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Tactical Applications of Space Systems

(Applications Tactiques des Systèmes Spatiaux)

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.460

Tactical Applications of Space Systems

(Applications Tactiques des Systèmes Spatiaux)

Papers presented at the Avionics Panel Symposium held in Colorado Springs, USA 16th—19th October 1989.

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According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;
- 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;
- Exchange of scientific and technical information;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
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Theme

The benefits, indeed the necessity of space systems to military operations have increased considerably in the past few years. Military communications satellites such as the NATO and SKYNET series as well as the US CONSATS have demonstrated their effectiveness as elements of military command and control systems. The various weather satellites are providing more accurate and timely weather forecasting and have become important to all military operations. The 18 satellite-Global Positioning System may revolutionize weapon systems navigation guidance over the next decade. New remote sensing systems such as the Space Based Radar and other systems are in study on various stages of development.

While the importance of space systems is becoming better appreciated by the leaders in the R & D community and by the military leaders in the NATO countries, the full potential of these systems has not been realized. The intent of this symposium was to bring into focus and to characterize the attributes of space systems which contribute to the effectiveness of tactical military operations.

The symposium brought together representatives from the industrial, government and scientific communities within NATO to discuss and explore Military User Operators and development problems associated with the Tactical Applications of Space Systems.

* *

Les avantages, voir la necessité, des systèmes spatiaux pour les opérations militaires se sont multipliés au cours des dernières années. Les satellites de télécommunications militaires, tels que le NATO et le SKYNET ainsi que le US CONSATS ont fait preuve de leur efficacité en tant qu'éléments de systèmes militaires de commandement et de contrôle. Les différents satellites météorologiques fournissent des prévisions météorologiques de plus en plus rapides et précises, et représentent désormais un facteur important dans toutes les opérations militaires. Le système de navigation mondial à 18 satellites GPS risque de révolutionner le guidage en navigation des systèmes de télédétection, tels que le radar spatial, sont à l'étude ou en cours de développement.

Quoique l'importance des systèmes spatiaux soit mieux appréhendée aujourd'hui par les dirigeants de la communnauté R & D, ainsi que par les chefs militaires des pays de l'OTAN, tout les potentiel de ces systèmes n'a pas encore été réalisé. Ce Symposium eut donc pour objet de faire une mise au point qui permettra de définir les attributs des systèmes spatiaux qui contribuent à assurer l'efficacité des opérations tactiques militaires.

Ce Symposium a réuni des représentants des communautés industrielles, gouvernementales et scientifiques des pays de l'OTAN, afin d'examiner et de discuter des problèmes de développement et des difficultés rencontrées par les utilisateurs militaires en ce qui concerne les applications tactiques des sytèmes spatiaux.

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TECHNICAL EVALUATION REPORT
SYMPOSIUM OF THE AGARD AVIONICS PANEL

on
Tactical Applications of Space Systems
Colorado Springs, USA
16-19 October 1989

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SUMMARY

A Symposium of the AGARD Avionics Panel on Tactical Applications of Space Systems was held in 1989 in Colorado Springs, USA. The topics of discussion included NATO requirements for weather (and associated oceanographic) forecasting, remote sensing, surveillance, navigation, and communications. Current and future space systems were assessed relative to their capabilities to satisfy these NATO requirements. This report evaluates the effectiveness of the symposium.

INTRODUCTION

In recent years, the benefits of space systems for tactical military applications have increased considerably. Communications satellites have demonstrated their effectiveness as elements of military command and control systems, and various weather satellites are providing critical data for more timely and accurate weather forecasting.

Prospects for future benefits are even more encouraging. The NAVSTAR Global Positioning System satellite constellation can revolutionize weapon systems navigation and guidance, and new satellite remote sensing systems now in study or under development, including Space Based Radar, could provide timely over-the-horizon information for tactical and theater commanders.

The symposium provided an opportunity to discuss current and future space systems, and to explore how these systems can best be utilized in the NATO tactical environment. Technical discussions focused on satellite systems for meteorology, remote sensing, space based radar, navigation, and communications.

In the keynote address, Gen. J. L. Piotrowski, US Space Command, emphasized that space systems can be of great value to NATO military operations, but there is a tendency to underestimate their capability under wartime conditions. He stated that NAVSTAR will provide excellent capability for tactical applications of a new generation of smart weapons, and future space-based surveillance systems will provide a powerful capability to track positions of all aircraft and ships. However, Gen. Piotrowski emphasized that NATO should clearly specify requirements for their systems, with such features as timely direct-reporting to tactical commanders, so that appropriate systems can be designed and developed.

Gen. Piotrowski challenged NATO to place increased focus on utilizing space systems to satisfy currently perceived tactical requirements and improve combat effectiveness. He recommended that NATO establish a formal organization to define space requirements that support tactical operations.

In a luncheon address, Brig. Gen. Jay W. Kelley, US Air Force Space Command, emphasized that space support to warfighters is not new. Space systems are reliable (with long-life satellites), responsive to needs of terrestrial forces, sufficiently survivable, and dependable (with over 75% of military long-haul communications passing through satellites). This broad range of capability should be recognized and exploited by NATO.

REQUIREMENTS

NATO requirements for navigation, meteorology, communications, and surveillance were discussed in the framework of potential satisfaction by current and future space systems.

For naval applications, navigation and communications were indicated as the most important current needs by Rear Adm. L. G. Mason (CA), SACLANT. Future naval requirements which could be potentially satisfied by space platforms were identified as surveillance capability to locate friendly, neutral, and enemy assets, and advanced meteorological systems capable of providing data above, on, and below the ocean surface.

The history of NATO communications satellites was traced and projected into the immediate future by the Lt. Gen. R. J. Donahue (US), NACISA, describing requirements for moderate expansion of conventional military communication satellite services from geosynchronous orbit.

The process by which NATO associates requirements with operational capabilities, was also discussed. More detailed discussions on technical requirements for NATO applications, were held as part of the technology area presentations.

To stimulate thought on requirements for NATO applications, Lt. Gen. D. L. Cromer, US Air Force Space Systems Division, described the capabilities which are now, or soon will be, operational in military space systems. With the formation of US Space Command these capabilities have moved from the research and development community to the realm of normal military operations. The potential warfighters must now specify their needs and serve as advocates for new capabilities. This advocacy role should reflect the fact that space systems are the "first forces on the scene", potentially denying an enemy the element of surprise because their actions can be expeditiously observed. In addition, navigation support, communications, and weather monitoring are already in place. NATO forces should plan to capitalize on current and future space resources.

METEOROLOGY

A thorough description of the US Defense Meteorological Satellite Program (DMSP) was presented, with primary emphasis on its application in a tactical environment. DMSP satellites have supplied tactical meteorological data for the US armed forces for over fifteen years. The DMSP mission is to provide global visible and infrared cloud data, and other specialized meteorological, oceanographic, and solar-geophysical data in support of worldwide military operations.

Weather forecasting in the NATO environment by the US Air Force Air Weather Service was described. Specific emphasis was placed on the use of meteorological satellite data from military and civilian sources. Current generation and future tactical weather forecasting terminals were described. New equipment and forecasting techniques will significantly improve US Air Force tactical weather prediction capability.

Weather prediction techniques in the United Kingdom, over land and sea, were described in some detail. The advantages of meteorological satellite data were discussed.

Weather satellites can acquire valuable information concerning the ocean environment which can be extremely valuable for naval operations. Sea surface temperature and wave conditions can be remotely sensed from space platforms. Presentations were made about how these data could be utilized for fleet operations.

A general description was provided of US plans for a military meteorological satellite for the post-2000 time-frame. Options were discussed to meet the needs for army, navy, and air force applications in both tactical and strategic environments.

REMOTE SENSING

A thorough description was given of the French earth observation satellite, SPOT. Since 1986, SPOT-1 has been revolving around the earth in a heliosynchronous orbit at an altitude of 832 kilometers. It has returned over a million 60x60 km images with resolution as fine as 10 meters. This system is available for military and commercial applications in four specific areas: (1) acquiring image databank information for decision making; (2) generating three dimensional digital terrain models; (3) thematic mapping; and (4) intelligence gathering. The services are available on a world-wide basis.

Enhancements for the SPOT satellite were discussed. These changes could provide finer resolution, enhanced field of view, and more frequent revisit times.

A concept was explored whereby visual images from a spacecraft, such as SPOT, could be used to provide navigation and guidance to anti-surface missiles. This would require extensive processing of satellite images to provide data in a suitable format for use by missile sensors.

An idea was discussed for a wide field infrared instrument for use on a small satellite to detect ship concentrations. The instrument would use a 256 X 6 detector array scanning in a "whisk broom" pattern, and would employ a passive cryogenic cooling system for the sensor focal plane.

Aircraft flying tactical missions require maps to support their missions. Paper maps are being replaced by digital maps, using data from such sources as SPOT satellite images. A process was discussed, whereby multiple images from a SPOT spacecraft can be used to calculate three dimensional terrain models for use in future attack aircraft operations.

A simulation program was described which can be used to evaluate specifications and features in satellite observation systems. The simulation can be used to analyze both optical and synthetic aperture radar imaging systems.

SPACE BASED RADAR

The concept of a space-based wide area surveillance system was extensively explored. Complementary infrared and radar sensors were discussed, with primary emphasis on two different types of radar sensors (rotating dish and synthetic aperture). This type of surveillance capability would be of value for a variety of NATO applications.

Radar imaging from spacecraft was discussed for a maritime environment. Different types of radar instruments provide varying levels of capability for target identification.

The advantage of imagery from synthetic aperture radar satellites was discussed. This technique is specifically valuable to view those parts of Europe which have frequent cloud cover.

Command and control for a space-based radar performing the wide area surveillance mission can prove to be a major development activity. Tasking and controlling the spacecraft, and processing and distributing data to appropriate commanders, were described as formidable challenges.

NAVIGATION

An overview presentation was made on the NAVSTAR Global Positioning System (GPS). The NAVSTAR satellite constellation provides radio-navigation signals that can be used for continuous, all-weather global positioning (with associated velocity and time information) by all users equipped with suitable GPS receiver sets.

An extensive discussion was given on the future applications of GPS to conventional weapons by Brig. Gen. S. M. McElroy, US Air Force Munitions Systems Division. Applications were cited in testing and training, terrain-following air attacks, integration with inertial navigation systems, and weapons delivery of smart munitions.

GPS system vulnerability was discussed in a broad context. Specific countermeasures were described which improve GPS navigation accuracy in a hostile environment, indicating the operational effectiveness of the system in a tactical environment. Of particular interest to NATO, was a presentation on the tactical applications of GPS in the arctic region.

An interesting development and test application of GPS was discussed, in which GPS radio-navigation signals, receiver equipment, and special data processing were used to demonstrate hover stability of a helicopter to extreme accuracy.

An extensive system of satellites and associated receiver equipment, like the NAVSTAR GPS system, can be considered to perform supplementary missions. In particular, a concept was presented that could make use of NAVSTAR satellites and receivers as a supplementary information dissemination system.

COMMUNICATIONS

A presentation was made on the US Defense Satellite Communications System (DSCS) and associated ground terminals. Though originally designed for long haul point-to-point communications, DSCS has now been adapted for use in tactical applications in addition to its original mission. It can provide efficient cross-service communications between army, navy, and air force elements.

An extensive review and future projection was given on the use of UHF communications by the US Navy. The limitations and advantages of UHF communications were highlighted in the discussions.

A very general description of the US MILSTAR system was provided. The objective of this EHF system, to operate throughout a full range of conflict, was outlined.

The US post-2000 Military Satellite Communications Architecture was described. Options are being considered for robustness and survivability. Small satellites are being considered to supplement larger geosynchronous satellites for quick service restoration and localized surge requirements.

A simulation system was described which will be used to evaluate options for a tactical communications satellite system. The satellite would employ a telephone-like switching system, employ narrow and earth coverage beams, and handle low and high priority calls.

A presentation was made on a UK perspective on tactical satellite communications. An extensive array of terminals were described, which communicate with Skynet IV. UHF and SHF are production capabilities, while EHF is being used experimentally. EHF could yield a significant improvement in survivability.

A study was presented in which small, lightweight EHF satellites are being considered to supplement larger more-conventional EHF satellites. Another study dealt with alternative orbits for EHF satellite communications for NATO, employing non-geostationary orbits favoring northern coverage.

Plans for future NATO communications satellites were presented. NATO IV will be used until 2000 with some expansion of robust communications in addition to peacetime trunk communications. Post-2000 considerations will include EHF for more robust links and polar orbiting spacecraft for better coverage in the North.

During discussions at the conference, it was observed that British and Canadian efforts on EHF communications for NATO are not coordinated with US activities on MILSTAR and other US communications satellites utilizing EHF. In fact, current US security barriers specifically restrict information exchange, which inevitably will lead to communications incompatibility.

SUMMARY SESSION

Discussions were held at the end of the symposium to review:

1. NATO requirements for tactical space systems
2. Short-falls in existing equipment to satisfy requirements
3. The way ahead

The discussion highlighted the fact that NATO does not have an organization to specifically address its requirements for space systems. However, a military user organization, like NATO, must formulate and state its requirements before appropriate systems can be developed to satisfy those requirements.

The following observations were made:

NATO adversaries should be aware that US/NATO space resources are always on the scene, prepared to support all necessary NATO defense activities.

All NATO nations should have access to US Military Meteorological data, with NATO developing exploitation methods.

SPOT satellite data has potential application in the NATO environment in tactical situations.

Tactical users must be convinced that NAVSTAR GPS navigation capability will be usable under wartime conditions.

EVALUATION

The symposium was organized to review the tactical applications of space systems in the NATO environment The intent was to present requirements, followed by an assessment of how well those requirements are being satisfied. Finally, future development plans were described and assessed in relation to NATO requirements.

The information presented in the requirements session was quite satisfactory; however, there was a significant gap due to the cancellation of a paper on NATO Land/Air Operational Requirements. Requirements for naval activities and communications were well covered, but there was no discussion of requirements that space systems could satisfy in a Land/Air engagement in Europe.

The technical sessions on meteorology, remote sensing, space-based radar, navigation, and communications were presented very well. The papers varied in technical content from general overviews to details of interest to only specialists in a particular field. Since attendees at a broad-based symposium such as this are unlikely to be specialists in more than one of the technical fields, the very detailed technical presentations could not be fully appreciated by a major portion of the audience.

The technical sessions dealt with current capabilities, new developments, and future plans. In general, they provided an excellent perspective in each of the technical fields.

The summary session was not very effective. The panel and the audience were clearly fatigued at the end of the last day of the symposium. The concept for such a summary sessions is excellent, but to be effective, it would have been necessary to devote the entire afternoon session of the last day to this function.

As an overall assessment, the symposium was excellent. The meeting was well organized, smoothly run, and enthusiastically appreciated by participants. The US Air Force Academy served as an excellent host facility.

RECOMMENDATIONS

1. Since this symposium was a valuable review of how NATO requirements can be met with space technology assets, a regular series of symposia on this topic should be considered (possibly at three year intervals).

2. At the symposium, it was noted that neither NATO nor AGARD have entities specifically addressing Space. Consideration should be given to organize such entities to concentrate on this increasingly important domain.

3. Attempts should be made to encourage the exchange of information on EHF satellite communication standards so that US and NATO communications satellites and ground terminals could exhibit some level of compatibility and interoperability for EHF operations.

KEYNOTE ADDRESS

by

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It's a pleasure to be here with you this morning to kick off your Symposium on the tactical applications of space. I can't think of anything I'd rather address. Thanks for the invite, Ed (Lassiter). NATO's Advisory Group for Aerospace Research and Development (AGARD) is well known for getting a broad spectrum of knowledgeable people together to tackle critical Alliance issues. Keep up the good work. You're making a difference!

This week's Symposium is no exception. I believe it's a significant step in the right direction, and one that could yield extremely important benefits, not only for the Western Alliance, but also for the Western Space Community as a whole.

Note that I said "could" yield extremely important benefits, and NOT "should" or "will" yield them. That large "high ground" we call space — and its military subsets we refer to as space leadership, space doctrine, and space requirements — has been the focus of countless well-intended symposia, conferences, special studies, and high-level meetings. While some would argue that the Western Space Community is making remarkable progress in deploying space systems designed to support the tactical warfighter, I, on the other hand, believe we've been long on discussion and short on action. My objective to you this morning is to *plant the seed* for fundamental change in NATO regarding the way the Alliance perceives tactical support from space.

As many of you know, NATO does not adequately consider space systems in seeking the most affordable and effective solution to its military needs and deficiencies. This may stem from a perception by some that space systems are too expensive and only appropriate for worldwide strategic missions, rather than conventional Alliance warfighting missions. As NATO prepares to enter the 21st century, I believe it must address military space requirements far beyond its current complement of NATO III and programmed NATO IV communications satellites.

Accordingly, it's in NATO's interest to increase focus on space systems as potential answers to operational needs *now*. Although there are over 250 armament and standardization type committees in NATO, none are dedicated to space system requirements. In fact, NATO's Navstar cooperation falls under a communication-oriented committee. Furthermore, nearly all far-reaching NATO studies of future requirements and capabilites are failing to adequately consider space systems.

The multivolume NATO Maritime Operations 2005 Study and the latest Defense Research Group's studies on Follow-On-Force-Attack (FOFA) surveillance and target acquisition are two recent examples. AGARD itself, in its application study on Tactical Ballistic Missile Defense (AGARD-25), essentially overlooked early warning from space assets, while concentrating on providing such information from vulnerable ground-based radars. While realizing national releasability problems exist, *the time has come* to face up to the fact that space systems are viable options for meeting the Alliance's military needs.

From an operational viewpoint, tomorrow's most pressing requirement is to make space systems more available and "user friendly" to battlefield commanders. NATO military forces, in all sectors, use space systems to perform their day-to-day and potential warfighting missions. However, many NATO commanders are unaware of how extensively they rely on space systems for support. They mistakenly view space as being "transparent", even though surveillance, communications, and navigation information derived from space systems are vital to NATO missions. Such support, from both US and NATO spaced systems, provides the tactical advantage needed for success on the modern battlefield.

Many NATO commanders also believe that space systems cannot be depended on in wartime and thus have little warfighting value. This lack of confidence is generated by a lack of understanding of space capabilities, as well as an apparent lack of awareness of the mechanisms currently in place to obtain or seek additional space support. War games and exercises, on both sides of the Atlantic, continue to highlight an overall lack of awareness with regard to how space systems can improve combat effectiveness and reduce battlefield attrition. Let's work together to change this.

Tomorrow's space operations will be pervasive in combat. While today's operations provide extensive support, tomorrow's must provide even more. We must show NATO commanders that they can depend on space as they now depend on tactical airlift, resupply by maritime forces, and artillery support. They have every right to expect this. Space operations tomorrow must be characterized by surveillance, communications, and navigation support to NATO forces that are more timely and readily available when they are needed most. One concept that we believe may have merit is an initiative called Tacsat or tactical satellite. The concept would be rooted within an inventory of ready-to-launch boosters and an interchangeable set of satellite mission packages tailored to provide *direct tactical* support to warfighters. While there is a range of analysis yet to be accomplished, we are hopeful that it will prove to be both cost effective and operationally feasible.

Let me transition here to where I believe we're headed in the tactical space arena. The proper vision for tactical use of space is one in which warfighting criteria, military doctrine, and an operations mind-set are constantly applied to the development and operation of space systems. The Soviets have had this mind-set for some time. Their Radar Ocean and ELINT Ocean Reconnaissance Satellites, RORSATs and EORSATs, and other Soviet reconnaissance satellites have flown above harm's way for years to locate NATO forces. NATO exercises are the training aids that keep these systems combat ready.

While Glasnost may be having an impact in other arenas, it's apparent to me that the Kremlin has made no effort to change its overall military space doctrine. By the mid-1990s, they'll have approximately 200 satellites in orbit, 150 of which will have purely military missions. The Soviets' large family of launch vehicles provides a wartime surge capability with which to launch military reconnaissance satellites, ASAT weapons, and other payloads with direct combat applications. It's apparent to me that we can learn a lot about the tactical applications of space by studying Soviet space doctrine, which has been stressing it for years.

Let me shift gears here and begin discussing how to make space less transparent to our warfighters. I've noticed that your Symposium's brochure specifically highlights *two* programs: one beginning its existence, the Global Positioning System (GPS), and one still in the acquisition arena, Space-Based Wide-Area Surveillance system (SBWAS). Tactical applications from space surely can and should be derived from such programs. Let me tell you why!

Navigation support from space is being revolutionized in a manner that in time will provide a true tactical advantage to Western land, sea, and air forces. The Navstar Global Positioning System's ongoing deployment to a constellation of 21 operational satellites will ultimately result in position accuracies to 16 meters or less. Tactical applications will include pinpointing troop assembly points and objectives, more accurate artillery and air strikes, enhanced station keeping at sea, better coordinated search and rescue missions, improved elecronic warfare targeting, and accurate all-weather resupply operations — to name just a few. The Soviets are testing their own version of GPS, GLONASS, which will provide Eastern Bloc forces position accuracies similar to GPS. Unlike our GPS, however, the GLONASS will be used *exclusively* by Warsaw Pact military forces.

Clearly, Navstar GPS will make smart weapons smarter and enable the type of precisely timed and coordinated operations that can wreak havoc on a less prepared foe. It's already saved lives. Western naval and commercial vessels transiting the Straits of Hormuz after Iranian mine laying operations utilized GPS data that pinpointed mine locations, thus expediting mine removal. Since NATO has a Navstar GPS program, many of our countries are already fully cognizant of the tactical applications of Navstar GPS and are incorporating it into your military force structure. Navstar GPS is an example of how to do things right on both sides of the Atlantic. Let's continue working together to ensure that *full* deployments occur.

In the surveillance arena, I'm convinced that a space-based wide area surveillance system, possibly a radar, would provide tactical commanders in the West with long-range surveillance, tracking and targeting information that would revolutionize Western tactics and deny the enemy the element of surprise. A recent US Navy and Air Force cooperative study on a space-based wide-area surveillance system has resulted in a ground swell of support from many US and European warfighters; the program faces a major Pentagon acquisition hurdle in less than two months when the dense acquisition board meets to decide the concept's future.

My advocacy for space-based surveillance is derived from the tactical applications it offers to warfighters. Now, whichever of the promising technologies is finally selected, the bottom line is clear: tactical military requirements must be met. A space-based wide-area surveillance constellation would have to provide continuous global, near real-time, all-weather coverage. It should be able to detect and track fighter-sized aircraft and detect and classify ships at sea. The capability to continuously track atmospheric threats from their points of origin would have an incredible impact on any future air defense operation and could go a long way toward solving NATO's air defense identification problem, which I understand is an area that NATO military authorities have asked AGARD for help in. By helping to dissipate the "fog of war", a space-based system would allow warfighters to see beyond the Forward Line Of Troops (FLOT) and employ their forces at the right place, at the right time, and in the right mix.

Perhaps most importantly, however, a tactically dedicated space-based system would provide its information *directly* to warfighters, thereby eliminating delays inherent when intermediate-ground stations process information. Could such a capability be a cost effective means to significantly enhance NATO's air defense and Follow On Forces Attack capabilities? I believe it could.

Quite simply, I believe the tactical advantages a space-based wide area surveillance system would offer warfighters, range from providing the ability to "see" beyond the FLOT, to allowing for the optimum posturing of tactical forces. Such a system would be difficult for the Soviets to defeat, and its continuous coverage could allow target characterization, threat axis identification, and assured detection of atmospheric or naval attack. Additionally, such surveillance would not depend on a cooperative target with respect to electronic emissions.

Let me conclude my remarks to you this morning with the challenge I brought up earlier. This AGARD Symposium on the tactical applications of space should result in a commitment to pursue action vice "discussion". Without action, the military balance in space will continue shifting, perhaps irrevocably, toward the Eastern Bloc. An AGARD recommendation that the Alliance needs a *formal* organizational structure to define space requirements that support tactical operations would be a major step in the right direction. Perhaps AGARD could become involved with a NATO tactical satellite system, probably small and relatively inexpensive, that would enhance NATO's warfighting capability. My staff has submitted such a study proposal, and I understand it has been forwarded to NATO's Military Committee for AGARD consideration.

Ed (Lassiter), if you and your colleagues agree that space systems can and should do a better job of supporting NATO forces, I'm confident that you will set into motion that chain of events that could, and I believe must, result in a more tactically-oriented Western space force structure.

Thank you and God bless!

HOW NATO TRANSLATES MILITARY REQUIREMENTS INTO OPERATIONAL CAPABILITIES

by

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The intention of this presentation is to give you a military perspective of NATO armaments planning, and its aims and expectations, with a view to providing you with some information on which you might base your decisions. In order to be able to better understand where we are now and where this may lead in the future, I have structured my presentation around the following main items:

- The International Military Staff in the NATO organization
- The problem
- Armaments co-operation in NATO
- The armaments planning system
- The future

Let's start with the first point.

The International Military Staff is the staff of the NATO Military Committee and therefore co-ordinates nations' military views on the major NATO commanders' requirements.

Figure 1 shows the structure of NATO headquarters and the relationship of the Military Committee within this structure. On the right you can see the military side, those responsible for determining operational requirements, while on the left is the civilian structure and of course it is their responsibility to provide the means to develop solutions to fill these requirements. AGARD is, as you are aware, an agency directly subordinate to the Military Committee. On the left, you will note the several civil committees, one of which is the Conference of National Armaments Directors (CNAD), whose role is to improve armaments co-operation between the nations of the Alliance.

CIVIL AND MILITARY STRUCTURE

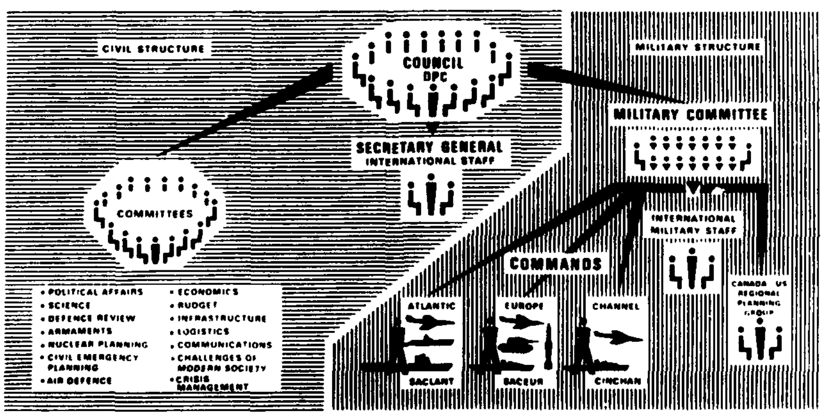

Figure 1

Let us Look at the Problem

There have been many attempts in NATO to improve armaments co-operation between the nations of the Alliance. These endeavours however, have not led as yet to a truly collective armaments planning system. The main reason for this is that defence procurement takes place entirely nationally and nations tend to offer different approaches to this field, as for example:

- Different threat perceptions and requirements
- Different defence industry interests
- Governmental constraints on technology transfer
- Competition and protection of employment needs

Moreover, nations want to keep their national sovereignty, and therefore they do not accept a supranational organization, which might attempt to influence their national decision making process.

As a result it can be argued that nations have not been making the best use of their resources. However, because of economic and budgetary constraints, nations have come to the realization that improved resources allocation along with countering the trends towards over-sophistication and the related affordability problems, constitutes the decisive rationale for enhanced armaments co-operation.

Now let me address the armaments co-operation in NATO. In this field the pertinent question is what has been done to improve NATO's defence posture, in particular through enhanced armaments co-operation? Well, in 1966, the Conference of National Armaments Directors, or CNAD, was established with the general aim of fostering NATO co-operative development of armaments. Mainly because of budgetary constraints and spiralling costs of technology, during the last seveal years, a number of initiatives have been taken to improve the armaments co-operation within NATO. Very fortunately the issuing of the Conceptual Military Framework or CMF in 1985 with its MNC's supporting document, laid the fundamental basis for long term planning.

The starting point for armaments activities remains the military requirements, now being defined more precisely for the longer term. A new initiative within the CNAD — the Conventional Armaments Planning System (CAPS) — is meant to be a tool to assist the long term research, development and procurement planning of equipment in the broadest sense, beginning at a very early stage, preferably even before specific research and development efforts have started. The main difference between CAPS and previous armaments cooperation efforts is that CAPS will, to some extent, take account of the long standing procedure of NATO force planning, whereas the previous armaments co-operation efforts did not.

What are the Tasks of CAPS?

The principal tasks of CAPS are:

- To provide guidance to the CNAD and orientation to the nations on how the military needs of the Alliance can best be met by national armaments programmes, individually and collectively.
- To help elaborate armaments co-operation opportunities and priorities for CNAD.

This will be set out in a so-called Conventional Armaments Plan, to be agreed by nations.

How will it Work?

The armaments plan will be based on so-called "National Armaments Goals" which nations will report to NATO, using armaments planning questionnaires. Countries participating in the integrated military structure of the Alliance are encouraged to base their National Armaments Goals on agreed (armaments related) force goals addressing long term requirements. Countries not participating in the integrated military structure of the Alliance will base their National Armaments Goals on national military requirements. Emphasis will be placed on long term goals. At the end of a long, iterative and analysing process, a draft Conventional Armaments Plan (CAP) describing commonalities in requirements, time frames and possible opportunities for collaboration will be devised. This plan will be submitted to the CNAD for their approval and the plan, together with the resultant recommendations, will be forwarded to the Council for their endorsement. An important feature of CAPS is to monitor and report the implications of the endorsed recommendations, very much similar to a feedback system. The resultant guidance will be forwarded to the CNAD main groups for implementation. Other NATO bodies (like AGARD for example), nations and industry will be informed about the output of the review so that it can be most effectively used in their work, fostering the co-operative development of equipment. The system will restart every two years with a fresh up-dated set of national armaments goals. Figure 2 diagnoses the process.

