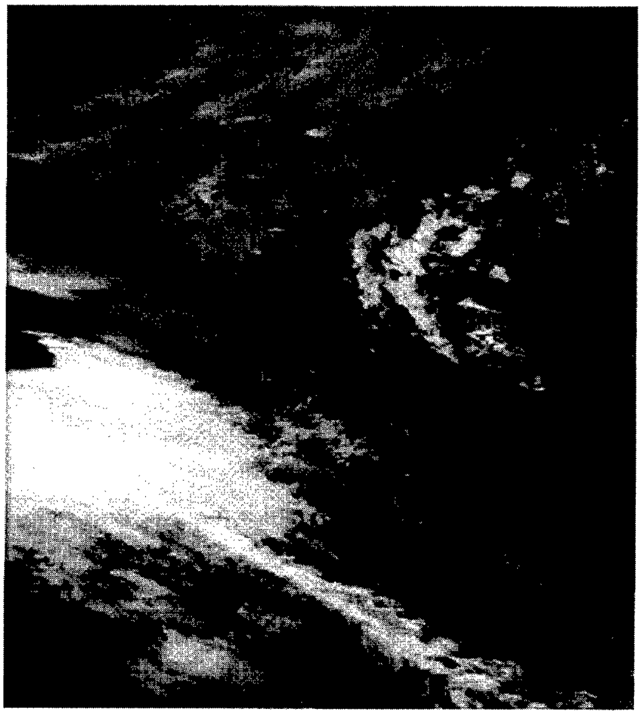
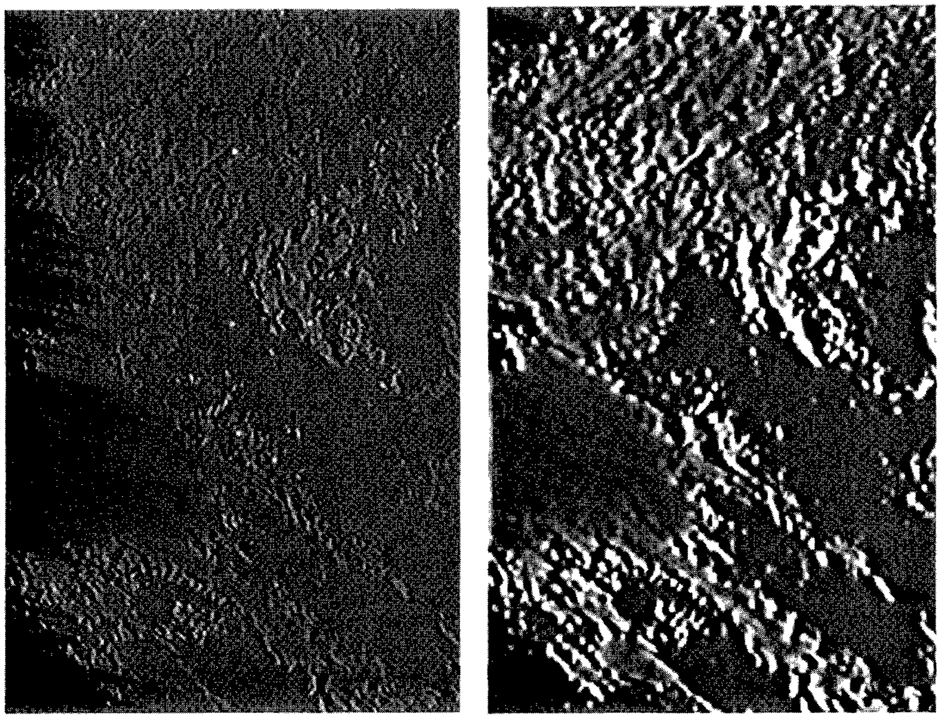


Figure 5. "Stressing" scene used for clutter performance analysis: 4 - 10 km altitude water/ice & ice clouds; 200 m resolution; mid-latitude summer atmosphere



(a) 1.8 km Footprint

(b) 3.6 km Footprint

Figure 6. IR scanner simulation against the stressing scene - AC-coupled outputs

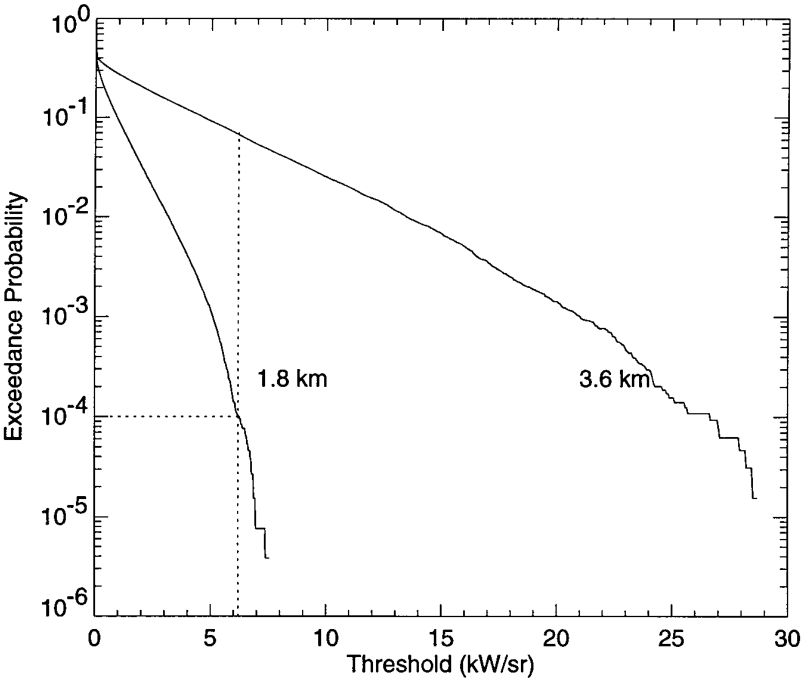


Figure 7. Probability of False Exceedance vs. Threshold for IR scanners against the stressing scene

noise characteristics of the sensor design under consideration (including photon noise, electronics noise, etc.), the sensor noise-equivalent target (NET) must be included in the threshold versus exceedance distribution. For a Gaussian clutter model, where the clutter is represented simply by the standard deviation of the output scene, the so-called clutter-equivalent target (CET) can be combined with the sensor NET to form the sensor-equivalent target (SET), with $SET^2 = NET^2 + CET^2$. Thus for a threshold T, a target intensity I_t and a standard deviation, σ = SET, the single-hit POD and the PFE are related by:

$$\mathrm{POD} = \frac{1}{\sqrt{2\pi}\,\sigma} \int_{z=T}^{\infty} dz\; e^{-(z-I_t)^2/2\sigma^2} \qquad (1)$$

$$\mathrm{PFE} = \frac{1}{\sqrt{2\pi}\,\sigma} \int_{z=T}^{\infty} dz\; e^{-z^2/2\sigma^2} \qquad (2)$$

or, with a change of variable,

$$\mathrm{POD} = 1/2 \left[1 - \mathrm{erf}\left(\frac{T - I_t}{\sqrt{2}\,\sigma}\right)\right] \qquad (3)$$

$$\mathrm{PFE} = 1/2 \left[1 - \mathrm{erf}\left(\frac{T}{\sqrt{2}\,\sigma}\right)\right] \qquad (4)$$

where:

$$1 - \mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_{z}^{\infty} e^{-t^2}\, dt \qquad (5)$$

Typically, one specifies three of these five variables and solves the two non-linear, algebraic equations for the remaining two. For example, given a POD, PFE and SET combination, we derive the threshold T and the minimum detectable target (MDT).

It is clear from Figure 7 that the scene-based clutter distributions are decidedly non-Gaussian. Fortunately, they can be well represented by a linear combination of weighted Gaussians which allows for a straightforward convolution with a zero-mean, Gaussian noise density function based on the NET as before. The cumulative distribution of this convolution then represents the overall system probability of false exceedance as a function of threshold. For the case where the clutter may be well-represented by the combination of two weighted Gaussians, we have:

$$\mathrm{POD} = \frac{W}{2\sqrt{2\pi}} \left[1 - \mathrm{erf}\left(\frac{T - I_t}{\sigma_1'}\right)\right] + \frac{(1-W)}{2\sqrt{2\pi}} \left[1 - \mathrm{erf}\left(\frac{T - I_t}{\sigma_2'}\right)\right] \qquad (6)$$

$$\mathrm{PFE} = \frac{W}{2\sqrt{2\pi}} \left[1 - \mathrm{erf}\left(\frac{T}{\sigma_1'}\right)\right] + \frac{(1-W)}{2\sqrt{2\pi}} \left[1 - \mathrm{erf}\left(\frac{T}{\sigma_2'}\right)\right] \qquad (7)$$

where:

$$\sigma_1'^2 = \sigma_1^2 + NET^2$$

$$\sigma_2'^2 = \sigma_2^2 + NET^2$$

$$0 < W \le 1$$

and σ_1, σ_2 and W are derived by fitting the output clutter distributions. An example of this double-Gaussian fit for a highly stressing clutter distribution is shown in Figure 8 along with the single Gaussian distribution based simply on the standard deviation of the output data. A comparison of these two distributions with the actual data reveals the limitations of assuming a Gaussian model for background clutter. As before, we may solve equations 6 and 7 for the required threshold T and the MDT given the required POD and PFE, a sensor NET and a clutter distribution fit.

TARGET RESPONSE

Target response is a scale factor that describes the attenuation of a target through the sensor system[7]. The target response for a point-source depends on the blurring due to the optics, the detector aperture, and, for a scanner, the temporal aperture due to the scan motion during the integration time. Other factors include the sampling of the blurred target by the focal plane (in particular, the target phasing, i.e., the location of the target relative to the center of a pixel), and the electronic filtering. For a staring system that performs temporal filtering, the target response also depends on the target velocity and its rate of intensity change.

For a scanner, the target response does not depend on the temporal characteristics of the target, so the calculation is fairly straightforward. A background scene is constructed, consisting of a grid of many 1 kW/sr point sources spaced far enough apart so there will be no interference from adjacent targets. Each target is offset randomly by a small amount to make the grid non-uniform, in order to ensure many different target phasings. This target grid is then passed through exactly the same simulation process as the scene backgrounds, namely blurring, downsampling, and filtering. The peak response from each target is determined. Generally, we use the mean value of this ensemble as the target response. All simulated clutter scenes are divided by the target response so they will be referenced to apparent intensities at the aperture.

CONSTELLATION PERFORMANCE

In order to evaluate the performance of a space-based, infrared surveillance architecture against a variety of targets and background conditions, the sensor response to both targets and backgrounds must be combined within a constellation-level simulation. After choosing one of the cloud data bases contained within the SSGM, we generate scenes spanning the entire range of viewing geometries and sun angles required for the adopted sensor constellation. The

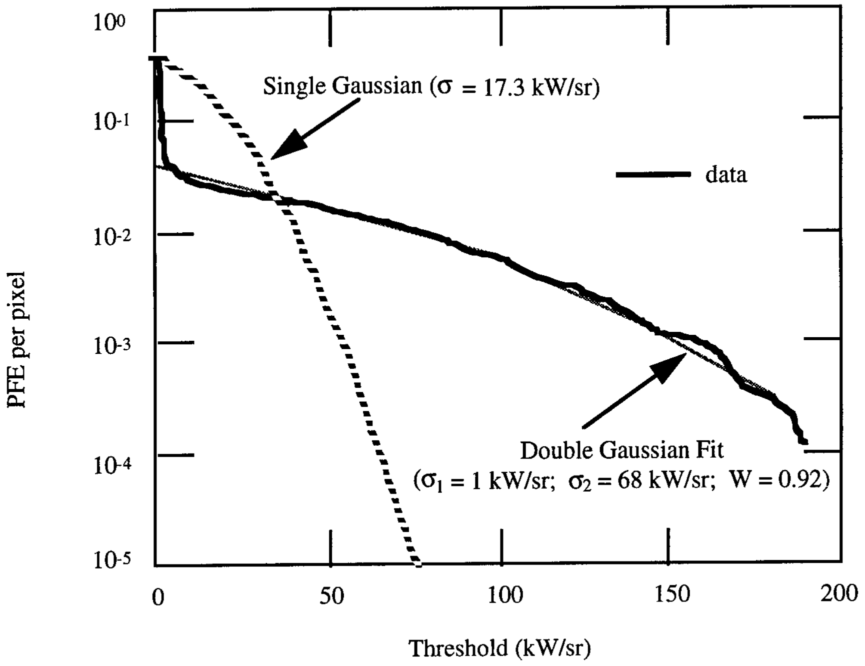


Figure 8. Probability of False Exceedance (PFE) distribution for stressing clutter.

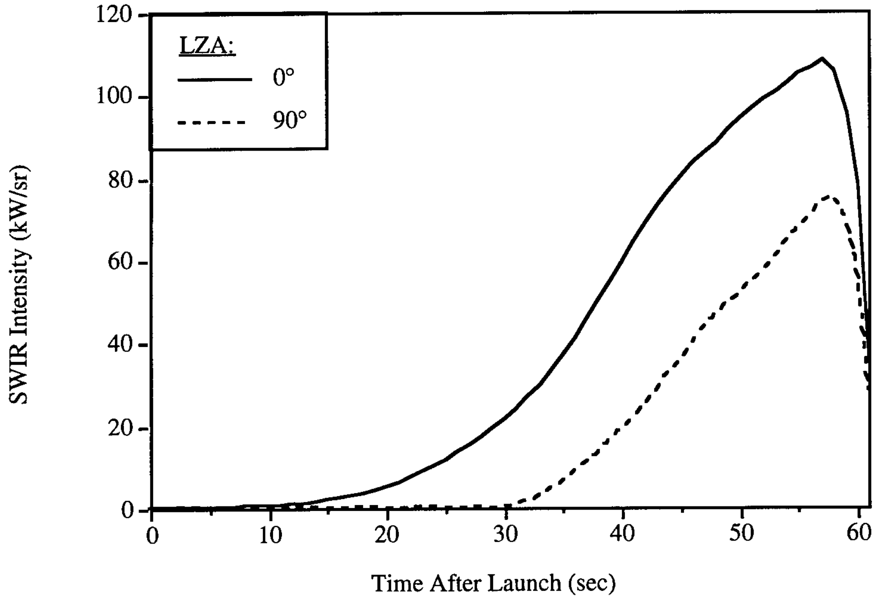


Figure 9. Theatre missile SWIR intensity vs. time after launch when viewed at nadir and the limb; includes attenuation by the atmosphere.

scenes are then processed through the detailed sensor simulation tool, VISTAS, to produce a set of PFE-threshold clutter distributions. An extremely useful attribute of these distributions is that they all have essentially the same shape for a given sensor design and background scene morphology, differing only by a threshold scale factor. This means we can use a single fit of weighted Gaussians to represent the mean clutter, while the variation with viewing geometry and sun angle is represented by a matrix of scale factors. In this way, we produce a clutter matrix as a function of LZA and SCA. This matrix is then incorporated within the constellation-level performance tool, TRADIX. After combining the appropriate clutter parameters with the sensor NET, TRADIX calculates the threshold and MDT as a function of LZA and SCA for the required POD and PFE combination.

Within TRADIX, the targets and satellites are propagated in Earth Centered Inertial (ECI) coordinates with an appropriate sampling intervel, typically 10 to 15 minutes for geostationary satellites. This is carried out usually over an entire day at various times of year, or epochs, in order to explore the effects of seasonal variations in the sun's latitude. For a geostationary constellation and a distribution of target launch sites which is biased towards the northern hemisphere, June 21 results in the most stressing solar scatter angles. We generally restrict our analyses to this worst-case epoch when background clutter is the dominant issue. On the other hand, solar straylight can also play an important role in limiting target detection, in which case late August through September is one of the most stressing epochs during the year. Each sensor-target LOS at each time step results in an LZA / SCA pair which, with the inclusion of the clutter matrices, sets an MDT threshold for that sensor. This in turn leads to a time of first detect for a missile launched at that location. Three out of four consecutive detections leads to a mono "3/4" report. Two such 3/4 reports by separate sensors during the missile's boost phase results in a stereo report for the constellation. Target detection and report time statistics are generated for each sensor design against each structured background for the mission of interest.

For a typical global missile warning (GMW) analysis, target launch sites are uniformly distributed over the surface of the earth from -90° to +90° latitude. We use a target spatial pattern with a resolution of 3° x 3°, resulting in 4586 distinct target launch locations. Each target represents an equal area of the surface of the earth. No attempt is made to distinguish between ocean and land areas. Missiles are usually launched in 4 orthogonal directions in order to allow for aspect angle effects on the apparent booster signature. The point of such an analysis is to obtain a measure of system performance which is not scenario driven.

It is important to point out here that it is well recognized that the entire surface of the earth is never completely covered with 6 km or 10 km clouds. In fact, 10 km is about the 85th percentile altitude for global cloud cover, and the frequency of occurrence of high-altitude clouds is very latitude dependent, being much more likely at lower latitudes. Our analysis should be viewed as generating the probability of missile warning (mono and/or stereo) when clouds of a given altitude are present at the locations of interest. Meteorological data must be used to address the frequency of given cloud types and altitudes at a given geographical location and time of year. Over NE Asia, the University of Wisconsin HIRS-2 data base indicates that clouds at 10 km or above occur, on average, about 20 to 30% of the time during the summer, whereas clouds at 6 km or above occur approximately 40 to 50% of the time. Note that these averages are based on six years worth of data, and that the maximum cloud cover percentages seen during those six years was about 40% for 10 km clouds and over 60% for clouds at 6 km and above .

TMW MISSION ANALYSIS

For the TMW mission, we have used a single representative theatre missile type. The apparent intensity profile of this missile is shown in Figure 9 for a 90° aspect angle (i.e., maximum intensity) at two extreme viewing geometries, namely nadir and the limb. The spatial resolution of the target grid pattern used is again 3° x 3°, resulting in approximately 51 distinct target locations per theatre. As discussed in the previous section, we will limit our analysis to the worst case epoch for clutter-limited detection of northern hemisphere targets, namely June 21. We have focused on two theatres of operation, each 2000 km x 2500 km in size, one located in the Middle East and the other in NE Asia. We selected a "pinched" 5 satellite geostationary constellation in order to provide excellent coverage over both of the geographically separated theatres simultaneously. The ability to optimize satellite locations, and thus trade between theatre performance and global coverage, is most easily accomplished with geostationary constellations. The longitudes of the 5 geostationary satellites are shown on a cylindrical projection of the earth in Figure 10, along with the boundaries of the two theatres and the constellation's mono, stereo and triplet LOS coverage. It may be seen that we have contrived to have essentially 100% triplet coverage over both of our theatres of operation. It remains to be seen whether or not this is sufficient to provide guaranteed TMW performance against all possible background conditions.

For the TMW mission, we have assumed a CONOPs where a minimum of two sensors are tasked to cover a pre-defined theatre. In other words, cuing of one sensor by another will not be necessary. The impact of such cuing would, of course, be a delay in obtaining a stereo track. However, it seems reasonable to assume that "hot" theatres would take precedence over most other missions.

We have chosen an IR line scanner as our sensor design option. While not necessarily the most effective design for good clutter performance, it does reduce the risk associated with the high level of platform LOS stability typically required by a staring sensor. The risk associated with focal plane producibility issues are also reduced. However, in order to achieve acceptable performance against highly structured backgrounds, simulations have shown that the footprint of such a scanner must be relatively small, 2 km or less. In order to explore the impact of varying this key design parameter, both in terms of clutter performance and payload weight, we shall consider three designs which have 1.8 km, 2.6 km and 3.6 km footprints, respectively.

The 1.8 km footprint design is summarized in Table 2. The optics are shown in cross-section in Figure 11. They consist of a triplet refractor and a 2-axis scanning entry flat.

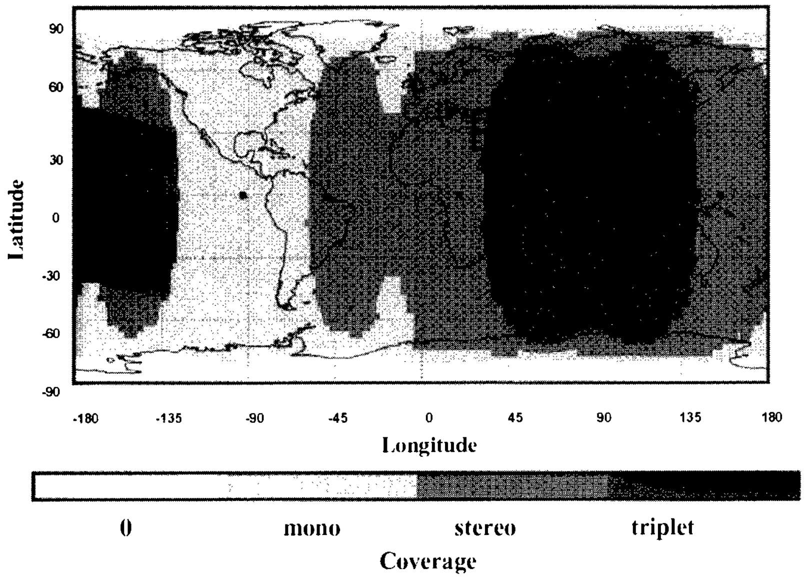


Figure 10. Instantaneous Line of Sight Coverage of 5 Pinched Geostationary Satellites with Middle East and NE Asia Theatres of Operation

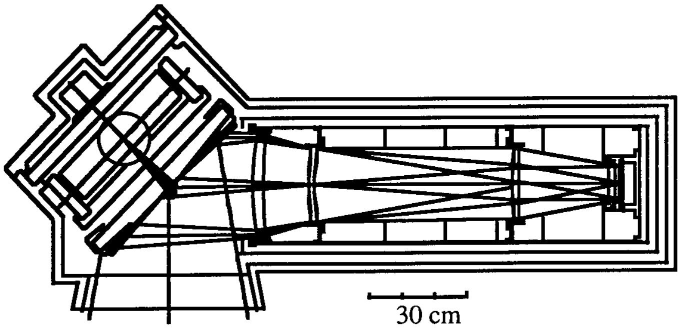


Figure 11. IR Scanning sensor optics: Triplet refractor, field flattened and a 2-axis entry scan mirror.

Table 2. 1.8 km footprint scanning sensor design

Optical Parameters		Detector Parameters	
Aperture (m)	0.27	Pixel Width (microns)	40
Focal Length (m)	0.8	Detector Quantum Efficiency	0.8
Focal Ratio	f/3	Ensquared Energy on Pixel	0.8
In-band Optics Transmission	0.65	Samples per dwell	1.5
Cross-scan Field of View (°)	6.3	Target Response	0.59
Pixel Field of View (microradians)	50	NET @ 4°/sec scan rate (kW/sr)	1.0

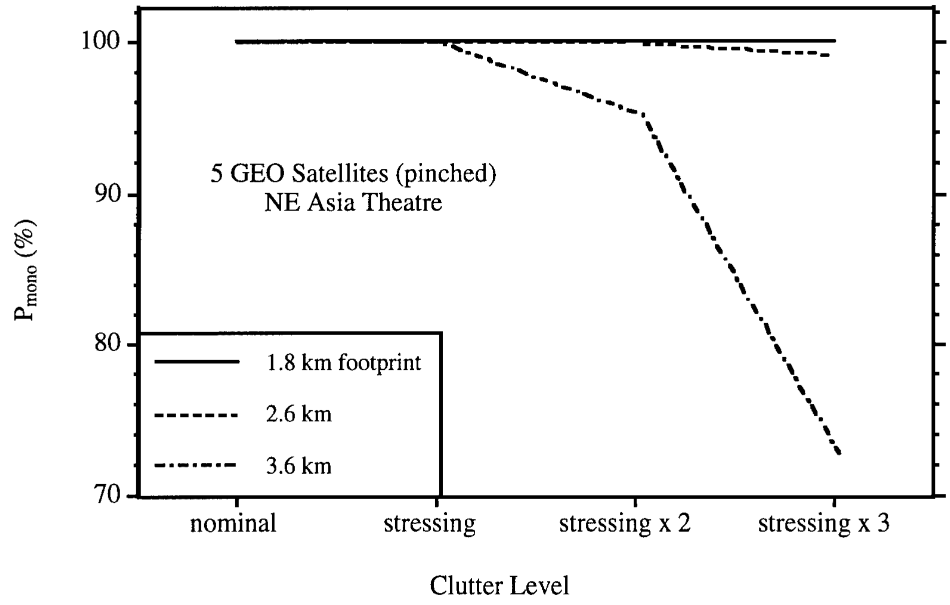


Figure 12. Mono Performance Sensitivity to Sensor Footprint and SWIR Clutter

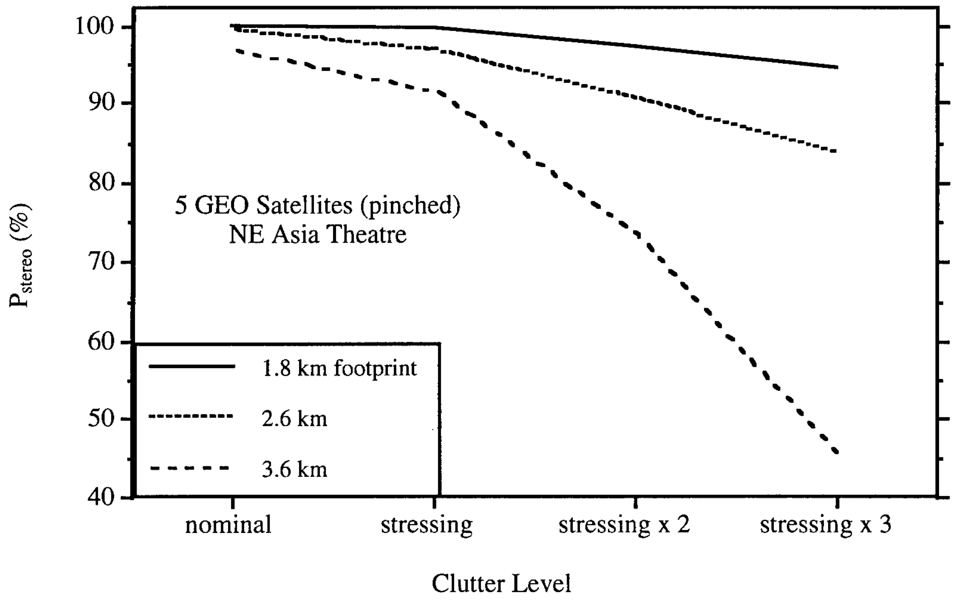


Figure 13. Stereo Performance Sensitivity to Sensor Footprint and SWIR Clutter

In order to achieve low NET performance, aperture is traded against TDI (time delay and integrate) capability on the focal plane. The result is a 27-cm aperture with 12 stages of TDI, the latter being limited by scan velocity mismatch problems. A 2-second revisit time is assumed for the TMW mission. This requires a scan rate of around 4°/sec and results in a NET of about 1 kW/sr, at nadir.