Future

Well, now this is what is happening today, but what about the future? The challenges of the 1990s are broad and difficult to assess: broad because of the many challenges which exist — arms control, changing of the threat perception, continued rapid technological changes, and the need to satisfy known and projected deficiences in NATO capabilities to name a few; difficult because of the uncertainty we face in the eventual outcome of these inter-related challenges. It is difficult to predict, for example, the outcome of a conventional arms control agreement. Nevertheless, we must plan for the future in the light of these uncertainties. So let me address what is probably the biggest challenge to the Alliance in the 1990s — arms control.

PROCESS

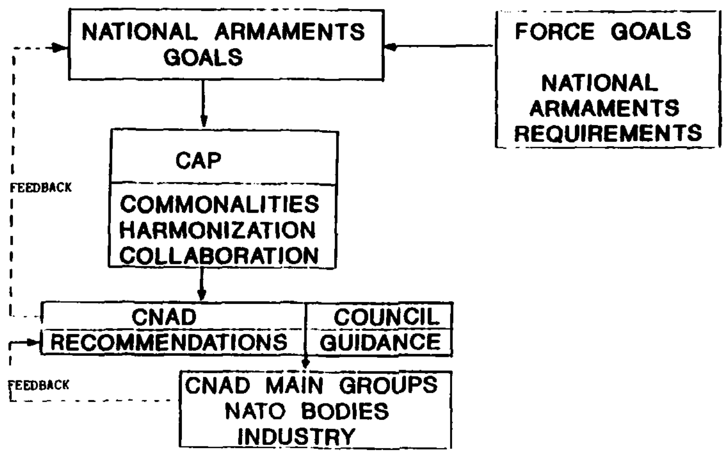

Figure 2

In any discussion of arms control, it is important to remember that NATO's strategy aims at maintaining the security of the Alliance at minimal cost and minimal risk through a defensive deterrent capability (forward defence and flexible response). What is new is the harmonization of Alliance defence planning and arms control so that Alliance security is maintained, although eventually at a minimum level of forces.

It was only this past spring that dramatic conventional arms control proposals where made by both East and West. We can expect significant reductions of numbers of tanks, APC, artillery, aircraft and helicopter holdings on both sides as a result of the arms control negotiations. This means that the remaining force structure must be more capable and versatile while at the same time eliminating known deficiencies that currently exist. In addition, there will no doubt be new requirements for surveillance capabilities of aerospace systems to monitor arms control agreements within the framework of an intrusive verification system. At the same time we must remedy deficiencies in our ability to attack follow-on forces — deficiencies in reconnaissance, surveillance, and target acqusition, communication, command and control, and weapons. This means that NATO will continue to rely on qualitatively superior weapon systems, as we have in the past. It is technology which has provided our qualitative edge in the past; it is technology which must provide our qualitative advantage in the future. I think we can say then, that technology is and will remain an essential element of our deterrence.

So the question is, how do we provide forces which afford the capabilities needed after an arms control agreement, while at the same time satisfying known deficiencies in what will be an even smaller force structure?

Such force planning perspectives in turn present technological challenges. Technology will be called upon to provide the means to satisfy the new — as well as the existing — military requirements in an arms control environment. Furthermore, there is the real possibility that the situation may change more rapidly than in the past. This will require an even more responsive defence planning and technology support process. This is a formidable yet crucial task which could, by the way, help us recapture some of the qualitative advantages we have lost over the past decade.

Let me also mention another and very important need, which technology must satisfy in the era before us. As the public perception of the threat changes, public support for defence spending may further constrain defence budgets. This means that, in addition to superior quality, technology must provide the means to field low cost and therefore affordable weapon systems, or, in other words, the military requirements must be expressed in such a way to avoid unnecessary oversophistication. This is a difficult yet important challenge for both the military planner and technology developer. Obviously they must work together and understand one another.

There are several challenges in the future and one of those may surely be arms control. As I have suggested this challenge could result in new requirements to which we must all be prepared to respond. The technical challenges, as I have outlined them, are:

- Continued qualitative superiority of our weapon system;
- Technical solutions for new requirements;
- Verification measures in a conventional arms control agreement;
- An even more responsive technology support process, and
- Low cost and affordable weapons.

Let me finish by saying something about the future of the NATO armaments planning procedures. The Alliance is exploring new territory; the CAPS trial has already resulted in a better common understanding on a new long term armaments strategy and the political will to implement this is growing. If the conventional armaments planning *system* is finally adopted to formulate a commonly agreed conventional armaments plan, collaborative armaments development may result in:

- Lower unit costs;
- Increased standardization; and
- A reinforced Alliance cohesion and solidarity to meet the Alliance armaments requirements.

The challenges can be handled by the proposed new CAPS which will allow the NATO force goal requirements to be better reflected in CNAD work through the national inputs to CAPS and should allow feedback into the force planning system.

This linkage will ask for both armaments and force planning communities to work more closely together. So, it is now even more important than ever that the required military capabilities, especially those for the longer term, should be formulated in an unambiguous and clear way, which is meaningful to national planners. NATO military authorities have been playing an important role throughout the process and progress is well underway. While keeping the national sovereignty untouched, the CAPS at least seeks to establish a planning relationship between Alliance military needs and priorities and the decisions of nations on research, development and production of equipment.

It will undoubtedly take a number of CAPS cycles before the system will be operating in an optimum way. Equally, there is some time to go before it is accepted as a meaningful tool and not just seen as a new kind of reporting system, causing an overload on national and international staffs which produces additional work, without obtaining results.

What will CAPS Achieve

One of the most important features of the CAPS is that it will establish a planning system which will take the force planning system, as used by the DPC nations, into account. This will further provide the CNAD with real opportunities to guide more closely the work of many of its groups and to allocate priorities for these groups. Furthermore, it provides industries with an approved reference on which they could base their long term strategies; it will also be much more easy to monitor the implementation of agreed recommendations during subsequent cycles of the CAP.

Finally, the decade ahead provides many challenges for which the co-operation development of technology will be an essential element in maintaining a credible defensive deterent. The Conventional Armaments Planning System, where fully implemented, will be responsive to this challenge.

Gentlemen, that concludes my presentation which I hope will help you in your understanding of the NATO armaments planning process, and of what the challenges of the 90s might be.

TACTICAL APPLICATIONS OF DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP) ENVIRONMENTAL DATA

by

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SUMMARY

Timely knowledge of weather conditions through the use of meteorological satellites is one of the major force multipliers for the United States and NATO countries. How the Defense Meteorological Satellite Program meets this need for timely data will be described.

The Defense Meteorological Satellite Program (DMSP) has for over fifteen years supplied tactical meteorological data to Air Force, Navy, Marine, and Army units. This fully operational system consists of at least two satellites, a command and control system, a strategic data processing system, and tactical processing systems. Specifically, the DMSP mission is to provide global visible and infrared cloud data and other specialized meteorological, oceanographic, and solar-geophysical data in support of worldwide DOD operations. Environmental data is acquired by various sensors aboard the DMSP satellites in two modes. In the first mode, the data are stored on board for relay to the strategic centers at the Air Force Global Weather Central and at the Navy Fleet Numerical Oceanography Center. Here, forecasters supporting a variety of tactical missions use these data to provide point and area forecasts to the military commanders. The second mode is the real-time direct broadcast of the environmental data to the land and sea-based tactical processing systems. All the environmental data are combined into one data stream and are broadcast in an encrypted mode on S band frequencies.

In order to support tactical users with the appropriate data, two dedicated ground stations located at Loring Air Force Base, Maine, and Fairchild Air Force Base, Washington, transmit commands and receive telemetry and stored sensor data from the DMSP satellites. The focal point for command and control of the DMSP space assets is the newly constructed Fairchild Satellite Operations Center (FSOC). In addition, limited support is provided by the Air Force Satellite Control Facility (AFSCF) with its Remote Tracking Stations in Hawaii and Thule, Greenland. From these sites, the satellites are commanded to change the type of data being provided depending on the precise need of the tactical user.

The primary sensor carried on each satellite is the Operational Linescan System (OLS), which provides global cloud imagery in the visible and infrared bands. This data can be sent to the tactical user with a resolution of .6 km in one channel and 2.8 km in the other channel. This data are normally displayed in real time as the data from the sensor are taken. In the future, a variety of secondary mission sensors will be used to provide a complementary quantitative measure of the environment.

There are a number of tactical users for DMSP data. The Air Force has sixteen DMSP receiving terminals around the world which acquire the tactical weather imagery from the satellite. The satellite data are immediately received by these terminals and retransmitted over the Satellite Imagery Dissemination System to a large number of users in each tactical area. The Navy has installed terminals on their major carriers and are planning to install an additional eighty shipboard and shore terminals. Also, the Marines have acquired Mark IV tactical van systems for direct support of their operations. All of these different DMSP receiving terminals provide timely night and day visible and infrared images of cloud cover to give the individual commanders accurate weather knowledge of their combat area. But beyond just the cloud cover information, DMSP and the Navy are expanding the capability of the terminals to exploit the excellent environmental data provided by DMSP's mission sensors. These changes will greatly enhance the ability of Air Weather Service to forecast critical weather conditions. Examples are given of DMSP's tactical data and their use in support of military operations under these conditions.

INTRODUCTION

Weather has contributed to the success or failure of military operations since battles have been waged. Weather in the form of storms will affect nearly all Army, Navy, or Air Force missions. With today's advanced technology, everyday weather phenomena (fog, clouds, smoke, ground temperature) will affect weapon selection. The success of sophisticated weapons systems such as infrared or laser-guided missiles are now compromised by inaccurate cloud information. Ground weather will influence operations while space weather, something earlier military commanders never had to worry about, will affect ground to ground radio communications, orbiting intelligence and communication satellites. Since, modification of the weather has not been practical, the military commander has to rely on his meteorologists to provide the most accurate forecasts available. The primary mission of the Defense Meteorological Satellite Program (DMSP) is to provide to the meteorologist and space forecasters, and thus to field commanders, timely and accurate meteorological and space weather information. Because of the advanced technology on the DMSP spacecraft, the ability of the commanders to factor weather into planning is enhanced so that forces can be adjusted to exploit areas where the weather is favorable and to postpone or modify missions where weather is likely to diminish success. Clearly the availability of cloud imagery allowed the launching of successful strike missions in Vietnam which otherwise would have been precarious due to lack of weather knowledge.

As technology has expanded our capabilities, it has also expanded the region of battle. The term battlefield has probably become obsolete for many mission requirements. Aircraft can be called upon which are stationed thousands of miles away from the conflict. Weather at refuelling sites also has to be taken into account. Thus providing weather information just over a local area is not meeting the tactical mission. In today's military, the tactical mission can nearly encompass the globe. The rapid flow of personnel and machines can be affected by airports that are closed due to dense fog and low stratus. The ability to forecast when an airport can reopen allows the flow to begin several hours earlier. Thus the Defense Meteorological Satellite Program has to provide the world wide weather data even to support a local operation.

This paper describes how this world wide weather data is collected, transmitted to the users, and processed into high quality imagery and environmental data. This data greatly enhances the ability of today's meteorologist to forecast not only the ground weather but the space weather as well.

SYSTEM OVERVIEW

As shown in Figure 1, the Defense Meteorological Satellite Program is composed of four basic segments: (1) a space segment, normally composed of two spacecraft and a sensor complement which can vary, (2) a command and control segment under the operation of Air Force Space Command, (3) a strategic user segment operated by Air Weather Service, and (4) a tactical user segment currently operated by the Air Force Communications Command. Outside of DMSP the Navy has developed additional terminals for processing DMSP data on-board ships.

The current satellites are placed into 833 kilometer sun synchronous polar orbits by Atlas E launch vehicles from Vandenberg AFB. Mission plans are generated at the Multipurpose Satellite Operations Center (MPSOC) located at Offutt AFB, Nebraska and spacecraft commanding can be done from either the MPSOC or the Fairchild Satellite Operations Center at Fairchild AFB, Washington. Earth receiving terminals are also located at Fairchild AFB, Washington, Loring AFB, Maine, Thule, Greenland, and the AF Remote Tracking Station, Hawaii. The world wide space and meteorological data which have been stored on board the satellite are played back through the receiving terminals and transmitted over commercial communication satellites to the centralized processing facilities at the Air Force Global Weather Central (AFGWC) at Offutt AFB, Nebraska, and the Navy's Fleet Numerical Oceanography Center (FNOC) in Monterey, California. Meanwhile, meteorological data from the direct real-time readout are transmitted from the spacecraft to Air Force, Marines, and Navy Ground Terminals located around the world.

SPACE SEGMENT

Although the tactical user doesn't care that the spacecraft, produced by General Electric's Astro-Space Division, is a three-axis stabilized vehicle with an on-orbit weight of 725 kilograms and 3.5 meters in length, nor that it has a 30-month mean mission duration, the user does care that the meteorological data will be available when needed. The spacecraft and the primary sensor are therefore required to have as much redundancy (nearly 100%) as possible. This demands that backup spacecraft on the ground must be available for launch within 90 days of a call-up. Our recent orbital history shows that the spacecraft is very reliable. Although taken out of active service, the F-6 spacecraft has been on orbit for over seven years with full redundancy still available.

Sensors

The primary data that the tactical user requires are day and night cloud imagery. Of critical importance to the military user is that the resolution of the imagery be uniform. As one cannot predict when or where a crisis will evolve, it is necessary that a military meteorological satellite system provides uniform quality over the entire globe. One of our main requirements on the primary data is that the resolution be uniform over the entire swath below the spacecraft. The primary sensor, the Operational Linescan System (OLS) built by Westinghouse Electric Corporation, achieves this nearly constant resolution by using a sinusoidal scan which compensates for earth curvature and by varying the effective detector size across the track. This instrument consists of a f/1.0 eight inch telescope oscillating back and forth at six times a second.

The uniform aspect of the imagery also applies to the scene illumination. Not only is the area of the tactical mission not known, the time of the mission is not known. With current technology, night time tactical missions are commonplace. We achieve the day/night capability in two ways. First, we use a thermal infrared channel in the 10 to 13 micrometer band which is unaffected by solar illumination. This band detects medium to high clouds as they have low enough temperatures that they contrast well with the background water and land. The image is naturally uniform because the solar reflectance is very low. Second, a visible band from 0.4 to 1.1 micrometers is used. As the solar and lunar illumination varies over a scene, the sensor is designed to have a dynamic range of ten million to one. With a complex gain control algorithm in the OLS, even the day/night terminator crossing is almost invisible in the output data.

The tactical user naturally wants the image to have the highest resolution possible. Meteorologists want to see if fog, smoke, small cirrus, or snow is present near the operational area. The better the areal resolution, the easier the distinction of small ground features that allow the user to deduce the presence of such weather phenomena that could affect the mission. The sensor has the capability of 0.6 kilometer world wide resolution. It would be preferable to always relay all the finest resolution to the user, but the cost of the communication and storage technology in the 1970's, when the instrument was designed, prevented it in our current system. A compromise was made to selectively store areas of high resolution (called "fine" data) and record world wide only "smooth" data of a much coarser areal resolution of 2.8 kilometers. Thus tactical use of DMSP data required efficient mission planning in the command and control segment. With mission planning, up to a quarter orbit of fine data over the tactical area can be recorded to be transmitted to the weather central. The real time tactical user also is limited to receiving only one channel at high resolution. Requirements for channel selection to the remote tactical user is also performed during mission planning.

It became apparent that cloud imagery itself was not enough to support the tactical user. The Army is vitally concerned about moisture content of the soil. The Navy is concerned about ocean winds and resulting waves. Just recognizing the clouds on the imagery was not enough to deduce the amount of rain or snow falling. Thus, more sensors were added to DMSP.

The latest sensor is the Microwave Imager, designed and built by Hughes Aircraft Corporation in El Segundo, California. Figure 2 shows its capability to detect rain bands in tropical cyclones. The basic requirements of the tactical user for uniform quality in terms of resolution is accomplished by using a conically scanned instrument with a 52 degree incident angle to the earth's surface. Since microwave radiation is polarized by water surfaces, a constant incident angle is required to give data uniformity. A cross track sensor similar to the Operational Linescan System was not possible. The microwave imager has a nominal resolution of 13 kilometers at its highest frequency of 85 GHz but degrades to 50 kilometers at its lowest frequency of 19 GHz. Since it is such a new instrument, its use is rapidly expanding. The Navy is using it to monitor ice development in the arctic regions and to measure ocean surface winds. The Air Force is using it to monitor tropical storm development. The Army will be utilizing it for soil moisture measurements.

In addition, to the somewhat qualitative imagery data, the microwave temperature sounder (SSM/T), which is built by GENCORP's Aerojet ElectroSystems in Azusa, California, provides a vertical temperature profile of the atmosphere. This data is used in numerical weather prediction models to improve the accuracy of the forecasts. Currently the SSM/T soundings supplement the conventional weather information provided by rawinsondes. Under tactical conditions, we would expect that conventional rawinsonde information would not be available over enemy territory so that the space based SSM/T soundings would be the only temperature sounding information available.

Space weather also has important implications for tactical communications. DMSP has a variety of space environmental sensors to measure the electron and ion temperatures, scintillation of the ionosphere, precipitating electron energy spectrum, and auroral oval boundaries. This data is sent to AFGWC for processing and provides a major input to their ionospheric models which are used to forecast the high frequency radio propagation through the ionosphere. These data are also important to the early warning and tracking radar network.

Attitude Determination and Control

The tactical user requirements for location knowledge requires the spacecraft to have an accurate attitude determination and control subsystem. This accuracy (0.01 degree) is achieved by three on-board orthogonal gyroscopes measuring short term variations in the spacecraft attitude. Long term variations are detected by a celestial star sensor. When compared with the on-board ephemeris data and star catalogs, small variations in spacecraft drift can be detected. The primary attitude control is provided by three reaction wheels in an active closed loop configuration, with excess momentum unloaded with magnetic coils when necessary. The data for attitude control has to be calculated by the mission planning function on the ground.

Communications and Telemetry

DMSP uses S-band links at 1.024 Mbps for the tactical real time transmissions, and 2.66 Mbps for the playback of the world-wide meteorological data to the ground centrals. The transmitters are 5 watt solid state units with a crossed dipole directive antennas mounted on the earth facing side. The antennas are designed to increase the gain of the transmission when the satellite is farther away from the tactical receiving site to provide a fairly constant signal level as the satellite passes from horizon to horizon. The satellite also has a separate omnidirectional antenna to pass the spacecraft health telemetry to the ground receiving stations.

Spacecraft commanding is done at L-band at a 2 Kbs rate with an omnidirectional antenna. The spacecraft computer handles commanding for attitude control while commands for the tactical data control are handled by the OLS.

Command and Control

Two central processing units are used, each having 28 K read/write memories. Telemetry data is monitored from the various spacecraft components (batteries, solar array, inertial guidance unit, sun sensor) for possible failures. The onboard software automatically switches to redundant units upon a detection of a fault. In addition, the on-board software monitors power consumption and will, if the need arises, turn off various components to conserve power.

The on-board software has recently been expanded to incorporate a satellite autonomy mode. This allows the satellite to operate without ground commands for up to 60 days and still provide imagery data to the direct readout tactical users.

COMMAND AND CONTROL SEGMENT

Without the command and control segment, the tactical user would not have the accurate mission data that is required. As stated earlier, the high resolution data selection requires ground commanding and the accurate spacecraft pointing requires constant ground updates. An extensive world wide system has been established to provide the necessary communication links. Four earth terminal locations are available for satellite readout, while telemetry and command backup are provided by the Air Force Satellite Control Facility's worldwide Remote Tracking Stations. All of these resources are presently connected by terrestrial or satellite links.

Multipurpose Satellite Operations Center

The Multipurpose Satellite Operations Center (MPSOC) at Omaha is the primary mission planning facility. In addition, it has a backup role in monitoring the spacecraft telemetry which has been taken over by the Fairchild Satellite Operations Center (FSOC).

The tactical unit's requirements for mission coverage are combined with engineering requests, satellite status information, power constraints, and other operational limitations such as conflict with another spacecraft's readout, to create the command files to be sent to the satellite. The necessary spacecraft commands, ephemeris, and star catalog data are then uploaded to the spacecraft.

During a satellite pass, the spacecraft's real-time telemetry is monitored for any abnormal events which may have happened during the orbit. The real-time processing system at the MPSOC monitors all the telemetry automatically for out-of-limit parameters which are then flagged to the operator. Once the satellite contact is over, the stored telemetry from the spacecraft is processed and merged with the real time telemetry to give a complete picture of the spacecraft's state of health.

Communication Links

The MPSOC communicates with the four earth terminals over commercial communication satellites. At each of the four sites, the meteorological and real time telemetry data are multiplexed together with site status data and a digital voice channel into a single 3.072 Mbps data stream. The channels from the three sites are uplinked to the communication satellite and relayed to terminals at AFGWC and FNOC. The data are demultiplexed at each receiving site with the meteorological data going to the weather centrals and the real time telemetry data and stored telemetry sent to MPSOC.

The primary link from MPSOC to the sites is a single time division multiplexed channel that contains digital voice and command and control data at 230.4 kbps. The command data is converted from a serial to ternary form as required by the spacecraft.

In addition, backup communications for telemetry alone is provided over terrestrial land-lines. Also, land-lines are used to route data to the spacecraft factory at GE and to Vandenberg AFB for launch and test support.

STRATEGIC USER SEGMENT

Although strategic processing is done at AFGWC and FNOC, almost all tactical missions are supported by special task teams. These special task teams rely on the many data bases built by normal operations, but supplemented by special runs of DMSP data (and NOAA if available). These teams use a combination of the conventional data (rawinsonde, radar, aircraft, station observations, ship reports, etc.) as well as the satellite data, to build an accurate representation of the weather over the tactical. The meteorologist uses the DMSP data in the form of transparencies which can be enhanced to bring out features which are important to the tactical operations, or can display the DMSP data on the Satellite Data Handling System in softcopy.

While the special team forecaster is analyzing the cloud imagery, the information from the OLS and other mission sensors are being fed into the large numerical weather prediction models which are run on a CRAY XMP computer. The temperature and future humidity (in the future) soundings fill in the various data void regions, improving the numerical forecasts. The output of the models predict the winds and cloud coverage that affect the local commander's strategy. The final cloud product is a three dimensional analysis of the predicted cloud conditions at a 40 kilometer resolution. This model output is sent back to the special task teams who compare the computer predictions with the conditions that they have just observed from the satellite information. They finalize the forecast and send it out to the tactical user.

TACTICAL SEGMENT

The tactical segment consists of 12 fixed sites and four mobile (MARK IV) terminals for the Air Force. In addition, the Navy plans to have twelve MARK IV's for the Marines. Outside of DMSP, the Navy is installing on all its aircraft carriers the SMQ-10 and SMQ-11 systems which receive the real time satellite transmissions from DMSP and NOAA satellites.

The Mark IV, which is built by Harris Corporation, Melbourne, Florida, is a compact reliable unit consisting of a six meter van and mobile generator unit as shown in Figure 3. Both units can be shipped on a C-130 or C-141 aircraft anywhere in the world. A 3-meter parabolic antenna is packed within the van and when deployed allows the operator to track the DMSP and NOAA satellites. Inside the van is a work area for the communications operator and Air Weather Service user. Although a softcopy display is available for quick look, the primary data is placed on a high resolution hardcopy unit which uses dry silver film. This data can then be immediately taken to the field commander to brief the latest weather conditions. Alternatively, the user in the van has the ability to transmit the data over tactical image dissemination systems to a maximum of four users, or broadcast the imagery over the satellite image dissemination system, a high quality fax device.

The Mark IV is designed to be collocated with theater commanders. They are deployed to Europe, Alaska, Far East, Central America, United Kingdom, and the CONUS.

For support of the tactical mission, the Mark IV also provides the user with the ability to enhance the imagery, to enlarge specific areas, and to place a latitude-longitude grid on the imagery. The area coverage of the Mark IV is about 4000 kilometers from its location, with a normal mode of producing images which are about 8000 km long by 3000 km wide. The full coverage is provided by monitoring passes on both sides of the central pass.

Enhancements to the Mark IV are being developed by Lockheed, Austin which will add the processing of the other DMSP sensors at the tactical sites. Advanced display techniques are being developed so that the tactical user can fully exploit the DMSP data.

CONCLUSION

This has been a brief description of the DMSP system and how it supports the tactical operations of the Air Force, Army, and Navy units. Weather influences all tactical operations and its affect on a high technology military is all the greater.

Weather data has high perishability so that it has to be accurately measured, transmitted, and analyzed in a matter of minutes. DMSP performs this mission with high performance sensors, reliable spacecraft, and ground systems which are capable of displaying Gigabits of information in a matter of seconds to the user. It performs this mission in a manner which allows us to make maximum use of our military resources. Its continual operation in support of the US and our allies requires the dedication of several thousand men and women of contractors and Armed Services. It is indispensable in peace and imperative in war.

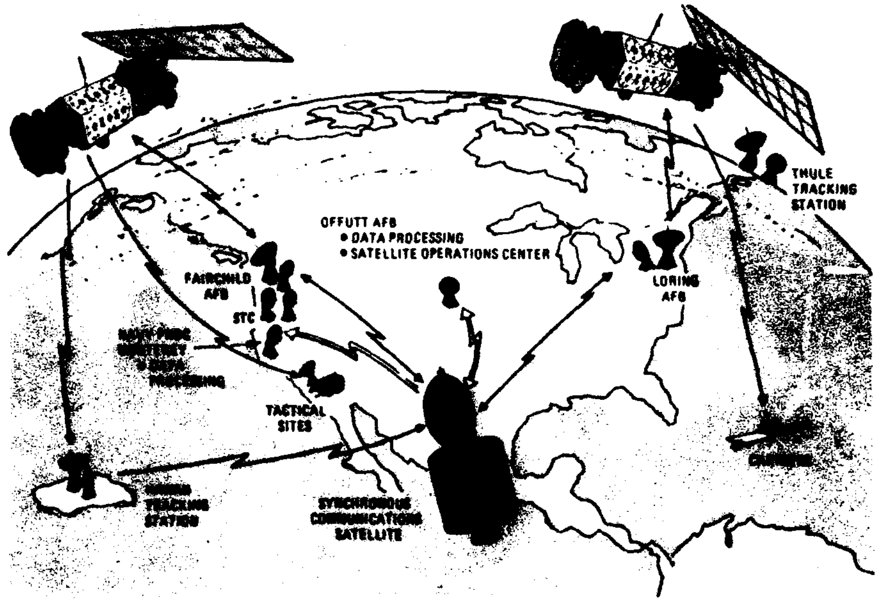
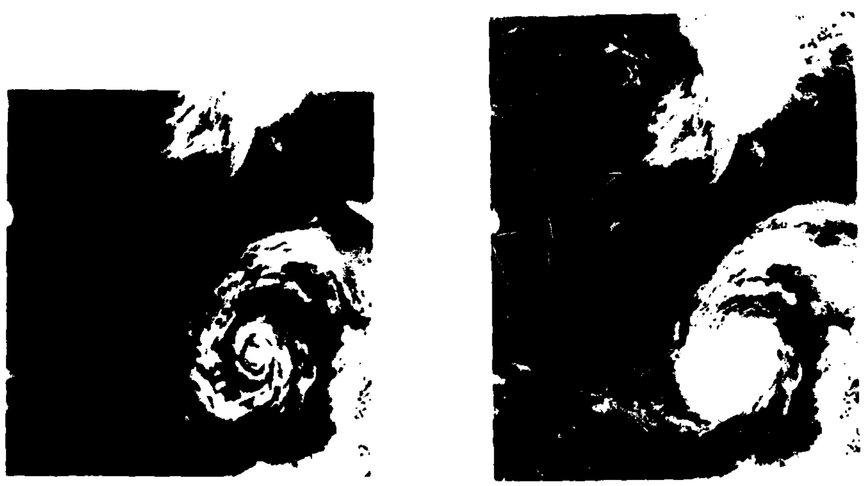


Figure 1 - An overview of the Defense Meteorological Satellite Program showing the major ground centers and the satellite communication links. The major ground receipt sites are at Fairchild AFB, Washington, Loring AFB, Maine, Thule, Greenland, and AF Remote Tracking Station, Hawaii. Data is processed at Air Force Global Weather Central, Offutt AFB, Nebraska and at Fleet Numerical Oceanography Center, Monterey, California. Telemetry processing and Mission Planning are done at Space Command's Satellite Operation Center, Offutt AFB.



(a) (b)

Figure 2 - Rain Detection for Tactical Users is provided by the Microwave Imager. This figure shows the rain bands (a) detected by the imager compared with OLS image (b) of the same scene.

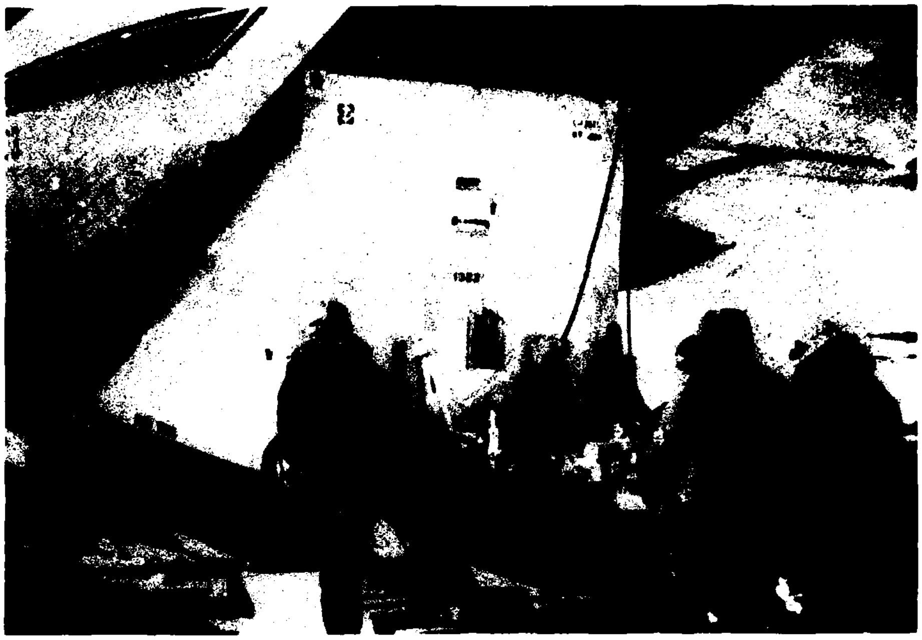


Figure 3 - A Mark IV system being deployed in Antarctica. Mark IV's are designed to go anywhere and be set up for operation within eight hours.

DISCUSSION

QUESTION D. P. Haworth

Since you are using DOMSATS to move around strategic meteorological information, have you considered the implications for times of stress when DOMSATS may no longer be available?

ANSWER

DMSP is as survivable as its supported forces. Geostationary DOMSATS are presently less vulnerable than low orbiters like DMSP. Additionally, military communications satellites could not guarantee 100% coverage for DMSP communications needs. Future DMSP systems, as they are more survivable, will use geostationary communication satellites that are more survivable.

QUESTION K. G. Brammer

Can you comment on whether or how the Tchernobyl nuclear reactor accident was detected, e.g. in the visible or infrared spectrum?

ANSWER

Because this type of detection is not part of the DMSP mission, it was not used in the Tchernobyl incident. In the visible spectrum, DMSP could only detect the situation if a large cloud was associated with the accident. The infrared sensor would not be able to detect this type of accident. In any case, US Air Weather Service does not look for this type of information.

APPLICATION OF METEOROLOGICAL SATELLITE (METSAT) DATA TO SUPPORT UNITED STATES FORCES IN THE NORTH ATLANTIC TREATY ORGANIZATION (NATO)

by

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SUMMARY

Meteorological satellites play an important role in observing the environment and predicting how the environment will change with time. Such knowledge is absolutely crucial to military operations whose success or failure can often be directly influenced by changing environmental conditions. United States forces in NATO receive METSAT data from several sources and routinely use these data for operational decision making. The types of data available and the application of these data to United States Air Force and Army tactical military operations in NATO will be discussed in this paper.

INTRODUCTION

United States Air Force and Army units are provided environmental support by the Air Force's Air Weather Service (AWS) with headquarters at Scott Air Force Base, Illinois. Worldwide centralized environmental support is provided by the Air Force Global Weather Central (AFGWC), Offutt Air Force Base, Nebraska, through the use of a worldwide data collection capability and global numerical modeling of environmental parameters. Direct support to US Air Force and Army units in NATO is the responsibility of the AWS 2d Weather Wing (2WW) with its three subordinate squadrons and 732 people deployed throughout Europe. Environmental support is based on a wide variety of sources including conventional data (collected by ground and air based systems) and METSAT data. The primary METSAT system used to support military operations is the US Defense Meteorological Satellite Program (DMSP) which is a military controlled system. Other METSAT systems, when available, are used to augment the DMSP, particularly in peacetime operations, and include the US National Oceanic and Atmospheric Administration (NOAA) polar-orbiting and geostationary satellites as well as the European Space Agency Geostationary Meteorological Satellite (METEOSAT). The complementary nature of all the available METSAT systems provides a wealth of environmental information which is used on both a global and regional scale to provide timely environmental information to US military commanders.

OPERATIONAL CONCEPT

The mission of the AFGWC is to provide centralized environmental support to US forces worldwide. To accomplish this mission, AFGWC relies on a worldwide conventional data collection network and data from various METSAT systems. Conventional data are collected and provided to AFGWC through the Automated Weather Network and consist of surface weather observations, atmospheric temperature and moisture profiles, radar reports, airborne weather observations, ship reports, forecast products, etc. These data are combined with METSAT data to produce the complete global data base that is the foundation of AFGWC's support. METSAT data are particularly important in data sparse areas such as oceans or lightly populated areas and in data denied areas where conventional data are intentionally restricted due to political or military reasons. At AFGWC, data are processed both in a purely automated mode and in a man-machine interactive mode where the weather forecaster assesses the quality of automated products and has the capability to selectively change or tailor the product if required. Centralized support to US forces in NATO is handled through the Western Hemisphere Section where global, regional, and synoptic scale products are produced for dissemination to weather units throughout Europe. METSAT data are particularly useful for cloud cover analysis. Worldwide DMSP cloud imagery data form the Satellite Global Data Base which is an input to the three-dimensional global cloud analysis model, the Real Time Nephanalysis. This analysis model is used by numerical prediction models to forecast various cloud parameters. Other data collected by DMSP are also used in various prediction models to produce the many facsimile charts and other analysis and forecast products produced daily at AFGWC. Additional METSAT data from NOAA and METEOSAT are also used to augment the DMSP data.

Direct support to US Air Force and Army units in NATO is the responsibility of 2WW with headquarters at Kapaun Barracks, Germany, and subordinate units deployed throughout Europe. Specific support responsibilities are allocated to 2WW's three subordinate squadrons. The 28th Weather Squadron (28WS) is headquartered at RAF Mildenhall, United Kingdom, and supports the US 3d Air Force and all Air Force units assigned in the United Kingdom. The 31st Weather Squadron (31WS) is headquartered at Sembach Air Base, Germany, and supports the US 17th Air Force and all Air Force units assigned on the continent. The 7th Weather Squadron (7WS) headquartered at Heidelberg Army Installation, Germany, supports all US Army units in NATO. Regional environmental support is provided by the European Forecast Unit (EFU), a 31WS detachment, collocated with the German Military Geophysical Office (Amt Fur Wehrgeophysic) at Traben-Trarbach. Through the EFU, 2WW units receive specialized products tailored for Europe by US forecasters and indigenous products from NATO countries. Each squadron provides tailored environmental support to individual operational units through weather detachments or operating locations (OLs) assigned with the supported unit. These detachments and OLs receive weather observations, analysis products, and forecast products from AFGWC and the EFU for local use. METSAT data are supplied through a regional dissemination system from two Air Force tactical readout terminals (TACTERMs), currently located at RAF Croughton, United Kingdom, and Bann, Germany, (near Ramstein Air Base). These TACTERMs can acquire cloud imagery data from DMSP, NOAA polar-orbiting and geostationary satellites, and METEOSAT. The combination of conventional data and METSAT data allows the local weather unit to provide complete weather support tailored specifically to the unique operational requirements of the supported unit mission.

METSAT OVERVIEW

Meteorological satellite data to support US forces in NATO come from four different satellite systems. The primary system is the US DMSP which is under complete military control through the United States Air Force. The DMSP consists of two polar-orbiting satellites in sun-synchronous 450 nm (833 km) circular orbits with orbital period of 101 minutes. The orbit times are selected based on operational support requirements with the current two satellites, F-8 and F-9, ascending across the equator at 0613 and 0934 local sun time respectively. The primary sensor on the DMSP satellite is the Operational Linescan System (OLS) which provides global cloud imagery in two data channels. Both the visible (0.4 to 1.1 microns) and long wave infrared (10.2 to 12.5 microns) channels can produce near-constant resolution cloud data in either fine mode (0.3 nm or 0.6 km) or smooth mode (1.5 nm or 2.8 km) across the 1600 nm (2963 km) swath. Smooth resolution data are collected globally for use at AFGWC with selected fine resolution data collected over user-selected areas of high interest. TACTERMs receive one channel in fine resolution and one channel in smooth resolution based on time of day. Infrared cloud data are collected continuously with visible cloud data collected on the daylight portion of the orbit. The DMSP satellite also has the unique capability to collect visible data at night when lunar illumination is sufficient to allow cloud detection by specialized optics on the satellite. Other sensors on the DMSP satellite are the SSM/T passive microwave temperature profiler, the SSM/I passive microwave imager, and sensors for monitoring the space environment. Future DMSP satellites will also carry the SSM/T-2 passive moisture profiler. The DMSP is a secure system which means all transmissions to and from the satellite for commanding and data receipt are encrypted to protect the satellite and deny the data to enemy forces.

In contrast to the DMSP, the NOAA polar-orbiting satellites are under civilian control and are configured to meet different requirements. NOAA also flies two polar-orbiters in sun-synchronous 450 nm (833 km) circular orbits, but at times selected to provide the best atmospheric sounding data for global numerical models. Currently, NOAA 10 ascends across the equator at 1933 local sun time while NOAA 11 ascends at 1347. The NOAA cloud sensor has five data channels (0.58-0.68, 0.73-1.0, 3.55-3.93, 10.5-11.5 and 11.4-12.4 microns), but has poorer spatial resolution than DMSP (1 km for high resolution and 4 km for low resolution) that varies considerably toward the edge of the data swath. The primary mission of the NOAA polar-orbiters is not cloud imagery, but global atmospheric temperature and moisture profiles to feed numerical weather prediction models. No commanding or data transmissions are encrypted on NOAA satellites since these satellites are designed to meet US civilian requirements and requirements of the World Meteorological Organization. Data from NOAA satellites are available to anyone who can receive the signal and are available in both High Resolution Picture Transmission (HRPT) and Automatic Picture Transmission (APT) modes.

NOAA also flies two civilian controlled Geostationary Operational Environmental Satellites (GOES) to provide detailed coverage of the United States. These two satellites are normally positioned at 65°W and 135°W and provide both cloud imagery and vertical atmospheric soundings. Cloud imagery is normally available in both visible (0.55-0.72 microns) and infrared (10.0-12.5 microns) with large scale moisture shown using a 6.7 micron mid-wave infrared channel. Geostationary satellites complement polar-orbiting satellites by providing more frequent coverage (full-disk images every 30 min) over their viewing areas, but they cannot provide global coverage. The GOES East satellite normally at 65°W longitude is particularly useful for NATO support since it covers much of the Atlantic and provides broad scale information for both air and sea movements between the US and Europe. Data are transmitted to the ground in two modes, a high resolution digital mode and a low resolution analog mode known as WEFAX.

Completing the complement of available METSATs is the European Space Agency geostationary satellite, METEOSAT. This civilian-controlled METSAT is very similar to the US GOES and provides cloud imagery in visible (0.5-0.9 microns) and infrared (10.5-12.5 microns) channels and moisture information in the 5.7-7.1 micron channel. The frequent coverage of METEOSAT is a strong complement to the polar-orbiting satellites, but the earth-curvature limitation of all geostationary satellites reduces the effectiveness of coverage over key areas of northern Europe. The location of METEOSAT at 0° longitude provides overlap coverage with GOES East and allows complete coverage of the Atlantic Ocean between the US and Europe. Like US GOES, METEOSAT provides data in both high resolution digital and low resolution analog (WEFAX) modes.

APPLICATIONS OF METSAT DATA

Air Weather Service policy on use of METSAT data dictates that DMSP is the primary METSAT system for AWS support to military operations since it is the only system under direct military control. However, this policy also recognizes the substantial data that non-military systems can provide, particularly during peacetime or limited contingency situations.

Both AFGWC and the TACTERMs in Europe routinely use all available systems in daily operations. At AFGWC, all polar-orbiter cloud data from both DMSP and NOAA are received and processed for global applications. In addition, AFGWC receives and processes all DMSP mission sensor data and also receives the atmospheric sounding data from the NOAA polar-orbiters for use in global environmental models. High resolution digital GOES data are received directly at AFGWC through a dedicated antenna and are incorporated into the man-machine interactive Satellite Data Handling System (SDHS) to modify and verify analysis and forecast products within the METSAT field of view. METEOSAT data are available in two modes. The first is the WEFAX mode through landline transmission from the NOAA readout site at Wallops Island, VA. The second mode is digital, but non-earth-locatable, imagery mode (GOES TAP format) from NOAA's Satellite Field Service Station at Kansas City, MO. METEOSAT data are used to augment polar-orbiter data over Europe and the Atlantic and can be entered into the production cycle through the SDHS either as an image by the GOES-Landline input port (GOES TAP) or by direct forecaster input of specific information from the WEFAX image. Final AFGWC products destined for AWS units in Europe are a synthesis of all the available data, both conventional and METSAT, and represent the synoptic and larger scale view of the environment. It is the responsibility of the units in Europe to tailor these products to the mesoscale atmospheric environment to best support the specific mission of the operational customer.

Currently, TACTERMs can only receive cloud imagery data and none of the other data such as atmospheric soundings or the environmental parameters from the DMSP microwave imager. The DMSP TACTERMs in Europe are the mobile Mark IV series and are transportable aboard C-130 or larger aircraft. However, these TACTERMs operate as fixed sites and do not have an operational mobility requirement. Imagery data received by the TACTERMs are disseminated to AWS units in Europe through a regional Satellite Imagery Dissemination System (SIDS) using analog laser facsimile equipment and landlines for transmission. Imagery from DMSP and NOAA polar-orbiters is first processed as a hard copy film transparency and then placed into an analog scanner for dissemination. Geostationary data are received using the same 10 foot (3.0 m) diameter antenna, but are disseminated directly over the SIDS without the intermediate film step.

The TACTERMs receive both DMSP OLS data channels with one channel (visible in daylight and infrared at night) in fine mode resolution and the other in smooth mode. All five NOAA polar-orbiting satellite channels can be received in the HRPT mode. The GOES East satellite can be received, but this satellite is not routinely used by the TACTERMs due to its location. Data from METEOSAT are routinely received in all three imagery channels in the WEFAX mode. The polar-orbiting data are enhanced in various ways using the capabilities of the Mark IV system to highlight important features such as low clouds or thunderstorm tops. Data requirements from AWS units are consolidated by the 2WW Meteorological Satellite Coordinator (MSC) for routine operation. The SIDS network supplies the same data to all units based on a daily schedule, but specialized requirements for specific mission applications can be satisfied on a case by case basis by the MSC.

Since the TACTERMs have only one antenna, readout availability must be shared among the METSAT systems with the MSC establishing readout priority based on the operational requirements. Each polar-orbiter can be tracked 4-6 orbits per day depending on the exact equator crossings for that day. Both DMSP and NOAA have 1600 nm (2963 km) data swaths and can cover the entire NATO theater twice per day per satellite. METEOSAT data are received in the interval between polar-orbiter passes and can preempt some lower priority polar-orbiter passes. The NOAA 3.7 micron channel (Channel 3) and the METEOSAT 6.7 micron water vapor channel are particularly useful since these channels are not covered by DMSP. The fine mode resolution and overhead view of the polar-orbiters provide fine detail over the entire theater. The METEOSAT geostationary capability provides hemispheric coverage for large scale analysis and high temporal resolution coverage for assessing changes in the meteorological environment. The combination of all available systems provides AWS forecasters with the METSAT data needed for the best possible weather support to US forces.

Air Weather Service units also supplement data received over the SIDS network through the use of commercially available APT/WEFAX receivers such as the German Wraase receiver system. These small terminals cannot receive DMSP data since the data are encrypted and are transmitted at too high of a rate (1.024 megabits per second (mbs)) for the receiver or antenna. Since these terminals cannot receive DMSP, they may only be useful in peacetime or limited contingency situations when non-DMSP data are available. The primary uses of these terminals are to provide METSAT data to AWS weather forecasters deployed in the field with US Army units and to supplement METEOSAT data received on the SIDS at Army garrison locations or air bases for forecasters supporting US Air Force units. The capability provided by these APT/WEFAX terminals for mobility, broader unit coverage than SIDS, and enhanced survivability due to small size and potentially large numbers of units has led AWS to investigate a similar capability for DMSP satellites.

All available METSAT data are used by AWS forecasters in NATO to complement conventional data supplied by AFGWC and the EFU. The specific methods of using METSAT data vary based on the supported mission. At the EFU, METSAT data are used to produce regional facsimile charts, verify and initialize products received from AFGWC and provide meteorological watch capability for limited duty AWS units that are not fully manned 24 hours per day. Limited duty base weather stations begin and end each day's operation with a coordinated meteorological discussion with EFU. METSAT data play a large role in these discussions. A specific application of DMSP and NOAA imagery at the EFU is the forecasting of mountain wave turbulence by identifying lenticular clouds and using these clouds to define the areas of turbulence. Forecasters at the EFU also have the responsibility of providing both regional and point warnings of severe weather for all US forces locations in Europe. METSAT data are used extensively for identifying areas critical to military operations. The overall effectiveness of METSAT data at the EFU will be improved in the near future when NOAA imagery data are incorporated into the interactive computer graphics terminals used by the forecasters.

The uses of METSAT data also vary at the base weather station level due to the specific requirements of the supported unit. Since METSAT data are only available in hardcopy image format from the SIDS, all merging with conventional data must be done manually. Routine uses of METSAT data include verifying and initializing products issued by AFGWC and EFU, identifying large scale weather patterns, improving local scale analyses and forecasts, and briefing unit staffs, commanders, and air crews. Each AWS unit has a local METSAT program to provide training on interpretation of the data and to tailor the use of the data to the local mission.

METSAT data can provide unique information that conventional data cannot due to the distances between reporting stations. For example, DMSP and NOAA polar-orbiter data can provide particularly useful information on low-lying fog and stratus. The use of the DMSP nighttime visual channel during the period near full moon and the 3.7 micron channel from NOAA help to identify the low clouds, fog, and land/sea boundaries much better than normal long wave infrared data or conventional weather observations. In particular, these data are successfully being used to aid the forecast of fog dissipation which can be critical to early morning aircraft launches.

Observation of the extensive cloudiness that often covers much of Europe in the winter provides a prime example of the advantages of METSAT data over conventional data alone. Many training areas, particularly for low-level fighter training, are sparsely covered with ground-based reporting stations. Often, the extrapolation of these surrounding ground-based observations will mask areas that are usable for training. METSAT data can help to identify these areas and turn potentially cancelled aircraft sorties into productive training flights. Similarly, even when low-level cloudiness is widespread and negates any low-level training, METSAT data can provide the information needed to switch low-level missions to high-level training in clear areas above the clouds. Refueling operations also greatly benefit from METSAT data in that refueling areas can be closely monitored for cirrus clouds that could make the area unsuitable. Information on thunderstorms or other identifiable rain areas is also useful to support Army ground operations since soil moisture and its effects on movement of heavy vehicles is a critical concern. Low cloudiness and fog are also problems for Army aviation because most Army helicopters fly very low "nap of the earth" missions. In peacetime operations, METSAT data enhance mission accomplishment by improving the effectiveness of required training and contributing to flight safety through early identification of potential flight hazards.

In a wartime or contingency scenario, METSAT data can play an even more important role since these data could be the only data available over large areas of the battlefield and particularly over enemy territory. Weapons selection for a particular mission may be affected due to the prevailing weather in the target area since many new "smart" weapons are electro-optical and require certain unobstructed visibility ranges for lock-on. The effectiveness of METSAT data is routinely demonstrated during various NATO and US exercises when wartime conditions are simulated. The importance of DMSP data, in particular, during wartime operations is the primary reason for improvements to the space and ground segments for survivability and better dissemination of data to more users in the field.

FUTURE IMPROVEMENTS

Since the DMSP is the primary source of METSAT data for the US military, the system is evolving to meet changing requirements of the military mission. The current satellite series, Block 5D-2 will be followed by a slightly larger Block 5D-3 satellite series to accommodate new sensors and increased satellite survivability. The 5D-2 passive microwave sensor suite of temperature profiler, moisture profiler, and microwave imager will be combined into a single new sensor package, the SSMIS, and will incorporate a new capability to profile temperature above the current 30km altitude limit to over 60km. The space environmental monitoring sensor package for 5D-3 will also be new and incorporate passive ultraviolet sensors for electron density profiling. While all additions or improvements to the overall system aid environmental support to US forces in NATO, there are certain specific capabilities that will directly influence that support. These capabilities are in both the space and ground segments of the program and point the way to the new generation of satellites for the 21st Century, DMSS Block 6.

The first of these new capabilities is the Mark IVB TACTERM that will replace the current Mark IV systems in the early 1990s. The Mark IVB is a substantial improvement over the Mark IV and will be delivered either as a fixed site (12 worldwide, 2 in Europe) or as a mobile (C-130 transportable) system (4 for worldwide contingency support). The fixed site Mark IVBs in Europe will be relocated to RAF Molesworth, United Kingdom, and Sembach Air Base, Germany, to better satisfy mission requirements. The Mark IVB will incorporate state-of-the-art computer processing and a separate interactive work station for the weather forecaster at the nearby weather facility. Other improvements over the current system include the addition of a second antenna for simultaneous readout of one polar-orbiter and one geostationary satellite, the ability to receive and process the atmospheric mission sensors (SSM/T, SSM/I, SSM/T-2, SSMIS) from DMSS, and greatly increased capabilities to manipulate, display, and apply METSAT data. The Mark IVB will continue to supply METSAT data to AWS units using the SIDS and will be able to synthesize METSAT data (such as tactical cloud analyses) as key inputs to electro-optical tactical decision aids for Air Force and Army combat forces. AWS also plans to upgrade the SIDS to a digital link to more effectively use the Mark IVB capabilities.

The effectiveness of the commercial APT/WEFAX systems used in 2WW has led AWS to investigate a similar capability on future DMSS satellites for wartime use. The DMSP Program Office is completing a study that indicates such a capability is feasible on either 5D-2 or 5D-3 satellites. This capability, if implemented, could provide a low data rate transmission (66 kilobits per sec (kbps) in 5D-2 or 88 kbps in 5D-3) of smooth resolution visible and infrared imagery and mission sensor data that could be received by a small antenna on the ground (approximately 1 meter or smaller diameter tracking dish or possibly omni-directional). The exact details of the transmission and type of antenna and receiver required on the ground are still being defined. However, AWS has requested that this capability, encrypted for operational use, be considered for implementation on future DMSP satellites. This capability could provide DMSP data (as well as APT and WEFAX) to a small, possibly man-portable, receiver terminal that could be located at any fixed location or deployed in the field for direct reception of DMSP data. This concept provides a survivable and enduring ground reception capability, independent of the Mark IVB SIDS, to ensure availability of critical data to the operational combat force. Once the required satellite modifications are defined, a final decision will be made on the implementation of this capability on future satellites.

A second AWS initiative to improve overall DMSP capability is to investigate the feasibility of adding additional data channels to the OLS. In particular, AWS has requested that the DMSP Program Office determine the feasibility of adding a 3.7 micron channel for low cloud detection and a 1.6 micron channel for snow/cloud discrimination. Initial studies indicate that the 1.6 micron channel is relatively easy to add, in terms of cost and schedule, while the 3.7 micron channel is significantly more difficult due to increased weight and complexity of the cooling requirements of an infrared channel. Since the final results of the feasibility study are not yet available, it is too early to know if one or both of these channels can be added to the OLS in the 5D series.

The continued evolution of the DMSP satellites to meet new and changing operational requirements for the 21st Century will require a major upgrade known as Block 6. This follow-on to the successful Block 5D series is still in a conceptual design phase, but significant innovation is expected due to improvements in sensors, on-orbit survivability, satellite design, and space-qualified computer hardware. Block 6 is structured with a baseline system to provide, at a minimum, the capabilities of the 5D-3 system at the same or less cost. Significant new capabilities are available as separately priced options that can be added to the baseline depending on funding and specific requirements. It is too early to definitively identify what capabilities Block 6 will eventually have, but several new capabilities are promising. Current plans call for a 4-year risk reduction phase to validate new technologies followed by full scale development and first launch in the year 2002. This program is on schedule and ensures DMSP capability to meet the critical requirements of military operations well into the 21st Century.

CONCLUSION

METSAT data, particularly DMSP data, are critical to the overall environmental support provided to US forces in NATO. The current array of available METSATs is fully exploited to use all data to maximize both the peacetime and wartime effectiveness of US forces in the defense of Europe. The DMSP is an effective military controlled system that provides required METSAT data across the full spectrum of potential conflict and denies that same data to the enemy. Air Weather Service units in NATO have access to critical METSAT data and effectively merge that data with conventional data to provide specialized support tailored to the mission of US combat forces. Continued improvements in both the space and ground segments of DMSP will enable AWS forecasters to continue to provide critical data on demand well into the 21st Century.

DMSP'S INTERACTIVE TACTICAL TERMINAL

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SUMMARY

DMSP is in the process of developing an interactive weather terminal as a functional replacement for their older tactical terminals. These new terminals will have fifty times the computer capability of the older Mark IV. This increase in computer capability allowed flexibility in developing system concepts. Four basic concepts were developed. The first was a build and apply concept for the operation of the system. In this concept, local data bases would be developed using the primary DMSP and NOAA sensors along with the microwave sensors. In addition, depending on the site location, various geosynchronous satellites would also be observed with that information added to the data base. The forecaster then would utilize this initial data base and build products. Another basic system concept was the quality control of the weather products. Quality control of the local data base environment was especially necessary because of immature sensor algorithms. Many functions were added for the purpose of quality control. In addition, since the forecaster is very busy with other tasks, the third system concept was to have a system which would collect data automatically and yet rapidly respond to the user when needed. The final system concept was 'graceful degradation', ie the ability to work with data dropouts, lack of individual sensor data, and other "normal" failures and yet still produce products.

The hardware design incorporates redundancy to meet a high availability requirement and yet keep the corrective maintenance actions to a minimum. Corrective maintenance actions are to be done under a variety of conditions. In addition, a large number of built in test functions allows rapid analysis of failure modes. The combination of 'graceful degradation' and the high availability requirements will produce a system that will work under tactical conditions.

INTRODUCTION

Developing a terminal to be used in a tactical arena requires consideration of a number of factors in the specification phase which can make large differences in the operability of a complex meteorological tactical terminal. Additional external factors come into play when considering a wartime environment that normally do not occur during peacetime use of the exact same meteorological data. A terminal developed just for peacetime could become quite cumbersome in a wartime environment where the user has to respond to more demanding requests from his many users. Perhaps he has also been ordered to wear cumbersome chemical warfare attire which inhibits his ability to operate the system. To overcome some of these difficulties, a system specification had to be defined which automated a large number of user functions, such as satellite reception and product generation, to minimize forecaster interactions. The system also would have the capability of switching over from a peacetime environment to a wartime environment by changing product generation priorities.

First, basic concepts of operation had to be developed. This meant deriving all the functions which would be required in peacetime or wartime conditions, yet making sure that simple operation under stressful conditions would be available. The approach used what we called a "build and apply" method. To the greatest extent possible, the tactical system automatically builds data bases while the forecaster is applying the data. Under normal conditions, the forecaster reviews the data quality within the data bases before they are used in further applications. The forecaster has the ability to modify any of these data bases through interactive routines using the raw input data. The complexity of this process is quite apparent when the derived data bases and the sources from which they are derived are reviewed. (See Table I.) Thus quality control of the environmental data bases was a second critical factor which had to be specified for a tactical meteorological system.

Manpower is also limited. Therefore a third system concept that had to be stressed was the automatic acquisition and processing of satellite passes. Furthermore, many processes in the system can be tuned so that the more frequent products are generated first. A seldom used product might be generated only when requested. Even in satellite acquisition, a seldom used satellite might only be acquired upon specific selection by the forecaster (as might be the case if most of the satellite sensors had failed, but the data from a working sensor was needed to fill in a data gap). This leads into the final system concept that is addressed: 'graceful degradation' which applies both to the on orbit hardware and that of the tactical system itself.

Table I The BUILD Database

Meteorological Parameter	Data Source
Cloud Imagery	DMSP, NOAA, GOES-NEXT, GMS, METEOSAT
Cloud Types	DMSP, NOAA
Cloud Tops	DMSP IR Data
Cloud Amount	DMSP, NOAA, SSM/I
Precipitation	SSM/I
Temperature	SSM/T, AMSU-A
Humidity	SSM/T-2, AMSU-B
Total Water Vapor	SSM/I
Liquid Water	SSM/I
Cloud Water	SSM/I
Soil Moisture	SSM/I
Vegetation	AVHRR
Surface Winds	SSM/I
Sea Ice	SSM/I
Snow Cover	SSM/I
Geostrophic Winds	SSM/T, AMSU

Notes to Table:

DMSP	-	Defense Meteorological Satellite Program
NOAA	-	National Oceanic and Atmospheric Administration TIROS Polar Orbiting Satellite
GOES-NEXT	-	NOAA Next Generation Geostationary Operational Environmental Satellite
GMS	-	Geostationary Meteorological Satellite (Japan)
METEOSAT	-	Meteorological Satellite (European Space Agency)
SSM/I	-	Microwave Imager (DMSP)
AVHRR	-	Advanced Very High Resolution Radiometer (NOAA)
SSM/T	-	Microwave Temperature Sounder (DMSP)
SSM/T-2	-	Microwave Humidity Sounder (DMSP)
AMSU	-	Advanced Microwave Sounder Unit (NOAA)
AMSU-B	-	Advanced Microwave Sounder Unit - Humidity (NOAA)

BUILD AND APPLY

The generation of meteorological products for external distribution is divided into two phases. The first phase, the build process, assembles the incoming satellite data into data bases of meteorological parameters. The second phase, the apply process, takes the data bases as "truth" and creates external products and product displays for the forecaster. This split allows the forecaster to review the quality of the data bases prior to the final product creation.

In the design of the build portion of the system, special functions were required to overcome some of the basic problems with remotely sensed data. Several major problems occur during this build process that the user has to monitor. First, his tactical area is covered by multiple passes of the satellites and that only portions of the tactical area are updated by each satellite pass. Some of the meteorological sensors do not update the entire tactical area as their swath coverage below 40 degrees latitude leaves gaps between passes. Depending on how long the derived parameter is valid, this may be a problem that the forecaster is required to correct by inserting his estimates for the missing data. A variety of functions are included in the system capabilities to allow him to modify parameters over specified areas. During the apply phase, these data bases are accessed and shipped to external systems. Thus it is critical that the user has the ability to update them. If he fails to update the area that has a critical time attached, the system will mark the parameter missing in areas where it has not been updated by a satellite pass. This feature would come into more and more use as the forecaster becomes more involved with other more demanding activities.

The next step in the process is the apply phase. In earlier tactical vans, the product was an "image" on film which was passed to the user. In the new tactical systems, the product is a transmission to another system of processed data. External communication is now a primary force multiplier in the system. It allows rapid dissemination of the data to where it can be applied to weapon selection or target selection. Uniform gridded data fields are created from the data base, rotated to the grid system of the external user, and transmitted to the Tactical Air Force and Army host computers. There, the meteorological fields are fused with electro-optical target acquisition and navigation system performance parameters and target parameters to create electro-optical data bases.