For the sensors under consideration, a PFE of ~1.E-05 leads to a tolerable false report rate for the TMW mission (around one mono false report per day for the 1.8 km scanner, somewhat less for the larger footprint designs with fewer pixels). A single-hit POD of 0.95 was chosen for this analysis, which, for a 3/4-hits detection algorithm, results in a cumulative probability of detection of 0.99. This POD / PFE combination leads to a MDT as a function of viewing geometry for each sensor design, background scene and clutter scale factor.

The TRADIX constellation analysis tool was used to evaluate the mono and stereo performance of all three sensor designs against the nominal x1 and stressing x 1, x 2 and x 3 clutter levels. Figure 12 shows the mono detection performance of each sensor design for the NE Asia theatre. The results for the Middle East theatre are very similar. Given three views to choose from, the 1.8 km and 2.6 km footprint designs have no difficulty providing a (mono) warning probability Pw = 99% or better before burnout. Note that the warning times of the 1.8 km scanner will always be earlier than those of the larger footprint designs, particularly at the higher clutter levels, but in this paper we will use the booster burnout time for our performance measures. Earlier warning time requirements will simply accentuate the impact of larger sensor footprints. As it is, the 3.6 km footprint design can barely provide 95% mono warning at the stressing x 2 clutter level and falls significantly at higher clutter levels.

The impact of the larger footprints on the stereo performance of the three sensor designs is more severe. The stereo results for the NE Asia theatre are summarized in Figure 13 and the stereo performance results across the entire Eurasian landmass are shown in Figures 14 through 16 for the stressing, stressing x 2 and stressing x 3 clutter levels, respectively. As indicated earlier, the results for the Middle East and NE Asia theatres are very similar. In either case, the 2.6 km design can only provide a 95% probability of stereo detection before burnout against the stressing x1 clutter level or below. The 3.6 km design can only meet this minimum criterion for success at the nominal x 1 clutter level or below. Recall that 10 km and 6 km clouds can be expected over NE Asia approximately 20% and 40% of the time, respectively, during the summer months. These designs would be further stressed if the constellation were required to perform additional missions simultaneously. However, we are concerned here only to show the impact of clutter and sensor design for one representative case.

TMW PERFORMANCE AND PAYLOAD WEIGHT

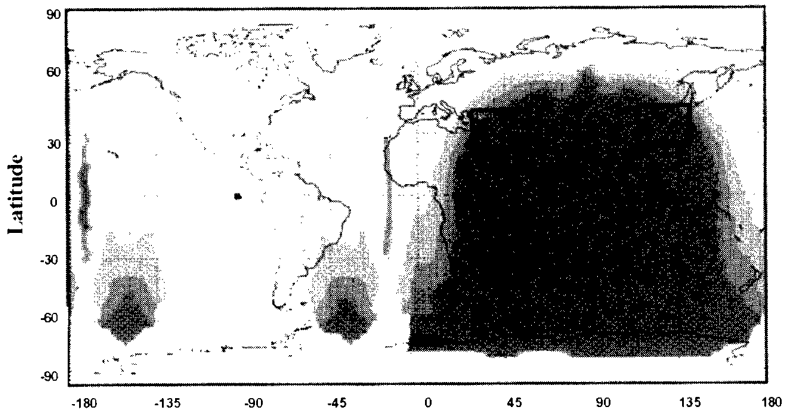
It is of interest to consider the cost of guaranteeing high TMW mission performance. Rather than attempt to carry out a detailed cost analysis of the sensor designs, we will focus on payload weight, which is more straightforward to estimate. Payload weight is also thought to be an adequate cost indicator, both in terms of the payload itself and that of the launch vehicle required to lift the payload and its satellite bus to geostationary orbit. For the 1.8 km footprint scanner, the volume of the telescope shown in Figure 11 is 200 cm x 88 cm x 66 cm and the telescope, sensor housing and scan mirror combined weigh 134 kg. The focal plane comprises 8 hybrid assemblies, each with two rows of detectors (to provide 2x cross-scan oversampling) which are 292 x 12 in TDI. Since the TDI is performed on the focal plane, the total number of detector channels which must be processed is 2 x 292 x 8 = 4672. The signal processor must be sized for the global mission, where the total analog sampling rate is approximately 96 Msamples/sec. This includes high and low gain samples from the focal plane, but only one of the samples is processed in the digital processor. Using current (1995) technology, the combined analog and digital signal processor weight and power are 17 kg and 90 W, respectively. The other payload subsystem weights are summarized in Table 3.

Also shown in Table 3 is the impact on the payload weight of increasing the ground footprint to 2.6 km and 3.6 km while maintaining the same NET performance for a given revisit time. Here we have traded on the increased sample time of the larger footprints to reduce the telescope aperture and hence its overall volume and weight. Reducing the number of detector channels by the ratio of the footprints also results in savings in the signal processing and thermal subsytems. The scan electronics and communications subsystems are assumed to remain constant in weight, although not necessarily so in power consumption. Figure 17 shows the stereo performance sensitivity to sensor footprint and payload weight at various clutter levels. Essentially, Figure 17 shows the cost of designing an IR sensor to have guaranteed performance against an uncertain level of background clutter. The larger footprint designs are less robust against increasing clutter levels. These results show that while there are significant savings to be made in payload weight (and power), the performance penalty in stereo track capability associated with a larger footprint design may be severe. On the other hand, if the solar scatter off clouds has been seriously *overestimated* within SSGM, then certainly larger footprint designs become more viable, neglecting other performance issues such as closely-spaced object discrimination and tracking errors. Advanced processing and sophisticated clutter rejection schemes are often invoked and should be used whenever possible, but such techniques cannot by themselves compensate for a poor sensor design.

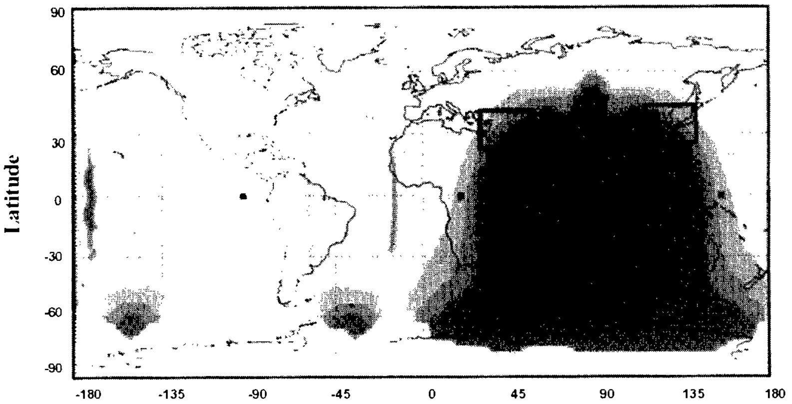
SUMMARY AND CONCLUSIONS

A methodology has been devised to evaluate the impact of structured backgrounds on the performance of space-based IR surveillance sensors. The integrated capability enables detailed sensor-level simulations and background models to impose meaningful constraints on system-level performance in a reasonably efficient manner. As an example of the application of this simulation methodology, the TMW mission performance of three IR scanning sensor designs operating in the SWIR water absorption band at 2.7 microns has been evaluated against varying levels of background structure. The geostationary constellation of 5 satellites was pinched in order to provide triplet coverage over two geographically-separated theatres of interest. Nevertheless, a level of uncertainty in the clutter corresponding to a factor of 3 in cloud scattering efficiency is found to have

(a) 1.8 km Scanner



(b) 2.6 km Scanner



(c) 3.6 km Scanner

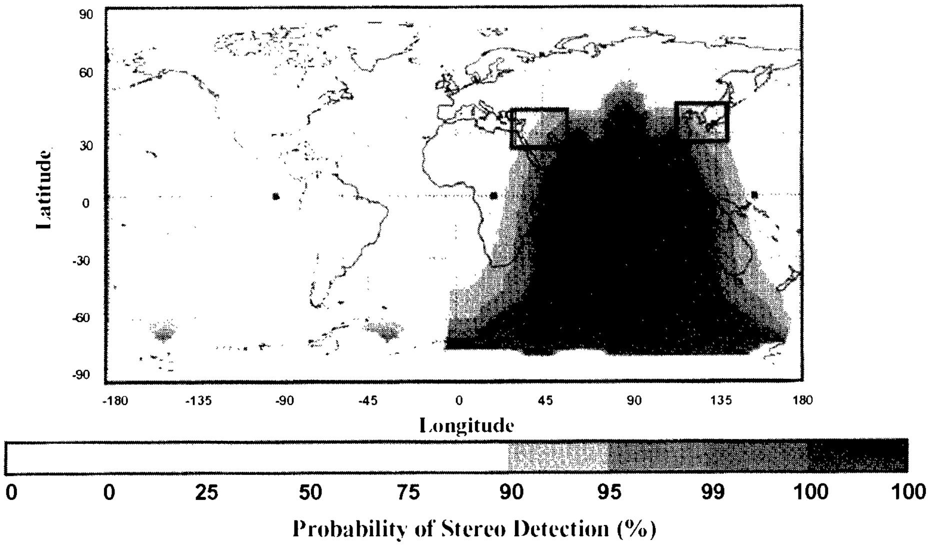
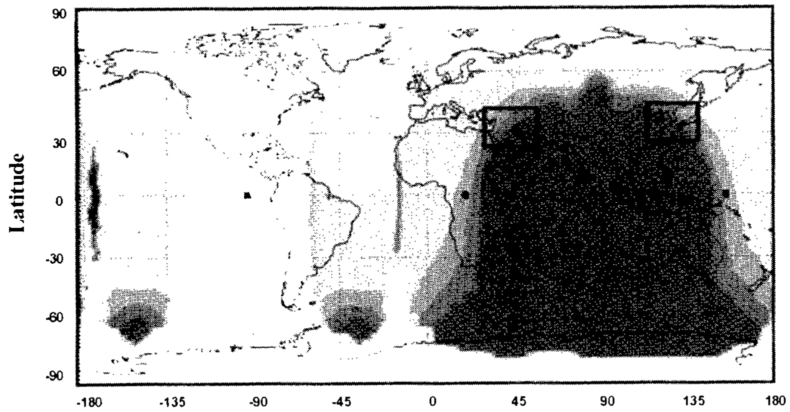
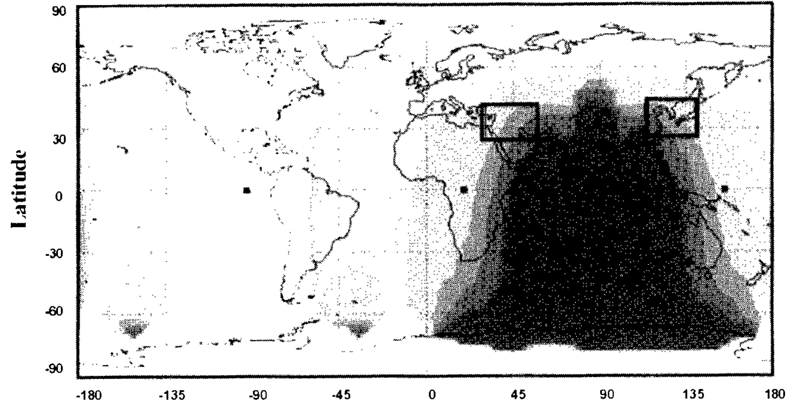


Figure 14. TMW performance of 5 pinched GEO satellites against stressing clutter

(a) 1.8 km Scanner



(b) 2.6 km Scanner



(c) 3.6 km Scanner

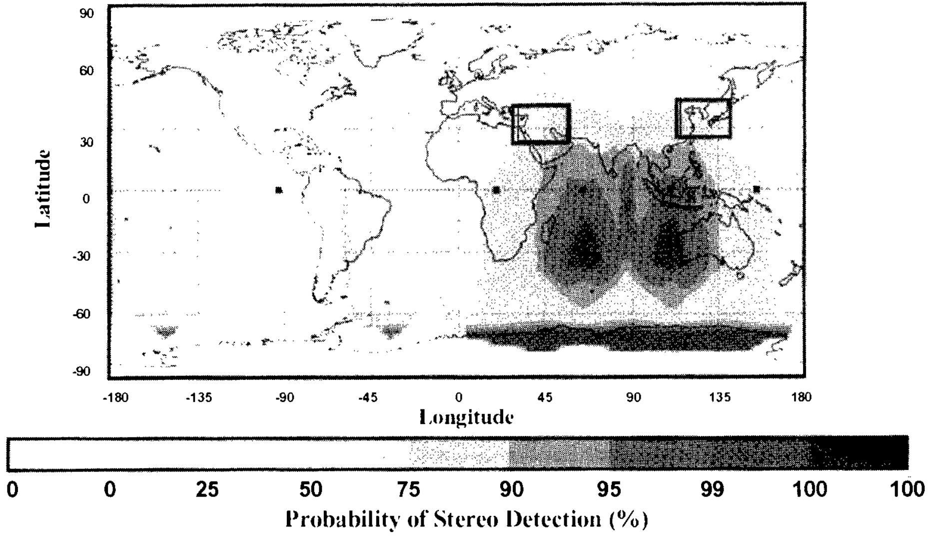
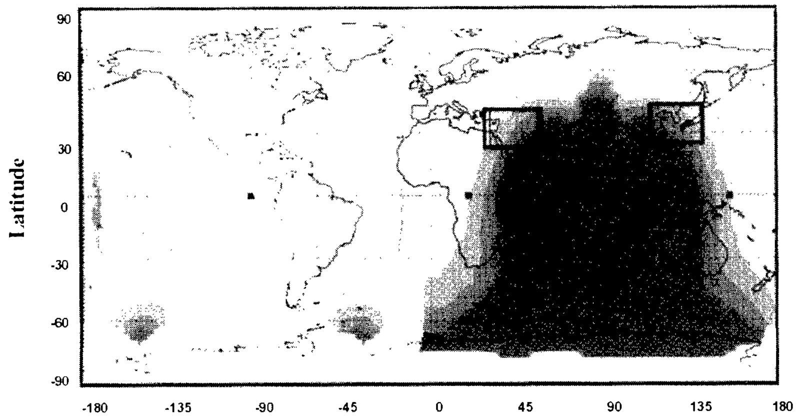
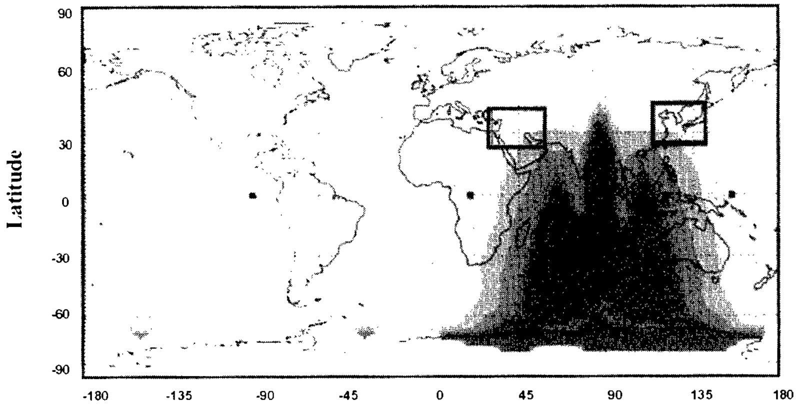


Figure 15. TMW performance of 5 pinched GEO satellites against stressing x 2 clutter

(a) 1.8 km Scanner



(b) 2.6 km Scanner



(c) 3.6 km Scanner

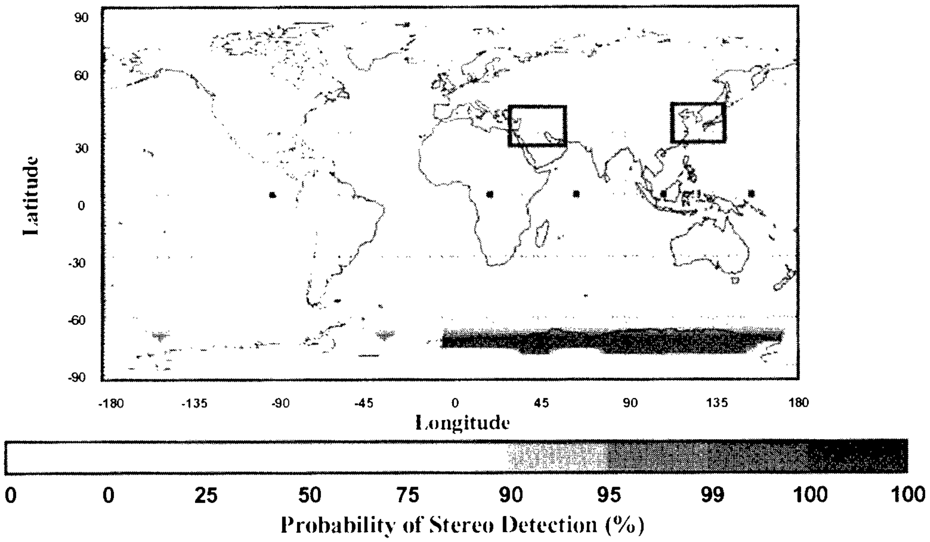


Figure 16. TMW performance of 5 pinched GEO satellites against stressing x 3 clutter

Table 3. Payload subsystem weights vs. scanner footprint

Footprint (km)	1.8	2.6	3.6
Aperture (m)	0.27	0.225	0.19
Telescope, sensor housing 2-axis scan mirror	134 kg	93 kg	67 kg
Signal Processor	17	11	8
Thermal Control	18	12	9
Scan Electronics	9	9	9
Communications	18	18	18
Total	196 kg	143 kg	111 kg

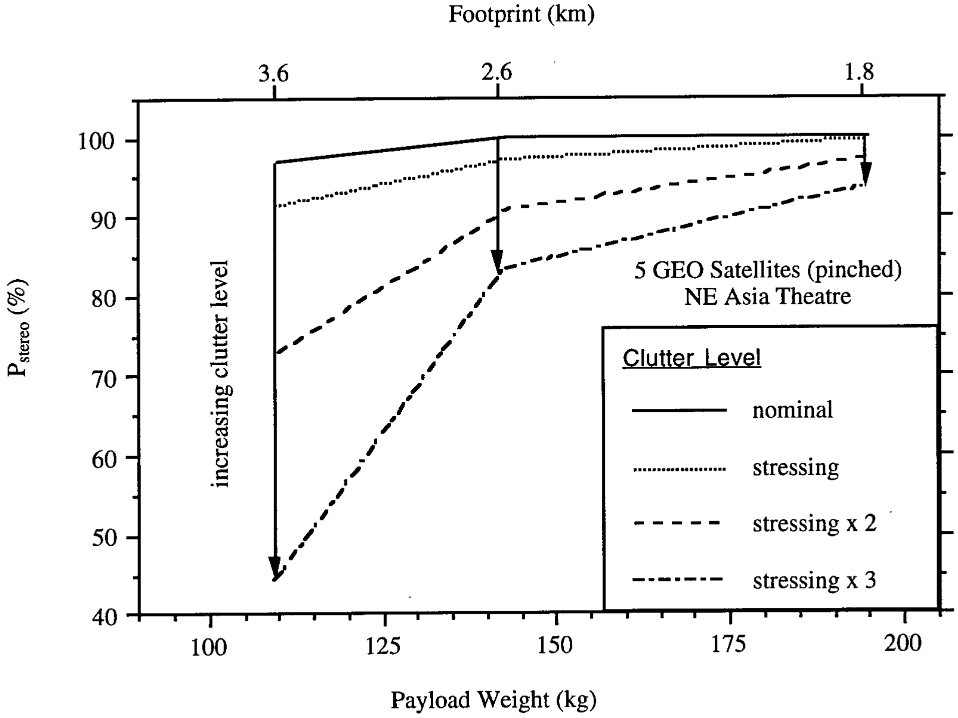


Figure 17. Weight and Performance Sensitivity to Sensor Footprint and SWIR Clutter

implications for the payload weight (and cost) of possible sensor designs. The potential for significant weight savings exists if the current SSGM is found to be too conservative in its cloud scatter model. On the other hand, if in fact the model turns out to underestimate the severity of the solar scatter problem, a conservative sensor design approach (i.e., smaller footprints) along with more sophisticated processing will be required to mitigate the system impact.

ACKNOWLEDGEMENTS

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INTEGRATED AIR DEPLOYED STRIKE SURVEILLANCE (IADSS)

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I. SUMMARY

The U.S. Navy's Integrated Air Deployed Strike Surveillance (IADSS) initiative is a pathfinder effort in defining the next generation sensor and mission management systems for unmanned air vehicles (UAV). The sensor suite in development will be capable of deterministic to fully autonomous operations. This includes the capabilities for dissimilar sensor queuing, automatic sensor search and automatic target recognition. A key developmental item is the autonomous management system (AMS) that will "manage" the expanded onboard sensor suite. The envisioned equipment suite includes signal detection equipment, imagery systems and a duplex communication system.

This paper is presented in three parts: an overview, the operational demonstrations and the supporting Science and Technology.

II. OVERVIEW

1. INTRODUCTION

The IADSS capability can support the NATO Defense Space Systems Mission. An organic surveillance asset with space connectivity that is capable of passive and active wide area surveillance supports tactical, strategic, intelligence and precision strike targeting missions. This initiative also advances the state-of-the-art in autonomous airborne sensor management in the areas of fusion, integration, processing and communications. The planned onboard sensor systems include Signal Intelligence (SIGINT) systems, Electro-Optical/ Infrared Sensors (EO/IR), and Synthetic Aperture Radar (SAR).

2. ORGANIZATION

The IADSS project organization, shown in Figure 1 is comprised of three Integrated Product Teams (IPTs): (a) S&T Development; (b) Demonstrations; and (c) Autonomous Management System (AMS). The IADSS management and technical staff are from the Office of Naval Research (ONR), the Naval Research Laboratory

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(NRL), the Naval Command Control and Ocean Surveillance Center (NCCOSC) and Naval Air Warfare Center (NAWC).

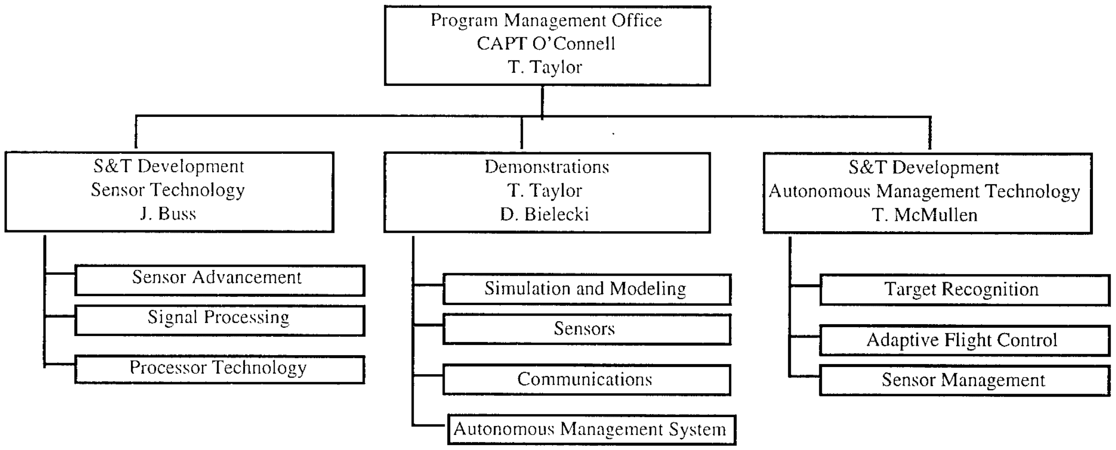

Figure 1 IADSS Program Organization

3. SYNERGIES

The IADSS program is complementary to ongoing efforts by the Defense Advanced Research Program Agency (DARPA), Defense Airborne Reconnaissance Office (DARO), and the Army Airborne Reconnaissance Low (ARL)-M program. Principal synergies between IADSS technology and other agencies focus on real-time on-board signal processing/fusing, automatic target recognition, cross sensor queuing, search algorithms, open system architecture issues and general autonomous collection management (sensor selection and cueing, adaptive flight and search planning and control, and data fusion) procedures. The working relationships established facilitate the technical exchange of ideas, approaches, and potentially some technology breakthroughs.