The primary display area for the meteorological data will be located at the base weather station or command center. There the forecaster can generate hardcopy of the displays for the tactical personnel. The display area is linked over fiber optic lines to the acquisition area which may be located up to ten miles away. No longer will film have to be driven from the acquisition site to the using facility. The satellite imagery dissemination system will also be directly linked to digital imagery. Currently it is supported by a fax transmission using the hardcopy film. The direct link will reduce the time it takes to get the imagery out into the field.

QUALITY CONTROL

The automatic processing of remotely sensed data may produce erroneous results. The processed data is not perfect due to the wide variety of backgrounds, abnormal environmental conditions, or lack of physical retrieval methods. Many of the processes are statistical approximations. At the weather centrals, there is enough manpower to look at the processed data and compare it to the raw imagery. There the man can correct the snow field that has been classified as a cloud. He can toss out the weather sounding that was contaminated by heavy precipitation. National Weather Service routinely deletes IR soundings from cloud covered regions. At a tactical site, this manpower does not exist and this is a major reason why DMSP has gone towards microwave instruments for sounding purposes. Second, the individual at the weather facility is an Air Weather Service officer or NCO with one to ten years experience. He may not have the scientific expertise to understand why the readings are off, but he will have an intuitive feel for the local affects on the weather and what observations make sense.

Therefore, at the tactical site, some reliance was placed on the forecaster to look at the processed parameter field before it is passed on into the apply phase of the tactical processing. The goal was to come up with display techniques which would (1) allow the forecaster to recognize erroneous data rapidly, (2) allow the forecaster to call up alternative raw data sources for comparisons, and (3) allow the forecaster to replace invalid data points. Data fusion techniques were necessary to make use of the raw data that ranges from .5 kilometer resolution to 250 kilometer resolution. Data taken from various look angles (0 degrees incident angle to 70 degrees incident angle) had to have various corrections applied so the data would appear to be angle independent. Routines for taking into account solar elevation and direction were added to the processing suite. Because wavelengths of alternative data sources (such as the NOAA IR channels) are different from the DMSP IR channel, merged channels were created that "look-like" DMSP channels. The forecaster, should not be able to tell if he is using the primary data source or the alternative.

Some of these transformations are performed in real time as the data is coming into the system. The NOAA channels are summed together and then converted from radiance values to temperature to match the DMSP output values during the pass. The NOAA data is merged into a polar-orbit projected data base with DMSP data. This polar-orbit projected data base contains the latest observation of an area by the polar satellites. The latest geosynchronous observations are kept in a separate data base to avoid saturation by the timely, but less accurate image data. The geosynchronous data is for animation for time lapse sequences with rapid updates. But the data is harder to process to extract environmental data because of low resolution and the lack of night time visible imagery.

Some functions are performed only as needed, such as the bidirectional reflectance distribution correction, bi-linear interpolations, and cross track thermal corrections. These functions have a lesser affect upon the data utility - although they are needed for certain critical operations that depend upon the actual cloud temperatures.

Finally, when the data are ready for final display, it has to be fused with the other types of data. Isocontour routines are provided for low resolution data such as the temperature field from the SSM/T sensor. This allows a graphical representation of the field to be placed over a corresponding visible or infrared image. Alternatively, the low resolution field can be expanded by bi-linear interpolation to an intermediate resolution and the high resolution data can be blurred to the approximately same resolution. The forecaster can then alternate between displays for comparison purposes. The purpose of the fusion techniques on the tactical system is not to produce a product for distribution but to allow the forecaster to correct his data bases. A full color image processing system allows separate sensor channels to be displayed simultaneously. By changing display enhancement tables, the user can bring out low cloud information.

AUTOMATIC ACQUISITION

Since the on-site manpower is limited, the system is designed to automatically acquire the satellite passes. Once a week, the meteorological coordinator reviews a pass schedule generated by the system. The pass schedule is created from ephemeris data which is contained within the DMSP data stream. This schedule lists all the DMSP and NOAA passes for the week. The system flags any conflicts between the satellites and allows the coordinator to change the initial selection. This initial selection is done on a preset priority basis of maximum elevation angle. The coordinator can review pass coverage displays which graphically illustrate to him the swath coverage of all the sensors.

The coordinator then reviews the geosynchronous schedule. The scheduling of geosychronous satellites is driven by the locations of severe weather as well as the area of tactical interest. It would be expected that this schedule would be modified on a daily basis.

After the schedule is set, the system will acquire the polar satellites as they rise above the horizon. The antenna system features both a program track and autotrack capability. From the ephemeris of the satellite, the system begins a program track search to acquire the satellite. From the predicted position of the satellite, the antenna performs a spiral search about the center of the predicted position. Once the signal is acquired, the antenna control switches to auto-track which uses reference feed horns to precisely locate the satellite.

Ephemeris maintenance has to be done for autonomous mode operation where the ephemeris is not updated from the information in the data stream. The tactical terminal is designed to update the ephemeris data from the shift observed between the imagery and land/sea boundaries.

GRACEFUL DEGRADATION

The new tactical system is a complex, interactive system, held together with miles of fiber optic cables. It has unmanned acquisition sites, where processing of gigabytes of data takes place every hour. The satellites after several years on orbit may have part failures and not all sensors may be available. The system will have to work under very imperfect conditions and be tested for those conditions. It has to work while the user is in chemical warfare attire and not be such that data cannot be entered because his gloves strikes two keys. The system cannot crash due to imperfect states of knowledge. This is very hard to achieve and very hard to test. But without it, the system would fail just at the time it is most needed.

Hardware failures are perhaps the easiest to overcome by installing redundant units. By requiring the system to fail over automatically to redundant units, the user will not have to react immediately to a failure. A warning alert will be flashed on the screen indicating that he should call maintenance. He can remain at the terminal and continue operation. In addition to switch over at detection of a failure, the system is required to check out the receiving hardware prior to the start of the pass. This prevents loss of critical data by allowing the hardware switchover prior to the pass.

Not all systems can be made redundant. The basic requirement for non-critical hardware subsystems is that their failure shall not cause the system to crash. Examples are interfaces that are handling data from conventional sources, geostationary satellite interfaces, hardcopy units, and tape storage devices. These items are fairly obvious and can be tested easily.

Of a more subtle nature are failures in the data sources or deliberate denial of civilian data sources that the system has been instructed to process. These sudden changes could be detrimental. The system has to successfully work on DMSP data alone. Not only that, but it has to have back up algorithms for partially failed sensors on the spacecraft. The algorithms for temperature soundings need to be supplied with 1000 mb height fields even if the conventional data is not available.

In a minimum configuration, the system has to be able to display a pass of DMSP visible or IR imagery. This can be done with failure of 75% of the processing power, 60% of the random access memory, and 90% of the disk storage. In this mode of operation, the user can review cloud imagery but does not obtain the quantitative meteorological field values.

CONCLUSION

The basic operational concepts have been described that went into the specification of the new tactical meteorological terminal for DMSP. Advanced technology has expanded what we can do for the meteorologist in displaying remotely sensed meteorological fields. This improves the forecasting ability in the field and helps in the movement of forces. At the same time, advanced technology, where failure of a key microchip not repairable in the field, cannot lower our operational availability. Fail over procedures have to be considered in the earliest part of the design effort. In fact, it has to be considered in the original specification prior to the design effort.

TACTICAL OCEANOGRAPHY FROM SPACE - THE NEXT DECADE

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Naval Oceanography from space is a tactical force multiplier. Space systems are playing an ever increasing role in command, control and communications; surveillance and targeting; navigation; and environmental remote sensing. Oceanographic and meteorological satellites are supporting the fleet today and will be even more important in the next decade. In this presentation, I will describe what we call "tactical oceanography from space" and briefly discuss our current plans to participate in space technology development.

Space and the sea are a natural combination. In fact, the language of the sea has become the language of space. From Melville to Clancy, authors have described the beauty, power, smell, and danger of the sea. Who would argue that the sea can capture the imagination like nothing else... except perhaps space? In fact, our crossing of the expanse of space is not at all unlike the experience of our early days of oceanic exploration. We've given the names of famous research ships to our space shuttles... ATLANTIS, DISCOVERY, and of course CHALLENGER. It's no wonder that science fiction has given us space heros with naval ranks and fleets of star ships.

More to the point than science fiction, many of our real world space heros have been naval officers: Alan Shepard and John Glenn were our first Americans in space and in orbit; John Young and Bob Crippen were our first space shuttle crew; Dan Brandenstein is our Chief of the NASA Astronaut Corps; Bruce McCandless is the senior active duty Navy officer among the astronauts and was the first free-flying human satellite. All of these men came from the ranks of Navy or Marine aviators. And Rear Admiral Dick Truly who commanded the first night launch and landing of the shuttle and who was our first Commander of the Naval Space Command is now the Administrator of NASA.

In order to extend the visual horizon, seamen have gone aloft on the masthead and from there they could best spot the approach of the enemy, whales, or heavy weather. Our astronauts have given us striking evidence that the "masthead" is now as high as the edge of space, an ideal vantage point from which to observe the environment. Extending our visual horizon extends our capability in environmental support to the fleet but it also challenges us to understand and interpret what we see.

Those who serve in the environmental support community of the Navy are responsible for determining what effect the sea and sky have on our platforms and weapons systems and then providing the commanders who take them to sea with forecast services that are timely and accurate. Because the marine environment in which we operate extends from the ocean bottom out to space, across several complex fluid interfaces, Naval Oceanography is a combination of five disciplines: oceanography; meteorology; mapping, charting, and geodesy (MC&G); and precise time and time interval, and astrometry. It is truly geophysical and astrophysical. The Naval Oceanography Command, with headquarters at the Stennis Space Center in Mississippi and worldwide facilities and the Naval Observatory and the Defense Mapping Agency in Washington, DC, all conduct operational Naval Oceanography. These commands are, of course, supported by research and development laboratories and organizations throughout the United States.

Tactical Oceanography, the topic of this briefing, is the focusing of Naval Oceanography on forecasting those **mesoscale (more descriptively called tactical scale) phenomena that impact battle group, amphibious assault group, or single platform operations over distances of several hundred kilometers and up to one hundred hours.** These phenomena may be in the undersea, on the sea-surface, in the sky, and in some instances, from the beach inland. And tactical oceanography from space is, of course, the application of satellite remote sensing in this task.

To understand our use of remote sensing, it is important to review which specific environmental phenomena are important to tactical naval warfare and how remote sensing is used to monitor these parameters. A sampling of environmental factors that we are interested in are shown here:

1) **Marine winds** create the **ocean waves** that affect many aspects of ship operations and also drive **currents** which are critical in mine warfare, amphibious assault, search and rescue. Wind speed is used to predict ambient acoustic noise for ASW. Wind determines aircraft carrier launch course and speed. Target wind affects bomber run-in and smoke patterns for follow-up attack and making

bomb damage assessment. Upper air wind affects aircraft routing and fuel consumption, ballistic missile and projectile flight performance, and chaff dispersal patterns.

2) **Sea and swell**, driven by wind patterns, affect ship stability, safe navigation, underway replenishment, aircraft launch and recovery, and beach surf. Ocean waves affect all naval ships from NIMITZ class carrier to a SEAL team's rubber raft. It's just a matter of scale.

3) **Atmospheric temperature and moisture content** determine cloud cover and ceiling, contrails, icing, and influences all other aspects of aircraft operations. A new understanding has developed in recent years of the atmosphere's refraction of electromagnetic energy which creates ducting and holes in radar, radio, and electronics countermeasures. **Precipitation** has an effect on radar propagation, electro-optical visibility, ambient noise, and flight safety.

4) Three dimensional **ocean temperature and salinity** structure and its spacial variability in the form of water mass fronts and eddies affect tactical acoustics. Accurate understanding of the ocean dynamics greatly improves acoustic search, contact prosecution, and torpedo settings and performance.

5) **Magnetic anomalies** degrade airborne magnetic sensor performance in air ASW.

6) **Sea ice** endangers surface navigation in high latitudes, greatly affects acoustic propagation and ambient noise, and the operation of submarines under the ice.

7) Coastal **bathymetry** and **geology**, **beach slope and firmness**, **soil moisture**, and **vegetation** affect landing craft performance and the ability of personnel and equipment to rapidly move ashore and inland.

8) **Tides and tidal currents** affect ship movements in and out of port and determine mine selection, settings, and the location and depth of moorings.

9) **Gravity** affects ballistic missile systems during flight and must be taken into account in fire control settings.

All of these phenomena can be either measured directly from space or inferred (i.e., calculated or extrapolated) from space-based remote sensing of other elements. For instance, remote sensing systems are not capable of directly measuring sub-surface temperature variability, a critical factor in tactical acoustic ASW. However, the location of thermal gradients on the surface, which we can see in infrared imagery, can be used in thermo-haline models to compute a realistic three-dimensional temperature structure that can be used in acoustic propagation models. These models, in turn, are used to generate acoustic propagation predictions and then tactical ASW decision aids. Local observations of the weather and satellite imagery, when available, can be used directly in the decision making process. These two kinds of satellite data, discrete measurements and imagery, are both very important in tactical oceanography.

Color-enhanced infrared images of the major ocean currents, such as the Gulf Stream, taken by a NOAA polar-orbiting satellite can be used to illustrate these applications. Of course these satellites image clouds. That is what they were designed to do. But when an ocean area is cloud-free, a technique called temperature slicing is used to determine the thermal gradients of ocean fronts and eddies. New techniques for image processing and display make these functions fast and easy. An image which is enhanced to reveal thermal fronts and eddies can be directly used in ASW as a planning aid in positioning ships or sensors. The next step of turning this information into computer-produced tactical ASW decision aids is not so easy, however, because the surface manifestations of the features must be combined with bathythermograph data and complex data bases of water mass temperature and salinity. All of these pieces of data (satellite surface temperature measurements, ship or aircraft dropped bathythermographs, and water mass temperature and salinity climatology) are used to create a three dimensional model of the ocean's pressure, temperature, and salinity which are the inputs needed to run acoustic propagation equations.

Work is underway to put satellite receivers and computers to sea to translate satellite observations of sea surface temperature, scattered bathythermograph soundings, and deep ocean temperature and salinity climatology into eddy-resolving numerical models of the ocean structure.

To map these ocean phenomena, passive infrared radiometers, with a resolving capability of about one kilometer per pixel, are the primary sensors on U.S.

operational weather satellites. The Advanced Very High Resolution Radiometer (AVHRR) on the TIROS-N polar orbiting satellites operated by NOAA and the Optical Line Scanner (OLS) on the Defense Meteorological Satellite System are used to determine day or night cloud cover, moisture content, and sea surface temperature in cloud-free areas. Figure (1) shows the NOAA Advanced TIROS-N (ATN) satellite. NOAA and DMSP satellites also image in the visual bands to provide daytime high resolution cloud imagery and other useful data such as snow cover, forest fire smoke, and volcanic ash plumes. Other infrared and microwave sensors on these polar-orbiting satellites are used for atmospheric temperature and moisture soundings which feed numerical weather prediction models.

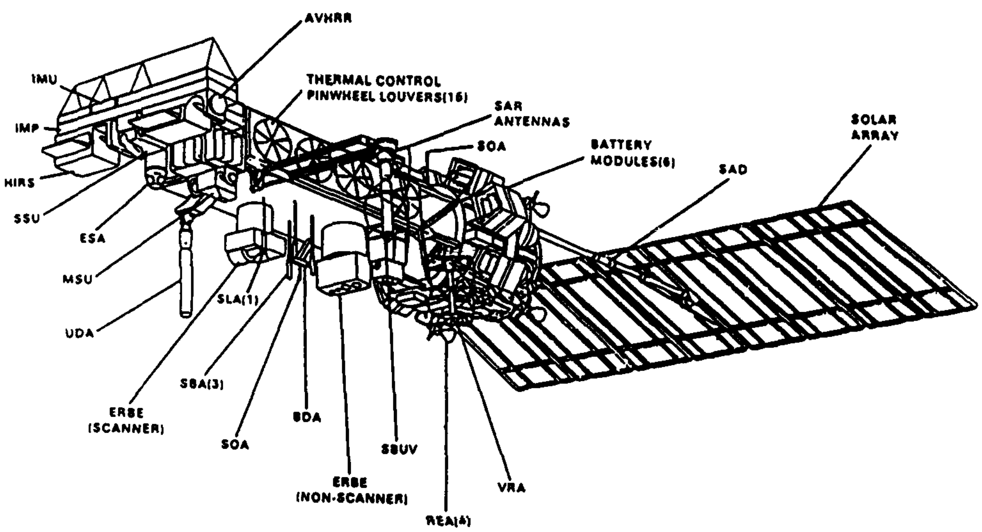

Figure (1): NOAA Advanced TIROS-N (ATN) Polar Orbiting Environmental Satellite

A more recent and very significant advance in remote sensing is the Special Sensor Microwave Imager (SSM/I) that now flies as an operational sensor on DMSP Block 5D satellites. The SSM/I is a passive radiometer that measures the earth's radiance in four frequencies in the microwave band. This allows all-weather measurement of the cover and age of sea ice, atmospheric moisture and precipitation, and scaler wind speed derived from the sea surface perturbation. SSM/I wind speed measurements are becoming a key source of input data to numerical weather models which are now are based primarily on surface pressure data. SSM/I moisture data, combined with wind speed measurements, are providing tropical cyclone forecasters with critical data on storm location, structure, and intensity.

In 1985, the GEOSAT-A launched with a radar altimeter as its only payload. Its mission was to collect a comprehensive measurement of the marine geoid - the surface of the ocean to which gravity is perpendicular. With its geodesy mission completed in September, 1987, GEOSAT was repositioned to a 17 day exact repeating orbit and began its oceanography mission. GEOSAT has expanded our understanding of altimetry's use in precise measurement of the wave height, and good measurement of wind speed. We have also established that ice edge location and water mass boundaries (fronts and eddies) are observable by the altimeter.

Building on the success of GEOSAT, the Navy is planning to launch another radar altimeter satellite next year. This new project, called the Special Purpose Inexpensive Satellite (SPINSAT) Altimeter (SALT). SALT's altimeter is the engineering development model originally planned as one of the four sensors for the cancelled Navy Remote Ocean Sensing System (N-ROSS). SALT is designed to prove the concept of small, reconsitutable, and relatively inexpensive satellites which can be launched from small boosters such as SCOUT or PEGASUS. It will also double the Navy's access to altimetric data and cut in half the 17 day revisit time which GEOSAT provides.

Visual and infrared imagers and sounders, multispectral imagers, microwave radiometers, and radar altimeters on the satellites we have been discussing provide a wealth of data. There are, however, other remote sensing technologies specifically designed for ocean measurements which have been flown, are planned for flight, or have been proposed. SEASAT was launched in 1978 and operated for three months before a massive power failure shut the system down but it thoroughly demonstrated what a synergistic suite of oceanographic sensors could accomplish. Its Synthetic Aperture Radar (SAR), Microwave Radiometer, Scatterometer, and Radar Altimeter all operated as planned and their data are still being examined today. Many of the technologies which were demonstrated are still awaiting operational implementation more than a decade later although Navy interest in them is high.

One of these sensors, SAR, was also flown on two Space Shuttle flights, is the premier sensor for very high-resolution ice imagery, as well as a potentially powerful sensor for understanding small scale ocean dynamics that other satellites cannot resolve. And yet high data rates and high cost are formidable obstacles to SAR's acceptance as an operational sensor.

Another unexploited technical achievement of SEASAT was the scatterometer, a multi-beam active radar that measured vector winds over the ocean, making possible a more accurate surface weather depiction. The benefits of this are far-reaching in that winds not only can be used to calculate and predict ocean waves but also ambient noise for ASW and almost all aspects of modeling both atmospheric and oceanic mixing dynamics. For these reasons, Navy interest in wind measurement using scatterometers is high.

Ocean color in the form of subtle blue-green shadings caused by phytoplankton abundance is another data type of interest to the Navy. An Ocean Color Imager (OCI) known as the Sea Wide Field Sensor (SeaWiFS) is under development in the private sector and may possibly be flown as a commercial venture. NASA has considerable experience in ocean color imagery from the Coastal Zone Color Scanner (CZCS) flown on NIMBUS-7 which proved very effective in revealing much about ocean biologics, a key factor in industrial fishing productivity. Ocean color can assist oceanographers in locating fronts and eddies and this, together with our operational infrared data, makes it valuable in tactical ASW support. We are waiting to see how this commercial remote sensing program develops.

More exotic but still interesting sensors such as laser sounders (LIDAR) and hyperspectral imagers are also waiting to begin the long transition from research to operations. The remote sensing community does not lack for challenges, but opportunities are unfortunately few and very expensive.

So where do we stand on remote sensing in the 1990's? From a spacecraft viewpoint, not very far from where we are today. DMSP, TIROS, and GOES will remain the operational remote sensing systems for tactical oceanography. DMSP Block 5D2 will upgrade to 5D3 and GOES will be improved in the I-M series upgrade, but functionally these redesigned spacecraft will not have new oceanographic capabilities. SALT, although it is primarily a research program, will also provide operationally useful data. Essentially no new sensors or capabilities will be available for operational use in tactical oceanography in the 1990's.

And what of new satellites? The next major engineering upgrade to the DMSP system will not be implemented until after the turn of the century, as you will hear in the next briefing. However, we are working with the Air Force and the aerospace industry to develop a possible "Navy Option" for DMSP Block 6 which incorporates some of the oceanographic sensors we have discussed. We are still in the conceptual planning phase of this program and I cannot provide details at this time.

In the meantime, Europe and Japan are setting the pace in the 90's with their multi-sensor Earth Remote Sensing Systems which incorporate several of the technologies discussed earlier. The NASA/ESA TOPEX/POSEIDON mission will also extend our technical capability and support global climate research. And of course, the NASA and ESA polar platforms will be the centerpiece programs in remote sensing for the next century; programs that are likely to remain strongly supported as public concern for global climatic change continues to grow. And finally, our astronauts will continue to take hands-on research into space on the space shuttle and eventually the space station FREEDOM. The SIR-C experiment, to be flown in the space shuttle in 1990 and 1991, will further enhance our understanding of synthetic aperture radar and man-in-space visual observation programs will continue into the space station era.

These research programs are exciting because they will affect our fundamental understanding of the environment by expanding our data bases providing insights into how complex the earth's ecosystem really is. But the focus of Navy attention in the next decade will be on operational rather than research programs. Data encryption or selective silencing is crucial to tactically useful systems and this is understandably incompatible with internationally developed research programs.

Naval Oceanography is looking hard at these issues. We plan to make maximum use of existing satellites through deploying receivers capable of pulling in the high resolution imagery from both DMSP and NOAA satellites directly to ships and shore stations. A new satellite receiver system, designated as the SMQ-11, is in production and being installed on major combatants and shore-based facilities. State-of-the-art image processing, regional scale ocean and atmospheric numerical models and a full suite of tactical decision aid software from radar refractivity to acoustic propagation will be resident in the Tactical Environmental Support System (TESS). TESS(3) is now in full scale engineering development and when it goes to sea with the SMQ-11 receiver, it will truly revolutionize tactical oceanography from space, even without new satellites.

In closing, let me emphasize that tactical oceanography from space is going to continue to mature. With the SMQ-11 receiver and TESS(3) computer systems going to sea in the 1990's, space will be considered in tactical warfighting decisions at virtually every level of command. As we look to the turn of the century, both the civilian research and defense communities are looking to major new programs in EOS and DMSP Block 6. Cooperative research with the space agencies of other nations will be investigated as well. The key factors in deciding the U.S. Navy's level of investment in new programs are these: warfighting enhancement value; ease of integration; operational security; and last, but not by any means least, affordability. The Fleet and Fleet Marine Force deserve the best environmental forecasting support we can afford.

Block 6: The Future DMSP Space Systems

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Summary

This paper describes the acquisition strategy and anticipated capabilities of the Defense Meteorological Satellite Program (DMSP) Block 6 satellite system. It includes brief discussions of previous satellites and the requirements which drove the Block 6 system acquisition. The first three phases of acquisition are discussed: concept study, risk reduction, and full scale development. Strategy and content of each phase are described in detail. The use of Total Quality Management in each phase is discussed.

Background

For over fifteen years, the U.S. Air Force has successfully orbited over twenty-five meteorological satellites in its Defense Meteorological Satellite Program (DMSP). The satellite constellation is comprised of spacecraft in early and late morning polar sun-synchronous orbits. DMSP provides the Department of Defense (DoD) strategic and tactical users with global cloud imagery and other atmospheric and geophysical information. The current block of satellites, designated 5D, has evolved to provide growth in size, power capacity and payload.

MJCS Environmental Requirements

On 1 Aug 1986 the Joint Chiefs of Staff issued MJCS 154-86. The purpose of this memorandum was to consolidate and prioritize the DoD data and system requirements for satellite monitoring of the environment to include meteorological, oceanographic, terrestrial and solar geophysical parameters. Stringent requirements were levied within this document especially in the areas of resolution and refresh of the various data parameters. A majority of the parameters such as cloud cover, cloud type, wind speed and wind direction required as little as 15 minute refresh. To satisfy such severe requirements in one step would be prohibitive from both a cost and technological point of view. However, by incorporating improvements in logical, incremental steps, significant progress can be made toward satisfying the MJCS requirements in a manner acceptable from both a cost and technological standpoint.

Block 5D-3 Capability

The first step in this process will be the next generation 5D satellite, 5D-3. 5D-3 incorporates several improvements over the 5D-2 spacecraft including: increased satellite length to extend payload capacity, increased design life from four years to five years, Titan II Expendable Launch Vehicle (ELV) compatibility, and improvements in existing payload sensors. Six 5D-3 satellites will be purchased with the first launch anticipated to be in the mid 1990's. The 5D-3 bus will take DMSP to the turn of the century. By that time, however, it will not be cost effective to again extend the design of the 1970's heritage 5D bus and on-board computer; a new design will be needed -- Block 6.

Block 6 Strategy

The acquisition strategy of the Block 6 baseline satellite system has a four-pronged approach. First, to assure continued access to today's data, Block 6 will provide the same quality data that will be provided by the 5D-3 system. Second, to ensure cost efficiency, Block 6 will provide this capability at the same or less cost than the 5D-3 system. Additionally, to ensure the ability to cost effectively utilize future instruments and capabilities which will be developed to meet MJCS requirements, flexibility and extendibility will be designed into the system from the beginning when full advantage can be gained from cost savings. Finally, because of its success since being implemented in the 5D program, Block 6 will continue to use the Total Quality approach to program management. Technology, cost, and schedule risks will be identified as they occur so they can be dealt with early when it is least expensive to correct or mitigate.

The actual acquisition will take place in three phases. The concept study phase is the first and will define the Block 6 system, identify risk areas and provide preliminary cost information. In the case of the Block 6 satellite system, four contractors were tasked to perform a concept study. Before the next phase, risk reduction, results of the four concept studies will be analyzed and consolidated by the government to produce a single Block 6 system. In the risk reduction phase high risk areas identified during the concept studies will be chosen for additional risk reduction efforts. The entire Block 6 system concept will be carried throughout the risk reduction phase so that any impacts or changes to other segments of the system identified during this phase will be tracked and assessed when they occur. The emphasis will be on bringing the risk to an acceptable level in order to move into the last phase, full scale development/initial production. During this phase the first of the Block 6 satellites and ground systems will be produced and the system readied for its initial operating capability(IOC).

Block 6 Concept Studies

The Block 6 concept studies, scheduled to be completed in 1990, are the first of three phases of the Block 6 satellite system acquisition designed to continue a successful and established history of meteorological satellites beyond the turn of the century. The studies are being conducted by direction of the DMSP Program Management Directive (PMD) using the strategy approved at a Jan 1986 briefing to Headquarters United States Air Force (HQ USAF). The strategy of the Block 6 acquisition is anchored in recognizing fiscal constraints while still moving towards satisfying the validated MJCS requirements. Two basic groundrules are being adhered to during the concept studies. First, the Block 6 satellite will meet but not exceed the projected 5D-3 environmental data capabilities and second, a life cycle cost (LCC) goal of $1.9 billion (1986 dollars) over ten years will not be exceeded. The $1.9 billion was the governments original projection of the cost of continuing the 5D-3 program for ten years. An independent cost estimate was conducted in conjunction with the Block 6 concept studies. The purpose of the estimate was to determine the cost of continuing the DMSP mission with a redesigned 5D-3 satellite bus, 5D-4. The results of the independent cost estimate verified it would be substantially more expensive than $1.9 billion to build a 5D-4 satellite, thereby confirming the advantages of proceeding with the Block 6 strategy.

In order to stimulate competition, four separate study contracts were awarded in January 1988. Contracts were awarded to Ford Aerospace Corporation, General Electric, Hughes Aircraft, and Lockheed Missile and Space Company. Each contract had identical requirements to ensure that results would have a common basis for comparison.

Each contractor's primary task was to design a Block 6 baseline system which would include a space, ground control and user segment. Each contractor has designed a baseline system which will meet but not exceed the projected 5D-3 environmental data capabilities. Within this baseline system the contractors included a 1993 technology freeze to reduce system risk; 25% payload growth capability for future expansion; design and operational flexibility; system, space and ground segment trade-offs to minimize impact on each segment; and a stable of candidate ELVs (Delta II, Titan II and Titan IV). Optional capabilities, defined by the government for study in this phase, were costed separate from the baseline $1.9 billion but were intended to compete for funding based on their own merit. These additional capabilities or options are desirable from a requirements viewpoint but may introduce risk into the baseline from a cost or technology viewpoint. The strategy for including an option to the Block 6 baseline is: (1) any option must significantly increase baseline capability or have the potential to satisfy additional MJCS requirements, (2) the user desiring a particular option will bear the responsibility for the cost of that option, therefore options will be costed separately from the baseline and (3) the addition or deletion of any optional capability will not degrade the performance of the baseline system thus ensuring the integrity of the baseline. The integrity of the baseline system is the most important aspect when considering any option since it is the baseline capability which continues the mission of the current system. Optional capabilities, which will be described in detail later, studied during this phase include: store and forward capability, active sensors, enhanced survivability, extended autonomy, surface data collection and distribution, satellite internetting, 50% and 100% payload growth margin, enhanced data capability, dual launch capability, Air Force Satellite Control Network (AFSCN) interoperability and separate Navy and Army options.

Block 6 Concept Study Options

Store and Forward: The store and forward option will allow the storing of environmental data and forecasts, developed at a central user site, onboard the satellite for later transmittal to tactical terminals. This data may include special, tailored forecasts developed for high priority missions under conditions of political unrest. Additionally it could include data for conventional conflicts that require macroscale forecasts for theatre commands, down to microscale forecasts for smaller tactical operations.

Active Sensors: The active sensor option was designed to provide an extended capability for the measurement of environmental parameters beyond the baseline such as wind direction and speed or precision vertical resolution measurements. The utility of these sensors were evaluated in terms of data elements measured and their quality, the reduction algorithms required, the percent of spacecraft support used by the active sensor, possible replacement or enhancement of other payload sensors, and feasibility and impact on central user sites and tactical terminals. In general, most active sensors put such a large burden on the baseline bus in terms of weight and power that they were not considered feasible for inclusion on the Block 6 satellite.

Enhanced Survivability: A level of survivability was designed into the baseline system and this option was intended to expand that level and determine the impacts to the Block 6 system in terms of weight, power, performance and degradation to sensors, if any.

Extended Autonomy: This option was to determine the feasibility of the satellite vehicle system satisfying all baseline requirements while operating for up to 180 days, or greater, without any uplink command or data transfer from the ground or other satellite. During autonomous operation, the satellite vehicle system maintains all capabilities and tolerances of the baseline concept relative to mission requirements and operations that are provided during non-autonomous operation. Mapping accuracy, however, was allowed to degrade to 46 km.

Surface Data Collection and Distribution: The goal here was to determine the system impact of employing a satellite to interrogate small military and/or civilian data collection systems deployed on remote buoys, surface/airborne/shipboard host vehicles, or fixed sites. Methods were to be evaluated using surface data to improve the quality of data products derived from satellite sensors. Recommendations for a selection of data elements, data transmission volume and rate, and a definition of the communication links were required. The data sources to be considered included the following types of equipment: platform transmitter terminals (PTTs) of the NOAA Argos system used with the TIROS-N satellite. These PTTs include boats, balloons, fixed stations, drifting and tethered buoys, and air dropped PTTs for monitoring surface environmental parameters in remote areas, unmanned air vehicles (UAVs) operated as part of the Pre-Strike Surveillance and Reconnaissance System (PRESSURS) environmental data acquisition, and data collection platforms (DCPs) used with the GOES satellites and tactical terminals currently deployed with the Army, Air Force and Navy.

Satellite Internetting: This option was used to determine the system impact of providing cross-links over which Block 6 commands, state-of-health information and critical mission data can be transferred to any command, control, and communication (C3) or user site. The objective of this system is to improve timeliness of the data and flexibility of commanding during emergencies. Internetting would also be useful as a means to enhance system survivability.

50% and 100% Payload Growth Margin: With this option the contractors were to develop design extensions of the baseline concept which extended payload growth margins to 50% and 100%. The characteristics and size of the space segment were to be chosen to enhance the incorporation of sensor and support elements developed over the entire life cycle of the DMSP Block 6 program. In addition, the contractors were to determine how flexible the design of the proposed baseline is to permit a payload design extension prior to full scale development. This option goes hand in hand with the TQM approach to program management. Since it is reasonable to assume that future growth will be required from the Block 6 satellite, it would be less expensive and decrease the LCC of the Block 6 system to build in growth and flexibility up front.

Enhanced Data Capability: The intent of this option was to determine the impacts and benefits of augmenting the baseline concept with the capability of providing three non-oceanographic mission improvements pertaining to the enhancement of existing environmental data or to satisfy requirements not previously satisfied by the baseline concept. Since the baseline concept was constrained to meet but not exceed the projected 5D-3 capability, it was desirable to learn whether or not any improvements to the baseline could be realized at a reasonable cost.

Dual Launch Capability: The purpose of this option was to determine the system impacts of providing Block 6 with dual-launch capability, allowing Block 6 to use either the baseline ELV and any additional ELV or the baseline ELV and the Space Transportation System (STS). This would enhance the availability of the Block 6 satellite system by mitigating the impact of booster unavailability or catastrophic booster failure.

AFSCN Interoperability: With this option the contractors were to develop a concept to incorporate AFSCN interoperability into the Block 6 baseline system. This option would enable the baseline system to make full and direct use of the AFSCN. This capability includes full command generation and satellite communications through the AFSCN. All hardware and software modifications to the Block 6 baseline system and associated costs were to be identified. The advantage of this option is in its utilization of an entire command and control network's resources rather than a few dedicated ground stations for commanding the satellite.

Navy Option: The purpose of the Navy option was to provide the Navy with continuous, near real time, specific area and global oceanographic data under all weather conditions. The oceanographic mission could be satisfied by a combination of the Block 6 baseline system and this option. The baseline system provides for the measurement of sea ice parameters including ice edge, ice cover, and ice age. The Navy option will satisfy the data requirements for sea surface wind speed and direction, sea surface temperature, significant height of ocean waves, and sea surface topography. Within the implementation of this option, the contractors were not constrained to use the Block 6 satellite. For example, they may have proposed a separate Navy platform to satisfy the requirements of this option.

Army Option: This option was to determine the most cost effective means of satisfying the Army data requirements as defined in the requirements document such as: topographic data and chemical cloud detection. The contractor was not constrained to using the Block 6 baseline system for this option. That is, a different satellite vehicle other than the baseline could be employed for purposes of cost effectiveness or optimizing the Army mission capabilities. Descriptions of all additions, modifications, and associated system impacts to the baseline Space, C3, and User segments were required. Modern weapons, sophisticated technology, and advancing doctrine have increased the Army's need for timely, accurate environmental data to even higher levels. Army commanders primarily require timely, accurate environmental data over their particular area of interest. The knowledge of the environment and its effects on weapons systems and soldiers will enable the commander to select the combination of soldiers and weapons systems which will ensure maximum combat power. The use of a small portable, yet highly capable tactical terminal was the emphasis of this option.

Risk Reduction Phase

The risk reduction phase is the next step in Block 6 system acquisition. As stated before, the purpose of this phase is to reduce the risk in identified areas to a level acceptable for FSD. This phase is an integral part of the TQM of the Block 6 system since money spent here will generate many times it's cost in savings during the subsequent phases.

In order to determine the level of user satisfaction with the Block 6 data products and to solicit user feedback, it is planned that products generated during this phase will be made available to the user. Data products from tests would be transmitted directly to existing land and shipboard tactical terminals for use and evaluation by the user. Data would also be transmitted to a test facility for archiving, analysis, and further distribution to central user sites such as Air Force Global Weather Central (AFGWC) and Fleet Numerical Oceanographic Center (FNOC). Feedback from the users would be invaluable in further improving and refining the Block 6 system.

Full Scale Development Phase

In the mid 1990s, it is anticipated that the FSD phase will begin. FSD is the third and last phase of the acquisition process that will be discussed. During this phase, the initial complement of Block 6 satellites will be built and the construction or modification of the command and control and user segments will commence. It is at this point, more than seven years since the concept studies began, that the TQM of the Block 6 system will have its largest impacts in terms of cost savings and quality products. During this phase the strategy of carrying the entire Block 6 system concept throughout the concept study phase and the risk reduction phase will reap its rewards. Since the changes and impacts to all segments of the system will have been identified, tracked, and planned for, the cost of incorporating these changes at this point in the acquisition process will be minimized and provide a significant savings to the government and a better product for the user.

Conclusion

The Block 6 satellite system acquisition was driven by the stringent requirements of the user community for better and more precise weather data. The need for high quality weather data will continue indefinitely and consequently existing weather data gathering systems will need to continually improve to satisfy those requirements. The Block 6 system is the logical, incremental next step in meeting those needs. Through the Total Quality Management approach a capable, expandable, and affordable satellite system can be realized to satisfy the user needs for weather data well into the 21st century.

DISCUSSION

QUESTION D. P. Haworth

What consideration have you given to the survivability of the communications links that you plan to use to disseminate meteorological information to the locations where it is used? It seems inadequate to rely on civil satellites in a survivable system.

ANSWER

It is understood that using civil satellites for data relay is not the optimum solution for DMSP. Several factors led to the current approach but will not be discussed here. However, this issue will be addressed in the current concept studies for the next generation DMSP Satellite (Block 6). Requirements identification and further planning will occur during the risk reduction phase of these studies to ensure that there will be suitable survivable communications links for the Block 6 system.

QUESTION

The US Defense Meteorological Satellite Program (DMSP) transmits encrypted data. Can this data be made available for use by all NATO members?

ANSWER

From a technical perspective, DMSP data can be accessed directly by those facilities equipped with suitable decryption equipment, or by relay of decrypted data from US forces. However, the real issue is US government policy on authorization to release this data to NATO members.

SPACE-BASED WIDE AREA SURVEILLANCE SYSTEM STUDIES

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The U.S. Department of Defense (DoD) is vigorously exploring and evaluating alternative concepts for conducting global wide area surveillance using space-based assets. The objective is to provide for the detection, identification, and tracking of atmospheric, ocean surface and ground targets on a 24-hour basis, worldwide and under all weather conditions. Candidate concepts include radar systems, infrared systems, and a combination of both.

The current effort is based on a series of engineering concept studies and designs conducted by the U.S. aerospace industry and government laboratories under DoD sponsorship over the past several years. The primary evaluation tool is an in-depth computer simulation that is being used to model each concept in a simulated operational environment. This simulation is described with several example operational missions and alternative space-based surveillance systems.

The U.S. Department of Defense (DoD) is conducting Cost and Operational Effectiveness Analyses (COEA) of the Space-Based Wide Area Surveillance System (SBWASS) concepts in preparation for a decision to start the demonstration/validation phase. The principal goal of the COEA effort is to develop detailed information about the ability of space-based systems to satisfy surveillance needs of operational forces beyond the range of existing sensors in an affordable, cost-effective manner. The SBWASS will provide global, all-weather, day/night, near-real-time tactical and strategic warning of air and surface attacks directly to operational forces.

The SBWASS consists of space and ground segments and communication links (Figure 1). Space-based radar (SBR) and infrared (IR) concepts are considered for baseline SBWASS sensors. Through space and ground communication networks, these sensors will report targets of interest directly to operational commanders in the field.

The SBWASS offers an opportunity to turn the world of aircraft and ship operations into a "fish bowl." The ultimate objective is to know all and to see all beyond the horizon bounds. The SBWASS will place the attack aircraft and naval forces at risk anywhere along their path of operation. The attacker will be led to believe that their intentions will be discovered and that they cannot position their forces for an attack without fear of a counterattack from U.S. forces (Figure 2).

The SBWASS will contribute advance information to the National Command Authority and our allies such that detection of the adversary air and naval operations will allow for collateral U.S. and allied responses in other areas of military operations. The outcome of these collateral responses can result in a risk increase to opposing military forces across a broad front by allowing for U.S. force projection instead of waiting for the attacker's action in the local theatre. In this regard, SBWASS will eliminate the current military situation of waiting for air and ship threats to come into the surveillance horizon of the threatened theatre; thus, providing for the prepositioning of U.S. defensive forces and/or bringing U.S. forces to bear along the path of the adversary either in an escort mode or an attack mode.

With SBR and IR, the physical and cost limitations and jammer avoidance considerations necessitate operating at lower satellite altitudes; but even at lower altitudes, global coverage is achieved. As one satellite passes out of a region, another prepares to enter. Space-based radar "paints" a target and gets a return whether it is day or night, regardless of the season. It is unaffected by the clouds or target altitude, and uninfluenced by the absence of radio transmissions.

SYSTEM EFFECTIVENESS

The goal of the system analysis methodology used to support the COEA is to provide a basis for equitable comparison of derived SBWASS radar/infrared/hybrid system architectures. This methodology will provide a basis for the Office of Secretary of Defense (OSD) comparison of SBWASS concepts.

A generalized concept of system effectiveness is used to describe overall attributes of a space system during its development and operation. These attributes are cost, availability, performance, and operational value. Cost includes expenditures to design, build, and operate a space system. Availability, as evaluated by a system user, relates to the user's ability to exploit the performance attributes of the system when needed and under circumstances dictated by the user. This notion is analytically related to the conventional notion of force tactical readiness. Availability is a probabilistic quality dependent on the multisegment system structure, subsystem failure characteristics, and threats to system integrity and operation. Performance is a quantity that denotes the ability to meet operational requirements for a given availability state. Operational value characterizes the user's willingness to allocate basic resources for a system of given availability and performance, and is allied with the notion of system affordability.

Effectiveness is an aggregate of these attributes. Individual measures of effectiveness (MOE) quantify different aspects of system effectiveness. Measures of effectiveness definitions are invariant across missions and targets. Their numerical values may vary for each mission, target class, user, and scenario specified by the user's operational requirements. Measures of effectiveness thresholds for COEA may be established by balancing operational value as expressed by different levels of operational requirements against several system concepts and designs. The minimal set of operational performance and availability MOE's is illustrated in Figure 3. These MOEs are computed using a SBWASS simulator.

SPACE-BASED WIDE AREA SURVEILLANCE SIMULATOR

The SBWASS simulator has been developed at the U.S. Air Force Space Systems Division (SSD) to support the evaluation of several different SBWASS concepts and their system architectures against a realistic set of user requirements. This evaluation process examines different sensor design options as well as different concepts of operation for both the space and ground segments of the system. The end product of the evaluation will be an assessment of the operational use of candidate SBWASS systems to potential users. As a side benefit, the SBWASS simulator will also be a tool to demonstrate the capabilities of candidate systems to operational users in unified and specified commands.

The SBWASS simulator has been structured to model all types of SBR systems under consideration (i.e., phased array, agile reflector, and rotating reflector systems) as well as scanning and starring IR systems that have also been proposed for wide area surveillance. The level of detail in the modeling was chosen to be as simple as possible (for run time considerations) while still retaining the capability to represent all the important features (e.g., power generation, background clutter, jamming) of both the SBWASS and its environment. The design is modular, allowing replacement of individual sections to upgrade fidelity or add other sensor types when needed. The SBWASS simulator runs on an IBM 3090, Cray XMP-1, and Convex mainframes. Outputs from each simulator run are saved and transferred to a MicroVax for storage in a database for use in production of both animation and performance graphic displays.

The inputs to the SBWASS simulator fall into three main categories, which are described herein and shown in Figure 4.

1. System Concept inputs describe the space and ground segments and the SBWASS system, including satellite constellation definition, sensor fields of view and agility constraints, sensor design parameters, and C3 architecture.

2. Surveillance covers the definition of search regions, search and track revisit times, and relative priorities for each requirement (both for search versus track and within search or track).

3. Targets reflect realistic movement profiles for ground, naval, and air units for red, white, and blue forces.

SYSTEM CONCEPTS

Figure 5 shows an artist's rendition of three promising SBWASS concepts: phased array radar (PA), rotating reflector radar (RR), and infrared scanner.

The space-based phased array radar has superb technical potential for detection, tracking, and electronic-countercounter measures (ECCM). The SBWASS simulator models all aspects of PA performance with particular emphasis on tasking and scheduling of radar beams and power resources.

The SBWASS simulators do not generate a search schedule for the infrared scanner. The infrared scanner is a passive sensor designed to sweep large areas and to provide target detections at a lower-per-satellite cost than PA.

The rotating reflector system combines the inherent advantages of a radar (all weather, all terrain, day/night, assured detection) with the simplicity of untasked wide area search sensors. This is accomplished by fixing radar scan near the horizon, i.e., in its most efficient area coverage mode. The rotating reflector has highest area coverage rate, low on-orbit constellation weight, simple concept of operations, and off-the-shelf technology. Target detections are processed on the ground to form tracks of aircraft and ships in the northern hemisphere.

Whether a radar, infrared, or hybrid SBWASS design concept is chosen, timely and responsive on-board and ground processing and dissemination of data are required to meet the combatant commands decision support needs. The compatibility of the SBWASS concept of operation with present and planned assets is a key attribute requested by the users. Data will be downlinked directly to the user. The SBWASS data will enter current/planned user systems at the level that will enable combat forces to most efficiently carry out their missions.

The real benefit from SBWASS comes from its synergism with other surveillance assets. The synergism is particularly effective for queuing of airborne surveillance, which has the advantage of high probability of detection when placed at the right range and location relative to threat aircraft/ships. The SBWASS can provide queuing of airborne assets so that they intercept the target along the most efficient path and, more importantly, it can be done in the silent mode. The main shortcomings of airborne surveillance systems lie in the following areas. The range falls far too short for what is required for a deep interdiction and wide area surveillance. Airbornes inherently have limited access to desired areas. Their limited numbers also deter from global deployment. Aircraft have a certain limited availability in terms of number of hours each month. These shortcomings will be addressed by the SBWASS.

SCENARIOS

Scenario inputs are provided to the SBWASS simulator for three purposes. First, they provide a means of assessing the adequacy of the search tasking for the SBWASS under evaluation. If the search regions specified do not cover the proper areas or do not have a sufficiently short revisit time, then an unacceptably large fraction of the threat will go undetected. Secondly, for those sensor systems that are taskable, the scenarios provide a realistic level of tracking requirements. Lastly, several COEA MOEs require scenario input for computation. An example of this is the percentage of threat targets detected.

A scenario is defined as a script detailing the unfolding of a set of events. These events are worldwide in coverage and occur over the course of a single day. They reflect events relating to a single conflict state in the world. Each scenario is composed of one or more scenario elements that may start at different times with respect to each other during the 1-day scenario duration.

Scenario elements are the building blocks from which scenarios are built. Each scenario element illustrates a single tactical or strategic event (e.g., an attack on a carrier battle group in the North Atlantic or an attack on West German airfields by enemy aircraft) and usually will be confined to a single theatre or geographic region. A scenario is made up of one or more scenario elements that may overlap each other in geographic area and/or time. Scenario elements contain all the information for individual targets. This information consists of target type, target information (if the target consists of more than one object), and track data (latitude, longitude, altitude, and speed) at a number of points along the target trajectory. Also included is the time phasing of the start of each target trajectory with respect to the start time for the scenario element as a whole.

The five scenarios scripted for use on the SBWASS simulator are set in the year 1997 and include the peace, buildup, crisis, conventional war, and nuclear war scenarios. Each reflects the events of an entire day at a single conflict state. The following three sample scenario elements (Figures 6, 7, and 8) may be of potential interest to the AGARD audience.

Figure 6 illustrates one possible Soviet BADGER aircraft route for attack on NATO airfields in the United Kingdom. Two waves of strike aircraft may depart Poland, fly over the Baltic and North Seas, and attack Lakenheath and Upper Hayford Air Bases. The strike aircraft are supported by electronic countermeasures aircraft (BADGER-J) from Poland, which act as stand-off jammers off the United Kingdom coast. The attack is escorted by FLANKER fighter aircraft that fly directly to the United Kingdom across West Germany and the Netherlands from East German airfields.

Figure 7 shows a national Soviet BACKFIRE attack on a U.S. Navy Carrier Group in the North Atlantic. The attack may originate from the Kola Peninsula, fly around North Cape and into the Atlantic through the Greenland-Iceland-Norway (GIN) gaps. Attack is supported by BEAR reconnaissance aircraft deployed along the same route several hours before. The BACKFIRES attack in three waves using AS-U cruise missiles and are supported by BADGER ECM aircraft deployed as stand-off jammers. The Soviet surface action group (SAG) departs Murmansk and sails around North Cape to conduct amphibious operations along the northern Norwegian coast in support of a Soviet invasion. The SAG is composed of several antisurface warfare and antiair warfare cruisers and destroyers, as well as several amphibious assault ships carrying Soviet landing troops. Soviet troops stage a helicopter assault across the Norwegian border in the Finmark area in northern Norway. A large number of both troop carriers and gunships, supported by fighter aircraft, crosses the border and lands at critical airfields, road junctions, and C3 centers in northern Norway.

Figure 8 shows a national Soviet BLACKJACK and BEAR bombers leading edge attack on CONUS over the North Pole using air-launched cruise missiles. The attack is composed of a precursor strike on the North warning system by BEAR-G bombers and followed by a strike on CONUS by BLACKJACK bombers.

These scenario elements are shown in the display animation film that illustrates SBWASS simulator outputs.

SYSTEM COMPARISONS

Two sets of SBWASS examples are compared in this section. The first set compares small constellations of six rotating reflector (RR), 12 infrared (IR), or six phased array (PA) satellites. Constellations with similar total weight on orbit have been chosen in order to fairly compare system costs. The second set compares larger constellations of 12 RRs, 24 IRs and 12 PAs. These two sets have been simulated against scenarios in the SBWASS simulator. Figures 9, 10, 11, and 12 illustrate selected measures of effectiveness for different systems against representative scenarios.

The percentage of targets detected is defined as the percentage of individual contacts detected while the targets are in all surveillance areas currently required for a given target type. Figure 9 shows summary statistics for the small constellation set and the large constellation set. Rotating reflector systems exhibit high percentage targets detected because of their ability to see through clouds and to search all required surveillance areas. Their search power is adjustable to target type/radar cross section. Bright target detection mode can be applied over large portions of the globe. Radar power may be increased in dim-target search areas to ensure higher probabilities of detection of lower cross section targets. Dim-target search areas may extend over several airland battle theatres that may be located anywhere on the Earth. The false alarm rate is kept at bay by confirmation dwells. Infrared may lose about 30 percent of targets due to clouds and lack of contrast signature in certain altitude bands, for some latitudes, and during the winter season.

Low-altitude, small phased-array radars with comparable on-orbit constellation weight have several times lower power-aperture product than reflectors. The PA constellation can search smaller areas of the earth or search larger areas less frequently. Either option lowers the overall percentage of targets detected. Larger phased arrays can deal with this issue by increasing array size and power at the risk of quickly becoming unaffordable.

Tracking accuracy is defined as the median distance between tracks presented to the users and the corresponding ground truth tracks for each target. Tracking accuracy characterizes the system's ability to vector other surveillance assets and interceptor aircraft against threat targets. Since these assets have their own acquisition sensors, 50 nm tracking accuracy at hand-off may be sufficient. Figure 10 shows summary statistics for tracking accuracy of small and large constellations against highly maneuverable targets. We have assumed that 90-degree turns and minimum-to-maximum speed variations are feasible between update reports. These maneuverability assumptions lead to upper bounds on tracking accuracy. Actual accuracies for less maneuvering nonevasive targets may be an order of magnitude better.

Intersatellite gaps drive tracking accuracy of all systems. Phased array radars have potential for additional track updates while targets are in the field of view. This potential can only be realized when sufficient power and dwell time are made available for tracking. Tracking of targets and background traffic has the effect of extending fences to cover entire flight paths. Tracking also requires more frequent revisits of surveillance regions. Phased array radars with comparable on-orbit weight lack sufficient power-aperture to accommodate the resource demands for tracking while maintaining desired search performance. Typically they provide no more than a few track updates for each satellite pass.

All SBWASS systems provide global access. However, their actual coverage may be more limited. Coverage is defined as the percentage of all required surveillance areas searched in a given time interval. Untasked sensors (RR, IR) can be sized to routinely search substantial portions of the globe. Figure 10 shows that RR has maximum search capability. This is because RR tends to search at low grazing angles, whereas the area covered in a single pass is the highest. In contrast, the phased array system with similar on-orbit weight has limited power-aperture (about 20 percent of RR) and it can search five times less area. This enables PA to only partially satisfy area search requirements. Figure 11 shows average percentage of surveillance area tiles searched within 15 and 10 minutes by small and large constellations, respectively. Although passive IR sensors can cover substantial portions of the globe, their availability to perform detection, tracking, and classification functions is in fact limited by cloud obscuration, grazing angles, high latitudes, and colder seasons.

Figure 12 shows summary statistics about availability of small and large constellation systems to perform detection functions. The availability is defined as the percentage of time that search function is not degraded in the presence of component malfunctions, adverse environmental conditions, or tasking conflicts. We assume that all SBWASS systems have sufficient built-in redundancy to mitigate component malfunctions during their design life. Rotating radar is unaffected by cloud obscuration or power deficiencies and it has highest availability. Single day simulations and long-term average cloud statistics indicate that 20 to 30 percent degradation in IR system availability may be caused by cloud obscuration. Finally, the average percentage of time that required surveillance areas are searched every 15 minutes by 6 PA and every 10 minutes by 12 PA satellites is shown in Figure 11. It should be emphasized, however, that radars have all-weather, all-altitude, all-seasons, day-night, and all-latitude capabilities.

SUMMARY

Space-based systems are being developed to satisfy wide area surveillance needs of operational forces and treaty monitoring needs of national authorities. The ability of the SBWASS system to meet these needs depends on its detection and tracking performance, on coverage extension beyond the range of revisit frequency of existing sensors, an assured availability under all-weather day/night conditions, on data timelines at user's location, and on system's affordability. The U.S. Air Force is using an in-depth computer simulation to evaluate operational effectiveness of several proposed SBWASS concepts. Sample results from these effectiveness studies have been presented in this paper. They encompass infrared scanner, phased array radar, and rotating reflector radar concepts. These sample results indicate that clouds tend to severely limit infrared sensor performance and availability. Power and aperture limitations of affordable phased arrays can restrict their search and track performance to a single theatre or mission, thus cancelling the benefits of the global/extent of space-based wide area surveillance assets. Simply operated search radars, such as the rotating radar, appear to provide a cost-effective solution to wide area surveillance needs of most users.

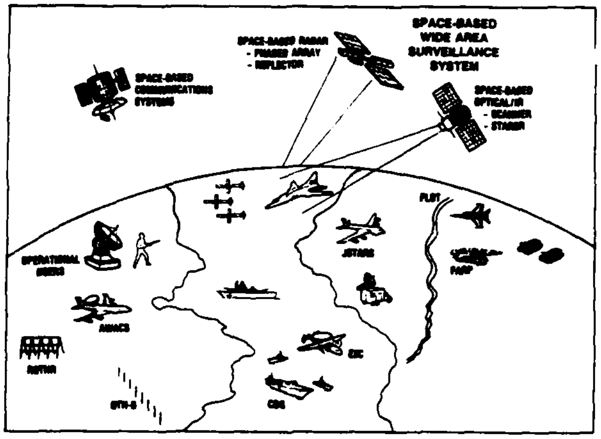

Figure 1. Wide Area Surveillance System Overview

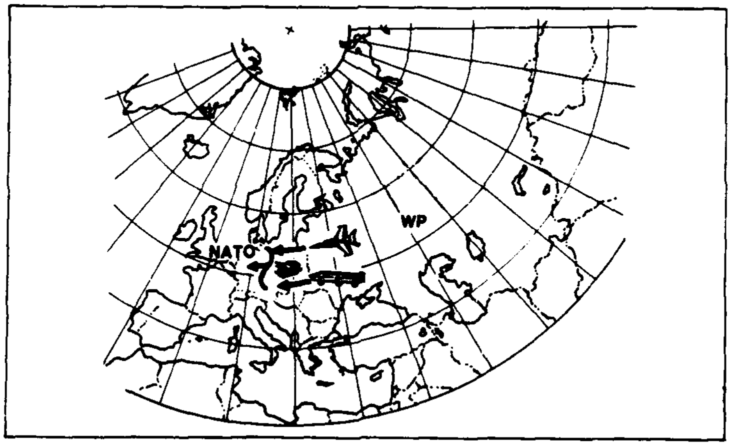

Figure 2. Force Deployment Treaty Monitoring

OPERATIONAL CONCERNS		MEASURES OF EFFECTIVENESS
FUNCTIONS AGAINST TARGET SET	DETECTION	VALID DETECTION RAID DETECTION RATIO RAID COUNT RATIO FALSE REPORT RATE LOCATION ACCURACY
	TRACKING	TRACKING ACCURACY TRACK MAINTENANCE CAPACITY
	CLASSIFICATION	CORRECT CLASSIFICATION INCORRECT CLASSIFICATION
REQUIRED OPERATING AREA		COVERAGE SEARCH PERIOD
AVAILABILITY		AVAILABILITY SYSTEM VULNERABILITY SYSTEM SURVIVABILITY
TIMELINESS AND ACCESSIBILITY TO OPERATIONAL FORCES		WARNING TIME REPORT TIME INTERVAL TASKING DELAY FEEDBACK TIME DELAY