4. CONCEPT OF OPERATIONS

The IADSS equipped UAV will be capable of flying in a variety of modes from a completely deterministic operation involving waypoints to fully autonomous operation. The IADSS equipped platform in the automatic mode will be capable of autonomously searching a designated area with multiple sensors and returning the data to "homeplate" with no human interface. The data forwarded to the tactical user would be a SAR or EO/IR target image annotated with Electronic Intelligence (ELINT) parametric data and includes, if determined, target identification, classification, location and intention. Typically, the system requires only mission objectives (candidate

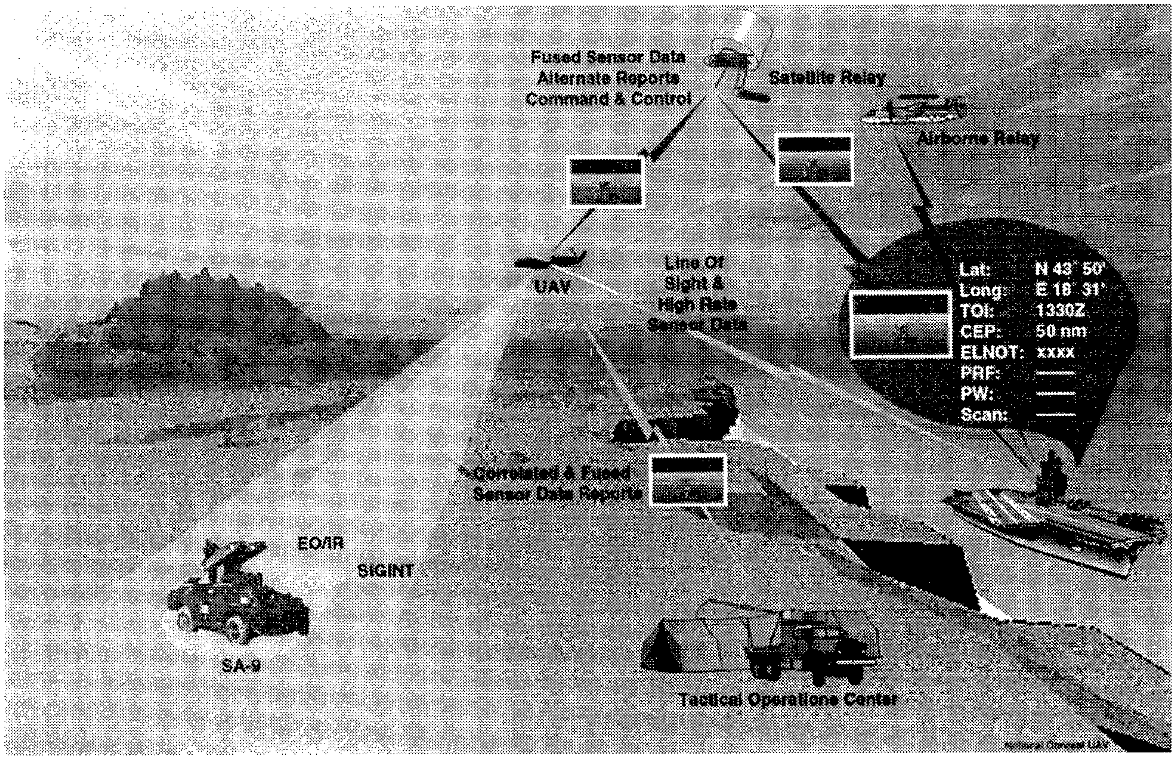

Figure 2 IADSS Concept of Operations

targets and priority), search area coordinates, ingress and egress time, and environmental conditions to operate and generate the IADSS product reports. The system will also be capable of receiving in-flight high priority search areas (i.e., from an AWACS or E2C platform) along with target parameters. This allows for ad hoc operations as well as virtually extending the capability of some manned airborne platform capabilities. The IADSS concept of operations is illustrated in Figure 2.

The target IADSS equipment platform is the DARO tier three minus next generation unmanned air vehicle (UAV). This is a long endurance, high flying, typically autonomous vehicle.

III. DEMONSTRATIONS

The IADDS implementation plan is a five year program that consists of three phases. See Figure 3. Phase I is System Definition, Phase II is the Testbed Development, and Phase III is a series of flight demonstrations.

The demonstrations will highlight all aspects of the development but particular emphasis will be on the Autonomous Management Systems capability. Some of the demonstration goals are:

- autonomous long range surveillance and wide area search,
- autonomous sensor suite management and correlation,
- integrated operation of a sophisticated sensor suite,

- annotated image with target classification from on-board processing,
- an efficient and flexible communication duplex link utilization with "joint" protocols,
- dynamic and autonomous inflight mission or profile reconfiguration based on real-time events,
- system survival and platform threat evasion capabilities, and
- a demonstration against multiple classes of targets (fixed and mobile) in the ground based/littoral ocean area.

The flight demonstrations take an incremental approach to meeting the planned IADSS goals. Measures of effectiveness (MOEs) will be developed for each set of demonstrations.

The first demonstration will be a fully deterministic mode of flight that focuses on the ELINT sensor cueing the EO/IR and/or SAR sensors. One of the MOEs for this demonstration will be whether the AMS sent the appropriate cue from the ELINT to the EO/IR and/or SAR sensor. All data will be recorded on-board and all processing will occur post mission.

Demonstration 2 will be partially autonomous and designed to demonstrate in-flight deviations from the preprogrammed plan. The variations may be illustrated by having weather dictate the selection of the SAR sensor, a change in the air vehicle altitude, or a delay in the collection of the target image. The AMS will focus on automatic target cueing and generating an image annotated with ELINT target classification information. Image and ELINT data will be downlinked to the ground for processing.

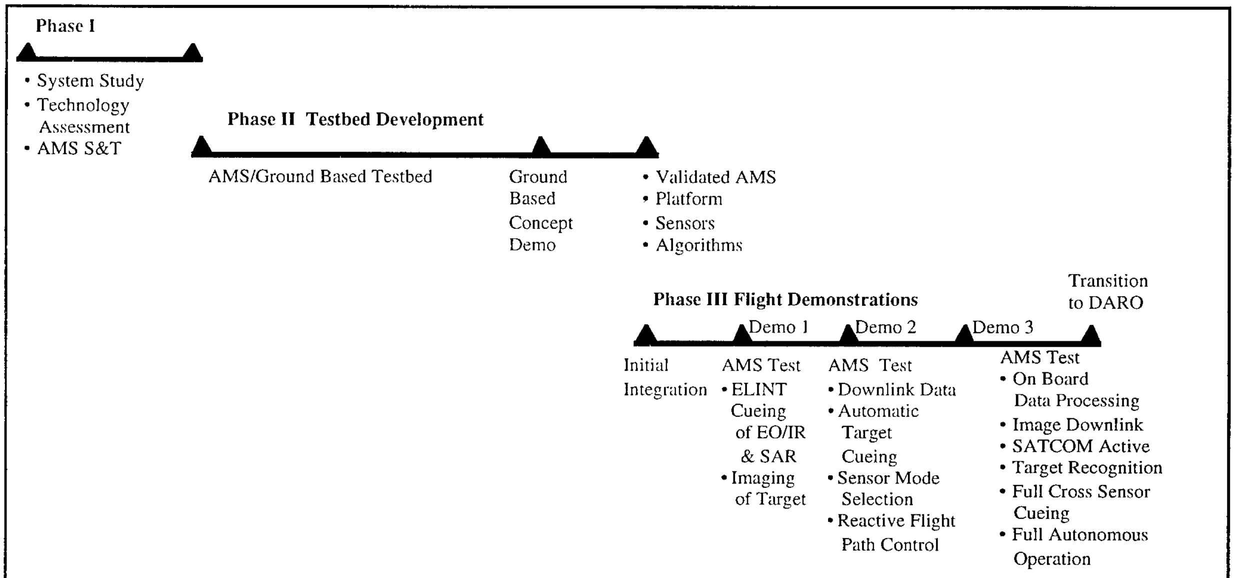

Figure 3 IADSS Implementation Plan

Demonstration 3 will be a fully autonomous test flight that examines the full range of AMS capabilities. Typical scenarios for this demonstration will require the vehicle to fly preplanned routes, general search routes and demonstrate a reactive capability. For example, a manned airborne platform will send tasking to IADSS to alter it's flight path, seek a non apriori target, generate an image and send this image to the airborne platform. The image will be annotated and downlinked to the originating command.

IV. TECHNOLOGY

The technology areas in the IADSS initiative focus on the AMS and the three onboard sensors - SIGINT, EO/IR, and SAR.

The AMS is expected to produce advancements in algorithmic developments in the area of sensor search, sensor cueing, target location, recognition and identification, and some form of flight control. Functional decomposition will be used to develop a modular architecture of the AMS. Modules include route planning, sensor performance models, sensor capability models, sensor management suite, vehicle rules, optimization, conflict resolution, automatic target cueing, automatic target recognition, and weather modules.

The SIGINT sensor used during the demonstrations will have a spectrum range of approximately 2-18 GHz. Expected geolocation accuracy of less than 1 km will be achieved through a hybrid of the Time Difference of Arrival (TDOA) technique and interferometric approach. The sensor technology will support the capability to detect frequency hopped or chirped signals. It will have a wide field of view with sidelobe detection sensitivity. This sidelobe capability will be able to detect and locate targets that employ a variety of scan types including track while scan radars. In order to imitate operational scenarios, the SIGINT tests will be conducted in high density environments. By the year 2000, the coverage is expected to be 0.8 GHz to 18 GHz.

The EO/IR sensor used in the demonstrations will employ long and medium wave infrared (LWIR) & (MWIR) along with visible bands with multispectral cueing capability. In addition, the system requirements for the EO/IR sensor include the capability of being cued by the SIGINT or SAR sensor.

The goal for the transition year is to have developed a multispectral IR system using a focal plane array (FPA) employing optical signal processing. This multispectral sensor will use scanning FPAs with separate scanner modules for the visible and IR multi-spectral imagers. One scan will search the area designated by the SIGINT sensor while a larger scan will be used to search the local area. S&T issues that need to be resolved include the registration and spectral purity of the images and the development of the multi-color FPA.

The SAR used for demonstrations will have 1 foot resolution and the ability to detect slow moving ground targets. The system requirements also include the capability of being cued from the SIGINT or the EO/IR sensor and to employ a ground moving target indicator (GMTI) mode. The SAR and the EO/IR sensor must be capable of recognition and detection in clutter along with precision tracking after recognition. By the year 2000 the resolution should have improved to 0.5 foot resolution. There are plans to have enhanced geolocation algorithms in place and to include moving target imaging.

IADSS S&T efforts will focus on advancing sensor capabilities and signal processing techniques to meet the requirements for autonomous operations and target classification and identification. During Phase I, S&T requirements will be defined, existing technology surveyed, ongoing S&T programs evaluated, and IADSS S&T tasks initiated. The relative value of S&T results will then be evaluated using modeling and simulation techniques. S&T efforts that are ready for inclusion in the operational demonstration will be integrated into the IADSS Phase II Ground Based Concept Demonstration and Phase III Flight Demonstrations.

The key S&T candidate thrust areas include;

- autonomous sensor management;
- high speed real-time signal processing;
- multi-sensor correlation;
- multi-spectral EO/IR sensors;
- ultra high resolution sensors, multi-spectral FPAs and associated signal and image processing methods;
- shared aperture and electronically or optically controlled shutters (for radar cross section reductions) for RF, SIGINT, and EO/IR sensors;
- lightweight antennas that operate over the SAR and SIGINT spectral range; and
- efficient, light weight prime power generation.

Of particular interest are "smart" multi-spectral FPAs where the readout circuits are integral to the FPA. The FPA must be dual-band with three bands being preferable. The IR device must be capable of providing "color" discrimination,

SIGINT improvements will focus on reducing the typical detractors from geolocation accuracy such as pulse correlation, timing issues, atmospheric corrections and self-diagnostic error budgets.

Platform or mission issues such as dynamic flight and search planning, near real-time battle damage assessment (BDA), and autonomous decision aids will be investigated.

V. CONCLUSIONS

The IADSS initiative will provide supporting developmental and empirical data to shape the future path of Unmanned Air Vehicles. The dissimilar sensor queuing and the Automatic Target Recognition algorithms, along with the Autonomous Management Prototype efforts are particularly useful in developing day-night, all weather surveillance capabilities for future operational systems. Further, the onboard duplex communications capability that is capable of receiving updated priorities and allows onboard images to be forwarded to satellites (for rebroadcast), airplanes, and surface units, allows this platform to be used as a tactical, strategic or intelligence asset.

Application-Specific Bandwidth Compression for Dissemination of Image Data

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SUMMARY

Image data collected in support of NATO forces continues to increase in quantities which exceed the available communications links. To address the mismatch in data volumes and communications lines, bandwidth compression techniques are being developed and implemented. We refer to the systems, both the hardware and software, used for compression and decompression of image data as **codecs** **co**mpressor/**dec**ompressor systems.

Codecs have traditionally been optimized for a number of different criteria, including: the speed of decompression, ability to recover from transmission errors, preservation of specific image attributes, maintainance of visual quality, and communication factors including target bit rates. This paper will examine a family of codec systems in terms of military support, and an analysis of selected codecs will be performed. The analysis is based on an expanded optimization criterion. The new codecs criterion includes the maintenance of image quality as related to machine processing for image understanding and information extraction. Consideration will also be given to the suitability of space implementation for the compression system.

INTRODUCTION

Compression/Decompression Systems

The digital representation of imagery inherently requires large bandwidths. Bandwidth compression of image data has an essential role in efficient transmission and storage of digital imagery. .Early developments in theory and software associated with digital image coding involved delta modulation and differential coding for lossy methods of bandwidth compression and entropy coding for lossless transmission of imagery data. These were one-dimensional techniques used for voice coding and were considered for image bandwidth compression in both commercial and space applications. Entropy coding techniques with well-defined standards are used for facsimile coding. Differential Pulse Code Modulation (DPCM) was the selected technique for long haul transmission of AT&T's Picturephone in the 1970's [1]. Later, Adaptive Delta modulators were considered for both commercial and space applications [2]. The first two-dimensional coding technique for image data was block transform coding that utilized a unitary two-dimensional transform with an optimum bit assignment and quantization of the transform coefficients [3]. This technique was shown to have superior performance but was too complex to implement.

Early improvements in compression techniques were related to using larger block sizes and adaptive coding strategies. Both of these techniques were made possible by improved processing technology and inexpensive data storage devices. The next generation of image coding systems utilized a combination of two or more techniques for improved performance. A hybrid coding technique that combines Discrete Cosine Transform (DCT) with DPCM is utilized as a standard method of video compression for anti-jam protection and drone control in Army Remotely Controlled Vehicles. The codec accepted as part of the Joint Photographic Experts Group (JPEG) standards for still imagery uses a two-dimensional DCT with an entropy coder that assigns variable length codes to two-dimensional DCT transform coefficients. A conceptual diagram of the JPEG DCT compression method is shown in Figure 1. The image is segmented into blocks of 8 by 8 pixels, prior to transformation and entropy encoding. The transformation of image data is useful in isolating insignificant information which may be compressed without significant losses in image quality.

EXAMINATION OF CODEC OPTIMIZATION CRITERIA:

Image Quality from Attributes of the Human Visual System

The selection of insignificant information, in transform coding, is related to properties of the human visual system. Transform algorithms, including the JPEG DCT, have been designed to exploit a feature of the human visual system (HVS), referred to as contrast-sensitivity. One attribute of the HVS is a reduced sensitivity for high spatial frequencies [4]. Figure 2 depicts contrast sensitivity as a function of spatial frequency. The transform blocks in compression systems attempt to minimize quality loss by discarding the "invisible" high frequency information beyond the sensitivity peak.

Unfortunately other features of the visual system are not treated kindly by JPEG DCT codec systems. The HVS has been compared to a processing system containing filter banks that are tuned to optimally detect lines and edges, at any orientation. This increased sensitivity to lines can be a problem when image sets are blocked for compression. The blocking used in JPEG DCT codecs is often visible in JPEG DCT imagery with compression ratios greater than 8 to 1. Figure 3(a) shows a portion of a LANDSAT band which has been compressed 10 to 1 with a standard JPEG codec. In this decompressed image data the 8 by 8 blocks are visible. The eye is very sensitive to these types of small linear features.

To reduce the effects from blocking and improve performance we have designed a codec system which replaces some of the functional blocks used in the JPEG DCT. The JPEG DCT process blocks are diagrammed in Figure 1. Our codec design, which we will refer to as MLT,

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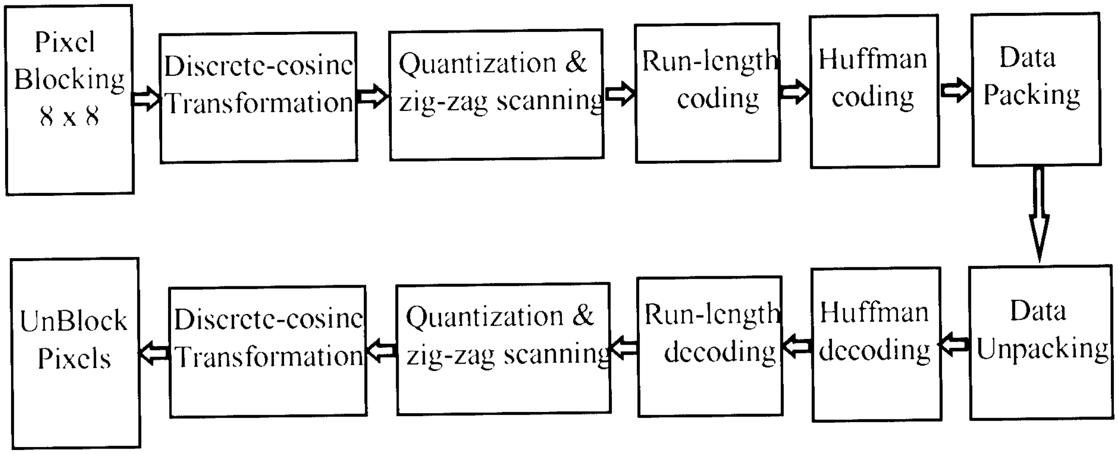

Figure 1 JPEG/DCT codec Process

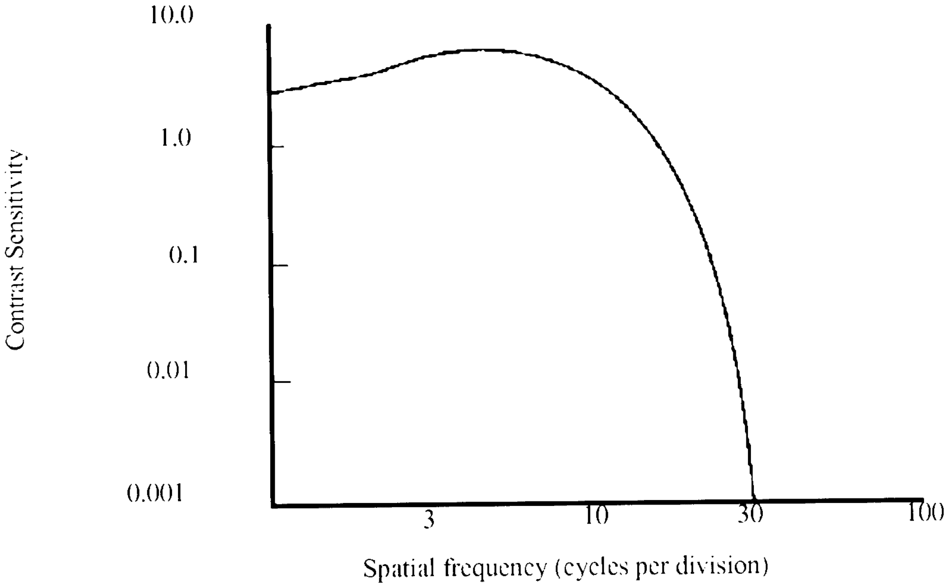

Figure 2 Contrast Sensitivity Function

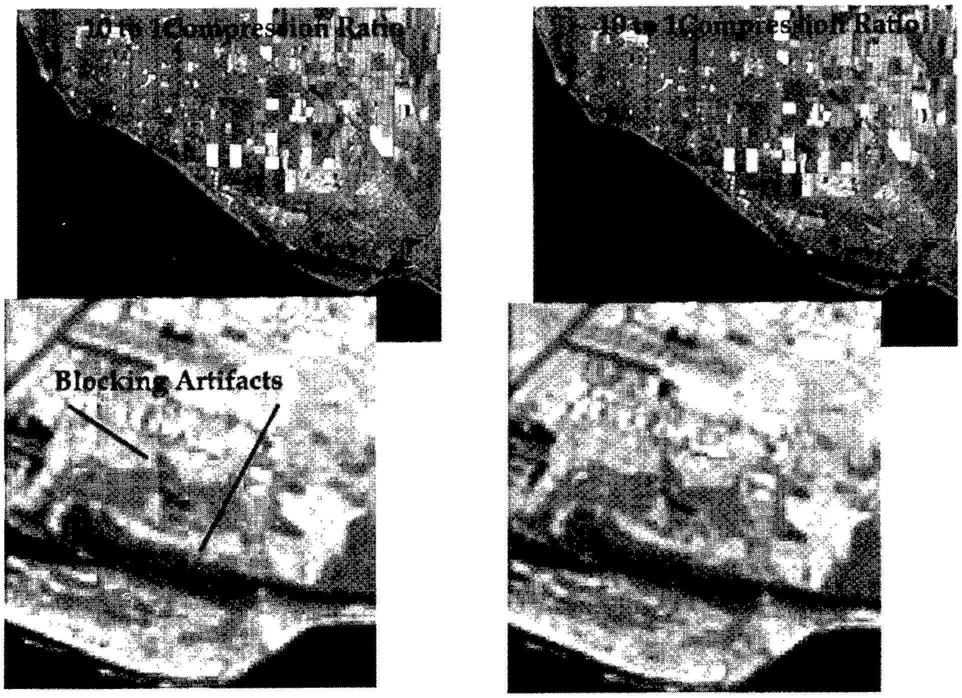

Figure 3 (a)
JPEG/DCT 10 to 1

Figure 3 (b)
MLT 10 to 1

LANDSAT TM Band 5

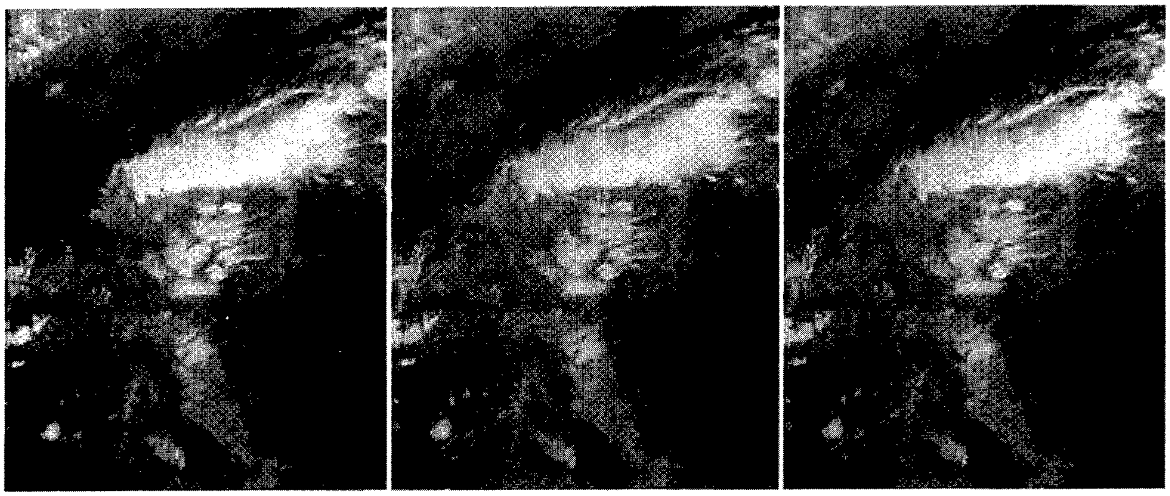

Figure 4 (a)
Uncompressed

Figure 4 (b)
JPEG/DCT 18 to 1

Figure 4 (c)
MLT 20 to 1

DMSP / OLS IR Channel

uses an overlapping block architecture and the DCT transform has been replaced by a hybrid transform, the Modified Lapped Transform (MLT). The modified lapped transform is a special type of subband filter bank that has been used in many branches of signal processing. At high compression ratios the MLT substantially reduces blocking artifacts. Figure 3(b) shows the same portion of a LANDSAT band, after MLT 10 to 1 compression. The reduction of blocking artifacts is achieved by the MLT codec architecture which employs overlapped windows. The image quality obtained from the MLT is not only superior to the JPEG / DCT but MLT image quality is also superior to other subband filters. The increase in MLT image quality is related to preservation of some high frequency information. Based on inspection by several analysts, including a trained photo interpreter, the visual quality of the MLT was judged superior to the JPEG / DCT using a variety of image sources, which had been compressed at several high compression ratios (8 to 1, 10 to 1 and 20 to 1).

Image Quality based on Machine Exploitation

The visual inspection can be used only as part of the codec optimization criteria. As the amount of image data increases there will also be increases in the machine processing of imagery. For our study we will present comparisons related to several types of automated algorithms which might typically be used by the military to exploit image data sets.

A large class of detection and automated classification techniques rely on brightness thresholding to identify areas of interest within an image. For these techniques, preservation of the pixel digital count is of the utmost importance. To measure the effect of our codec systems on this class of algorithms we examine root-mean square (RMS) errors. Table 1 is a compilation of RMS errors for a variety of image data types which have been compressed at a number of different rates. The MLT codec system has produced lower root-mean squared errors when compared to JPEG / DCT for cases with the same compression ratios.