Figure 3. COEA Measures of Effectiveness

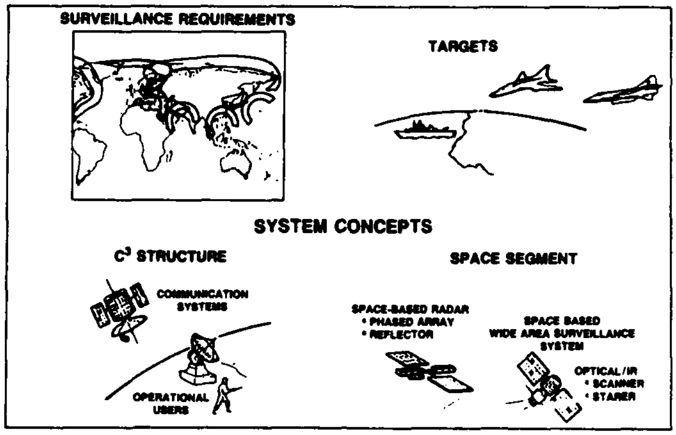

Figure 4. Major Simulator Inputs

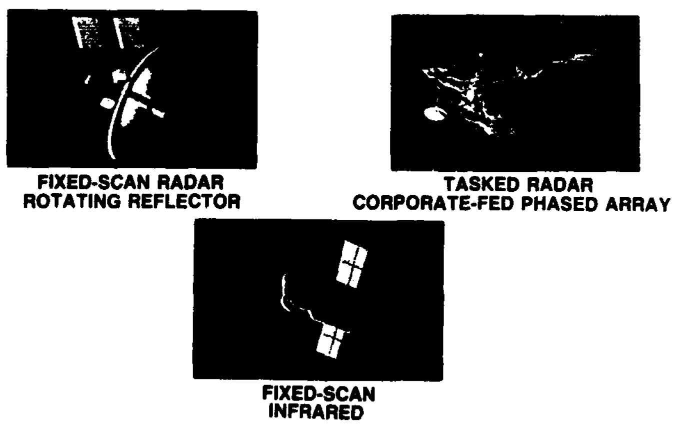

Figure 5. Space-Based Wide Area Surveillance Concepts

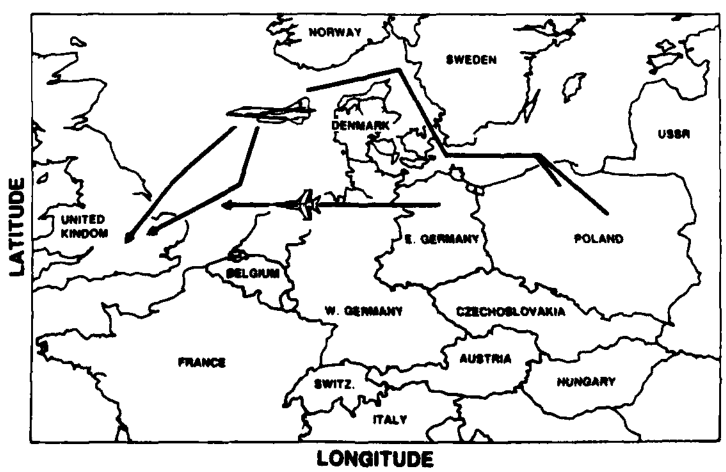

Figure 6. Badger Attack on United Kingdom Airfields

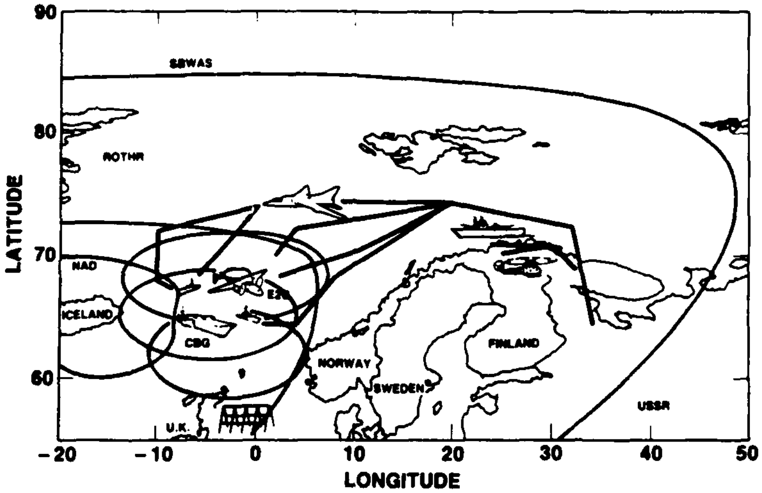

Figure 7. Fleet Defense/Maritime OPS

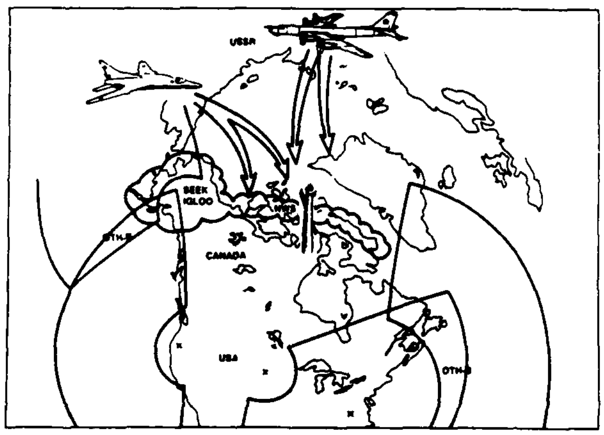

Figure 8. North American Defense

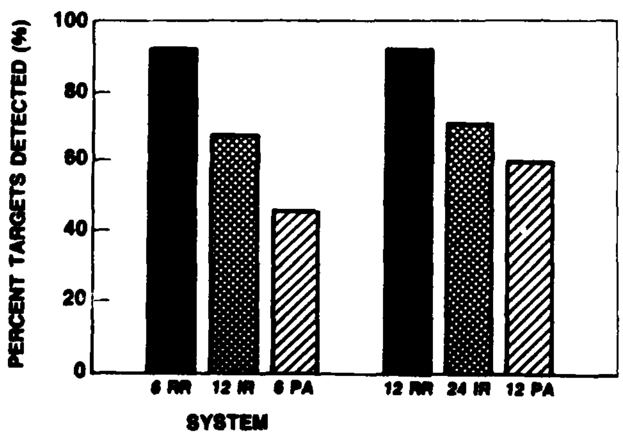

Figure 9. Percentage Targets Detected

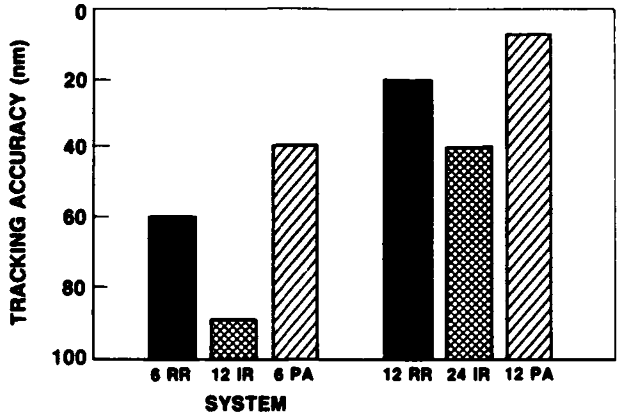

Figure 10. Tracking Accuracy

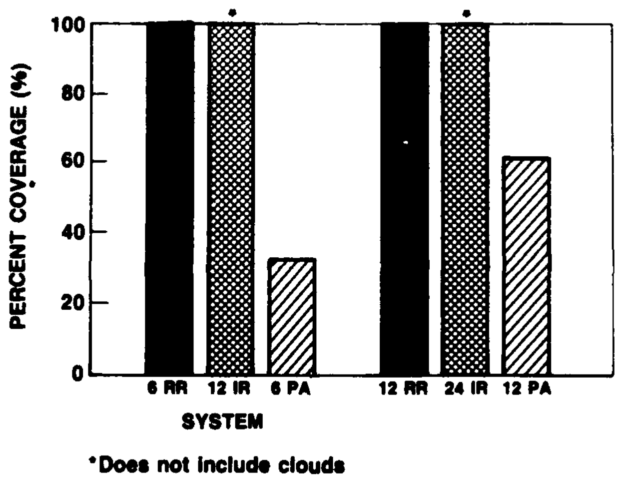

Figure 11. Coverage

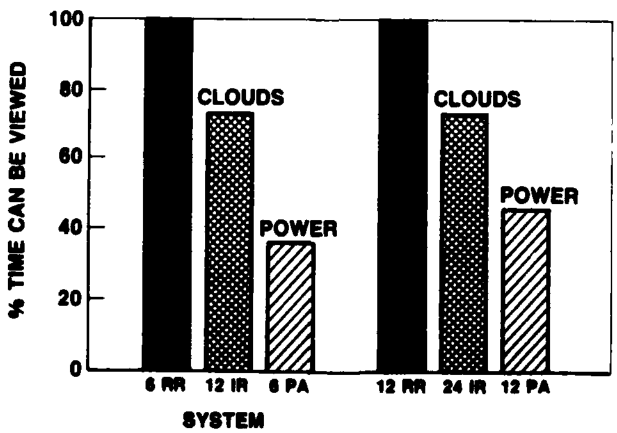

Figure 12. Availability for Search

DISCUSSION

QUESTION P. J. Scarlett

Does the simulation incorporate the use of Displaced Phase Center Array (DPCA) techniques to reject clutter for phase area surveillance? This technique is not applicable to reflectors.

Does the simulation consider the increased cost in raising a "constant orbital weight" to the higher altitude required by a reflector-type radar satellite?

ANSWER

Yes, the simulation incorporates DPCA techniques for the phased array radar to meet minimum detectable velocity requirements. DPCA is not applicable to reflector-type radar; hence it requires higher altitude and/or higher frequency to achieve a comparable minimum detectable velocity to a phased array radar with DPCA.

The cost to raise a "constant orbital weight" to the higher altitude required by reflector-type radar is driven by the type of launch vehicle. In the current space based radar study, all satellites were sized to fly at low altitudes and use medium-size launch vehicles. If a constellation was placed at higher altitude, it would require heavy launch vehicles. High altitude total constellation cost is estimated at $10-15B versus lower altitude cost of $5-6B. Reflectors can be placed at higher altitudes and achieve good performance due to the large power aperture product available at a given satellite weight. However, in this study, other factors favored lower altitude.

QUESTION P. J. Scarlett

What is the impact of selecting a reflector or phased array on side lobes, electronic counter-counter measure (ECCM) requirements, and probability of detection?

ANSWER

Reflector and phased array side lobes compare within 0-10db depending on selected reflector feed technology and variations in expert opinion. Current analysis indicates that the potential for large ground-based jamming threats is so great that any ECCM advantage for the phased array is not realized. Both reflectors and phased arrays will have ECCM capability to operate through aircraft and ship threats, but will be largely dependent on terrain masking for large round-based threats. Since both systems are susceptible to main beam and side lobe jamming, outages would be experienced around jammers ranging from 0-30 minutes depending on the satellite orbit and radar operating mode.

However, except for a small spot around each jammer, no area is permanently denied to space based radar. Simulations are currently being run to quantify probability of detection and system availability for each type of radar in the presence of jammers.

DISCUSSION

QUESTION D. Pichoud

Since the beam of the space based radar is necessarily wider than a synthetic aperture radar, the signal returned from a stationary or slowly moving target could be completely hidden by clutter. Does your simulator take this into account? Will it really be feasible to detect ships with the proposed system?

ANSWER

Yes, the simulator models the effects of ocean clutter. The large radar cross section for ships gives good resolution for slow moving ships. Search for ships will be at a standard scan rate but at reduced power consistent with target radar cross section.

QUESTION K. G. Brammer

The advantages of space based radar were outlined. A major drawback of ground based radar (relative to passive sensors) is their beacon property. Presuming that in space there is not much difference between detecting a radar satellite or an electro-optical satellite, there may be a disadvantage for radar systems from the threat by anti-radiation weapons (missiles) homing on the radar emission. Did you analyze this problem in your studies (and did you consider any countermeasures)?

ANSWER

No, this particular problem was not analyzed. As a result of these questions, homing threats and necessary countermeasures will be studied in order to provide an appropriate response.

DISCUSSION

QUESTION R. Klemm

The paper indicates that phased arrays are the worst option for space based radar. However, phased arrays can be superior to reflector antennas with respect to multi-function operation, ECCM, protection against radiation-homing devices, and DPCA provided that multi-channel outputs are available. How is this superior technological performance of phased arrays consistent with the conclusions in the paper?

ANSWER

The poor showing of phased arrays in this paper is not based on any technological disadvantage for that type of system other than weighing about three times as much as a reflector system with the same power-aperture. There is no dispute about the favorable technological attributes of phased arrays.

The simulations reported in this paper compare rotating reflector radar, phased array radar, and infrared satellite systems with equal weight on orbit. This constrains the power-aperture of each phased array to approximately 1/5 that of the rotating reflector. As a consequence, the full potential of the phased array are not realized.

This study was driven by a search for an affordable system that provides the most performance at a given cost. The rotating reflector, on balance, provides the most capability when complete system affordability is the measuring criterion.

COMMAND AND CONTROL IN THE AGE OF SPACE-BASED SURVEILLANCE

by

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SUMMARY

The Canadian and United States defence departments are currently investigating requirements and technologies appropriate to a constellation of radar satellites providing global surveillance against targets such as cruise missiles, long-range bombers, strategic fighters and surface ships. Command and Control of Canadian forces using data obtained from this Space-Based Radar (SBR) satellite system will pose an intricate set of problems, complicated by data transfer requirements and the potential number of agencies involved with different aspects of SBR operations. Since extensive on board processing is unlikely during the early years of SBR, data will need to be downlinked to a central facility, processed and distributed to appropriate regional stations. Operational tasking requirements from regional stations will have to be coordinated by the central control station and uplinked to the satellite. All of these processes will need to be carried out within the real-time constraints of a surveillance operation. This paper discusses the data transfer and processing constraints in the context of the command and control issues that will arise with the advent of SBR.

1. BACKGROUND

Space-based surveillance is nothing new. The superpowers have depended heavily on space-based surveillance systems for intelligence and treaty monitoring since the early 1960s. However, these systems have been strategic rather than tactical. Their information has been available to only select agencies and often required extensive amounts of time for processing and assessment.

In the near future, the development of wide area space-based surveillance systems will add a new dimension to these capabilities. The Canadian and United States defence departments are currently investigating requirements and technologies appropriate to the development and deployment of a space-based wide area surveillance system which would provide tactical and strategic data to a wide spectrum of users. While both infrared and radar systems are under consideration, the emphasis is on space-based radar (SBR) because of its inherent all weather capabilities.

A space-based wide area surveillance system could provide global coverage of many types of targets. It is technically feasible to develop a system in the near future for surveillance of land, sea and air vehicles. For this reason, there are a number of agencies interested in participating in the program. The predominant interests at present appear to be in detection, classification and tracking of air and sea targets. In Canada, the requirements are to support the North American Aerospace Defense (NORAD) air defence mission.

The wide area surveillance system envisaged will consist of a constellation of satellites in polar or near polar orbits. As shown in Figure 1, these satellites could detect threats crossing a barrier or "fence" at long range from strategic approach points to North America, as well as detecting concentrations of forces. The satellites could also be used for tracking and classifying targets in their field of view ahead and behind the barriers.

As each satellite sweeps past one coverage area, it must transfer its data and surveillance responsibilities to another satellite entering into the area it is leaving. All data must also be relayed down to the ground processing and data distribution centres for forward transmission to the end users. There will be enormous amounts of data available from a space-based wide area surveillance system. The issues raised by this are discussed in Section 2. Also, in the development and deployment of such a system, care must be taken to develop the command and control (C^2) doctrine and system in parallel with the surveillance system. Section 3 discusses the C^2 issues that must be addressed as we move into the age of space-based surveillance if we are to capitalize on the inherent capabilities of such a system.

2. DATA HANDLING ISSUES

Over the past several years, there has been a number of studies into wide area surveillance technology which presented a variety of concepts for the deployment of a space-based system. To date, the specific system architecture has not been chosen. Therefore, any discussion of command and control issues must be based on broad system concepts rather than specific implementation criteria. However, regardless of the exact nature of the final design deployed, there will be a new level of magnitude of data to be transferred, analysed and used.

Current terrestrial or air-based surveillance systems are limited in their capacity by their field of view and the constraints imposed by land features and earth curvature. The focus in the past has been to increase a systems ability to "see" by using ionospheric reflection, high altitude, speed or some other convenient mechanism. With a space-based system, the field of view is not a major issue. The primary concern will be to use effectively the satellites' wide area coverage.

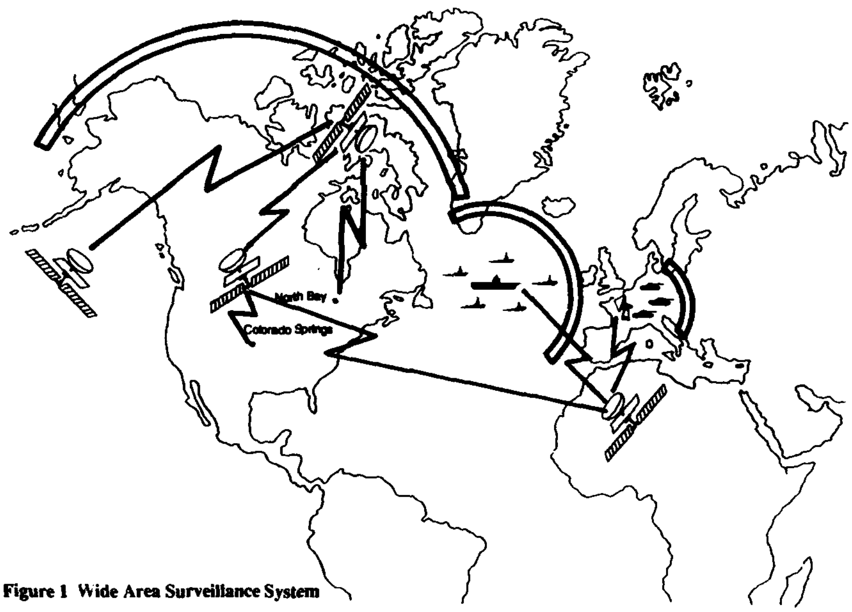

Figure 1 Wide Area Surveillance System

There are two general types of data to be considered from a space-based system. First, for the air defence and tactical warning roles, a system capable of detecting, tracking and classifying airborne targets over a wide area will be needed. The data for this role will have to be available in real-time for operator assessment and reaction. This implies bringing the data down from the spacecraft and presenting it to the operators responsible for the particular area. Some portion of this data must be sent to forward users for tactical support. For example, an air defence scenario could include detection and tracking of an aircraft, determining its identity or lack of known friendly status, assessing the track in an operational control centre, and forwarding the track data to an interceptor or surveillance aircraft. A naval environment would likely use a ship as an operational control centre, but the general mission of monitoring all air traffic, assessing the traffic and supporting an appropriate response to perceived threats requires real-time processing and assessment of data from the entire area of surveillance of the space-based system.

The second type of data that can be obtained by a space-based system is detailed information about a small area, likely in the form of radar imagery produced by a synthetic aperture processing technique. The imaging role of the system will impose even greater demands on the command and control system. There will be imaging requirements identified before the pass of each satellite as well as immediate response to targets of interest detected and displayed in real-time. Depending on the number of end users, processing and rationalizing these requirements could be a major task. These requirements must then be passed to the satellite controllers for command input. Once the data has been collected, it must then be processed and forwarded to the end users. While not all of the processing will need to be done in real-time, any lengthy processing needed could result in backlogs of data waiting to be analyzed and the requirement for large support centres.

If space-based surveillance is to be responsive to the tactical user, a considerable increase in current data processing speed and system command and control will be required. As an example, the current northern air surveillance system, the North Warning System, covers a relatively thin band based on line of sight from the radars to an aircraft at a particular altitude. A representative area of coverage is illustrated in Figure 2. While any air targets that enter this region will be detected and tracked in real time, the size of this region is minute relative to the expanse ranging from at least the domestic Canadian air routes to the Soviet Union that would be covered routinely by a space-based system. An even greater contrast can be made between space-based surveillance and airborne surveillance systems such as the Airborne Warning and Control System (AWACS). Considering these relatively different areas of coverage alone, it is not unreasonable to assume that a space-based wide area surveillance system would monitor at least 100 times the targets in a particular time frame compared to current surveillance systems used in the Canadian area of air surveillance in support of NORAD.

Comparison to civilian space-based radar systems is not totally valid because of the different roles, but does lead to some conclusions on the relative data handling challenges. For example, the former SEASAT imaging satellite was operational for less than four months, yet the data was analysed for a number of years. The proposed Canadian RADARSAT and ERS-1 will be synthetic aperture radar imaging systems with a relatively small field of view consisting only of a swath along the satellite track, yet these systems will require operations centres for task coordination, satellite tasking, data reduction and data dissemination. It will take approximately one hour to process a minute of data, and several days or even weeks notice prior to collecting data. While it is possible to point to these civilian imaging satellites as examples of space qualified radar systems, there is no basis for comparison of their C^2

Figure 2 Current North Warning System Radar Coverage

challenges or systems with that of a military space-based radar system. The advent of a space-based wide area surveillance system with global coverage will require a completely new approach to system management to support the tactical user.

The need for some level of real-time assessment of data from the system makes the data handling technologies the key to system implementation. The tradeoffs between on-board and ground-based data processing must include the need for system growth and development while providing the capability to process high data rates, 200 to 300 MBS, for the tactical user. The technical issues of data handling have been studied for a number of years. Implementation of a satisfactory system will be challenging but feasible. However, there are a number of command and control issues that must be resolved before selecting a particular approach to the implementation of a space-based surveillance system.

Another data handling issue concerns the reduction, display and management of data. Even now, managers and commanders are becoming overloaded with information. The task of selecting only the pertinent data and displaying it in a usable fashion is receiving increased attention. The age of space-based surveillance will show a dramatic increase in the quantity and quality of data available to commanders. Position and force will become increasingly important as the element of surprise is lost to both sides. The advantage will rest with the side that can better manage the data available to them.

A space-based surveillance system with the ability to detect and classify targets under all weather conditions, day or night, with wide area or global coverage will provide truly open skies to commanders, but also present a formidable data handling challenge. The potential increase in data for the Canadian NORAD role was referred to earlier. A similar increase in data handling can be anticipated for other roles as well. For example, only a few years ago, the information available to the commander of a maritime force consisting of long-range maritime patrol aircraft, short range shipborne aircraft and surface units was limited by the ability of the force to "see" and to report. Units of the force operating at beyond line of sight range tended to operate independently in assigned areas and report by HF voice radio. Tactical data was processed and assessed by these units with only the minimal necessary information being passed back to the force commander. Data handling was largely manual, and a commander had to rely heavily on judgement and overall assessment of the tactical situation.

A modern maritime force commander will monitor several satellite communications channels and have a much better appreciation of the tactical picture. Improved communications capabilities have increased a commander's ability to use data obtained by remote units, but at the cost of substantially increased data handling and display requirements. Providing an order of magnitude more data from a space-based surveillance system will dramatically alter planning and tactics, but only if this data is presented in a clear manageable fashion.

3. COMMAND AND CONTROL ISSUES

The last decade has brought about significant advances in the ability to transmit large quantities of data over long distances and process this data in near real-time, with consequent changes in C^2 concepts. Now central staff at higher levels have immediate access to data on tactical situations, which is blurring the traditional lines between staff and line functions. The coming age of space-based, wide area surveillance will pose more significant questions on the relative roles between field forces and staff units. The technical capability to monitor air, land and sea forces from a central command unit will allow tactical control of missions from a central staff unit. While the scientists and engineers develop the surveillance technology, there must be a corresponding development in the concepts of C^2. How much tactical control can, or should, be centralized for different mission types? To what degree should non-military trained personnel be a part of tactical decision making and at what level? The advent of space-based surveillance will provide the capability to present tactical data in central headquarters and to political bodies. How far is it advisable to move tactical control from the on-scene commander?

A space-based surveillance system is not likely to change the C^2 concepts for air defence. The NORAD command and control system is based on Regional Operational Control Centres (ROCCs). Each of these centres is responsible for the air activity in its defined area. The data from the current land- and air-based surveillance systems is processed regionally and distributed to central or tactical users as required. Command and control in the current NORAD context can be considered centralized with the end limitation being the interceptor aircraft communication equipment.

While there will be more data, the end limitation of the aircraft equipment and crew size cannot be expected to change significantly with the introduction of SBR. Although improved surveillance has resulted in some centralization of C^2 in the past, the current system, centralized along national and geographic lines, provides an appropriate structure for space-based surveillance data.

However, the capabilities of a space-based system will result in a dramatic increase in the amount of information available with a corresponding increase in the number and type of end users of the data. The current emphasis on an air defence command, control and communications (C^3) structure could shift towards a multi-user support system, including non-military users. Piotrowski refers to surveillance of the Caribbean basin to support drug control operations.[1] Space-based surveillance data will also be invaluable for air traffic control[2] and Search and Rescue. Since these functions will use the data on a daily basis, there will have to be a growth in C^3 capabilities to provide the required level of real-time support to the appropriate non-military agencies. While a military-funded, space-based surveillance system will be driven by military requirements, the value of the data to other national users will thus increase the command and control tasks and structure of the current system.

Maritime operations tend to be more limited in geographic scope than continental air defence. With a space-based surveillance system that performs the ship detection and classification mission as well as air defence detection and tracking, the impact on current C^3 is more significant. With real-time data on surface forces and air traffic, the naval force commander will be able to position and direct his assets much more effectively. As has happened in the air defence mission, the impact of improved surveillance will be to centralize C^2. The surveillance data, along with secure beyond line of sight communications, will allow tactical force direction from a command unit physically removed from the scene of action. If the satellite data processing is also centralized in a single (or few) units for technical or cost reasons, there will be even more incentive to provide direction rather than data to tactical forces. The anticipated result will be a lessening of authority for the on-scene or task force commander, even if the current doctrine does not immediately change with the advent of space-based surveillance.

Land operations are even more limited in geographical scope than maritime. For example, the region in central Europe separating NATO and Warsaw Pact forces only covers about 8° of latitude. In a nominal 110-minute polar orbit, a satellite would pass over this area in about 2-1/2 minutes. Even allowing for extended line of sight coverage from orbital altitude, continuous support to NATO land forces will require considerable data transfer from satellites in subsequent passes with the attendant tracking and processing requirements. In this environment, distributed data processing would be difficult, especially for early generation space-based systems which will likely require considerable ground-based data processing. Therefore, system management and data processing can be expected to be centralized. The provision of this real-time data on land force location and makeup will allow the commander to give tactical direction to forces from a centralized location. Again, the anticipated result will be a lessening of local command authority with a blurring of the traditional division between line and staff responsibilities.

Although not a traditional C^2 issue, the management of the satellites must also be addressed as part of the overall C^3 doctrine and architecture. The command level that receives and processes satellite data would logically want to be able to task the satellites in near real-time to obtain more information on a particular target or area of interest, particularly in response to a rapidly changing tactical situation. For the NORAD air defence mission, this tactical control is not so critical because the global surveillance capabilities of a space-based system would provide a continuous air picture. Also, a shared Canada/United States development and deployment of a space-based surveillance system to meet NORAD wide area surveillance requirements (among others) should not lead to conflict in resource allocation. The Commander in Chief NORAD is responsible for North American surveillance and is in constant consultation with his Canadian deputy. Both military and political channels of communication are well established and have worked for over 30 years in cooperative surveillance and defence of North American airspace.

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1. *Gen. John L. Piotrowski, USAF, "Space Based Wide Area Surveillance." SIGNAL, May 1989, pp.30-34.*

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2. *Murray MacDonald "Space-Based Radar as an Air Traffic Control Sensor." Proceedings of the Airshow Canada Symposium, August 1989, Vancouver, Canada.*

The satellite C^2 situation is somewhat different for maritime or land use where imaging, or surface target classification is required in relatively small areas. Tactical control of the satellites becomes increasingly important and the energy expenditures are more difficult to accurately predict. To pick only one illustration of a possible conflict in resource allocation, the transit of a large naval force from the central Atlantic Ocean to the North Sea could require both wide area surveillance and considerable ship classification, imaging, to support the transit. If the force commander had to contend with bad weather and heavy air and surface traffic, he would want extensive use of the surveillance system. This situation would only be temporary, yet, if not provided for in system design, could result in excessive demands on the satellites and a degradation of the ability of those satellites orbiting northward from over the Atlantic region to support the NORAD surveillance mission. Obviously, there are many combinations of surveillance requirements which must be considered and provided for in the design and development stages of a wide area surveillance system. The final considerations will depend on the agencies that require and fund the system.

Given that there will be land, air and maritime missions to be supported by the space-based surveillance system, a workable concept could be to provide the level of C^2 necessary for each type of mission with assignment of a proportion of system capability to each user. For example, the NORAD mission could be supported by centralized data processing and C^3. The resources necessary to support this mission would be agreed to with appropriate funding levels assigned prior to system deployment. Similarly, maritime and land forces could identify the level of support they required and provide the appropriate funding for their part of the system usage. Invariably, priorities and demands on the system will change; however, agreement and proportional funding support prior to system deployment would minimize the problems in assigning surveillance capability.

4. SUMMARY

The age of space-based surveillance offers a dramatic leap in capabilities. No longer will systems be limited by line of sight or ionospheric restrictions. Satellites will have global coverage of air, land and sea forces and have the ability to provide this information to commanders wherever required. This capability raises a number of issues and questions that must be addressed in the development of the space-based surveillance system. The trend in C^3 has been to centralize data integration and display. Increasingly, central agencies have access to real-time tactical data. The advent of space-based surveillance will have a significant impact on C^2 capabilities and doctrine. We face a threefold challenge in the immediate future:

1. the technical development of a space-based, wide area surveillance system,

2. the development of appropriate data handling and display systems, and

3. the development of C^2 doctrine to capitalize on the capabilities of the age of space-based surveillance.

GLOBAL POSITIONING SYSTEM OVERVIEW/STATUS

by
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This paper summarizes the GPS program status and provides a review of the system concept and several applications.

1. System Concept

GPS is a space based radio-navigational system that provides all weather, continuous, global position, velocity and time information to users. The system consists of three segments, Space, User and Control (See Figure 1).

The Space Segment spacecraft broadcasts the navigation signals which consists of two carrier signals, called L_1 (1575 MHz) and L_2 (1227 MHz), two ranging codes, the Coarse/Acquisition (C/A) and the Precision (P) code, and a navigation message which is superimposed on each code. The P code is broadcast on both L_1 and L_2 while the C/A code is broadcast only on L_1. Each spacecraft has its own C/A and P code. The Space Segment will eventually consist of 24 spacecraft distributed in 6 planes at an altitude of 11,000 nm (half-synchronous). There are currently 10 Block I Spacecraft in orbit of which 6 are still in operation. These spacecraft were launched between 1978 and 1985 and were designed to demonstrate system feasibility. There are in addition 3 Block II operational spacecraft in orbit which have been launched this year. Two of these are currently set healthy and the third is about to be set healthy.

The User Segment consists of GPS receivers of various types that process the incoming signals to generate a navigation solution. This is accomplished by having the receiver generate the C/A codes of all spacecraft in view. This permits tracking of the P Code, the carrier and navigation message. The navigation message provides information on satellite position and GPS time, while the code is used to determine the distance between the User and the spacecraft. (See Figure 2.) A User can determine 3 dimensional position and time by taking ranging measurements to 4 spacecraft, and through the use of doppler tracking of the carrier, 3 dimensional velocity as well.

User equipment is being designed to meet platform requirements (See Figure 3). For high performance aircraft, a set is being provided that permits simultaneous tracking of 5 spacecraft (5 Channel Applications) and a modified version of this set is being used for shipboard applications. The 2 Channel Application is being provided for helicopters while the 1 channel set can be carried by infantryman or used by land vehicles.