Another important example of machine exploitation is terrain categorization (TERCAT). A TERCAT is an image derived from sorting multispectral pixels into a number of categories. The pixels are clustered into groups representing different terrain types and land covers. A TERCAT is the automated counterpart to a number of Intelligence Preparation of the Battlefield (IPB) products. The TERCAT generation process is subject to performance degradations that are related to some aspects of codec system performance.

To evaluate our codecs we performed unsupervised classifications on a five band subset of a multispectral LANDSAT scene. The unsupervised training was used to group pixels with similar spectral characteristics into classes on the basis of statistical patterns that are inherent in the data. The results of the classifications are compared to the original uncompressed image categories. The MLT compressed image has an 89% accuracy (pixels classed the same as the original scene) and the JPEG has an 81% accuracy. These cases are based on the independent compression, at a ratio of 10 to 1, of a five band subset of the LANDSAT scene.

Another automated analysis which was examined is derived from algorithms used for cloud detection and typing [5]. For this analysis, satellite sensor data from the Defense Meteorological Satellite Program / Operational Linescan System (OLS) was used. These image data sets consist of dual band images, collected from the infrared (IR) and visible (VIS) channels. The cloud scene data has very different attributes when compared to the LANDSAT scene. For example, the cloud scene has no linear features and channel brightness values span a range more than twice the dynamic range of LANDSAT band brightness values. The VIS image is originally collected at 6 bits per pixel, subsequent processing of the VIS channel expands the data to 8 bits per pixel. This dynamic range expansion results in an uneven histogram with peaks of high frequency noise. These differences in image types and exploitation algorithms will provide some insight into the suitability of our codec system across a range of applications.

For this application cloud typing is accomplished in two stages. The first stage, used primarily for detection, analyzes the two dimensional IR and VIS bands, with *a priori* knowledge of the underlying terrain typing, to divide pixels into nine classification regions. A combination of thresholds and rules are used to classify pixels into the nine bins, which are used to produce a cloud mask. The second stage of cloud typing uses the cloud mask from stage 1 and the raw IR image to stratify the clouds into layers. Formation of the layers is based on unsupervised classification of the IR pixel values. Pixels within a layer are clustered to form contiguous cloud regions. The size of regions of connected pixels within a layer is used for cloud type determination. The cloud pixels are classed as either cumuliform or stratiform.

For this study the OLS scene was compressed at several high compression ratios, which ranged from 8 to 1 to 20 to 1. The cloud typing results are reported in Table 2. In this instance, there were only marginal changes in classification accuracies for the different compression rates and systems. The classification results may be related to the introduction of high frequency noise in the visible channel. For this reason, we plan to continue investigations with this data set to include compression and classification of image data sets with the VIS data represented in the 6 bit collection values. The modest loss in cloud typing accuracy suggests the consideration of very aggressive compression schemes with this data. The 20 to 1 compression ratios also did not appear to have a severe effect on visual quality. A visual comparison of the original IR band (Figure 4a), with the 20 to 1 codec results from JPEG / DCT (Figure 4b) and MLT (Figure 4c) is given.

SPACE BASED COMPRESSION/DECOMPRESSION SYSTEMS:

Hardware Implementation

We have shown that transform coding compression systems retain image quality at high compression ratios. The challenge is to design and build a compression system for space with the quality required for intelligence products. Currently the only space based codec system which utilizes transform coding is a system based on the JPEG DCT. For space implementations, the MLT codec requires a fast method of implementing Modulated Lapped Transforms. One fast method of implementing a MLT is to decompose

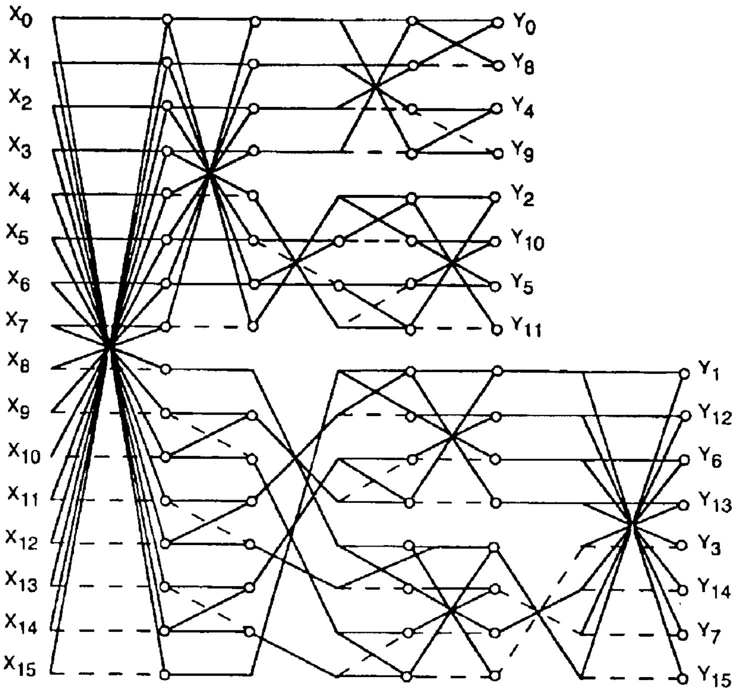

Figure 5 Split Radix Model

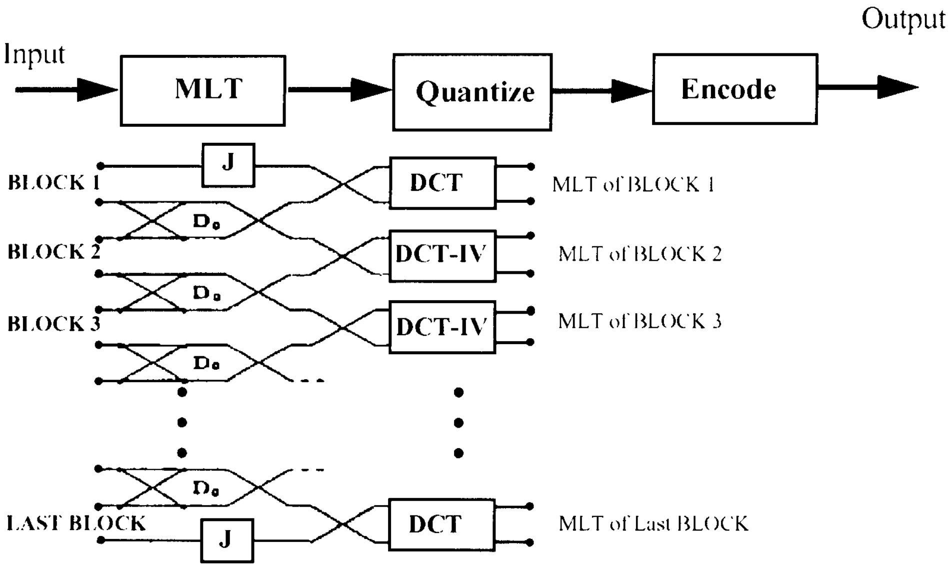

Figure 6 MLT Signal Flow Diagram

Image	2-D Transform	Bitrate	Compress Ratio	RMS Error
DMSP/OLS T	MLT	0.8007	10 to 1	4.3571
	JPEG/DCT	0.8013	10 to 1	4.5278
AVHRR CH1	MLT	0.8019	10 to 1	4.9089
	JPEG/DCT	0.8016	10 to 1	5.2985
AVHRR CH4	MLT	0.7976	10 to 1	2.1367
	JPEG/DCT	0.7903	10 to 1	2.2857
LANDSAT	MLT	0.8053	10 to 1	2.5956
Band 5 rural	JPEG/DCT	0.8027	10 to 1	2.7311
LANDSAT	MLT	1.0008	8 to 1	2.1064
Band5 Urban	JPEG/DCT	1.0009	8 to 1	2.2489

Table 1 Compression Results

2-D Transform	Compress Ratio	% Correct
JPEG/DCT	8 to 1	96.31
MLT	10 to 1	96.17
JPEG/DCT	18 to 1	95.33
MLT	20 to 1	94.50

Table 2 Cloud Typing Accuracy

the MLT into a butterfly bank followed by DCT blocks. This process has been described in a number of publications [6,7,8].

A fast DCT processor designed according to the Split-Radix, invented and patented by H.S. Hou [9] has been used for all compression labeled previously as the MLT codec. The patented Split-Radix DCT and the signal flow diagrams of the butterfly MLT for 8 bit inputs are shown in Figures 5 and 6. We have used the fast MLT and DCT methods to process image data on a general purpose computer and on a programmable digital signal processor. We are working to tailor the method for VLSI chip implementations. Based on recently developed algorithms and architectures, we have found methods for designing the forward and inverse MLT with limited interconnects. Decreasing the number of interconnects saves valuable silicon areas in a VLSI chip and simplifies the layouts and routing design. A high speed pipelined architecture for MLT compression and decompression has been implemented with Field Programmable Gate Arrays (FPGA). A prototype PC board containing these FPGA and memory chips has been built at The Aerospace Corporation. The design of a space ready MLT codec system with Application Specific Integrated Circuits (ASIC) is about to commence.

CONCLUSION

As NATO increasingly utilizes image data, the importance of optimized compression / decompression schemes will expand. Image data from satellites to cockpits will utilize codecs for the timely delivery of large data sets. Codecs will facilitate image data transfers and if the systems are selected with consideration given to operational processing we will provide time critical information to all NATO forces. The MLT codec provides a system which optimizes compact hardware packaging, a reliable compression scheme, visual quality , low bit rate transmissions , and preservation of image details required for machine exploitation.

ACKNOWLEDGMENTS

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RESULTS OF GLOBAL POSITIONING SYSTEM GUIDANCE PACKAGE (GGP) TECHNOLOGY DEMONSTRATION

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I. INTRODUCTION

The Advanced Research Projects Agency (ARPA) began a program in May 1983 to demonstrate the necessary solid-state technologies to miniaturize full military precision (P/Y) GPS receivers. The "Virginia Slims" miniature GPS receiver (MGR) program was successfully completed in December 1989 with the demonstration of an MGR the size of a cigarette package. Military products derived from the "Virginia Slims" MGR chip set include the Tomahawk Land Attack Missile GPS receiver, the Precision Location GPS Receiver (PLGR), and the Miniature Airborne GPS Receiver (MAGR), as well as several commercial GPS "engines (e.g., Navcore, Tracker).

Expanding on the success of the achieved miniaturization, ARPA initiated the GGP program [1,2] to develop and demonstrate technologies for a new generation of affordable, all solid-state miniature navigation units. Phase 1 of the GGP Program was initiated in 1990. Under a contract awarded to a prime/subcontractor development team of Litton Industries and Rockwell-Collins, two Phase 1 brassboard GGP units were developed. The Phase 1 brassboards are 295 cubic inches in volume, weigh 15 pounds, and draw 31.8 watts of power. The GGP tightly couples the direct sensor outputs from a 10-channel MGR and a miniature inertial measurement unit (MIMU). A real time data processor provides the tightly coupled integration as well as system alignment, mode control, and navigation computation functions. The objective of the follow-on Phase 2 effort is to develop a smaller GGP package (7 lb, 100 cubic inch, 20 watt) while meeting more stringent military environmental requirements.

The three principal subsystems of the GGP are the MGR and MIMU kinematic sensors, together with the 26 state, real time Kalman Filter hosted on a digital processor (DP). The MGR is a direct descendant of the original two-channel "Virginia Slims" MGR. The MIMU is composed of three axes, each having a miniature linear accelerometer and an interferometric fiber optic gyro (IFOG) rotation rate sensor to provide navigation grade of performance. In addition to providing the navigation solution once a second, the GGP also outputs velocity, acceleration, and rotation rate data needed by the host vehicle. The subsystem structure is shown in Figure 1. The MIMU performance goals and contractor results of the GGP Phase 1 are summarized in Table 1.

The two GGP Phase 1 brassboards were demonstrated using the M981 FIST-V as a test platform. The FIST-V, shown in Figure 2, is a fully tracked armored vehicle carrying a laser range finder to geolocate targets for field artillery indirect fire support. The FIST-V combines the azimuth and elevation (az-el) angle measurements from its laser telescope with the laser determined target range to obtain precise position of the target relative to the FIST-V. Relative target position when combined with accurate location of the FIST-V itself (e.g., GPS/PLGR) is then translated into the appropriate Universal Transverse Mercator (UTM) coordinates and radioed back to the indirect fire control/director.

The precision az-el laser telescope angles are measured using a mechanical (air-bearing, spinning mass) gyroscope referred to as a North Seeking Gyro (NSG). The NSG must be realigned every time the FIST-V comes to a halt to "engage" (i.e., geolocate) a target. A meaningful amount of time (minutes) is consumed during the NSG alignment; thus, extending the engagement time, reducing the number of targets engageable, and increasing the possible exposure time of the FIST-V to counterfire by the enemy.

Two FIST-Vs supported the controlled field demonstration. In FIST Vehicle 1, a GGP Phase 1 brassboard unit replaced the FIST-V North Seeking Gyro (NSG) in the targeting head. In Figure 3, a side-by-side comparison of the NSG and GGP is provided. The GGP was interfaced to the FIST Mission Equipment (FME) via the Targeting Station Control and Display (TSCD). The control FIST Vehicle 2 conformed to the operationally fielded sys-

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tem configuration except that it was also equipped with a handheld PLGR to provide vehicle self-location data. The two vehicles were operated in tandem to allow for a side-by-side comparison of the results.

II. TEST RANGE AND DEMONSTRATION CONDITIONS

The goals of the demonstration were to develop a set of statistically meaningful data on both the GGP-equipped FIST-V and the conventional, NSG-equipped FIST-V. The demonstration test was conducted by three different FIST-V military operators, none of whom had any prior exposure to GGP. The primary data obtained were as follows: (1) targeting accuracy (and its az-el components) and (2) target engagement time. Additionally, GGP data were taken for (3) integrated GPS/INS navigation accuracy over a surveyed route and (4) free-inertial performance (no GPS) for a ten-minute interval in a FIST-V dynamic environment. Table 2, below, summarizes the demonstration performance goals and the statistically averaged results.

The demonstration was conducted at Redstone Technical Test Center's Missile Flight Range, Test Area 1 (TA-1) at Redstone Arsenal, Alabama. Targets, Firing Points, and Navigation Points were surveyed to within 0.1 meters Spherical Error Probable (SEP) and delimited with barriers to ensure position repeatability. In addition, a surveyed point outside of TA-1 was used to initialize the systems and provide a reference point to determine the GGP's ability to maintain positioning accuracy following the transit to the test range. The demonstration was conducted during daylight hours on June 10 and 12, 1995. The majority of the data was taken during the first day, when the ambient conditions exceeded 90 degrees F. The measured temperature within the FIST-V equipment bays containing the GGP and NSG exceeded 130 degrees F. During transit of the FIST-Vs to the test range, the equipment was subjected to average integrated vibration levels in excess of three Gs. The overall test environment was considered to be consistent with combat vehicles operating over rough terrain in a warm climate. Neither the GGP nor NSG suffered any failures, despite the heat and vibration.

A map of the test area, with the driving course route and surveyed reference points and targets is shown in Figure 4. Two firing points (FPs), located approximately 200 meters from one another, were used as the reference points from which targets were located. The three surveyed targets were salvaged ground vehicles typical of enemy tanks, missile launchers or armored personnel carriers that might be designated with the FIST-V Range Finder. These targets were located between 1000 and 3750 meters downrange, were at different relative elevations, and were separated in angle by at least 800 mils (total). Targets were marked with an aiming reference point clearly visible through the FIST-V sighting system from both firing points.

A course was laid out with five (5) navigation points (NPs) located approximately two (2) kilometers apart. These points were surveyed to within 0.1 meters SEP. The navigation points (Figure 4) were identified by railroad ties placed along the route segments. The vehicles were driven on the navigation course at planned speeds of 18–20 miles per hour between the surveyed points. A portion of the navigation course was also used for the demonstration of the GGP navigation performance in an inertial-only mode (i.e., the MGR was disabled by disconnecting the GPS antenna). The shortened, ten-minute course was traversed in the same manner above, but navigation and positioning data were based on MIMU measurements only.

III. ERROR DETERMINATION

The FIST-V self-location and target location error data were obtained by differencing the NSG or GGP systems' output and the surveyed values. The errors in both Northings and Eastings were determined; and the square root of the sum of the squares of the Northings and Eastings errors formed the amplitude of the horizontal error. The median of the amplitude error is comparable to the Circular Error Probable (CEP) because 50 percent of the data lies within this value.

The errors in self-location were part of the total error budget for target location errors. The targeting and pointing errors were derived in much the same way that self-location errors were. The "true" target location and pointing values were calculated based on the known (surveyed) positions of firing points and targets and the lever arms for the sensors.

Demonstration data were analyzed using an order statistics approach. The data were arranged in ascending/descending order, with the value of the midpoint of the array being the median. The median is comparable to the average value if the data are symmetric. There is a major advantage to using the median. Since it is not affected by the value of outliers, it is considered to be a more robust statistic.

In addition to determining accuracy relative to the presurveyed fixed points, the navigation accuracy of the GGP-equipped vehicle was determined while it was in motion. An Ashtech Z-12 Differential GPS (DGPS) instrumentation was used as the reference system for determining the GGP accuracy during the demonstration. The Ashtech system provides position accuracies of better than one meter and velocity accuracies to 0.1 m/s. The reference system had three elements which recorded data simultaneously throughout the test period:

- A fixed base station was located on a surveyed point near the range. It ran throughout the demonstration recording its data to a portable computer.
- A roving receiver was installed in the GGP-equipped FIST-V vehicle. Data from this receiver were recorded on a dedicated computer inside the vehicle. The roving receiver used its own GPS antenna that was separate from that used by the GGP.
- A third personal computer, also inside Vehicle 1, recorded the data generated by the GGP.

The data of interest include the following:

- Target engagement time; both vehicles (GGP and NSG)
- Target location accuracy; both vehicles
- Inertial navigation accuracy; Vehicle 1 (GGP)

IV. DEMONSTRATION RESULTS

A. Target Engagement Time

Repeatedly, three separate targets were geolocated by both vehicles from two separate locations ("firing" points) on the laser range. The most dramatic performance gain in the GGP-equipped FIST-V over that of the NSG-equipped vehicle resulted from the capability of the GGP's inertial components to maintain precise stability after the GGP was first initialized at the beginning of a mission. The GGP-equipped vehicle could engage the targets immediately upon arrival at each firing point. In contrast, every time that the NSG-equipped FIST-V stopped at a firing point, on the order of 7-1/2 minutes were required for the NSG to stabilize. The average engagement time data, summarized in Figure 5, show almost a fourfold reduction in engagement time using the GGP.

B. Target Location Errors

Both the GGP and NSG far exceeded the target location performance goal of 40 meters. A graphical comparison of the average performance obtained (see Figure 6) is less than this value. Figure 7 provides a comparison of all target location errors (NSG and GGP).

Only those biases associated with the GGP installation could be minimized. Additional, uncompensated bias resulted from physical factors within the Laser Range Finder Assembly as well as the manner in which the gunner laid the crosshairs across the target. This experiment did not allow the individual sources of error to be isolated and evaluated. The systems were boresighted in the field environment and no experiments were conducted to determine systematic errors.

From the target location error data shown in Figure 7, the GGP has a CEP value of 6.4 meters and the NSG has a CEP value of 8.9 meters. Both are well within the performance goal of 20 meters CEP. Note that the GGP data are more statistically significant since a larger number of data points were obtained (more than three times that of the NSG).

Figure 8 is the scatter diagram for the pointing errors of the GGP and NSG vehicles. The angles in elevation and azimuth were measured and contain a small amount of residual bias in both angular directions. In both vehicles the pointing errors were within the requirements.

C. Inertial Navigation System Test

In order to test the GGP's free inertial performance, a test was conducted with the GPS antenna disconnected, effectively disabling the MGR portion of the system. The vehicle was then run over a portion of the navigation course, and "INS-only" self-location data were recorded at the surveyed navigation points.

The GGP-equipped FIST-V was operated for more than 20 minutes with the MGR disabled, and the results are shown in Figure 9. The resulting plot shows that at ten minutes (600 seconds), the total error was approximately 20 meters—well within the GGP specification of 100 meters accuracy after ten minutes.

D. Tactical Exercises

Enumerated below are a set of features demonstrated by the GGP-equipped vehicle not covered by the formal procedures of this demonstration.

Camouflage Net. A radar camouflage net was placed over the GGP-equipped FIST-V. The number of satellites and the signal strength were monitored both before and after the net was in place. During both sets of tests, six satellites were tracked with no noticeable effect on reception, signal strength, or GGP performance. Results are shown in Table 3.

Trees. The GGP-equipped FIST-V was driven to an area of heavy trees. Before the vehicle moved into the trees, the GGP receiver was tracking, in State 5, seven satellites. (State designation indicates level of quality of the signal being received. State 5 indicates that both pseudorange and delta range measurements are of high quality, where State 3 indicates that only the pseudorange measure is of high quality.) Measurements were taken when the vehicle was sitting just inside the tree line and when it was under a single canopy of overhead foliage. In both cases, the GGP maintained track on all seven satellites, five in carrier lock and two in code lock, with a three dB decrease in signal to noise ratio. There was no significant impact in positioning performance noted.

Align and Move. The GGP has an "in-flight alignment" capability. To test this, the crew turned on system power, allowed the GGP to perform a stationary alignment of only one minute, and then drove the vehicle for five minutes. The performance of the GGP was then monitored and was found to be similar to that obtained after a seven-minute stationary alignment.

Shorten Timelines. To test some of the advantages offered by the GGP, the crew was able to move into position at slow speeds while raising the laser Range Finder Assembly. Without the need to realign, manually enter self-location data, or record targeting data, they demonstrated the ability to find three targets and generate targeting solutions in one minute, 45 seconds.

Initialization on a 30-Degree Slope. The NSG will not realign on slopes greater than 20 degrees. The GGP was able to align on a 30-degree slope, the steepest slope available on the test range.

CONCLUSIONS

The GGP met or exceeded all performance goals. Its integration in the FIST-V provided a marked improvement over the existing FIST-V mission configuration in the areas of survivability, positioning/navigation performance, and targeting performance. The GGP was compatible with the FIST-V operating environment and its demonstrated performance opened the way to tactics or concepts of operation that promise even further mission improvements.

Tests of the two GGP Phase 1 brassboards are planned on an F/A-18 aircraft in late summer/early fall 1996 to include high g turns and combat maneuvers. Phase 2 GGP is being competitively developed by two contractor teams led by Honeywell International Corporation and Litton (Guidance and Control) Corporation.

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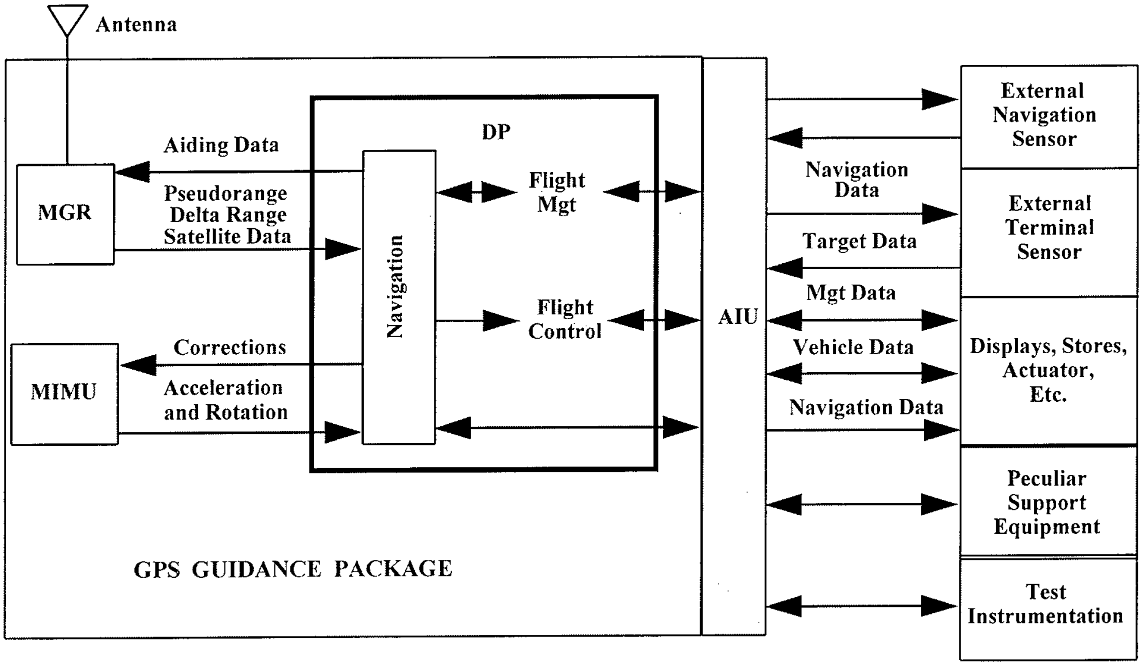

- Miniature GPS Receiver (MGR)
  - MMIC
  - 12-Channel Ops
  - Anti-Jamming
  - SA/AS
- Miniature Inertial Measurement Unit (MIMU)
  - Fiber Optic Gyros
  - Solid State Accelerometers
  - Enhanced Optical Sources
  - Integrated Optic Circuits
- Digital Processor
  - GGP Mode Control
    - GPS/INS Navigation
    - MGR Only; MIMU Only
    - Receiver Management
- Adaptable Interface Unit
  - GGP/Host Vehicle Interface
    - Mil-Std 1553
    - RS-422 Test Instrumentation
    - KYK-13 Interface
    - Control/Data Unit and Loader

Figure 1. GGP Subsystem Structure

Table 1

GGP Performance Using A-4 Production Accelerometers

Parameter		Specification	Test Results
Gyro			
Bias	(°/hr)	≤ 0.01	0.013
Scale Factor	(ppm)	≤ 50	21
Misalignment	(μrad)	≤ 10	3.6
Random Walk	($°/\sqrt{hr}$)	≤ 0.005	0.0048
Accelerometer			
Bias	(μg)	≤ 50	13
Scale Factor	(ppm)	≤ 100	43
Misalignment	(μrad)	≤ 50	5.4
White Noise	($\mu g/\sqrt{Hz}$)	≤ 50	25

Notes:

Tests of free inertial, no vibration input; unit serial no. 2
Residuals are RMS of all axes after modeling over -40 to 55°C
Source: Litton Systems, March 15, 1995

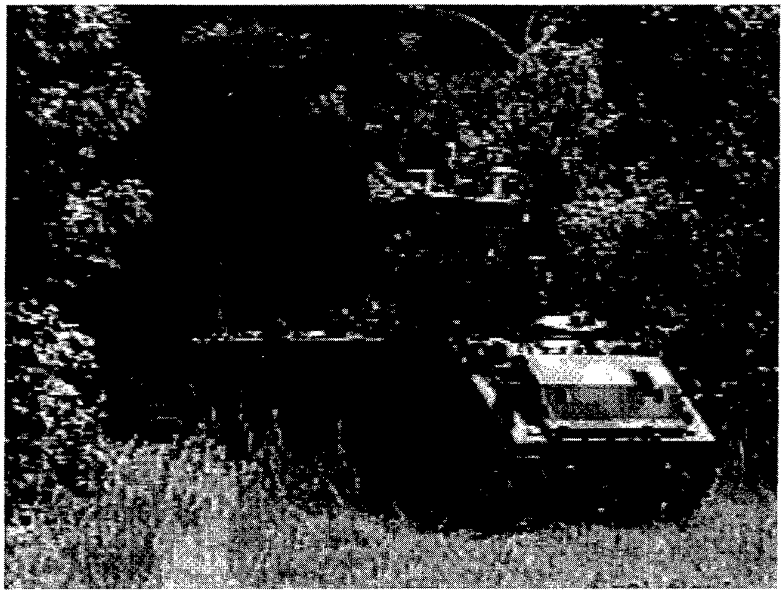

Figure 2. M981 FIST Vehicle

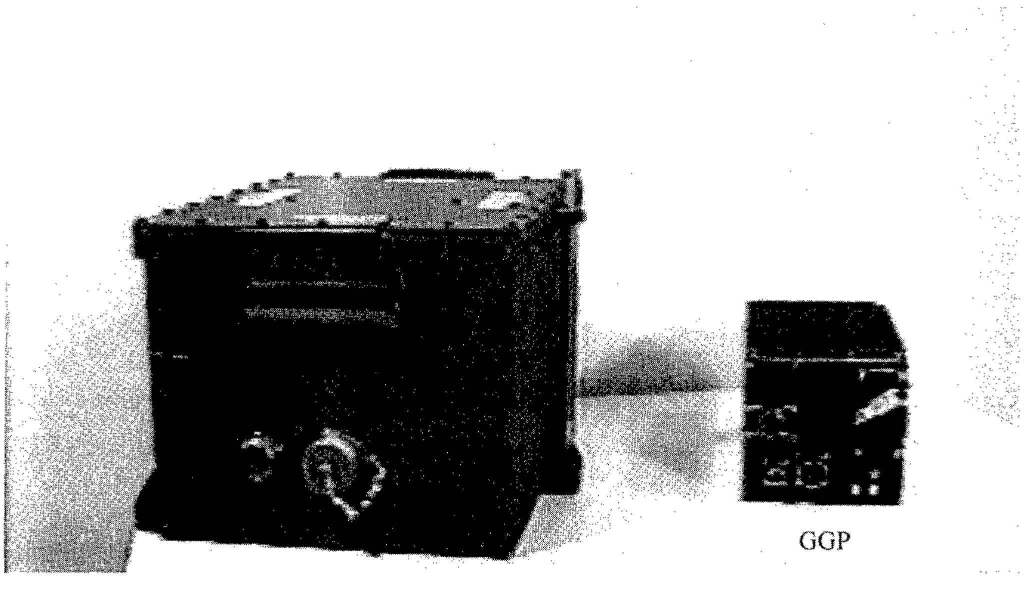

Figure 3. Comparison of the North Seeking Gyro and GPS Guidance Package Units

Table 2. Performance Goals and Demonstrated Results of the FISTV Demonstration

	Performance Goals		Results	
	GGP	NSG/PLGR	GGP	NSG/PLGR
Startup	≤ 10 min	≤ 10 min	7 min	9 min
Realign Time	Continuous	3-5 min	Note 1	7 min
Data Entry	Automatic	Manual	Automatic	Manual
Self-Location Error	10 meters	10 meters	2.6 meters	3.9 meters
Targeting Error CEP	≤ 40 meters	≤ 40 meters	6.4 meters	8.9 meters
Pointing Error (Az)	4.0 mils	4.0 mils	1.0 mils	2.3 mils
Pointing Error (El)	1.0 mils	4.0 mils	0.6 mils	0.7 mils
Offensive Timelines	≤ 2 min	≤ 6 min	≤ 2 min	9.0 min
Drift	1.0 mils/hr	4.0 mils/hr	0.1 mils/hr	Note 2

Note 1 GGP does not require realignment.
Note 2 NSG drift rate was not measured due to instrumentation limitations.

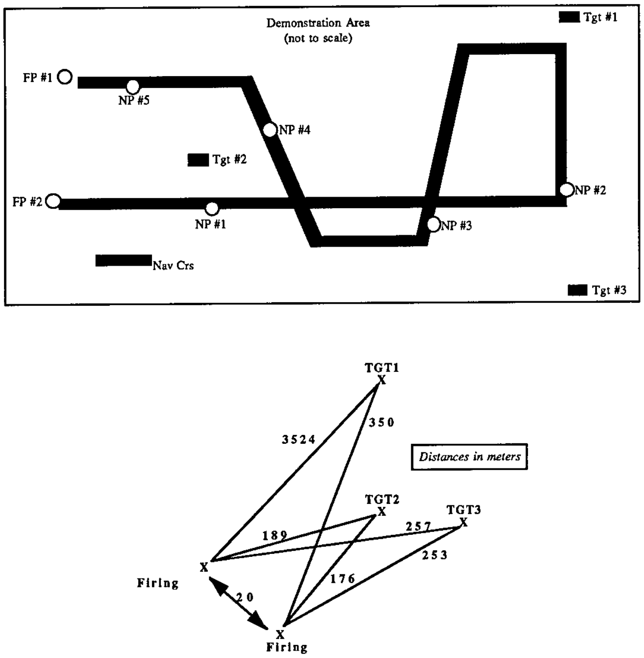

Figure 4. Test Area 1: Driving Course and Layout of Firing Points and Targets

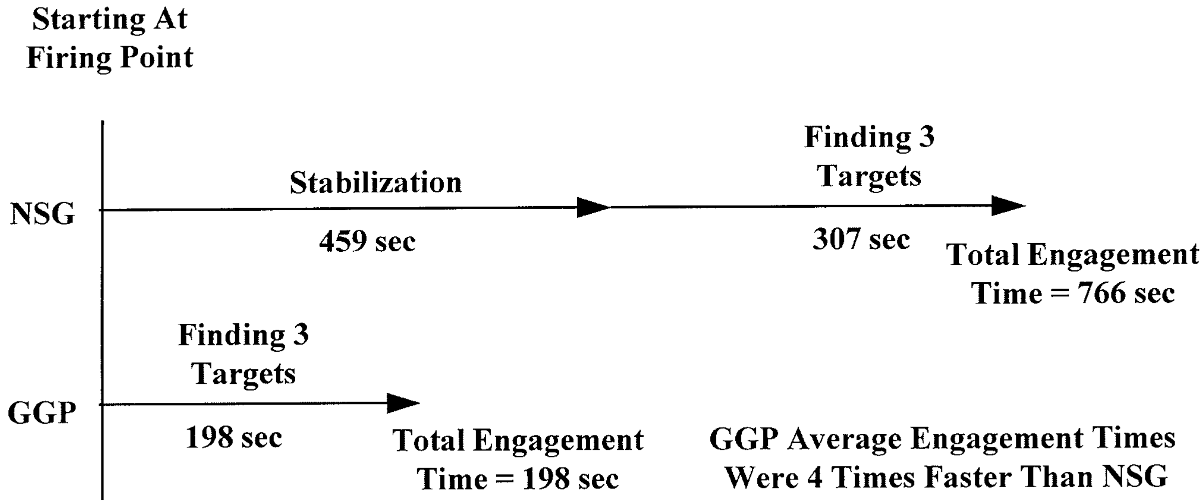

Figure 5. Average Engagement Times

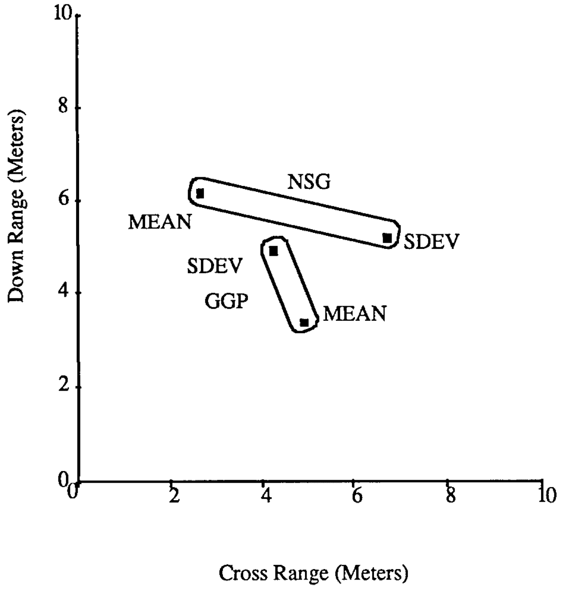

Figure 6. Comparison of Target Location Errors (Magnitude)

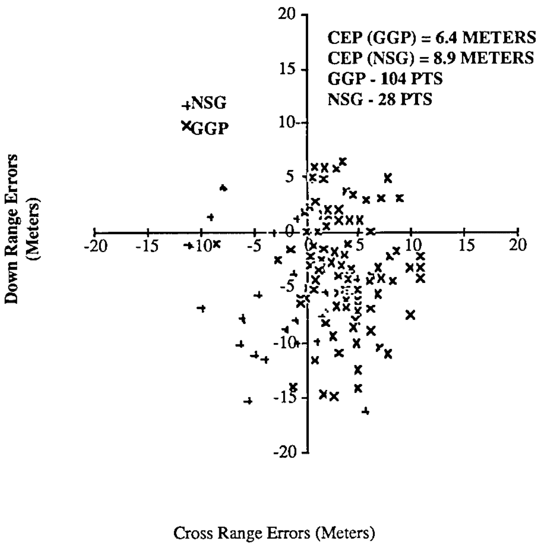

Figure 7. Comparison of Target Location Errors (All Data)

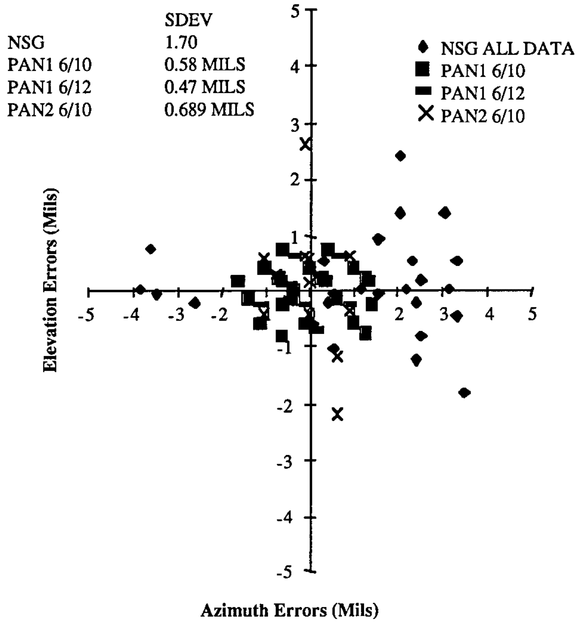

Figure 8. Comparison of Pointing Errors (All Data, Bias Removed)

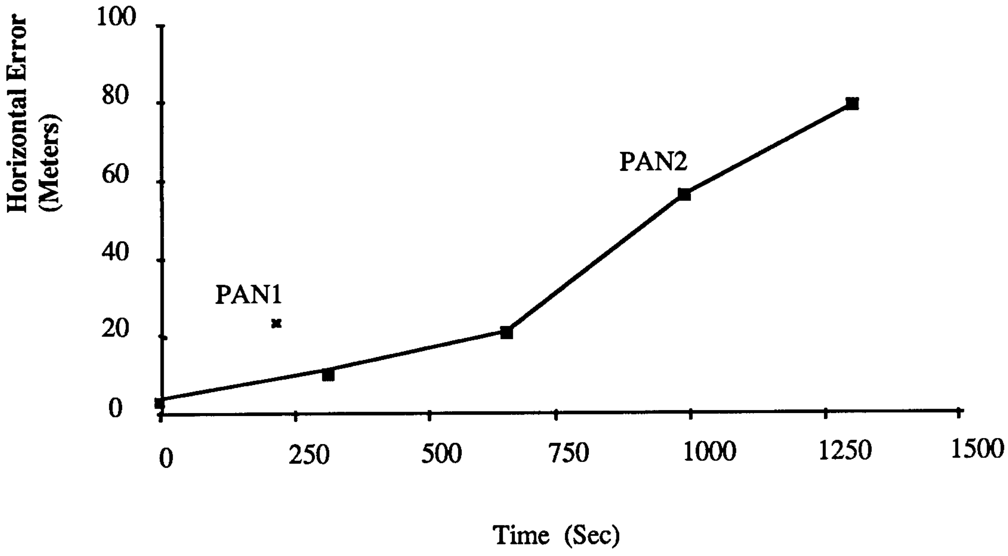

Figure 9. Inertial Only Navigation Errors

Table 3. Camouflage Net Effect Upon the GPS Signal

	Signal Strength dB			
	Camouflage/Radar (With Net)		Camouflage/Radar (Without Net)	
	Experiment 1	Experiment 2	Experiment 3	Experiment 4
	44	44	44	44
	34	35	31	32
	45	45	45	45
	41	41	41	41
	43	42	43	44
	44	43	37	41
Average	41.83	41.67	40.17	41.17
Total Average	41.75		40.67	

FUTURE SPACE TRANSPORTATION SYSTEMS AND THEIR POTENTIAL CONTRIBUTION TO THE NATO MISSION

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1. SUMMARY

Space systems are now an essential part of military operations and, in the Western World, the reliability and operability of these systems is crucial to the success of the military mission. At the same time, overall western military budgets universally are suffering severe cuts.

Although the Cold War is over, the threat to world peace, if anything, has increased rather than decreased. The threat is also much more difficult to contain. The well-defined, single-source, monolithic threat of the Cold War has been replaced by a multi-source, distributed threat. The questions arise - how has the NATO peacekeeping or warfighting mission changed in response to the new world environment; are the space resources of the Cold War the ones that can be effective in the future; how can dwindling government military budgets be augmented by the use of internationally shared or commercial space assets; and how can emerging space technologies and capabilities, whether developed by the government or the commercial sector, contribute to world peace?

The effective support that space systems can provide to the war-fighter is critically dependent on on-demand, assured access to space. Launch services customers will have, in the next century, a wide choice of launchers to deliver, maintain, and possibly recover their space assets. Large spacecraft will still be dependent on mainline expendable launchers similar to those that exist today; however, more choice will be available. Numerous initiatives are underway world-wide to develop commercial spaceports capable of launching small satellites, possibly from ballistic missile derivatives. The result will be to provide more choice in launch location. There is also an interest in the major spacefaring nations to develop reusable launch vehicles, perhaps developed by private rather than government funding, and perhaps developed as international cooperative endeavors. This paper describes the space transportation systems that are expected to be available in the next century and how they may be applied to meet the peacekeeper's needs.

2. INTRODUCTION

Overall western military budgets are suffering severe cutbacks, although the United States (U.S.) Department of Defense (DoD) space budget, in recognition of the importance of military space, is expected to rise about 12 percent in fiscal year 1997. Civil space is contracting, as the non-military government sector attempts to off-load more funding responsibility on to the commercial sector; commercial space, which did not exist ten years ago, is expanding rapidly, and in some areas leading in new development and innovation. The military sector, in the light of the end of the Cold War, is still re-evaluating its role in the new world order and how to exploit space assets, whether military, civil or commercial, to meet a globally distributed rather than a monolithic threat.

There is a perception in the United States (U.S.) military command that space has been developed and shaped by functional specialists, not operators.[1] It took a warfighting event - Desert Storm - to reveal to the warfighter the potential of space. The warfighter was surprised at what was available for improved battlefield situational awareness, for innovative operational agility, and for vastly improved targeting and damage assessment. Traditionally, military space has been dominated by national-level intelligence, reconnaissance, surveillance, and early warning interests.[1] These are functional areas. In the new environment, exemplified by the lessons of the Persian Gulf War, it is clear that military exploitation of space needs operational focus. Command systems were suited to the Cold War era, but demand systems are needed to meet the new threat. This is leading to a review of the roles, missions, and functions of the armed forces.[2]

A serious concern is that the Western Alliance is not postured to fight more than one major regional conflict at the same time. If the Alliance is to function effectively as peacemaker and peacekeeper, space needs to be exploited by developing a global presence through electronic as well as physical means.[3] The changing needs can be summarized as providing:

- Global view - making full use of the high ground of space.
- Global presence - augment limited, regional physical presence with global virtual presence.
- Global reach - world-wide dominance in information warfare.
- Global power - deliver precision attack munitions world-wide, on demand.

Implementation of this doctrine places increased demands on the means to access space.[4, 5]

3. THE CHANGING ROLE OF NATO

The proliferation of precision standoff weapon delivery systems was reported by SPACE MAGAZINE in 1992 (See Figure 1). Even if they have a range of only a few hundred miles, in the hands of warlords these weapons pose a significant menace to both military and civilian targets. Unfortunately, many of the rogue nations (such as Iraq, Iran, Libya and North Korea) have, or are accumulating arsenals of chemical, biological and possibly nuclear weapons and have, or are acquiring, the missile systems to deliver them. According to DEFENSE NEWS, low intensity conflicts stretch from the Balkans to Southeast Asia, with United Nations (UN) troops serving in 13 locations.[6] There are close to 50 private

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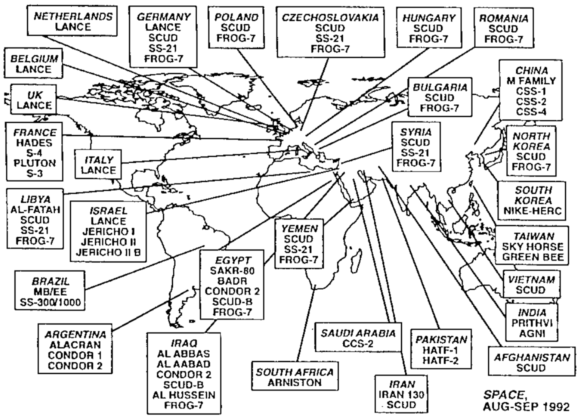


SPACE,
AUG-SEP 1992

Figure 1. Proliferating Weapons Delivery Threat

armies currently operating in the world, mostly in Africa and Asia. The suffering of the civilian populations, in the form of pestilience and famine, and the demands on the Western Allies for humanitarian relief, are natural follow-ons. Possible crises that the Western Alliance may have to face are generated by:

- Expansionism / imperialism
- Treaty violation
- Border disputes
- Nuclear contamination
- Nationalism
- Earthquakes
- Civil war
- Famine
- Political strife
- Narcotics trade
- Tribal/ethnic/religious strife
- International terrorism

Traditionally, NATO has been postured to deal with the first item only - expansionism/imperialism - and the consequent threat of nuclear war. Out of economic self-interest alone, the NATO Alliance may have to re-orient itself to face this more diverse set of crises, and to face it on a global and not solely a European basis.

4. THE EVOLVING NATO MISSION

The war in Southeastern Europe has brought out the need to re-assess the role of NATO. The traditional NATO mission has been to:

- Provide a stable security and defense environment in Western Europe.
  - Deter nuclear attack from the Soviet Union
  - Defend NATO member-states' national borders
- Provide the link which ties the security and defense of North America to that of Europe.

The broader, evolving mission includes:

- Cooperation on security and defense with Central and Eastern Europe, the Russian Federation, the FSU Republics, and possibly even South Pacific nations such as Australia, The Republic of China (Taiwan), and Japan.
- Monitoring and countering the proliferation of chemical, biological, and nuclear weapons of mass destruction.
- Peacemaking and peacekeeping in support of the UN.
  - Defense of non-member states
  - Military action outside the borders of NATO allies
- Coordination of policy and actions with other common-interest organizations.
  - United Nations (UN)
  - European Union (EU)
  - Western European Union (WEU)
  - Organization for Security and Cooperation in Europe (OSCE)
  - The Russian Federation
- Humanitarian as well as military crisis management.

To perform the expanded mission, the NATO Alliance will need to maintain a dominant role in:

- Defense of member-state national borders
- Nuclear deterrence
- Military action outside NATO member's borders
- Treaty monitoring - assuring international agreements are respected
- Crisis prevention - monitoring strategic sites
- Peacemaking
- Peacekeeping
- Monitoring low intensity conflict in several theaters of war
- Damage assessment
- Non-lethal containment
- Humanitarian exercises

This scenario revives the possible need to re-examine the proposal for an International Satellite Monitoring Agency (ISMA) made by France in 1978 and debated sporadically since.[7] NATO could develop a new role by taking a lead in developing this initiative.

5. FUTURE MISSION REQUIREMENTS

The first step in preparing for a military mission in unfamiliar territory is to learn as much as possible about the battle zone, especially the terrain and the formation of hostile forces. The ability of the combatants to shoot down U.S. and French aircraft over Bosnia emphasizes that in these kind of regional conflicts, the Western Allies will need to fully exploit the availability of new information technologies and precision attack munitions to provide the situation awareness, the strategic agility, and the surgical lethality that is needed to protect the lives of the peacemakers. Advanced requirements could include:

- Trouble-free Command, Control, Communications, Computers and Intelligence (c^4I) across service and national boundaries.
- Extraction and dissemination of timely, high quality, secure, easily-accessed, easily-interpreted information.
- Regional and global presence through electronic means to augment physical presence.
- Mobile communications.
- Instant response to multiple, simultaneous regional conflicts.

- Defense against unprovoked ballistic missile attacks on ground-based assets.
- Rapid neutralization of dispersed, mobile, hostile weaponry (aircraft / missiles).
- Instant jamming of hostile forces' communications.
- Rapid forward deployment of peacekeeping forces into hostile territory.
- Joint and coalition operations.
- Operational capability in two or more regional conflicts in far-flung locations at the same time.

Interoperability across service lines, theaters, echelons and national forces is essential for coalition warfare. Space-based information systems therefore will be an inevitable part of future conflict. However, 90 percent of bulk military data passes through commercial channels, subjecting the system to low-cost attack by cyber-terrorists. Traditional methods of gathering and acting on information could become ineffective against this future threat.[8] New, innovative systems may be needed.

6. ACCESS TO SPACE - POST 2000

Ever since the Space Shuttle failed to meet its expectations, numerous august bodies have called for a space transportation system that will provide responsive, inexpensive assured access to space. Satisfying these requirements is not easy, but a new U.S. space transportation policy statement was signed by President Clinton on August 4, 1994.[9] This policy is based on the results of extensive national studies by both the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD).[10,11] The Clinton space transportation policy can be summarized as follows:

- Upgrade the performance of the Space Shuttle in the near-term to enable it to perform its Space Station Freedom (SSF) role; but plan to replace it in the far-term.
- Improve the reliability and cost-effectiveness of the U.S. medium and heavy lift capability by awarding contracts for the development of a DoD-managed Evolved Expendable Launch Vehicle (EELV) family. This would eventually replace the existing Delta, Atlas and Titan launchers for servicing national military, classified, and civil mission models.
- Embark on a NASA-led Reusable Launch Vehicle (RLV) program to demonstrate a fully reusable system to replace the Space Shuttle in the next century.
- Encourage innovative government-industry and private sector partnerships to develop a more competitive U.S. commercial space industry.
- Retain for government use, or destroy, excess ballistic missiles declared surplus by the Treaty between the United States of America and the Union of Soviet Socialist Republics (USSR) on the Reduction and Limitations of Strategic Offensive Arms of July 31, 1991. (Note: This treaty is being subjected to considerable question and interpretation.)

7. FUTURE SPACE TRANSPORTATION SYSTEMS

The Clinton space policy is expected to shape the contribution of the U.S. to the NATO Alliance space transportation needs in the next century. The European Ariane 5 will also support NATO missions. If political and economic stability is achieved in the FSU and the Russian Federation begins to participate in global peacekeeping, it is possible Russian and Ukranian launchers will also play a beneficial role. Other national systems exist or are coming on line, and could play beneficial or threatening roles, depending on the future world order.[12, 13] Some of the more significant ones are described below.