The Control Segment consists of 5 monitor stations located at Hawaii, Kwajalein, Colorado Springs, Ascension and Diego Garcia, 3 Ground Antenna collocated with monitor stations in Kwajalein, Ascension and Diego Garcia and the Master Control Station (MCS) at the Consolidated Space Operations Center (CSOC) in Colorado Springs. The monitor stations which are at fixed, known locations, receive the spacecraft navigation signals and forward ranging data to the MCS. The MCS uses this information to make estimates and predictions of spacecraft ephemeris and clock offsets from GPS time. Periodically, the control segment transmits fresh ephemeris and clock predictions to the spacecraft using the ground antenna. The ground antenna are also used for monitoring spacecraft health and for sending commands.

It is expected that when each spacecraft is provided a new prediction every 10 hours, that the worldwide system position accuracy will be 16 M SEP when a full constellation of spacecraft are deployed. However, this level of accuracy may not be provided to civil or unauthorized users. Present policy calls for providing such users a worldwide accuracy of 100 M 2dRMS (95% of all solutions will be within a circle of 100m in a horizontal plane). In addition, use of the P code may be denied to unauthorized users.

2. Program Status

A. Space Segment

The first three operational Block II spacecraft have been launched this year and two additional launches are planned before the first of next year. An operational constellation of 21 Block II spacecraft should be available by the second quarter of FY 1993 (See Figure 4). The remainder of the 28 spacecraft contracted for with Rockwell-Seal Beach will be used to maintain the constellation in future years. It is expected, however, that additional spacecraft will be needed in 1996 to support the constellation. In June of this year the GPS Joint Program Office awarded a design contract to General Electric with production options for 20 spacecraft which are designated as Block IIR spacecraft. It is expected that Block IIR spacecraft will maintain the GPS constellation into the 21st century.

B. Control Segment

The GPS Control Segment has been in operation for more than 10 years. Space Command personnel are currently operating the system with contractor and JPO support. Program management responsibility for the control system hardware has already been turned over to Air Force Logistics Command and it is planned to turn over mission operations responsibility to Air Force Space Command next year. Space Command is currently performing maintenance on the control system hardware.

C. User Equipment

Current plans call for purchase of approximately 26,000 sets over a 13 year period (See Figure 5). Low Rate Initial Production (LRIP) was initiated with Rockwell-Collins in 1986 after review and approval by the Defense Systems Acquisition Review Council (DSARC). In June 1990 the Defense Acquisition Board (DAB) will review program status and test results prior to deciding on full rate production. In preparation for this review all three services have been conducting development and operational tests using operational sets provided by the LRIP (See Figure 6). Figure 7 shows some recent results from a F-16 test where GPS results are compared to an INS that is periodically updated. CEP with GPS was in the 5m range, while with an INS CEP varied from 15-70m.

3. Applications

Figures 8 and 9 list potential GPS military and civil applications for which analysis have been completed. GPS is currently being used in surveying and range instrumentation and there are plans for use in en route navigation, nonprecision approach, rendezvous, maritime navigation and for satellites. A GPS receiver was used on the LANDSAT satellite in the early 1980s. Figure 10 shows orbital position errors over a 5 hour time period for LANDSAT. The results are very good particularly since only a few GPS spacecraft were in orbit at that time. The results of a more extensive study (Reference 1) of orbit determination accuracy using GPS is shown in Figure 11 where it is assumed that a full GPS constellation was in orbit. For low altitude spacecraft GPS can provide a 10m (one-Sigma) position accuracy, while for a synchronous satellite, which can only obtain range measurements on the other side of earth, a 100m (one-Sigma) accuracy can be obtained.

4. Summary

The GPS system appears well on its way to becoming a fully operational system. A full constellation should be available by FY 1993 and full scale user set production is expected during 1990. As the system becomes operational new applications will become apparent and less accurate methods for navigation will likely be replaced by GPS.

Reference: Ananda, M. and Jorgensen, P., "Orbit Determination of Geostationary Satellites Using the GPS." Proceedings of the Symposium on Space Dynamics for Geostationary Satellites, CNES, Toulouse, France, October 1985.

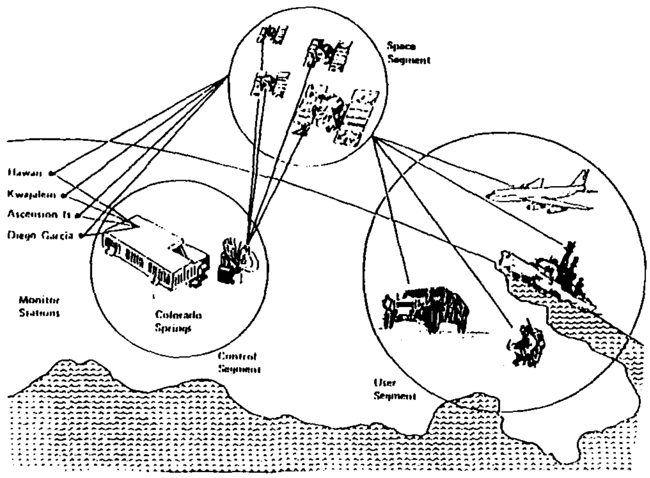

Figure 1. GPS SYSTEM

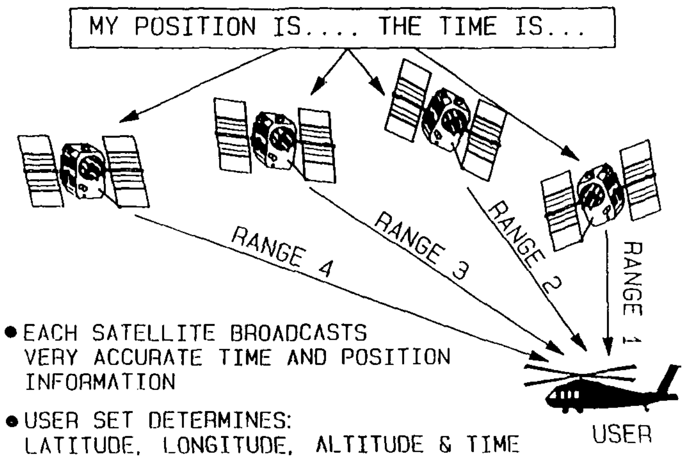

Figure 2. HOW GPS WORKS

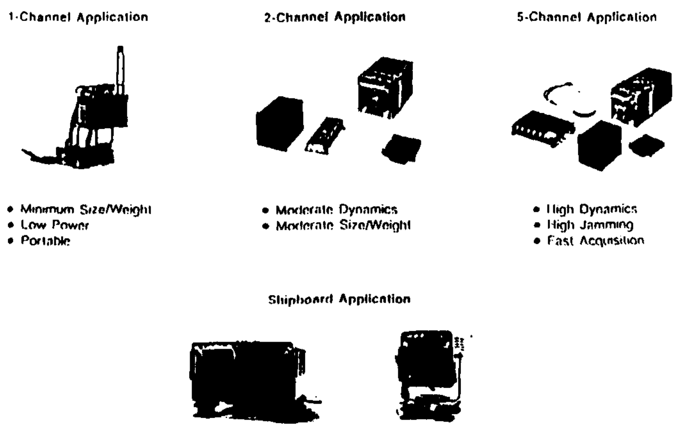

Figure 3. SYSTEMS APPLICATIONS

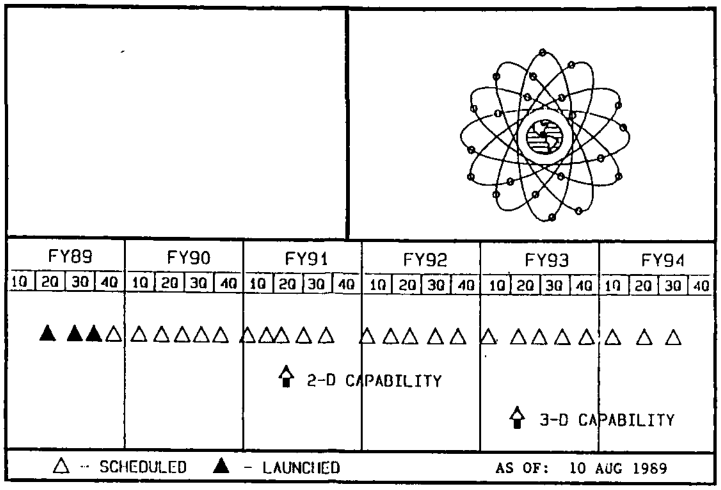

Figure 4. GPS BLOCK II LAUNCH SCHEDULE

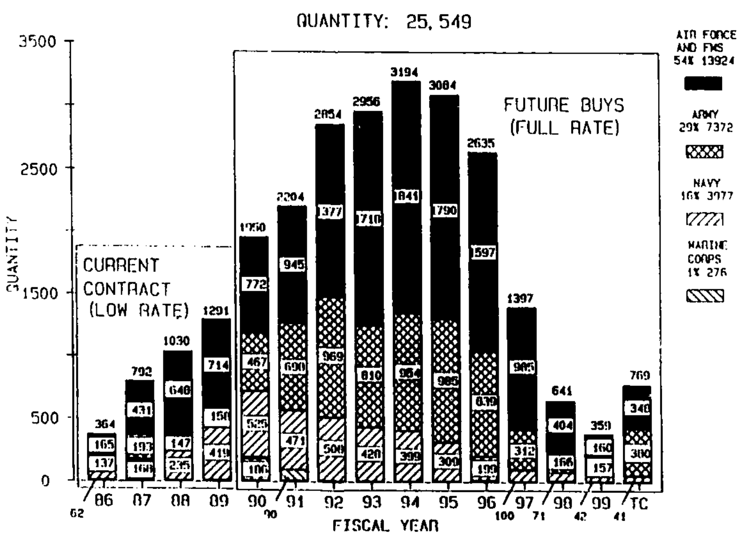

Figure 5. GPS USER EQUIPMENT PRODUCTION

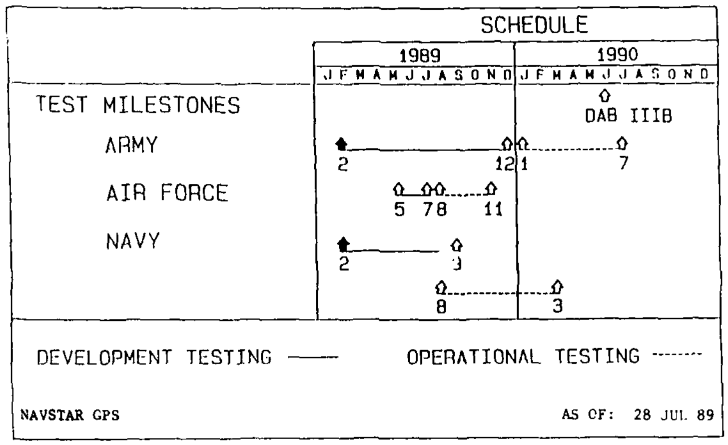

Figure 6. GPS USER EQUIPMENT TEST PROGRAM

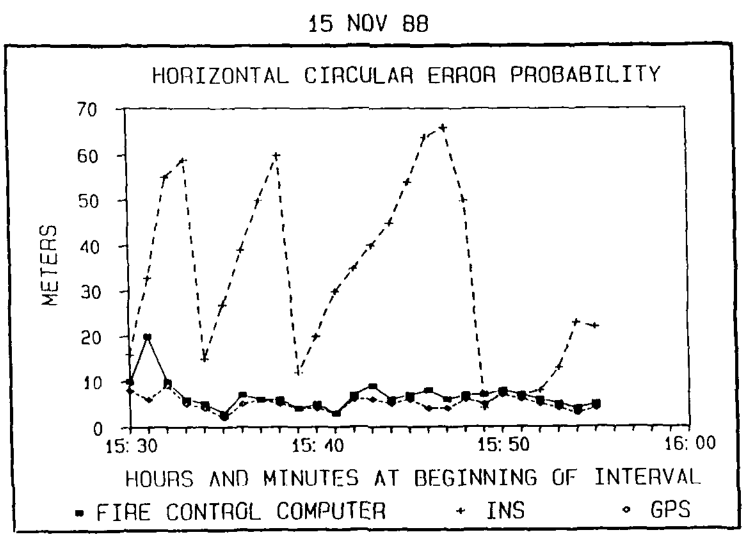

Figure 7. F-16 FLIGHT TEST

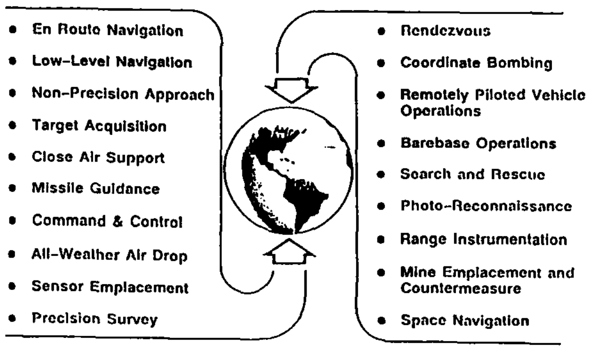

Figure 8. GPS MILITARY APPLICATIONS

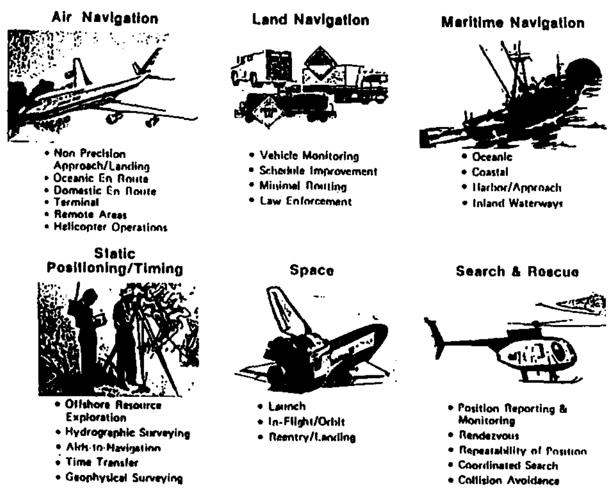

Figure 9. GPS CIVIL APPLICATIONS

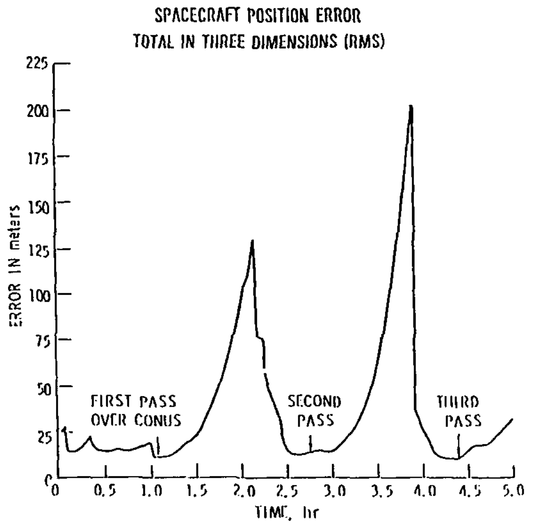

Figure 10. LANDSAT-4 EPHEMERIS ERROR BASED ON ACCURACY ANALYSIS

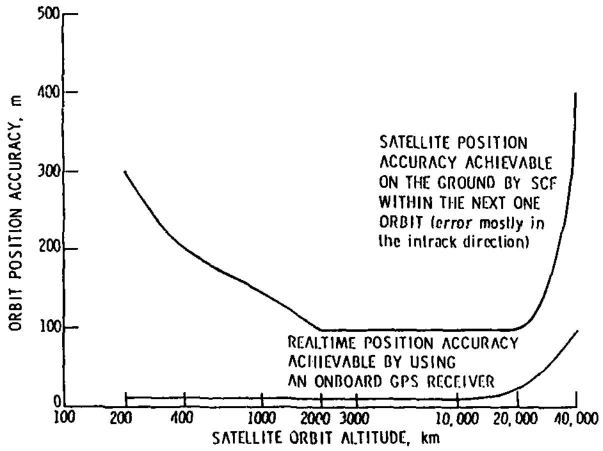

Figure 11. SATELLITE ORBIT DETERMINATION ACCURACY AS A FUNCTION OF ORBIT ALTITUDE

FUTURE APPLICATIONS OF GPS TO CONVENTIONAL WEAPONS

by

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SUMMARY

This paper discusses the potential role of GPS in future conventional weapon applications. Short range weapons can benefit from accurate GPS initialization, while medium and long range standoff weapons could incorporate GPS in their navigation systems. The problem of jamming and design techniques to improve the capabilities of GPS will be discussed. Several important integration issues will also be highlighted.

1.0 INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a space-based RF multilateration navigation system which provides world-wide position and velocity updates to users. The position accuracy is about ten meters, and the velocity accuracy is 0.1 meters/second. This high level of performance is very attractive to designers looking for solutions to weapon guidance problems.

The GPS system has been under development for more than 20 years, and once it becomes fully operational, it will probably be in use for at least that long. GPS represents a huge investment by the U. S. in terms of satellites, ground stations, and user equipment. Therefore, almost by definition, it will be used. Our challenge is how best to apply it to conventional weapon applications.

Potential applications of GPS cover a broad spectrum. There are short range weapon applications such as GPS aided bombing, or using GPS to calibrate and align low-cost inertial systems in Inertially Aided Munitions (IAM). Many medium and long range standoff weapon designs including the Standoff Land Attack Missile (SLAM), the Joint Standoff Weapon (JSOW), and conventional cruise missiles, like the Tomahawk Land Attack Missile (TLAM), incorporate a GPS receiver for midcourse navigation. Testing and training are important adjuncts to weapon development, and GPS has already made significant contributions in these areas.

GPS is extremely accurate; it can be used for navigation over water and flat areas that defeat terrain referenced systems; it is available world wide, is passive, has no pracical weather limitations, and offers great operational flexibility. Despite its many advantages, users are reluctant to rely on GPS because of its perceived vulnerability. Jamming appears to be the greatest threat to GPS in a tactical environment.

2.0 GPS APPLICATIONS IN TESTING AND TRAINING

Some of the problems of using GPS in a wartime environment, such as jamming, are not present in testing and training activities so GPS has won rapid acceptance there. The potential of GPS is enormous; it can turn the whole world into a test range. It frees users from the constraints of limited operating ranges and weather, which are associated with tracking and data collection systems like cinetheodolites, radar and laser trackers. Equipment being developed for GPS range applications will provide instantaneous readout of highly accurate Time Space Position Information (TSPI) for dozens of users in testing activities and slightly less accurate TSPI for thousands of participants in training exercises. The accuracy of data achieved during tests is better than the standard specified GPS accuracy because differential GPS techniques are employed. A GPS receiver at an accurately surveyed location is used to estimate systematic biases and data link corrections to other GPS users. Position accuracies of three meters can be achieved.

The Range Applications Joint Program Office of the Air Force Munitions Systems Division is leading the development of the hardware shown in Figure 1. The Position Location Module (PLM) provides TSPI in high density training exercises and can operate in harsh field environments such as in tanks. The position information it provides can be used for kill determination in wargames. The Translator is a small, inexpensive, throw away GPS tracking unit used for destructive tests (RPVs, missiles, etc.). GPS signals are retransmitted to the Translator Processing System (TPS) located on the ground where the majority of signal processing takes place. In addition to real time, highly accurate TSPI, a dynamic simulator is available to replay missions. Figure 2 illustrates an application of Translators and the TPS in support of the Strategic Defense

Initiative program. The Low Dynamic Instrumentation Set (LDIS) uses a single channel GPS receiver for applications in ground vehicles, ships, and by infantry. The High Dynamics Instrumentation Set (HDIS) has a five-channel receiver and an optional inertial measurement unit to extend dynamic performance out to ten Gs for use in helicopters, aircraft pods, and drones. The HDIS and LDIS feature flexible interfaces for range interoperability, raw data collection for post test analysis and onboard data recording capability. The Ground Transmitter or "pseudo satellite" transmits standard GPS signals and is used to augment GPS satellite coverage or provide greater accuracy through improved geometry.

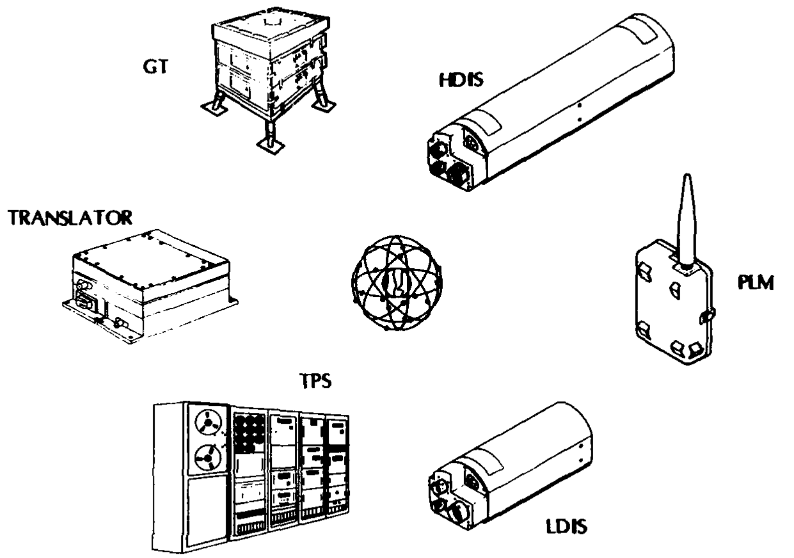

Figure 1. GPS Range Applications Equipment

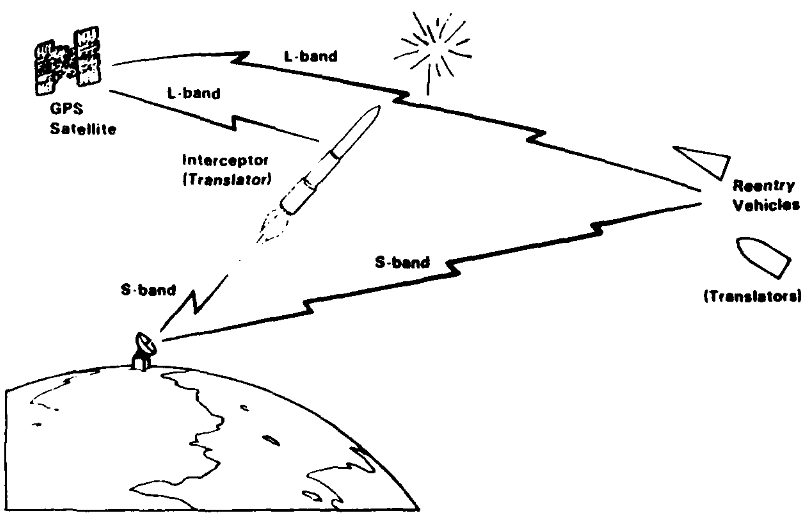

Figure 2. GPS Application to SDI Test

3.0 GPS SYSTEM VULNERABILITY

Figure 3 shows the three segments which comprise the GPS system along with various threats and the design features which counter them. The use of the tactical or conventional weapons discussed in this paper presupposes a level of conflict which is unlikely to threaten the satellites or ground stations. Therefore, it appears that jamming is the greatest threat to GPS operation in a tactical environment.

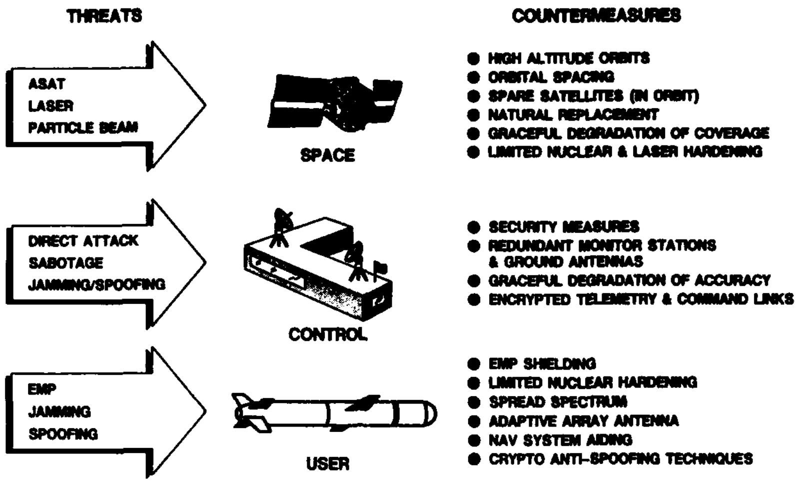

Figure 3. GPS Vulnerability/Survivability

A review of available work on the susceptibility of GPS to jamming reveals widely disparate opinions ranging from the few who claim that GPS is "jam proof" to the many who say it is "easily jammed." This perceived vulnerability has contributed greatly to the military users' reluctance to accept and rely on GPS for weapons guidance. It is true that given enough power and a clear line-of-sight any GPS receiver can be jammed. However, there are other factors relating to GPS receiver design, antenna implementation, reacquisition strategies, GPS/INS integration, and terrain shielding which can increase jamming resistance and allow the weapon to be effectively employed.

3.1 ANTENNAS

Antenna design is a major factor in improving the anti-jam capability of GPS guided weapons. Figure 4 portrays a cross section of gain patterns of candidate weapon antennas. The fixed reception pattern antenna (FRPA) is low cost and small in size but is most susceptibe to ground-based jammers. The switched FRPA has an additional element with an upward pointing gain pattern that reduces ground-based jammer interference. This pattern also suppresses signals from satellites at low elevation angles, forcing the receiver to track higher satellites which reduces horizontal navigation accuracy. However, this is preferable to the complete loss of GPS aiding. The roll-steered antenna is a phased array design which maintains an upward pointing beam during weapon roll maneuvers. This approach allows reduced gain at low elevation angles. The null steering antenna can create steep nulls (30-50 db) in the direction of sensed jammers and is extremely effective unless a large number of jammers are present. This type of antenna requires a large aperture and is costly. The beam steering design forms narrow gain patterns which are directed toward the desired satellites. This is most costly and complex of the antenna design options presented. More attention needs to be focused on antenna designs for weapons, especially low-cost weapons.

3.2 EFFECTIVE USE OF TERRAIN

Low altitude, terrain following flight paths have been shown to improve aircraft and weapon survivability in high air defense threat environments and are a key consideration in mission planning. These same trajectories can also play an important role in countering jamming. Terrain features which block the line-of-sight between a GPS receiver and jammers can greatly reduce the number of interference sources with which the system must contend. Outages due to jamming will also be temporary because of the changing geometry and, assuming a properly integrated system, rapid reacquisition of GPS updates is likely.

Figure 5 shows a jamming scenario and weapon flight path used in a recent study of GPS weapon guidance applications (Ref 1). With earth curvature and actual terrain elevation data factored in, Figure 6 shows how a terrain following profile (50 meters clearance) reduces the exposure of the system to jamming interference.

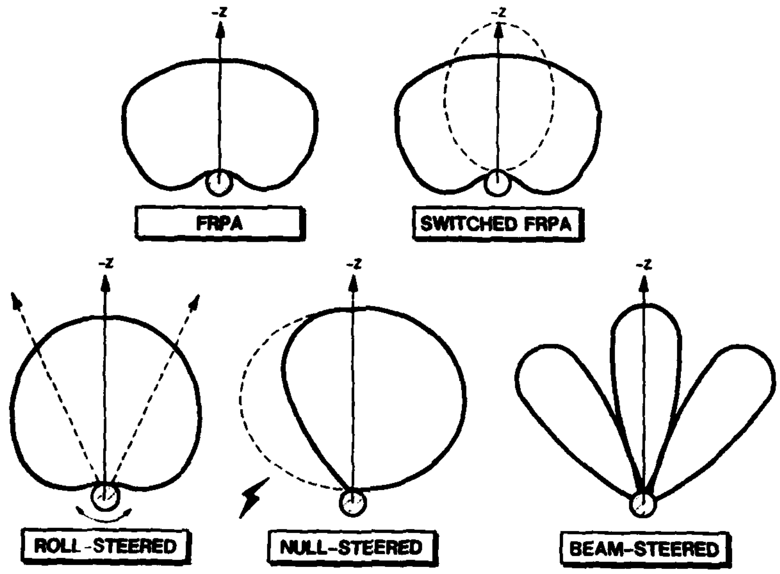

Figure 4. GPS Antennas For Weapon Applications

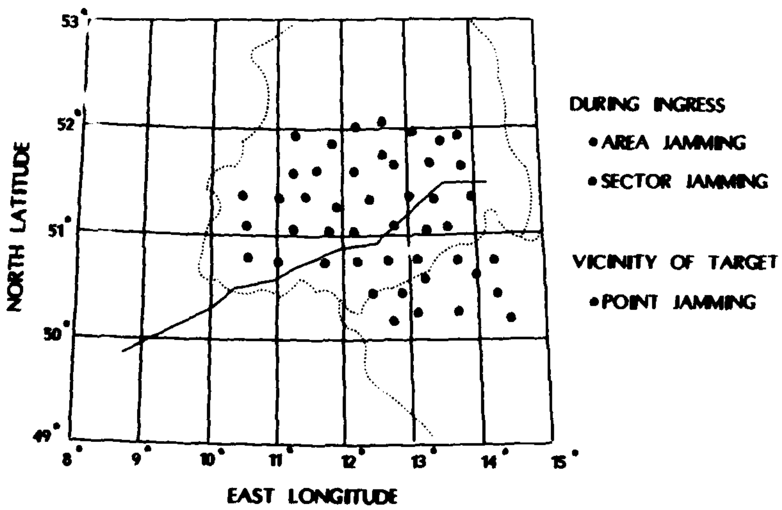

Figure 5. Jamming Scenario

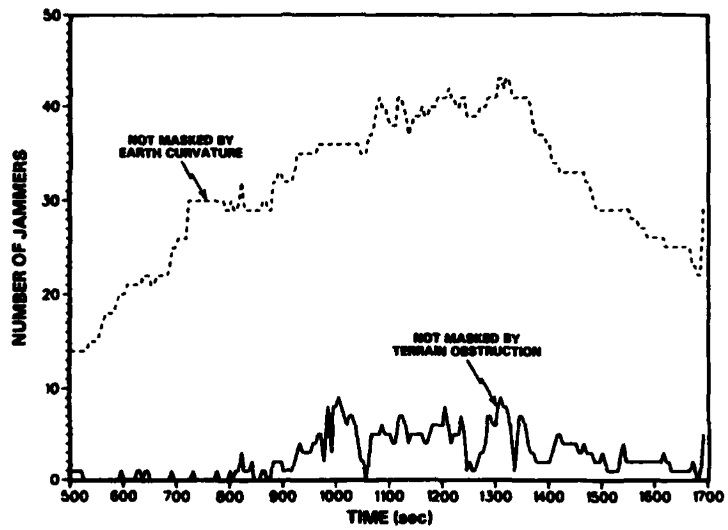

Figure 6. Effect of Terrain Masking on Number of Visible Jammers

3.3 GPS/INS INTEGRATION

Numerous studies have demonstrated that there is a synergy that results from integrating an inertial navigation system (INS) with GPS. While it is possible to use a GPS receiver alone in a static or low dynamic environment, applications to aircraft and weapons require a closely integrated system. GPS provides long-term position and velocity accuracy and continually aligns and calibrates the inertial system. The INS provides short-term velocity accuracy, aids the code tracking loop, shortens acquisition and reacquisition time, allows navigation during GPS outages, and provides acceleration and attitude data for flight control.