7.1 Upgraded U.S. Space Shuttle

Although the high cost of the U.S. Space Shuttle operations detracts from its utility and the NASA Outlook for Space Study called for its replacement, it is expected to be flying well into the next century.[10] In order for it to support the International Space Station (ISS), its payload capability is being increased by replacing the current External Tank (ET) with a super-lightweight tank and by making modifications to the Space Shuttle Main Engine (SSME). The design will be frozen after these changes. There are no plans to build additional vehicles.

To reduce the cost per flight, NASA is also making drastic cuts in the number of government and contractor personnel involved in Shuttle operations. Privatization of Shuttle operations has been discussed, but the present plan is to consolidate Shuttle operations under a single sole-source Space Flight Operations Contract (SFOC) with United Space Alliance, a 50-50 joint venture by Lockheed Martin and Rockwell International in order to launch the first Space Station element in December, 1997. Presently, the two companies control almost 70 percent of the current Shuttle operations contracts.

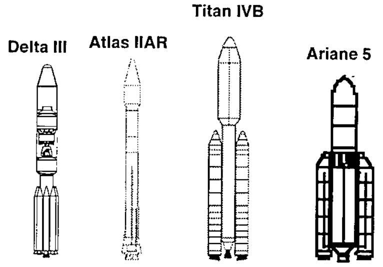
The Space Shuttle has already made several rendezvous flights to the ex-Soviet space station, Mir, and will be expected to deliver 20,000 to 25,000 lb (9,000 to 11,250 kg) to SSF orbit. The first flight to the ISS is planned for 1998.

7.2 Upgraded U.S. Expendable Launch Vehicles

The U.S. mainline launcher producers, McDonnell Douglas and Lockheed Martin, are taking steps to make their current stables of vehicles more competitive in the commercial market. McDonnell Douglas is planning to field the Delta III; Lockheed Martin is spending $300 million to upgrade the Atlas and the Titan IV families of vehicles. The characteristics of the three upgraded vehicles are illustrated in Figure 2.

7.2.1 *Delta III*

McDonnell Douglas has been motivated to develop the Delta III (the largest space transportation system ever developed by private funding) by a commitment from Hughes Telecommunications and Space to serve as anchor customer for 10 launches between 1998 and 2002. The two-stage Delta III will be capable of placing about 8,400 lb (3,810 kg) into geotransfer orbit (GTO); the three-stage Delta II can launch up to 4,060 lb (1,840 kg) into GTO. The Delta III will use a new high energy single-engined upper stage and longer solid strap-ons than Delta II. Initial Operating Capability (IOC) is planned for 1997.



Performance lb (kg)	Delta III	Atlas IIAR	Titan IVB	Ariane 5
LEO Polar	-	-	39,000 (17,700)	-
LEO Due East	18,400 (8,350)	-	47,000 (21,300)	-
GTO	8,400 (3,810)	8,400 (3,810)	-	15,000 (6,800)
GEO	-	-	10,000 (4,530)	-

Figure 2. Western Expendable Launchers - 2000

Mitsubishi Heavy Industries will provide the first stage cryogenic fuel tanks and second stage liquid oxygen tanks for Delta III, under an agreement approved by the Japanese Ministry of International Trade and Industry (MITI). In return, Mitsubishi will import major components for the H-II launcher that it builds for the Japanese National Space Development Agency (NASDA). The Japanese would like to enter the commercial market with the H-II but have been unable to produce the vehicle at a competitive cost. This agreement with McDonnell Douglas may help to make the H-II more cost competitive.

7.2.2 *Atlas IIAR*

The Lockheed Martin Atlas IIAR is a planned derivative of the Atlas IIAS with a new, throttleable main engine capable of delivering 400,000 lbf (1,779,400 kN) of thrust, compared to 250,000 lbf (1,112,100 kN) for current engines. Lockheed Martin has selected the RD-180, a two thrust-chambered derivative of the Russian Energomash four-chambered RD-170, used on the Zenit launcher as the main engine. The engine will be produced and marketed by Pratt and Whitney. First flight is planned for September, 1998.

The IIAR will deliver 8,400 lb (3810 kg) to GTO. The existing Atlas launcher uses nine engines; the IIAR will use just two or three. The IIAR will also replace the current Centaur two-engined upper stage with a one-engined version, reducing the number of staging events from four to one. These radical design changes plus plans to manifest two satellites per flight, are expected to increase reliability, decrease processing times, and reduce costs.

International Launch Services (ILS), formally known as Lockheed-Khrunichev-Energia International (LKEI), a U.S./Russian joint venture led by Lockheed Martin, will market both the Atlas and the Russian Proton. The ILS marketing strategy is to offer the two vehicles as a package to provide mutual backup if one of the vehicles is grounded. Lockheed Martin expects to be able to provide a complete range of expendable launch vehicles, including the Lockheed Launch Vehicle (LLV) for small to medium payloads, the Atlas and Proton for medium to intermediate payloads, and the Titan IV for heavy lift.

7.2.3 *Titan IVB*

The Lockheed Martin Titan IVB will have upgraded solid rocket motors to achieve a 25 percent increase in payload capability over the current system. The current Titan IV can place 39,000 lb (17,680 kg) into low earth orbit (LEO), or more than 10,000 lb (4,530 kg) into geosynchronous orbit (GEO). The Titan IVB will launch 47,000 lb (21,300 kg) into LEO.

7.3 U.S. Evolved Expendable Launch Vehicle

The Evolved Expendable Launch Vehicle (EELV) program is the DoD implementation of the Clinton space policy and follows the recommendations of the space launch modernization study led by General Moorman in 1994.[14] The program represents a change in acquisition policy and is unique in DoD procurement history in that no military specifications or standards are called for and documentation is to be paperless and kept to a minimum.[15] The program office size, including military and civilian management, engineering and support, is also limited.[16]

The fundamental objective of the EELV is to develop a single family of expendable launch vehicles (ELVs) that will service the U.S. medium and heavy lift National Mission Model (NMM) at a lower cost of launch to the nation than the present expendable launch systems. The portion of the NMM targeted includes military, classified and civil payloads, but at present specifically excludes crew-rated and cargo return missions. These could be added later.

Low Cost Concept Validation (LCCV) phase, $30 million-15 month contracts were awarded on 24 August, 1995, to four contractors: Alliant Techsystems, Boeing Aerospace, Lockheed Martin, and McDonnell Douglas. The Alliant Techsystems team initially included a non-U.S. member - Arianespace - but is now a purely U.S. consortium. The contractors are permitted to propose foreign component, such as rocket engines, if they see fit. However, if, for instance, a Russian-designed engine is proposed, a production line will have to set up in the U.S. within a limited period of time. The program's next milestone is the pre-Engineering, Manufacturing and Development (PEMD) phase in 1966, when two contracts will be let; EMD, when one contractor will be selected, is scheduled for 1998. The EELV family will fly from both east and west coast launch sites.

EELV payload requirements range from 2,000 to 45,000 lb (910 to 20,400 kg). The overall program schedule has been developed to accommodate payload block changes and the transition from the current launchers. System test flights are scheduled for FY01 and FY03.

While the government is not funding system improvements or development for strictly commercial requirements, it is expected that the vast majority of commercial requirements will be satisfied through coverage of the government requirements. *"We're not just building an Air Force system; we're building an American system. The EELV will be a national resource, one that's equally viable to meet commercial or military needs,"* said Secretary of the Air Force, Sheila E. Widnall.[17]

7.4 Non-U.S. Mainline Expendable Launch Vehicles

The expanding commercialization of space will increase the number of launchers available for the warfighter.

7.4.1 *Europe*

The Ariane family of launch vehicles represents Europe's contribution to Western launch capability. The current Ariane 4 family will be gradually replaced by the Ariane 5 during the late 1990s. The Ariane program has clearly demonstrated that international launch vehicle development is feasible.

7.4.1.1 ***Ariane 5.*** The Ariane 5 is scheduled for its maiden flight in June, 1996. It will be capable of delivering 13,160 to 15,00 lb (5,970 to 6,800 kg) to GTO and therefore will be capable of launching two high-powered Hughes HS-601 or Lockheed Martin A2100 satellites at once. The current Ariane 4-44L has a payload limit of 9,810 lb (4,460 kg) to GTO when two payloads are manifested. The Ariane 4 has been very successful, having captured more than 60 percent of the commercial market.

The Ariane launchers are marketed and operated by Arianespace Inc. On 10 June, 1995, Arianespace signed a $2.4 billion contract with European industry for the first batch of 14 Ariane 5 launchers to cover its needs until the year 2000. The contract is expected to lead to a second batch of 50 launchers. These will be available for commercial, civil and military launches well into the next century.

A planned Ariane 5 upgrade of the payload fairing (Sylda 5) will provide an 880 lb (400 kg) increase in payload; a second upgrade would redesign the solid rocket motors to permit a further 330 lb (150 kg) of payload; a third upgrade being considered would involve developing a second-generation Vulcain main engine, increasing the payload capability by a further 1760 lb (800 kg). An Ariane 6, which could possibly use liquid rocket boosters or be partially recoverable, is only in the very preliminary design phase.

7.4.2 *Russia*

The utility of Russian launchers to the Western Alliance is subject to a number of factors, including the degree of political and economic stability achieved in Russia, the quotas placed by Europe and the U.S. on the number of Russian commercial launches, the various cooperative arrangements that are developing between Russian and Western private industry, and the outcome of various political agreements and treaties that are being negotiated under the auspices of the Organization for Security and Cooperation in Europe (OSCE), the North Atlantic Cooperation Council (NACC), the Treaty on Conventional Forces in Europe (CFE), and the second set of Strategic Arms Reduction Talks (START II) agreements.

7.4.2.1 ***Proton.*** At present, the Proton is launched from the Baikonur Cosmodrome in Kazakhstan. In addition to being marketed by ILS in the West it will also be available as a purely Russian launcher. It can place 46,000 lb (20,900 kg) into LEO, 12,100 lb (5,500 kg) into GTO, or 4,850 lb (2,200 kg) into GEO.

7.4.2.2 ***Kosmos.*** The medium-class, two-stage SL-8 Kosmos is now launched solely from the Plesetsk Cosmodrome in Russia, but is the only ex-Soviet launch vehicle to have flown from all three launch sites (Plesetsk, Kapustin Yar, and Tyuratam). It can deliver 2,400 to 3,100 lb (1,100 to 1,400 kg) into low to medium orbits. Attempts are being made to market it in the West, as discussed below.

7.4.3 *Ukraine*

Discussions between the U.S. and Ukranian governments concerning the disposition of the Ukranian nuclear arsenal are impacting the availability of Ukranian launchers. Negotiations are underway which would permit the Ukraine to launch a limited number of U.S. commercial satellites through the year 2001. The offer is expected to be similar to the one that allows the Peoples Republic of China (PRC) to launch U.S. commercial satellites.

7.4.3.1 ***Zenit.*** The SL-16 Zenit uses Russian engines but is built by the Yuzhnoye Design Bureau in Dnepropetrovsk, Ukraine, and flies out of Baikonor. The two-stage Zenit delivers 28,700 lb (13 tonnes) to LEO. Negotiations are going on between Boeing Aerospace and the Ukranians to launch the Zenit as a commercial venture from a floating platform in the Pacific Ocean. The Yushnoye Design Bureau is designing a Zenit payload dispenser to place 12 Globalstar communications satellites into LEO with a single launch in anticipation of commercial business.

7.4.3.2 ***Tsyklon.*** The Tsyklon family (SL-11 and SL-14) can deliver up to 7,900 lb (3,600 kg) to LEO. The SL-14 flies from a highly automated launch complex in Plesetsk, Russia, which minimizes manual activites during launch processing. It was developed by the Yuzhnoye Design Bureau; primary assembly takes place at MZ Yuzhmash in Dnepropetrovsk.

7.4.4 *Peoples Republic of China (PRC)*

Chinese launchers are strong competitors in the commercial marketplace, since the U.S. government has agreed to allow the PRC to launch 15 to 20 U.S. commercial satellites through December 31, 2001. However, they have had a recent run of spectacular failures.

7.4.4.1 ***Long March.*** The Chinese Long March family of vehicles, manufactured by the China Great Wall Industry, presents a strong challenge to the Western launch services providers because of lower cost. Several western satellites have been launched by the Long March and, in spite of reliability problems, more are planned. The Long March 3A can place 5,700 lb (2,600 kg) into GTO. In spite of three un-diagnosed failures in five attempted flights, Hughes Communications International has not cancelled an agreement which gives it options for 10 Long March launches over the next four years. China is developing a variant of its Long March 2E (the Long March 2E/TS) to place 12 Globalstarmobile telephone communications satellites into LEO with a single launch.

7.4.5 *Japan*

Although the Japanese government would like to commercialize their H-II launcher, the system is currently not cost-competitive. To overcome this, Japan has decided to import foreign components to upgrade the vehicle. Some technology interchange between McDonnell Douglas, Aerojet, Pratt and Whitney, Rockwell International, and some European Ariane subcontractors and the Japanese is being considered which may help the H-II become more competitive.

7.4.5.1 ***H-II.*** The H-II can deliver 23,000 lb (10,500 kg) to LEO, 8,800 lb (4,000 kg) to GTO, and 4,800 lb (2,200 kg) to GEO. Its launch rate is restricted by seasonal launch window constraints imposed by the government.

7.4.6 *India*

India is an example of a developing nation which is building an autonomous capability in military space. The Bangalore-based Indian Space Research Organization (ISRO) and the Dehradun-based Defense Electronics Research Laboratory (DERL) are working on a range of satellite-based surveillance devices intended to shift the present ground-based intelligence gathering effort to a satellite-based one within the next five years. India has several on-going missile programs (the Agni, Prithvi, Trishul and Akash), and is assumed to possess chemical, biological and nuclear weapons. The Agni IRBM is capable of delivering a 2,200 lb (1 tonne) warhead more than 1,350 nm (2,500 km).

7.4.6.1 ***Geostationary Satellite Launch Vehicle (GSLV).*** The next-generation Indian launcher, the GSLV, will launch about 11,000 lb (5,000 kg) into LEO or 5,500 lb (2,500 kg) into GTO. This kind of capability, with its corresponding capability to deliver weapons of mass destruction is expected to proliferate throughout several of the developing nations.

7.5 Small U.S. Expendable Launch Vehicles

The miniaturization of electronics and lightweight structures are enabling satellites to be reduced in size and yet still perform useful missions. This has resulted in a number of small launch vehicles becoming available on the commercial market.

7.5.1 *Delta Lite*

The Delta Lite is a McDonnell Douglas launcher sized to meet a NASA requirement for a capability to launch *"half the payload of the Delta for half the cost."* Development has been delayed since the cost objective has been found hard to achieve.

7.5.2 *Lockheed Martin Launch Vehicle (LMLV)*

The smallest member of the Lockheed Martin family has flown once, unsuccessfully. When operational, the LMLV commercial launcher is expected to deliver 1,755 to 8,060 lb (800 to 3,655 kg) to LEO.

7.5.3 *Pegasus XL*

The Pegasus XL is an Orbital Sciences' launcher which is launched from a Lockheed L-1011 air-breathing launch platform. It has all-azimuth launch capability and can deliver 1,015 lb (460 kg) to LEO. It is the only operational air-launched Western launcher and can operate from non-U.S. launch sites. It is illustrated in Figure 3. After two failures it finally achieved a successful flight on 9 March, 1996.

7.5.4 *Taurus*

The Taurus is an Orbital Sciences' ground-launched commercial vehicle capable of delivering 3,100 lb (1,400 kg) to LEO or 2,340 lb (1,060 kg) to GTO.

7.5.5 *Conestoga*

The Conestoga family of vehicles is marketed by EER Systems. The largest vehicle can deliver 1,960 lb (889 kg) to LEO. The maiden flight of the Conestoga was unsuccessful.

7.6 Small Non-U.S. Expendable Launch Vehicles

Many nations other than the U.S. have shown an interest in developing their own small launchers as a means of achieving autonomy in space or as a means to develop a ballistic missile capability. Some of the more significant are described below.

7.6.1 *India*

India has successfully launched its third generation launch vehicle, the PSLV, placing the 1,7770 lb (804 kg) IRS-P2 remote sensing satellite into a 488 nm x 533 nm (802 km x 875 km) polar sun synchronous orbit. Two small launchers are in current production.

7.6.1.1 ***Augmented Satellite Launch Vehicle (ASLV).*** The ASLV can deliver 330 lb (150 kg) into LEO.

7.6.1.2 ***Polar Satellite Launch Vehicle (PSLV).*** The PSLV can deliver 6,400 lb (2,900 kg) into LEO or 990 lb (450 kg) to GTO.

7.6.2 *Israel*

7.6.2.1 ***Shavit (Comet).*** The Israeli 4-stage Shavit has been proposed as an ultralite launcher capable of delivering 660 lb (300 kg) to LEO from Vandenberg Air Force Base (VAFB) or greater than 660 lb to GEO from Wallops Island. Because the OSC Pegasus suffered two failures in succession, TRW proposed using Shavit to orbit the Tri-Service Experiment Mission 5 for the Ballistic Missile Defense Organization (BMDO). At this time, Israel is not a signatory to the Missile Technology Control Regime (MTCR) agreement.

7.6.3 *Russia*

Numerous small launcher proposals have come out of the FSU since the end of the Cold War. The Burlak is typical.

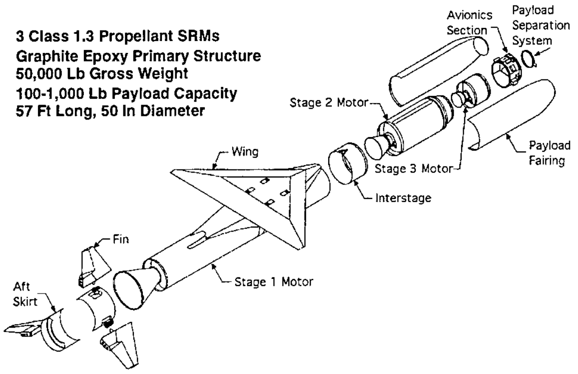


Figure 3. Pegasus Launch System

7.6.3.1 ***Burlak.*** The Russian Burlak is seen as a competitor to the U.S. Pegasus since it is an air-launched, all-azimuth vehicle, capable of being launched from foreign launch sites. However, it is launched from a supersonic (the TU-160 Blackjack), rather than a subsonic, air-breathing platform. It is capable of delivering 2,200 lb (1,000 kg) to LEO.

7.6.4 *Japan*

Two Japanese organizations are concerned with launch vehicle development, the National Space Development Agency of Japan (NASDA) and the Institute of Space and Astronautical Science (ISAS). NASDA is responsible for the H-vehicles; ISAS is currently developing the new M-vehicle, the M-V. To fill a need for a new class of satellite launchers, NASDA is developing the J-1, which combines the NASDA-developed H-2 solid rocket booster and the ISAS-developed M-3SII upper stage and payload fairing.

7.6.4.1 ***J-1.*** The J-1 can deliver 1,800 lb (830 kg) to LEO. A primary mission is the Hypersonic Flight Experiment (HYFLEX), an aerodynamic winged body designed to collect hypersonic data for the H-2 Orbiting Plane (HOPE). Recovery of the re-entry vehicle was not achieved on the first flight.

7.6.4.2 ***MV.*** In 1989, ISAS began the development of the new solid propellant launcher, the MV, to replace the M-3SII currently in use. The MV can deliver 4,000 lb (1,800 kg) to LEO.

7.7 Westernized Former Soviet Union (FSU) Launch Systems

Several cooperative international agreements have been made which will add to the selection of launchers available in the Western commercial market place. Flight availability of mainline systems, however, will be dependent on U.S. and European government agreements on level of access of Former Soviet Union (FSU) launchers to the global commercial launch market. Cooperative agreements, sanctioned by government, to authorize the launch of ballistic missile derivatives outside national boundaries could expand the number of launch sites available to launch NATO space assets.[18]

Cooperative engine development activities in particular have gone a long way.[19] Pratt and Whitney is marketing a two-chambered version (the RD-180) of the the LOX/Kerosene NPO Energomash RD-170, the NPO Energomash RD-701/704 tri-propellant engine, and the NPO-EM RD-120 for small launch vehicles. GenCorp-Aerojet is marketing the NK-33 engine.

7.7.1 *Proton*

As stated above, the highly successful Russian Proton launcher is being marketed in the West by ILS, a U.S./Russian joint venture led by Lockheed before the merger of Lockheed and Martin. The Proton is currently launched from Baikonur, but other launch locations, such as: Cape Canaveral, Florida; Kourou, French Guiana; Northern Australia; and Northern Brazil have been suggested. The Proton can place 46,000 lb (20,900 kg) into LEO, 12,100 lb (5,500 kg) into GTO, or 4,850 lb (2,200 kg) into GEO.

7.7.2 *Zenit*

Ukraine's two-stage Zenit rocket is capable of placing 28,700 lb (13 tonnes) payloads into LEO from Baikonor Cosmodrome. The Boeing Sea Launch Company, formed by Boeing Defense and Space Company, is proposing to add a third stage to the Zenit and launch from an off-shore platform near the equator. Boeing's international partners are Zenit builder, NPO Yuzhnoye, of Dnepropetrovsk, Ukraine; NPO Energia, of Moscow; and Kvaerner Group of Oslo, Norway. [Ukraine signed the Nuclear Non-Proliferation Treaty and is a signatory to the terms of the Missile Technology Control Regime (MTCR)].

Zenit-3 will launch 11,420 lb (5,180 kg) into GTO or 3,380 lb (1,530 kg) into GEO from Tyuratam. Zenit launches are highly automated; the Zenit can be launched within 21 hours from arrival at the launch pad.

7.7.3 *Kosmos*

The Russian Kosmos is manufactured by the Polyot Design Bureau in Omsk, Russia. At least two U.S. companies - Assured Space Access of Arlington, Virginia, and Final Analysis Inc. (FAI) of Greenbelt, Maryland, are interested in marketing the launcher in the West. FAI has already flown a satellite (FAIsat I) on Kosmos. A German company - OHB-System - and a British company - Plowshare Technology Ltd. - also have an interest in marketing the launcher. Cosmos International GmbH, a joint venture of Aerospace Association Polyot and OHB System GmbH based in Bremen, Germany, is currently advertising Kosmos launch services.

Kosmos was proposed to fill the gap in the U.S. small experimental satellite launch capability, when two consecutive failures of the air-launched Pegasus occurred, but was rejected by the U.S. government.

7.8 Ballistic Missile Derivatives

Russian Defense Minister Pavel Grachev and U.S. Defense Secretary William Perry, together, set off an explosion that destroyed a Minuteman II intercontinental ballistic missile silo. This symbolic gesture of cooperation was meant to affirm the two countries' commitment to nuclear arms reductions mandated by the first Strategic Arms Reduction Treaty (START I), signed in 1991. At the height of the Cold War, the FSU had 2,500 strategic missiles and heavy bombers and the U.S. had 2,250, but under START I, the arsenals will be cut to 1,600 on both sides by December 2001. However, the START II agreement of 1993 has not been ratified and is presently under some stress because of Russian concern that NATO is encroaching into Eastern Europe and also the rise of nationalistic sentiment in the FSU. In contrast, the agreement on the disposition of surplus ballistic missiles or their stages is already being subjected to wide interpretation not necessarily in consonance with the Clinton space policy. For instance, Joint Statement Number 21 of the Joint Compliance and Inspection Commission, issued 28 September, 1995, in Geneva, states, *"....the first stage of an SS-25 ICBM that is incorporated into a space launch vehicle, designated by the Russian Federation as the START space launch vehicle .... do not result in SS-25 ICBM (derivatives) to be considered ICBMs .... he Treaty does not prohibit a Party from moving ICBM used for delivering objects into .... space .... to a launch facility outside its national territory."* [20] Such statements suggest that a multitude of ballistic missile-derived launchers could find their way on to world markets.

It should be noted that France, Japan and the PRC are not subject to the terms of the treaty. Also, in practice, all space launch vehicles, commercial or military, are derived from ballistic missiles, which leaves considerable leeway for legal debate.

7.8.1 *United States*

7.8.1.1 ***Titan II Space Launch Vehicle (SLV).*** Lockheed Martin has converted 14 Titan II ICBMs to space launchers; about 40 surplus missiles remain in inventory. The Titan II can deliver 4,200 lb (1,905 kg) to LEO.

7.8.1.2 ***USAF MultiService Launch System (MSLS) Minuteman II Derivatives.*** A number of small launch vehicles using Minuteman II stages have been proposed for both suborbital and orbital use. Lockheed Martin won a contract in 1992 to develop MSLV for the Space and Missile Systems Center (SMC) at Kirtland AFB, but its use as a space launcher must be approved by the Secretary of Defense. The current schedule calls for three suborbital missions in 1996; orbital flights have not yet been budgeted The suborbital MSLV can carry an 850 lb (385 kg) payload about 4,200 nm (7,800 kg).

Lockheed Martin is restricted from marketing MSLV commercially by the Clinton policy which restricts the use of refurbished missiles for commercial use. However, interpretations of the disposition of surplus ballistic missile agreements are still being made.[20] Current plans are to permit the MSLV to orbit five experimental payloads.

7.8.1.3 ***Polaris / Trident / Poseidon Derivatives.*** Several small launch vehicles using surplus Polaris, Trident, or Poseiden submarine-launched ballistic missile (SLBM) stages have been proposed.[12] The availability of surplus hardware will be dependent on the outcome of the START II arms reduction treaty.

7.8.1.4 ***MX (Peacekeeper).*** Space launchers derived from MX components have also been proposed.[12] The START II agreements call for the decommissioning of Peacekeeper, but until START II is ratified the system will remain operational and therefore not available for conversion.

7.8.2 *Russia*

7.8.2.1 ***Start (SS-25 Sickle Road-Mobile ICBM Derivative).*** The Start vehicles are based on the SS-25 road-mobile ICBM and are launched from an SS-25 mobile launch platform; they are the smallest FSU launchers and also the only ones known to employ all-solid propellants. In theory, they can be launched from any suitable location in the world, providing the country from which the launch takes place is a signatory of the Missile Technology Control Regime (MTCR), although, at this time, flights have only been made from Plesetsk Cosmodrome. They have been offered to a number of countries, including Norway and South Africa, to be flown out of their national spaceports; remote launches would require payload processing, encapsulation, and integration at an appropriate facility before transporting to the launch location. The Australian Space Office is negotiating the launch of the Start from Australia, but is also discussing a joint venture with Russia to develop an industrial base in Australia to build a submarine-launched ballistic missile (SLBM) based launcher called Seagull, and offer commercial launch services from either Woomera or from a location in the Northern Territories.

The Start family of vehicles will deliver up to 1,260 lb (570 kg) into LEO. The vehicles are marketed by STC Complex, a joint stock company formed in 1991 by the Moscow Institute of Heat Technology (MIHT), the developer of the SS-25.

7.8.2.2 ***Rokot (SS-19 Stiletto ICBM Derivative).*** The Russian-German Rokot is expected to operate out of Plesetsk Cosmodrome in 1997. The three-stage launcher is based on the Soviet SS-19 ballistic missile and will launch payloads of about 800 to 1,500 kg (1,760 to 3,300 lb). The vehicle is a product of a team effort between Khrunichev State Research and Production Space Center of Moscow (the primary builder of the Proton rocket) and Daimler-Benz Aerospace's Orbital Systems Division of Bremen, Germany. The marketing company, Eurockot, will be based in Bremen.

7.8.3 *Ukraine*

7.8.3.1 ***Ikar (SS-18 Satan heavy ICBM Derivative).*** In accordance with the START II agreements, 308 SS-18 ballistic missiles are being decommissioned and removed from their silos. The Ikar (Icarus)-1 and -2 space launchers are derived from the SS-18 and will be launched from two SS-18 silos at the Baikonur Cosmodrome; it is expected that they will be transported in, and launched from, protective canisters. The Ikar family of vehicles is manufactured by NPO Yuzhnoye and will deliver up to 8,900 lb (4,050 kg) to LEO.

7.9 Reusable Launch Vehicles (RLVs)

Many commentators believe that the only way to make serious cuts in the cost of access to space is by developing fully reusable systems, preferably single stage. Numerous reusable and partially reusable launch vehicle (RLV) designs have been proposed over the last 35 years, including Single-Stage-To-Orbit (SSTO) and Two-Stage-To-Orbit (TSTO). Advances in propulsion, structures and manufacturing technology are bringing RLVs closer to reality.

7.9.1 *U.S. Reusable Launch Vehicles*

Both ground-launched and air-launched reusable systems are being considered in the U.S.

7.9.1.1 ***Ground Launch.*** Although funding is severely restricted, several ground-launched, reusable launch vehicle programs are underway in the U.S.

7.9.1.1.1 *DC-X (Delta Clipper).* The McDonnell Douglas Vertical Take-Off / Vertical Landing (VTO/VL) DC-X program aims to demonstrate some of the technologies and operational features needed by a fully-reusable SSTO system. The DC-X has already demonstrated vertical take-off and landing, and rapid refueling and turn-around. The advanced DC-XA vehicle incorporates a Russian 1460 aluminum-lithium propellant tank intended to demonstrate low structure factor and reusability. The Delta Clipper program is funded partly by NASA and partly by the U.S. Air Force.

7.9.1.1.2 *X-30 National AeroSpace Plane (NASP).* Aerospace planes with capabilities for hypersonic flight in the atmosphere and for earth-to-orbit missions have been investigated since the early 1960s, but are still only in the very early stages of development. Nations world-wide, including France, Germany, India, Japan, Russia, the United Kingdom, and the United States are involved in these studies although a practical system is a long way off. The X-30 National Aerospace Plane (NASP) program, a joint NASA/DoD initiative in the U.S., is a typical example. Although having considerable momentum initially, budget cuts have severely impacted the X-30 program which was intended to lead to a demonstration vehicle but has been cancelled. However, engine experiments are continuing under the Hypersonic System Technology Program (HySTP). Mach 7 scramjet tests are being conducted on a one-third scale Concept Demonstration Engine (CDE) at NASA's Langley Research Center (NASA/LaRC) and at the Central Institute of Aviation Motors (CIAM) in Moscow. CIAM is also investigating a RAMJET/SCRAMJET dual mode engine. Computer-based design of various Mach 10 hypersonic vehicles is also continuing at low budgetary levels.

7.9.1.1.3 *X-33.* The NASA X-33 SSTO program is responding to the Clinton space transportation policy directive. An industry / NASA partnership has been formed to develop and demonstrate, by ground and flight test, the key technologies required to achieve a highly operable RLV commercial capabilility. Three X-33 teams are participating: Boeing/McDonnell Douglas, Lockheed Martin and Rockwell International. The initial 15-month Phase I (Conceptual Design) effort, ending in mid-1996, is to design an experimental two-thirds scale technology demonstration vehicle which will begin flight testing in 1999. Boeing/McDonnell is proposing a Vertical-Take-Off-Vertical-Landing (VTO/VL) semi-ballistic vehicle, Lockheed Martin is proposing a Vertical-Take-Off-Horizontal-Landing (VTO/HL) lifting body vehicle, and Rockwell International is proposing a Vertical-Take-Off-Horizontal-Landing (VTO/HL) wing-body vehicle. The three concepts are shown in Figure 4.

A notional sequence to an operational system is illustrated in Figure 5.

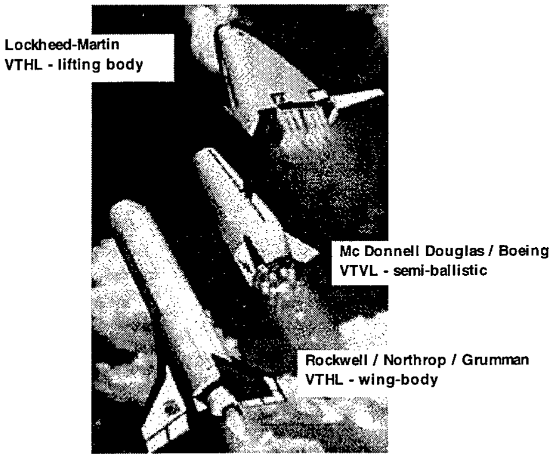


Figure 4. X-33 Vehicle Concept

NASA is planning for private sector financing to be the major source of funds for Phase III (Full-Scale Development). However, industry officials have already warned Congress that private funding will not be available unless the U.S. government agrees to be the anchor tenant, guaranteeing to purchase a number of launches and reducing the risk to private investment. Some industrial commentators claim that the program guidelines need to be relaxed to permit consideration of a two-stage system and a variety of payload goals if the program is to be commercially viable.

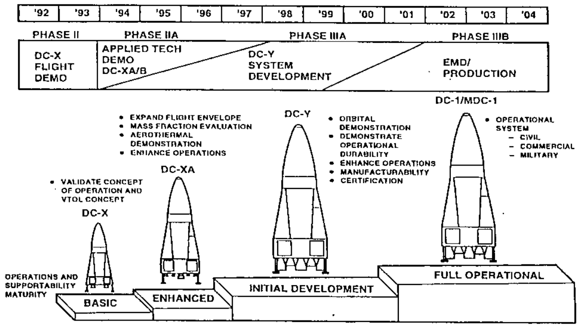


Figure 5. DC-X Delta Clipper Development Schedule

7.9.1.1.4 *TransAtmospheric Vehicle (TAV).* Although the Clinton launch policy gave NASA the lead in the fully reusable SSTO X-33 commercial launcher program, the U.S. Air Force is also contributing $65 million to lay a technology foundation for a military system called the TransAtmospheric Vehicle (TAV). This military capability has been discussed since the early 1960s and was also recommended in the 1994 Spacecast 2020 report.[5] As well as a space launch function, it would perform an advanced military role, upgrading the current functions of the Air Force's SR-71 reconnaissance plane, the Predator Unmanned Aerial Vehicle (UAV) program vehicles, and the Airborne Warning and Control System (AWACS), and leading to a lethal or non-lethal force projection role. The increasing vulnerability of both airborne and space-based reconnaissance nad surveillance assets makes the TAV application increasingly attractive.[21]

In order to play an effective military role, the TAV would need to meet the following requirements:

- On-demand, all-weather launch.
- Autonomous operations - data to user within 150 minutes of alert.
- Survivable in a hostile environment.
- All-azimuth launch from widely-dispersed bases.
- Operate over any point on earth within 100 minutes of alert.
- Land at widely-dispersed refueling bases or refuel in flight.
- Recall capability.
- Cost-effective.

7.9.1.2 ***Air Launch.*** Orbital delivery from an air-breathing platform has been studied in the U.S. since the early 1960s; the Boeing B-52 and the Lockheed C5-A being favorite candidates for the launch platform. In 1982 the United States Air Force (USAF) studied a Space Sortie mission which proposed to launch a small reusable vehicle from a Boeing 747-200 into LEO. In theory the vehicle could have flown over any point on the Earth's surface within 90 minutes of takeoff. In practice the carrying capacity of the Boeing 747 could only deliver about 3,000 kg into a 28.5 degree orbit and less than 1,000 kg into polar orbit. Conceptual designs of new rocket thrust augmented subsonic and hypersonic air-breathing platforms were also studied.

7.9.1.2.1 *X-34.* Under a NASA-funded contract, American Space Lines, which is jointly owned by Orbital Science Corporation (OSC) and Rockwell International (RI), began development of the X-34 vehicle, a reusable version of the OSC air-launched Pegasus. Two versions were considered: the X-34A designed for launch from the Lockheed L-1011, and a larger X-34B for launch from the Space Shuttle Boeing 747 carrier aircraft. The X-34B would deliver 1,000 to 2,000 lb (450 to 900 kg) to LEO.

Although opposed by RI, a Russian engine, marketed in the West by Pratt and Whitney, was favored by NASA and OSC. The first orbital flight was planned for mid-1998, but the program was discontinued when the industrial partners found the program not to be commercially viable. NASA is resolved to continue the program and has issued a Request for Proposal (RFP) for a contract to be let to develop and demonstrate an X-34 vehicle.

7.9.2 ***Non-U.S. Reusable Launch Vehicles*** Many countries other than the U.S. have proposed reusable launch vehicle designs, including France, Germany, India, Japan, and the Russian Federation. These have included both SSTOs and TSTO vehicles with air-breathing first stages.

Non-U.S. proponents of air-launch have considered the Russian An-225 transport as an ideal launch platform. The An-225 aircraft is a development of the Antonov design bureau, located in Kiev in the Ukraine. It is a larger version of the An-124 which was a Soviet equivalent of the United States C-5A military transport. It can carry a payload of more than 600 thousand pounds (275 tonnes) and has a range of 5,400 nm (10,000 km). The An-225 suitability as a SSTO carrier is not only its payload capacity. It has built-in hard-points and provisions for many of the other systems needed for such a mission and sufficient structural margin to add engines if required. It has been proposed as a launch platform for several different vehicles.

8. APPLICATIONS TO THE FUTURE NATO MISSION In the current tight military budget environment, combined with the evolving threat scenario described above, emphasis must be given to demand systems suited to the needs of the war-fighter rather than the command systems of the Cold War era. Conventional mainline launch systems will still be needed to support the traditional communications and intelligence gathering military systems shown in Figure 6. However, there will be opportunities to exploit other emerging applications to provide the situation awareness, strategic agility, and surgical lethality that is currently lacking in the post-Cold War NATO arsenal. The development of the AeroSpace Plane is probably far in the distant future. However, the TAV could be a feasible approach to provide needed space access capabilities that cannot be provided by expendable vehicles.

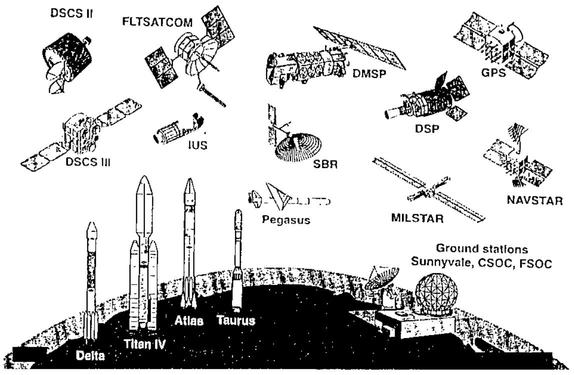


Figure 6. U.S. Military Space Systems

8.1 Mainline Upgraded Expendable Systems.

Upgraded or evolved mainline expendable systems are expected to satisfy the access to space demands of conventional communications and information gathering and processing satellites. The Western Alliance will have a choice of a broad set of launchers and the option to launch from several different launch sites.[13, 18]

8.2 Small Expendable Systems.

The end of the Cold War and eventual agreement on the disposition of ballistic missiles could release considerable rocket hardware for developing small launchers. These will be available to launch small tactical satellites from a wide range of global launch sites. If the predictions of the advocates of nanosatellites are realized, downsizing of mainline satellites may take place, expanding the market for small launchers.

8.3 Proliferated Commercial Spaceports.

Many nations and, in the U.S. even individual states, are establishing their own commercial spaceports as a prelude to a predicted expansion of space traffic comparable to the way in which the commercial air transportation industry developed in the 1920s. These have developed either to compensate for reduced government spending in a particular geographical region or in the interest of establishing a level of national launch autonomy, but the result will be to provide more choice in launch location. The U.S. Office of Commercial Space (OCST), now part of the Federal Administration (FAA), has received Transportation Aviation applications for commercial spaceports from the states of Alaska, California, Florida, New Mexico, and Virginia. Spaceports in countries such as Australia, Brazil, Canada, Norway and Scotland are under serious consideration. This proliferation (as illustrated in Figure 7) may help to provide the agility characteristic needed for NATO's response to crisis.

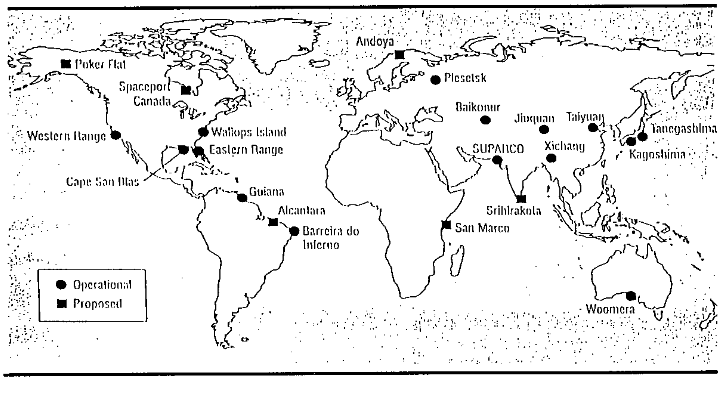


Figure 7. Global Launch Sites

8.4 Air Launch.

Air launched systems can supply the launch flexibility and survivability characteristics needed for reconstitution in a hostile, post-engagement environment.

8.5 TransAtmospheric Vehicle.

Advocates of TAV development do not claim that it will replace the launch of scheduled military satellites by conventional upgraded or evolved expendable launchers. The TAV is conceived as on-demand, mission performance-oriented to carry out the following missions in a stressful environment:

- Terrestrial reconnaissance and surveillance.
- Space reconnaissance and surveillance.
- Damage assessment.
- On-demand tacsat delivery / replacement.
- Target acquisition for airborne and ground-based weapon delivery systems.
- Timely meteorological data gathering and reporting.
- Terrestrial weapon delivery.
- All altitude anti-satellite.
- Non-lethal surgical containment of hostile forces.

The TAV could provide a survivable way of linking the Cold War-era communications system with modern day television broadcast technology to enable field commanders to receive secure reconnaissance imagery in the field. It could use the Defense Satellite Communications System (DSCS) and Single Channel Transponder Receiver terminals to pass everything from air tasking orders to armed forces radio and television broadcasts to troops around the world.

Some commentators have suggested that the only feasible way to develop a cost-effective RLV is by international cooperation, either in the civil or the military sector.[19] The perception of a military need by the Western Alliance for a TAV could possibly lead to an internationally-funded RLV development for military, civil and commercial use.

9. SUMMARY / CONCLUSIONS

As the roles and responsibilities of NATO, the WEU, the UN and the ex-Warsaw Pact countries change, Europe, the United States, and Russia may have to share a common responsibility for the stability and security of the free world. This shared responsibility must allow for the expression of national and regional autonomy, and interdependence at the same time. In summary:

- The NATO role is changing drastically.
  - Becoming more global
  - Number of coalition partners increasing (11 non-NATO nations in Bosnian peacekeeping effort)
  - Will include broadened global pacification/humanitarin action
- The NATO mission depends increasingly on space support.
  - Reliable, low-cost, assured access to space mandatory
- The NATO function will demand resources technically superior to those available today to combat expanding capability in the unstable regions of the world.
- A wider choice of improved expendable launch vehicles will be available.
  - Augment traditional space support role
- A wider choice of launch sites will be available, particularly small commercial spaceports intended primarily for launching small satellites.
- Ballistic missile derived launchers could provide small tacsat deployment and agile reconstitution.

- Air-launched systems could provide greater survivability and perform new functions.
  - Dispersed launch locations
  - All-azimuth launch
- The TransAtmospheric Vehicle (TAV), although having limited advocacy at this time, could fill a critical post-2000 perceived peace-making/peace keeping need by providing:
  - Situation awareness
  - Strategic agility
  - Recallable surgical lethality
  - Immunity to information warfare
  - Survivable
- The increasing interdependence between the Western Alliance nations could lead to international development of the TAV becoming a feasible possibility.

There is a need for standardization and cooperation so that coalition nations can concentrate suppression resources instantly on a single common target. Improved versions of current space transportation systems and a proliferation of choices of launchers and launch sites will enhance

NATO space warfighting capability. However, in the long term, in order to perform the expanding functions new missions may demand in an increasingly hostile environment, the NATO Alliance could make effective use of advanced, innovative "clean-sheet" systems, such as the TAV, that may require international cooperative funding to develop.

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Multi-Launch Vehicles for Satellites Integration Issues

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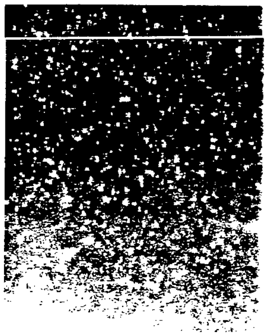
INTRODUCTION

Most satellites are designed to optimize their operability in space; optimizing their ability to arrive in space is secondary. Regardless of how well a satellite system is produced, it cannot have the opportunity to operate if the launch vehicle it was designed for is unavailable. Access to space can be optimized by providing launch vehicles with a "fitness for use" approach.

The ability to launch a satellite on different launch vehicles with minimal or no modifications to either the satellite or the launch vehicle is highly desirable in both the defense and emerging commercial markets.

History has shown that the reliance on one launch vehicle system can result in lengthy and costly delays when the fleet is grounded due to in-flight or ground anomalies. Reliance on the space shuttle for military payloads in the 1980 delayed the deployment of many military satellites because of the Challenger failure. This spawned a rebirth of expendable launch vehicles such as Atlas and Delta. However these also proved less than 100% reliable despite their years of successful flights as shown by the two Atlas Centaur failures which led to a grounding of the fleet for approximately one year. Design modifications necessary to adapt a spacecraft to a different launch vehicle than the one it was designed to is also very expensive and time consuming. In order to avoid these pitfalls, the U.S. Air Force initiated the Medium Launch Vehicle (MLV) Standard Interface Definition Study.

Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.



BACKGROUND

The Medium Launch Vehicle (MLV) Standard Interface Definition Study was a joint effort among three launch vehicle contractors under the direction of USAF Space and Missile Systems Center and the technical cognizance of The Aerospace Corporation. The study was to establish an interface baseline for future MLV payload integration activities. The purpose of the standard interface was to provide a level of interface and design criteria commonality among launch vehicles with respect to future spacecraft. Consequently, spacecraft designed to these criteria are capable of being launched by a secondary MLV with a relatively short delay should a circumstance prevent launching on the primary MLV.

The study surfaced the inherent differences in integration methods and philosophies among different launch vehicle contractors. This paper discusses these differences, along with solutions, which led to the standard interface requirements document. Manufacturing benefits, lessons learned, and ideas to expand and refine the standard interface concept are also discussed

STUDY SCOPE

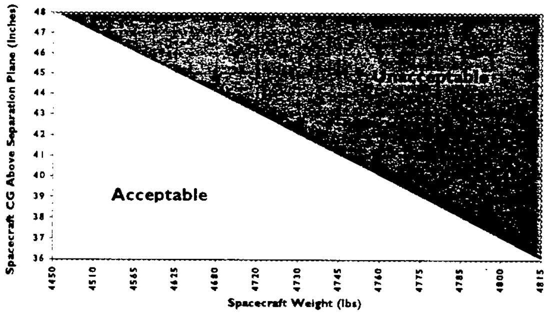
Initially it became apparent to the parties involved that the scope of the study had to be limited and well defined in terms of spacecraft weight, size, and orbit requirements. The selected interface baseline was for spacecraft less than 4800 pounds going to geosynchronous orbit. This encompassed the Global Positioning System (GPS) Block IIR spacecraft, which would serve as the test case for the study, despite the fact it was already well into its design phase.

SPACECRAFT STRUCTURAL INTERFACE AND FAIRING

STRUCTURAL INTERFACE

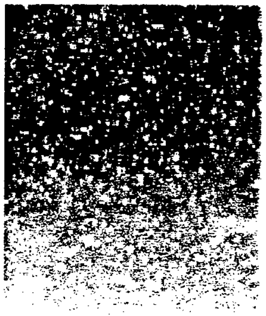
Payloads are generally attached to an adapter mounted to the upper tank structure of the launch vehicle. The structural interface to the spacecraft, called the payload attach fitting, or PAF, is constructed of aluminum and is 37 inches in diameter. This PAF was chosen because it is both a standard size for the contractors and presented little in the way of constraints on spacecraft design, other than spacecraft center-of-gravity height (Figure 1). The spacecraft separation system uses compressed springs to ensure no recontact between spacecraft and booster with low tip-off rates and launch vehicle verified separation. An optional system to allow spacecraft monitored separation is also available.

FIGURE 1: ALLOWABLE SPACECRAFT WEIGHT VS. CENTER OF GRAVITY



FAIRING

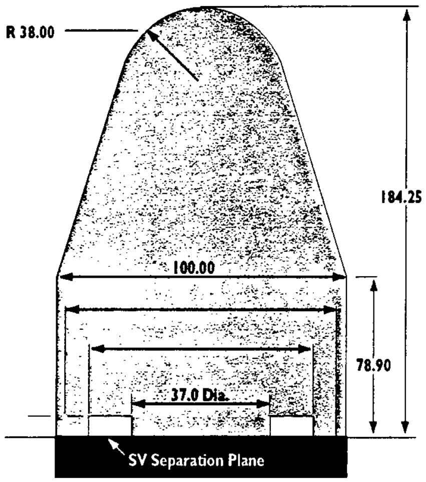
Defining a fairing presented a more complex challenge The standard fairings used on the different launch vehicles varied greatly in size, usable volume, and internal environments during pre-launch and ascent The development of a new fairing which could be used on all the launch vehicles



was a simple but expensive solution. Instead it was decided to compare several fairings and derive spacecraft interface requirements that could be met by all their designs.

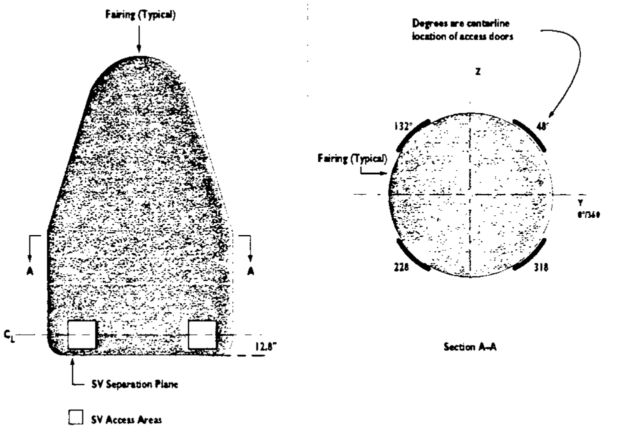
One example of this approach was determining the spacecraft's usable volume. Drawings of each of the fairings were overlaid to derive the maximum allowable volume the spacecraft could use. This resulted in the envelope shown in Figure 2. This volume encompasses most spacecraft in the study weight class.

FIGURE 2



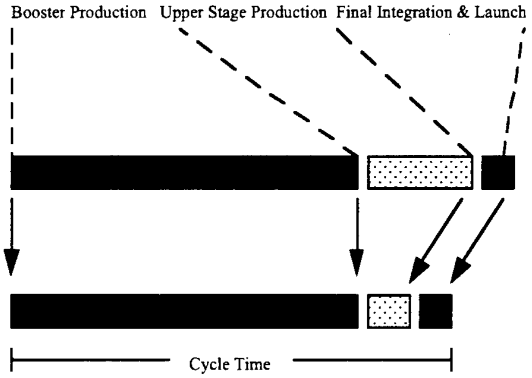
A more difficult task was in providing standardized access to the spacecraft once the fairing is attached to the launch vehicle. Most payload fairings will provide access doors cut into the fairing at specific locations for each spacecraft. However this would be unacceptable to the study's objective of enhanced processing time. By overlaying the fairing drawings and determining the areas where access doors could be located, four standard access doors, each 90 degrees apart, were established. (See Figure 3). They were made large enough to allow complete 360 degree access to the spacecraft

FIGURE 3



Time savings are depicted in Figure 4 below.

Figure 4: Processing Time Reductions with Standardized Interface



MANUFACTURING IMPLICATIONS

The standardization of both the structural interface and fairing previously described would optimize processing time for launch vehicle manufacturers and consequently the orbit delivery time for spacecraft. Presently launch vehicle manufacturers incorporate mission modifications for each spacecraft customer. Manufacturers have little control over customer's need dates, and therefore must modify production planning, scheduling, and control. In summary, this discontinuous manufacturing flow negatively impacts:

- *Productivity*
- *Producibility*
- *Quality of Interface Hardware*
- *Rework and Repair*
- *Cycle Times*
- *Part Count & Inventory of Parts*
- *Material and Labor Costs*
- *Design-to-Production Process*

In addition, the following tasks and obstacles could be potentially eliminated with a standardized interface:

- *Specialized tooling*
- *Specialized testing*
- *Specialized procedures*
- *Detailed and customized Engineering reviews*
- *Last-minute customer requirements changes*

(Note: Upper Stage production times can range from 10% to 30% of total production time among the different launch vehicles.)

FUTURE MANUFACTURING CONSIDERATIONS

Presently, both launch vehicle and satellite manufacturers must perform an initial "fit-check" to ensure the accurate integration of the launch vehicle upper stage and the new spacecraft. Structural, mechanical, and electrical connections are verified in preparation for the launch vehicle and spacecraft mating on the launch pad. The fit-check process consumes at least one month of processing time and associated material, testing, and transportation costs. Clearly, a standardized interface would greatly reduce the complexity and potentially the need for fit-checks

To mitigate risk and to maintain the same level of confidence of the fit-check, launch vehicle and spacecraft manufacturers should consider the following in its replacement:

- *Interface master tooling*
- *Computer models*
- *Formal process and procedures to manufacture to the master tool*

LAUNCH VEHICLE ENVIRONMENTS

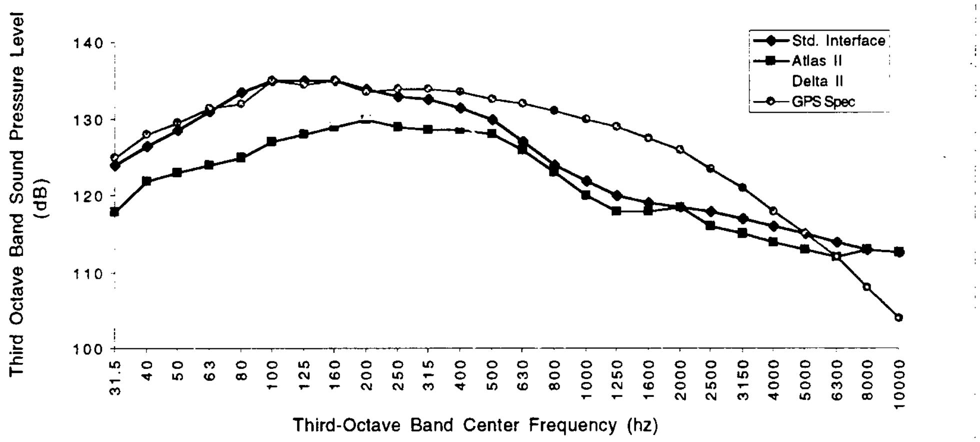
Spacecraft are subjected to a variety of environments during liftoff and ascent. These environments are specific for each launch vehicle and must be provided to spacecraft designers early in the design phase. Environmental testing requirements are then generated for each spacecraft to ensure they can survive these harsh conditions. Deriving a set of environments that would cover all three launch vehicles was in some cases achievable yet not practical in others. Following is a discussion of the environmental issues and their solutions.

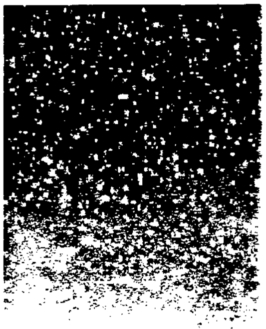
ACOUSTICS

The acoustic environment and subsequent dynamic excitation of the spacecraft during liftoff and ascent must be addressed during the design phase. Typically, acoustic levels for the spacecraft are provided by the launch vehicle contractor. Spacecraft are then typically placed in an acoustic testing chamber where they are subjected to the worst case acoustic levels they can expect in flight. This environment is largely influenced by the launch vehicle fairing and its particular acoustic attenuation system.

By comparing the acoustic levels of each fairing and tuning the acoustic attenuation systems, one set of acoustic requirements was derived which each launch vehicle fairing could meet. This requirement was on the order of two to three decibels higher overall than each particular fairing's acoustic level, but not high enough to negatively impact most spacecraft design. Figure 5 compares typical booster and spacecraft specification acoustic levels with the standard interface level.

FIGURE 5: STANDARD INTERFACE ACOUSTICS VS. OTHER VEHICLES





THERMAL

Another environmental factor which proved to be more difficult in defining a baseline was the free molecular heating (FMH) which occurs during ascent. These rates are highly dependent on the specific trajectory flown. Guidelines for FMH were established, but it was decided that the variability of these rates vs. trajectory was too large to standardize. Trajectory simulations to address this are discussed later.

SPACECRAFT DESIGN LOADS

Spacecraft contractors must design their structures to withstand dynamic accelerations imposed on them during flight. These accelerations are maximized at flight events such as liftoff, transonic flight, launch vehicle engine shutdowns, fairing separation, and spacecraft separation. In a typical spacecraft integration, design load factors (DLF) are supplied by the launch vehicle contractor. The DLF are intended for application at the spacecraft's center of gravity to evaluate the primary structure. Once a preliminary spacecraft dynamic model is developed, a preliminary coupled loads analysis (PCLA) is done which combines the dynamic models of both the spacecraft and launch vehicle. This supplies the spacecraft designers with accelerations, deflections, and margins of safety, which are used to evaluate the current design. Once the spacecraft design is finalized, a final coupled loads analysis (FCLA) is performed to ensure that design changes from the PCLA are acceptable.

Deriving load factors for this study was difficult in that an envelope of the three different launch vehicles would be overly conservative, but load factors which were too low would could cause the spacecraft to be undersigned structurally. Finally a set of DLFs were derived which was believed to encompass the more severe events for each launch vehicle, as shown in Table 1

TABLE 1. SPACECRAFT LIMIT LOAD FACTORS(G'S)

Flight Condition	Axial	Lateral
Max Lateral	+1.0, -2.5	+/- 3.0
Max Axial	+3.0, -6.9	+/- 1.0
Max Combined	+3.0, -6.0	+/- 2.5

Note: (+) Tension (-) Compression

Two methods were considered for performing the CLAs. One was to try and synthesize dynamic models and forcing functions which would encompass all three launch vehicles' characteristics. However, this method soon proved to be quite formidable due to the differences in launch vehicle structural characteristics and forcing functions and their effect on spacecraft loads. Instead it was decided to run a separate CLA for each launch vehicle/spacecraft. While this method goes against the standard interface concept, it is cost-effective while meeting the objective of a quick call-up. The concept of developing a standard launch vehicle model and forcing functions is intriguing, and should be the subject of further study.

TRAJECTORY ANALYSES

A large part of mission integration is in trying to optimize the trajectory flown by the launch vehicle. Parameters such as sun angles, eclipse periods, thermal maneuvers, ground station coverage, and launch windows are derived from this process. It proved to be much too complex to derive a standardized trajectory which would cover all launch vehicles. Similar to the coupled loads analyses, it was determined to be more effective to provide three separate trajectory analyses to the spacecraft mission planners. Trajectory optimization could be performed after a specific launch vehicle was established.

GROUND SYSTEMS AND SPACECRAFT HANDLING

When a spacecraft is on the ground, it requires a number of services which are typically supplied by the launch vehicle contractor. Table 2 lists some of these services. Military and scientific spacecraft typically have greater service requirements than less complex commercial spacecraft.

The interfaces at the launch sites were some of the most difficult to standardize. How launch vehicles were processed at their launch sites varied greatly. For instance, one encapsulated the payload inside the fairing before transport and erection, one encapsulated after launch vehicle attachment, and one preferred that the spacecraft provide their own transportation to the launch pad. Despite these differences certain ground system and handling interfaces were established which influence spacecraft design.

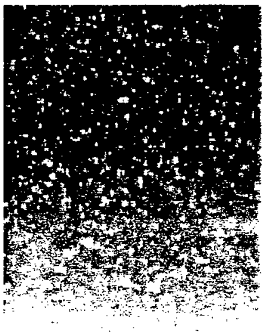


TABLE 2: LAUNCH SYSTEM-SUPPLIED PAYLOAD SERVICES

Analyses & Documentation

- *Accident risk assessment*
- *Flight safety data package*
- *Launch operations plan*
- *Mission specification*
- *Orbital requirements document*
- *Preliminary mission analysis*

Command, Control, and Communications

Electrical Power

Environmental Control

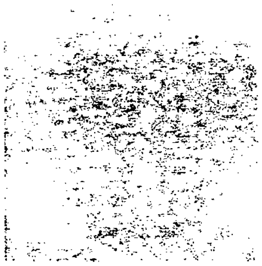
- *Air conditioning*
- *Cleanliness*
- *Special purges*
- *Factory test integration*
- *Fairing access*
- *Flight termination system*
- *Hazardous venting*
- *Payload integration facilities*
- *Launch site scheduling*
- *Lightning protection*
- *Ordnance installation*
- *Payload access*
- *Payload console in Launch Control Ctr*
- *Payload processing facilities*
- *Payload test support*

Pneumatic & Fluids

- *Liquid and gaseous Nitrogen*
- *Gaseous Helium*

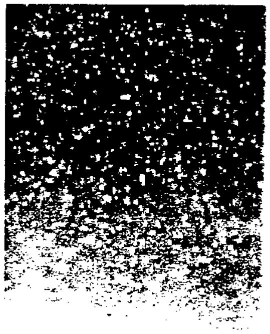
Propellant Servicing

- *Spin balancing*



These interfaces were divided into two categories: spacecraft-provided transport, and launch vehicle-provided transport. Figure 6 illustrates this concept. Physical, electrical, and environmental interfaces, including contamination protection, are provided for the launch vehicle-provided encapsulated transport, Additionally, safety monitoring and spacecraft personnel requirements are also specified.

For the option of spacecraft provided encapsulation and transport, spacecraft hoisting and mating operational requirement are provided, as well as post-mate and spacecraft personnel requirements



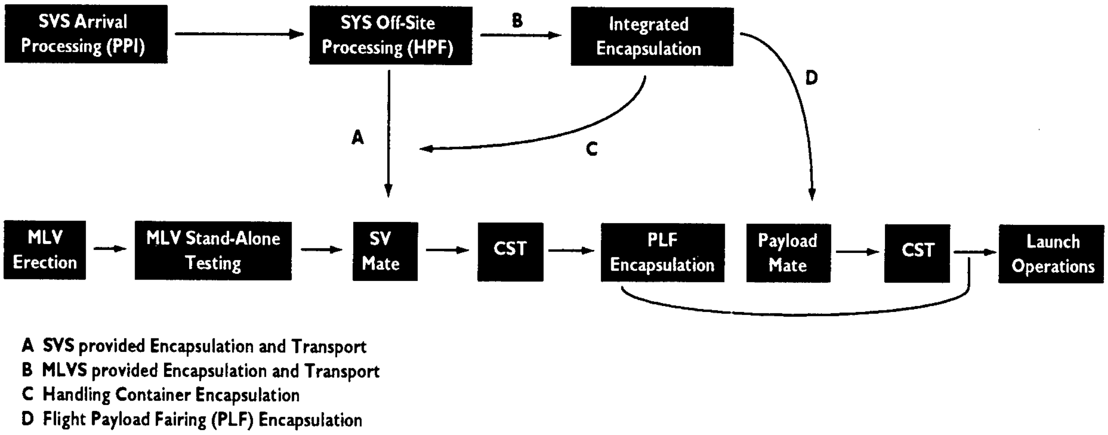
For either option, specifications for electrical ground power, fairing air conditioning temperatures and cleanliness, and backup power and air conditioning are also provided. The requirements listed in the standard interface document allows spacecraft designers to plan for their ground handling regardless of which launch vehicle is ultimately used. Unique launch vehicle schedules and descriptions of integrated operations are no longer needed in the spacecraft design phase.

CONFIGURATION CONTROL

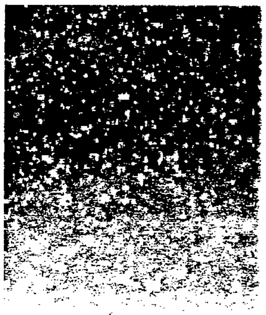
The standard interface requirements document (IRD) is intended to be maintained and controlled to reflect the latest launch vehicle configurations as changes evolve. This task is best taken by the Air Force/Aerospace Corporation team. They are in a position to be cognizant of any launch vehicle changes that would affect the IRD. This is a very important subject because the IRD becomes less effective if design modifications have to be made to the spacecraft or launch vehicle because upgrades to the launch vehicles were not incorporated.

A standardized interface design would minimize timely and costly engineering, configuration, and contracting changes. The typical processing time, from the change of a requirement to its implementation, is approximately 200 to 300 days for both launch vehicle and spacecraft contractors. Launch vehicle manufacturing processing is frequently impacted as queues and bottlenecks build up as a result of slow and past-due engineering changes.

FIGURE 6



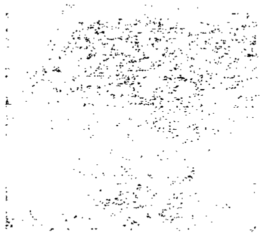
Note: CST = Combined Systems Test



SUMMARY

The Medium Launch Vehicle Standard Interface Study was undertaken by launch vehicle contractors and the Air Force to establish an interface baseline for future payloads. This facilitates multi-launch vehicle usage for satellites designed to these parameters. Both defense and commercial satellite customers can realize time and cost savings as a result of a standardized interface. Access to space is a motivating force behind this effort.

The study concluded that individual analyses for dynamic loads and trajectories was warranted due to the large differences between launch vehicles in these areas. Requirements for structural interfaces, launch vehicle environments, and ground system/spacecraft handling were developed which are common to all three launch vehicle contractors. Clearly there are numerous manufacturing benefits to consider and assess in order to optimize efficiency as well as risk. Future studies should be undertaken to broaden the scope of the standard interface to include other orbits and payload weights. Additionally, the concept of a standardized launch vehicle dynamic model and forcing functions should be investigated.



STRAWMAN CONCEPT AND PANEL DISCUSSION

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SUMMARY

The Strawman Concept provided a focus for a discussion which was initiated by the symposium steering commitee and then expanded to include discussion with members of the symposium as a whole.

This paper presents an account of the proposition put to the symposium prior to the Discussion, of the issues raised for discussion, and of the arguments and issues raised by the symposium members as a part of the panel discussion.

1.0 Introduction

The final session of the symposium drew the proceedings to a conclusion by discussion of a notional "strawman" system involving many interacting aspects of space systems. Prime purpose of the strawman was to act as a focus for the panel discussion that marked the final technical activity of the symposium.

As the discussions presented during the symposium progressed, it become clear that the dream of an exotic, multi-element space system for NATO would need to evolve into a more modest form in order to retain credibility. Thus, the concept described a space system that would provide the essential components of the NATO Command, Control and Information System. Such a system could potentially be realised by NATO in the near to mid-term, given sufficient strength of purpose.

Presentations at the symposium reinforced the view that space is here to stay, and that while NATO has already made a major commitment to Satcoms, it needs to have a greater awareness that the benefits of space extend beyond Satcoms to surveillance, meteorology and navigation. Ownership of space assets requires a long-term commitment in terms of both investment money and infrastructure.

Additionally, NATO has to realise that space will bring advantages to adversaries. Therefore, it needs to understand these advantages and to prepare measures to counter them.

2.0 Concept Description

Nato's SATCOM capability is already a core component of the NATO communications system. Space can similarly provide capabilities in surveillance, navigation and meteorological services to meet NATO needs.

An expansion of the NATO C^2I system to include these new capabilities can be envisaged with the establishment of interfaces to facilitate their introduction. Figure 1 summarises these new capabilities, some of which have been addressed during the Symposium, and indicates how they can interface with those that currently exist.

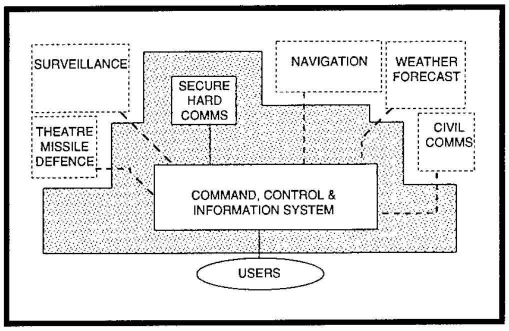

Figure 1 Space Capabilities for NATO C^2I

They include the following;

- expanded communications
- navigation
- surveillance
- weather forecasting
- theatre missile alerting

The fundamental question now facing NATO is what steps should it take to ensure that these benefits are realised, given the constraints of a budget sufficiently limited that its ability to commit to the major capital expense of additional space capabilities must be questioned.

Three options can be envisaged for filling the capability slots.

- NATO can accept services from the national means of member nations,
- procure services from the civil/commercial community under a lease/buy relationship,
- purchase complete system elements, specifically designed for NATO.

Paper presented at the AGARD MSP 5th Symposium on "Space Systems as Contributors to the NATO Defence Mission", held in Cannes, France, 3-6 June 1996, and published in CP-580.

Decisions of this type would certainly be significant policy issues that would need to be decided by NATO and may also need to be agreed by the member nations.

3 Issues Raised

Each of these options for space service raise a number of issues that need to be considered in the context of service provision to NATO. These issues were outlined to the symposium in two categories, issues that essentially impact on NATO policy, and issues that impact on particular capabilities from which NATO might benefit.

3.1 Issues Impacting NATO Policy

The three issues addressed in this domain cover the potential procurement options for filling the technical capability slots identified in the early section.

(a) The National Means Option

National Means refers to the provision of service from a nationally owned space capability. Such capabilities are usually of a sensitive nature, and the provision of service from them may well be associated with caveats, nation-to-nation agreements rather than intra-NATO release, and the possibility of a veto in particular circumstances. In making a decision to accept such service provision on a regular basis, NATO would need to agree with the contributor nations, the associated mechanisms and modalities.

This issue met with general agreement but was qualified by the response that such a procedure would need to be supported by nation to nation understandings and agreements.

(b) *The Lease/Buy Option*

Examples of the commercial businesses from which NATO could lease or buy service include Inmarsat, Radarsat and Spot Image - and there are more. In making a decision to follow such a course, NATO needs to consider at least these issues;

- the priority access which it requires to such systems demands up-front action to establish participation in the Programmes
- it will need to consider the cost-effectiveness of guaranteed use/access to communications satellites
- it will need to understand whether the operations charter of such organisations allow their use for military activities in times of crisis and conflict
- it will need to provide an infrastructure to manage and exploit the resources it plans to use

Both the panel and the symposium felt that this area provided a positive opportunity for NATO to gain useful capabilities, affordably. However, concern was expressed that the same assets can provide corresponding benefits to adversaries and that techniques need to be explored to assess the benefit to potential adversaries, and where necessary, to mitigate that benefit.

Typical areas where such analysis is needed include the GPS navigation service and communications services from international agencies such as INMARSAT. It was felt that international agencies presented a greater potential threat than (NATO) national agencies. Concern was anticipated from some non-NATO nations (and indeed from within member nations) if any interference were made to the service which they enjoy.

Nevertheless, real benefits to NATO were acknowledged and the ease of interoperability across national boundaries that such international systems provide, was seen as a particular benefit. This benefit was also seen as an example from which future military system designers may learn.

(c) *The Direct Purchase Option*

The direct purchase of complete space systems usually comes at an appreciable price. If NATO were to follow this course, it would have to undertake careful preparations.

- requirements placed on the systems would need to be explicit and agreed
- costs and funding arrangements would need to be defined
- infrastructures to manage and exploit the systems would have to be provided

The potential for NATO to make direct purchases of major system elements was acknowledged as being limited. However, earlier discussions during consideration of the lease/buy option were recalled to emphasise the need for a dedicated, hardened communications capability for NATO and the great value of such a system being wholly owned and controlled by NATO.

3.2 Issues Impacting Capabilities

The four capabilities addressed in this domain included communications, surveillance, navigation, and meteorology.

(a) Communications

A number of issues, some inter-related and some distinct, were identified for discussion in this area.

- what will be the impact of direct broadcast television and reporting services in the information wars that are regularly associated with conflicts and expected by the public?
- how will NATO manage and control these services in such circumstances?
- what will be the impact of the messaging capabilities that are expected to be globally/universally available ?
- what will be the impact of video conferencing to both civil and military users ?
- how valuable will these services be to an adversary ?

Then apart from these issues that derive essentially from the civil/commercial domain, the issues relating to frequency band i.e. UHF, SHF and EHF are still to be resolved in the military domain .

(b) Surveillance

Issues identified in the surveillance domain include the following;

- what is the NATO's requirement on surveillance information? Is it a requirement for information products already extracted from raw imagery by Information Providers, or is it for raw imagery to be operated on by NATO staffs?
- if the latter, NATO will need to provide an infrastructure to manage and exploit the extraction of information from the raw imagery
- in times of tension, will NATO be able to compete successfully with existing image providers. Competition can be expected from the international media and from adversaries?

(c) Navigation

There was agreement that the issue of navigation was already well covered by GPS and agreement that such data is vital for battle management. However, it was appreciated that the civil world has now become so enormously reliant on GPS that removal of the service from the civil community during military conflict is unthinkable.

Therefore the issues posed to the navigation service providers are

- is denial of the service a credible option, given the proliferation of its use by civil services?
- how can its use be denied to an adversary while still maintaining a service to the civil community?
- although (it is understood that) the USA has promised to pay for GPS “for some time”, NATO need to consider the implications of who will be paying for maintenance of the service into the longer term future

(d) Meteorological Services

Weather data is vital for battle management and during crises. However, although the military user has access to dedicated military meteorological satellites, the civil community has access to similar assets.

Access to the military meteorological satellites can be denied to an adversary by data down-link encryption. However, the issue that remain are as follows;

- will it be possible similarly to deny access to metsats in GEO and/or LEO i.e. does the hardware provide a downlink encryption capability?
- will the charters of operation allow such denial?
- is the mere availability of raw Met-sat data actually so important?

4.0 ISSUES RAISED IN DISCUSSION

In addition to the invited topics addressed in the panel discussion, a number of additional issues were raised from the floor. These included the following;

Training and Exercising

There was general agreement that space systems can provide an important capability to NATO and to adversaries. Therefore, there is a need to include such systems in training exercises so that NATO forces learn how to exploit them, and how to counter the advantage that they may bring to an adversary.

This issue is encapsulated in the philosophy, 'train the way we fight, fight the way we train'. A step in the right direction to achieve this would be the setting up of a NATO Space Warfare Centre

Interoperability

It was noted that a significant step towards interoperability would be the design of systems providing products to a standard information transfer format. System designers were reminded of the many NATO standards (Stanags) that exist and commended to make use of them to achieve the desired goal.

This has worked in the communications area, but it was noted that although the WEU has established an image interpretation system (Torrejon), NATO does not have such a system. It was reported that the Agard Special Study, AAS-42, recommended that NATO should start by buying in imagery and perhaps first level information products from the commercial sector. However, higher level products should be generated by NATO staff.

It was suggested that it may be possible to use the NATO Satcoms experience as training to how to integrate other space data sources.

Asset Denial to an Adversary

Denial of assets was agreed to be a difficult task. For example, in the meteorology area it was pointed out that a growing number of nations are developing and using their own satellites and that NATO has no control over such data sources.

The difficulty of restricting the navigation service provided by GPS was re-affirmed. Additionally, a further difficulty was posed in anticipation of the GPS service being handed over to a multi-national organisation within the next 15 years.

Purchasing and Asset Acquisition

Further discussion of this topic raised a linkage that interoperability would be facilitated within a NATO purchased system. However, it was pointed out that NATO should only purchase where absolutely necessary, and that system architectures would need to be studied before NATO makes such a decision.

5.0 CONCLUSIONS

The panel discussion session concluded that the importance of space to NATO is so great that NATO be recommended to establish a policy for space, and a programme office from which to co-ordinate that policy.

Generally, discussion and comment both from the panel and from the floor, raised issues and questions that such a policy would need to address. Responses to those questions would be ideally co-ordinated from such an office.

In summary the principal issues identified were as follows;

- NATO needs to maintain its hardened communications core element as an ultimate guarantee of communications and control during crises.
- civil/commercial assets can potentially provide a useful capability but NATO needs to set appropriate arrangements in place to acquire those services
- NATO needs to study carefully the issues and impacts raised by availability of commercial services to an adversary, together with techniques for their denial
- training exercises for NATO forces need to include all space systems intended for use in conflict

Finally, space is here to stay and NATO needs to establish a policy for space.

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14. Abstract

This volume contains the Technical Evaluation Report and the 19 unclassified papers, presented at the Mission Systems Panel Symposium held in Cannes, France, 3-6 June 1996.

The papers presented cover the following headings:

- Invited Papers;
- Military Applications of Civil Systems;
- Communications (Systems);
- Communications (Technology);
- Surveillance (Reconnaissance);
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