Figure 7 details the interplay of the GPS and INS data for an integrated navigation system. The high data rate output of the INS processor is used to generate the nominal navigation solution. The GPS pseudoranges and delta ranges are processed by a Kalman filter to estimate and correct navigation errors. The error estimates can also be used to reset the INS if desired. Velocity data aids the code and carrier tracking loops in following signals during periods of high vehicle dynamics and allows narrowed tracking loop bandwidths, thereby reducing susceptibility to both thermal noise and jamming. The navigation data is also used to speed up the acquisition/reacquisition process.

One of the major advantages of a properly integrated GPS/INS system is a relaxation of the accuracy requirements imposed on the INS. There is a danger in carrying this logic to an extreme, however. It must be remembered that the INS carries on the navigation function through GPS outages, and accuracy is critical to speedy reacquisition. Figure 8 shows that error growth, even in an INS that was calibrated by GPS, is highly dependent on instrument quality.

GPS is viewed by the airplane avionics community as a navigation aid, and its role in weapon delivery is unfortunately relegated to one of secondary importance. Weapon delivery performance may be compromised as a result of poor GPS/INS integration in the aircraft. For example, consider the scenario in which GPS position data is used to correct the airplane INS based navigation solution. This is acceptable from a navigation point of view, especially since the aircraft will eventually leave any area of high jamming, and very accurate navigation will resume. Figure 9 shows the weapon delivery impact of this type of integration when the target is protected by a co-located jammer and the aircraft must fly for several minutes without GPS aiding in order to deliver an Inertially Aided Munition. INS errors, which were not corrected when GPS was available, now propogate and result in poor weapon initialization. This contrasts dramatically with the performanc obtained with good GPS/INS integration. In the context of this discussion, good integration means that GPS aiding allowed corrections to be made for position, velocity and tilt errors, and inertial instrument errors such as gyro drifts and accelerometer biases. Many weapon designer would like to have the raw GPS data (pseudoranges and delta ranges) at the weapon station rather than the highly filtered data available at "standard" interfaces. This would allow greater design flexibility and better performance from future weapons. After all, the primary mission of fighter aircraft is not navigation but delivering weapons that destroy targets.

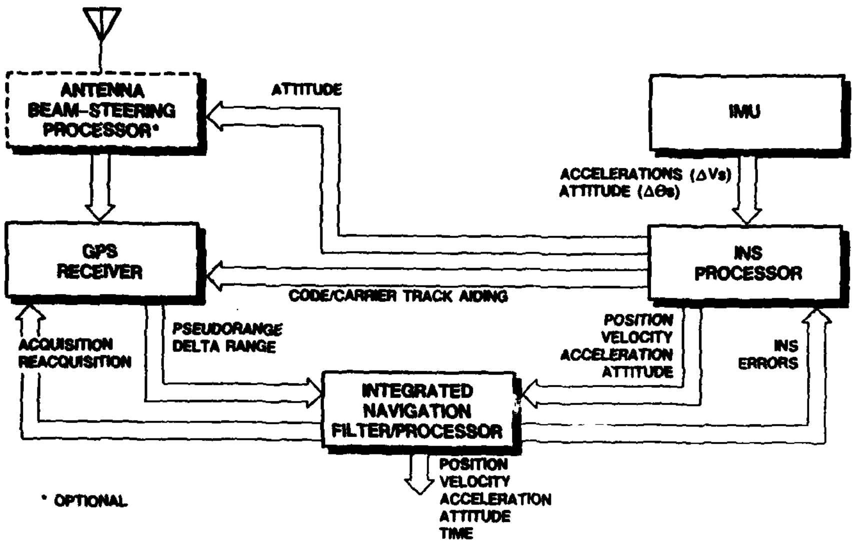

Figure 7. Generic GPS/INS Integration

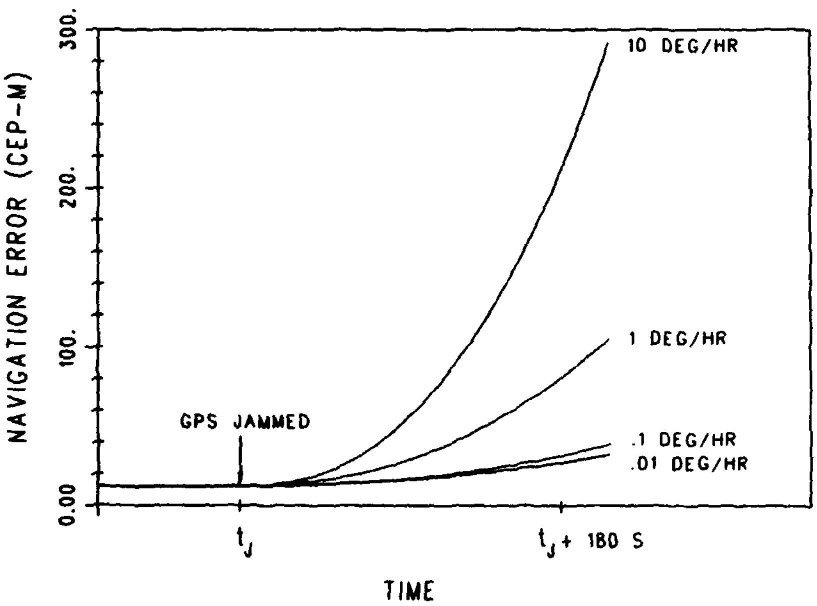

Figure 8. Effect of INS Quality on Navigation Accuracy

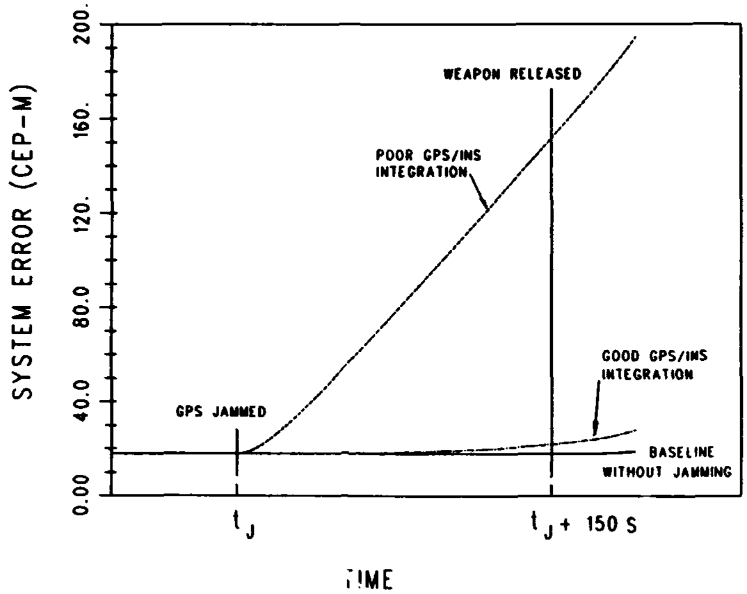

Figure 9. Effect of Integration on System Accuracy

4.0 WEAPON APPLICATIONS OF GPS

It clearly makes no sense to put a GPS receiver in a short range weapon whose flight time is less than the GPS time-to-first-fix or whose maximum range is less than the effective range of jammers. So, one must divide the applications of GPS to tactical weapons guidance into two range dependent categories: GPS-in-Aircraft and GPS-in-Weapon. Figure 10 illustrates this idea and shows the relative benefit of GPS to each of these concepts. Presently, it is uncertain at what range one concept merges into the other, but the trend must be in the direction of reduced cost and time-to-first-fix.

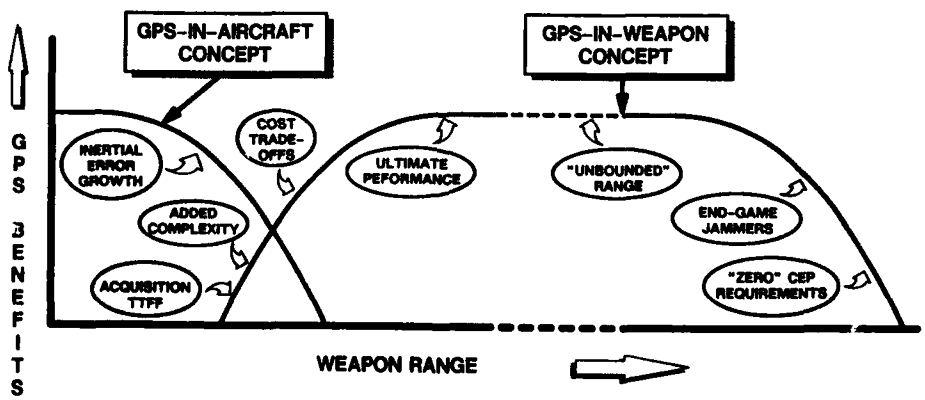

Figure 10. GPS-in-Aircraft & GPS-in-Weapon Concepts And Relative Benefit To Weapon Guidance

4.1 GPS-IN-AIRCRAFT CONCEPT

The position and velocity data derived from GPS can be used to improve the fire control solution when delivering "dumb" bombs. This technique works well when initialization errors predominate, such as weapons delivered by diving on or directly over flying the target. System effectiveness is substantially reduced when bombs are delivered in the more survivable toss or loft modes where post release factors (ejection forces, ballistic errors, wind, etc.) are dominant.

The minimum configuration necessary to fully exploit the accuracy advantages of GPS is an Inertially Aided Munition (IAM). GPS is used to calibrate, align, and initialize a low-cost weapon inertial system. After release, the weapon is inertially guided to the target coordinates. The coordinates can be either absolute, that is obtained from maps or Defense Mapping Agency data bases, or relative, generated by the aircraft's own onboard targeting sensors. The IAM concept takes advantage of the downwardly spiraling cost trend of tactical grade strapdown inertial measurement units (IMU). Previously unguided inventory weapons such as the MK80 series general purpose bombs, the BLU 109 (improved 2000-lb bomb), and the tactical munitions dispenser (TMD) can be turned into low-cost guided weapons by the addition of an IMU based guidance kit. Significant improvements are realized in delivery accuracy, tactical flexibility, and aircraft survivability. Figure 11 pictorializes the weapon delivery advantage of IAM. Several different targets can be attacked on a single pass, or several weapons can be accurately directed to a single hard target. Delivery accuracy of about 15 meters CEP (exclusive of target location error) can be achieved because of the excellent initialization provided by GPS and relatively short weapon flight times.

In order to validate the IAM concept, the Air Force and Navy jointly undertook the Inertial Guidance Technology Demonstration (IGTD) program. The Air Force awarded parallel contracts to the Boeing Military Aircraft Company and Northrop Precision Products Division to build low-cost guidance kits for MK82 (500 lb) bombs. The program demonstrated transfer alignment with a GPS aided carrier aircraft INS, and drop tests were conducted under a variety of release conditions. The Northrop drop test unit is illustrated in Figure 12. The inertial system uses conventional single degree of freedom gyros with an accuracy of 7 degrees/hour. The Boeing design is similar in layout but uses electro-mechanical actuators rather than pnenumatic ones, and the inertial system is a multisensor type (gyro and accelerometer function combined) with an accuracy of 10 degrees/hour. Figure 13 shows the Boeing unit.

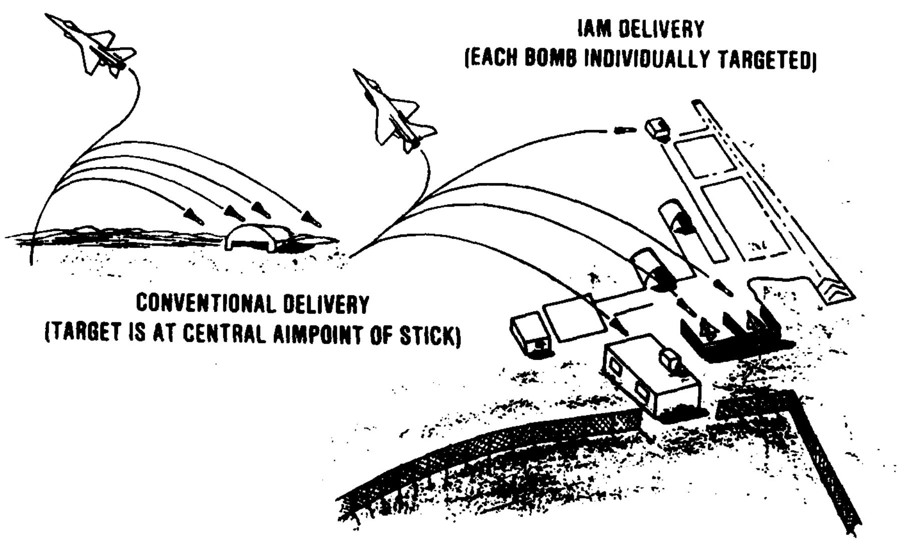

Figure 11. IAM Weapons Delivery Advantage

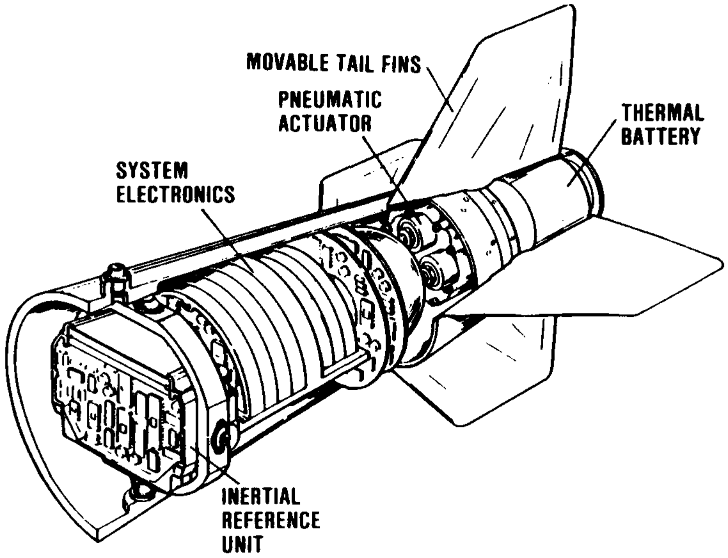

Figure 12. Northrop IGTD Drop Test Unit

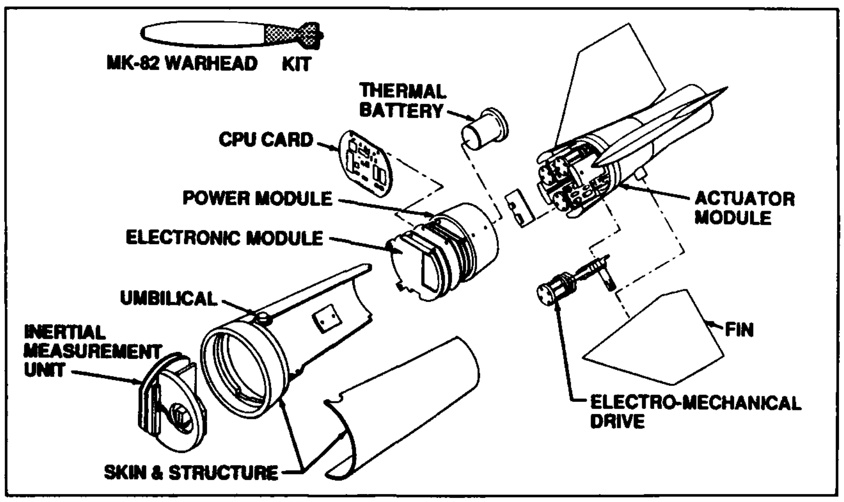

Figure 13. Boeing IGTD Kit (Exploded View)

Air Force testing was conducted at Eglin AFB. The IGTD test configuration is shown in Figure 14. An instrumentation pod on the left wing of an F-4 contains a Rockwell-Collins Phase II GPS receiver and a Litton LN-39 INS. A MIL STD 1553B digital data bus connects the pod to the drop test unit. This test arrangement emulates the environment of a GPS-equipped F-16 aircraft. Prior to weapon release, a transfer alignment was performed between the low-cost bomb inertial unit and the much higher quality LN-39 resulting in alignment and calibration of the inertial components. For example, gyro accuracy was improved to about 1 degree/hour. Test conditions included low altitude loft deliveries and high altitude releases (20,000 ft). The tests demonstrated the capability to deliver munitions off boresight and at ranges well beyond the normal ballistic range. Similar tests were conducted at the Naval Weapon Center but without the benefit of GPS. Instead, the Navy used an A-6 aircraft equipped with their Target Recognition Attack Multisenor (TRAM) system, a FLIR/laser combination, to track the target and update the aircraft INS. The tracking data at the long ranges permitted by IGTD were noisy due to target contrast problems. Flight test results, Figure 15, show how dramatically GPS improves delivery accuracy against well located fixed targets. These results include four drops which were made at night and in cloudy weather with the target enshrouded in fog.

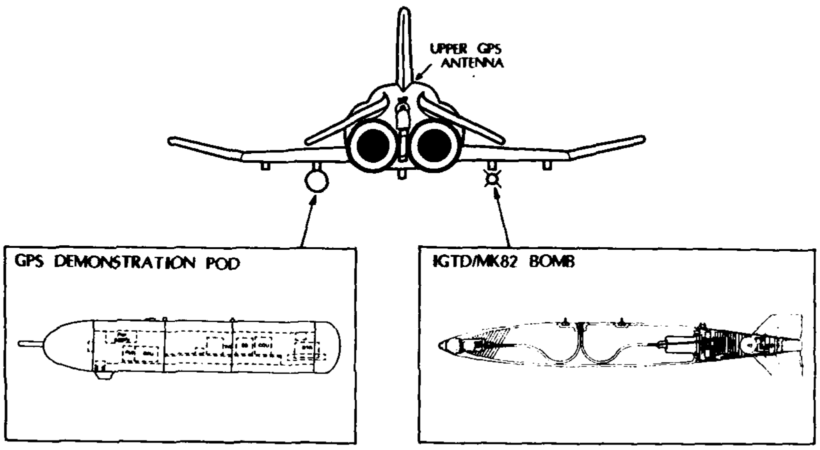

Figure 14. IGTD Flight Test Elements

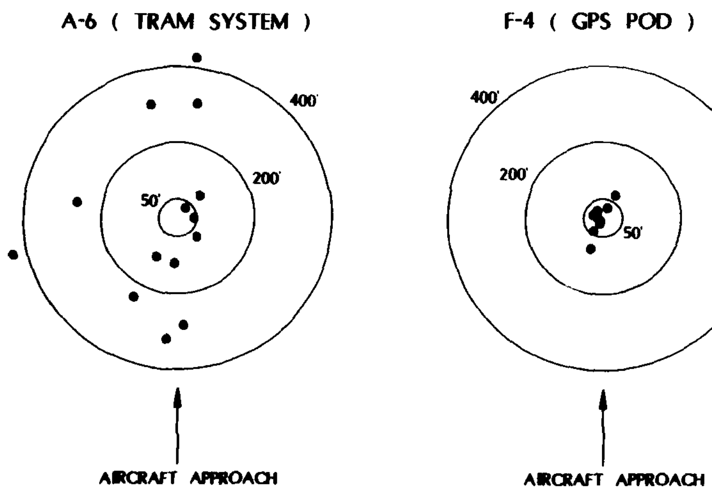

Figure 15. IGTD Drop Test Results

4.2 GPS-IN-WEAPON

The GPS-in-Aircraft concept is fairly well formulated. The services have chosen the GPS receiver for aircraft use (Receiver 3A), and most interfaces have been standardized. In contrast, the GPS-in-Weapon concept is relatively undefined and open to design optimization. This section will discuss some important implementation aspects and suggest some weapon concepts.

The prevailing conventional wisdom has been that aircraft receivers would be of the multi-channel continuous type (typically five channels) and weapon receivers would be one or two channel sequential or multiplex designs. This view was motivated by the perception that the number of channels was the primary driver in GPS system cost and size. In fact, the two weapon systems which have firm GPS implementation plans, SLAM and TLAM, are one and two-channel sequential designs, respectively. A review of industry IR&D efforts reveals a trend toward "channel-on-a-chip" designs with high speed A/D conversion (20 MHz) and maximum use of digital signal processing. RF front ends will employ advanced GaAs Monolithic Microwave Integrated Circuits. Advanced receiver architecture will use multiple correlators and multiple channels (more than four, permitting over-determined solutions) with new algorithms which promise orders of magnitude reduction in search time. There is a corresponding trend in inertial components such as ring laser gyros, multisensors, fiber optic gyros, solid state accelerometers, etc., which can be integrated with GPS receivers to produce a unified navigation system. These trends will lead to systems that are small, affordable, and modular so that they can be configured to fit a variety of tactical missile airframes.

An issue that is still unresolved is the aircraft/weapon interface. One aspect was alluded to earlier in a discussion of what GPS data would be available for weapon initialization. A more fundamental aspect of this problem is whether there will be a standard interface at all. U. S. MIL STDs, 1553B, and 1760A address the digital data bus structure and the electrical connection at weapon pylons, and offer a workable solution to standard interfaces. However, not all aircraft, not even all new aircraft, will have this interface available at every weapon station. Nor is there a plan to modify ejector racks, which are used for multiple stores carriage, to accommodate the interface. In desperation, several "work around" concepts have been proposed to data link information from the aircraft to the weapon it is carrying. Whatever the approach, it is critical that pertinent aircraft data be made available to stores for transfer alignment, initialization, targeting, etc., or future weapon development will be stifled.

A related issue which specifically impacts GPS guidance is whether the weapon receiver acquires the satellite signals before or after launch. Without an interface, the weapon is on its own, and there is a real problem of aircraft structures masking the satellite signals. The problem is compounded by a lack of GPS status indication to the flightcrew. Future weapons may be carried inverted or stored internally, and this precludes acquisition before launch altogether. Acquisition after launch, without an interface, requires an upload of precise time, almanac data, and expected launch parameters (position and velocity) before take-off. Time-to-first-fix could still be unacceptably long. With an appropriate aircraft/weapon interface the GPS RF signals could be routed to the weapon for prelaunch acquisition. However, there could be high signal losses in the cabling, and the weapon receiver would still have to reacquire after launch. The most reasonable approach seems to be to transfer, through the standard interface, position, velocity, timing, and ephemeris data which is readily available on the aircraft data bus. If this data is transferred just prior to weapon launch, search uncertainty is minimized, and direct P-code acquisition is likely.

Cost, complexity, range, and mission requirements support a further subdivision of the GPS-in-Weapon concept into medium range and long range applications. GPS applications to existing weapons like GBU-15 or AGM-130 are possible but unlikely. The range of these weapons is still too short to guarantee a high probability of acquisition after launch. What is needed in the medium range regime (maximum range of 30 - 60 mi) is a relatively inexpensive weapon, perhaps based on the HAVE SLICK airframe, with GPS/INS guidance which would be accurate enough to dispense appropriate submunitions against airfields, massed armor, etc. This is illustrated in Figure 16. With the addition of a terminal seeker, the concept can be extended to a unitary warhead version. Additionally, the accurate GPS/INS midcourse guidance would greatly relax terminal seeker search area requirements, reduce false alarms, and make target acquisition much more likely.

Long range missions could be performed by the joint Navy/Air Force Long Range Conventional Standoff Weapon (LRCSOW). GPS would act as an adjunct to the primary navigation system based on terrain referenced navigation, point and linear feature updates, doppler velocimetry, and a high resolution imaging sensor. Laser radars are the prime candidates to perform these functions in future cruise missiles. GPS would support navigation over water and flat, featureless terrain, greatly reduce the mission planning burden, and extend operations to regions of the world for which adequate terrain and imaging data bases are not available.

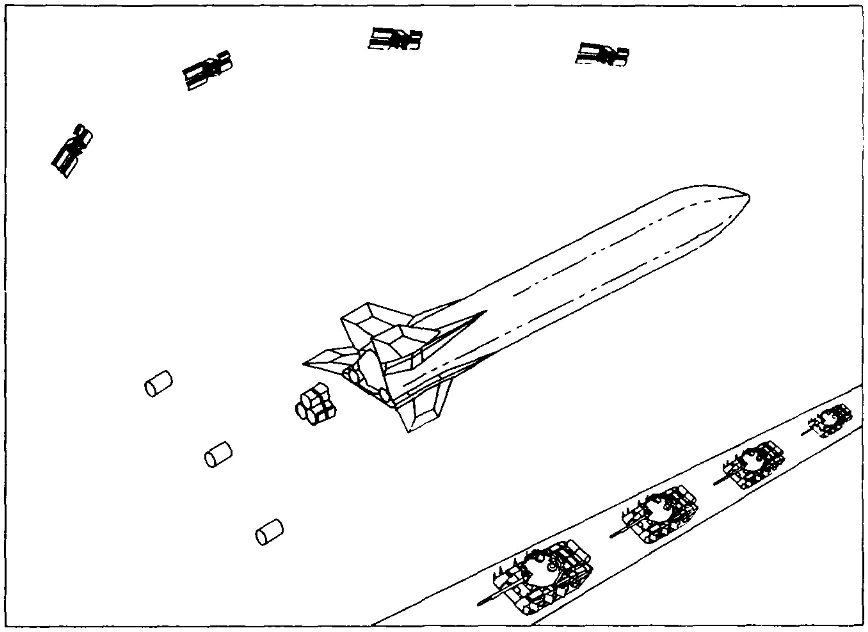

Figure 16. Medium Range Weapon Concept

5.0 CONCLUSIONS

The integration of GPS with tactical aircraft is currently underway. The role of GPS can be extended from navigation to weapon initialization provided that data from the host aircraft can be transferred to the weapon. The benefits of this aircraft-to-weapon data transfer cannot be over-emphasized. So the aircraft avionics community is challenged not to be the limiting factor in future weapon development. They must work with weapon designers to see that the desired data is available to the weapon, ideally through the 1553/1760 interface, but if need be, by means of a "work around" solution.

The size and cost reductions of GPS and INS components support improvements in standoff weapon capabilities. Future receivers will be designed using the "channel-on-a-chip" technologies now being pursued by industry. Low cost, effective antennas are critical in weapon applications.

A total system approach is needed for navigation and guidance. The GPS receiver, INS, and terminal seeker should be fully integrated to take advantage of their mutually beneficial properties. Lower costs should result through reduced seeker complexity, relaxed INS accuracy requirements, and simplified receiver design.

Future receiver design efforts need to be directed toward improving anti-jam capability. Areas that need further exploration include: multi-channel (6, 8, or 10) receiver architectures, tight GPS/INS coupling, advanced acquisition/reacquisition strategies employing multiple correlators, and new antenna designs.

Finally, weapon developers and users must work together to see that the potential of GPS is realized.

6.0 REFERENCE

Fountain, G. V. and Matchett, G. A., "GPS Applications to Conventional Weapons Guidance," The Analytic Sciences Corp., Report No. TR-5486-1, June 1989.

DISCUSSION

QUESTION D. R. Andrews

How can target coordinates be found to the same accuracy as GPS, so that fixed targets can be attacked without terminal guidance?

ANSWER

Locations of high value fixed targets will be obtained primarily from Defense Mapping Agency data bases.

An alternative is relative targeting using on-board aircraft sensors, such as SAR (F-15), LANTIRN (F-16), etc. GPS is still useful since it provides accurate velocity information. For short time-of-flight (<60 sec.) inertial guided weapons, the velocity initialization error from the delivery aircraft is the primary contributor to miss distance.

Hover Position Sensing System

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Summary:

The US Army's LHX aircraft has a requirement for a Hover Hold System with a desired accuracy of 1 meter RMS for a 3 minute period. AVRADA (Avionics Research & Development Activity) recently completed a demonstration program which indicated that an error of 0.6 meter or less is achievable with the LHX navigation sensor suite. The demonstration program and results are presented in this paper.

LHX - LIGHT HELICOPTER EXPERIMENTAL
GPS - GLOBAL POSITIONING SYSTEM
INS - INERTIAL NAVIGATION SYSTEM

Introduction:

The US Army's LHX aircraft has a documented requirement for a Hover Hold capability with an accuracy of 2 meters RMS over a 2 minute period. The LHX requirement also has a desired capability of 1 meter RMS for 3 minutes. AVRADA felt that the desired capability was achievable and initiated the GPS Hover Hold Demonstration Program to determine if the emerging GPS technology could support the accuracies required. Therefore, the term requirement, as used throughout this paper, refers to the desired capability.

Hovering a helicopter could be accomplished using a Hover Hold Sensor System to drive a cockpit display. Such a display would provide the pilot with a sense of relative position when no visual references were available. In the case of the LHX aircraft, the Hover Hold Sensor System would drive the flight controls directly, providing a "hands-off" capability.

The Hover Hold System error budget, as shown in Table I, was allocated between Navigation (referred to here as Hover Hold Sensor System) and Flight Controls. The error budget was established by informal technical discussions between AVRADA and knowledgeable flight control system engineers.

The Hover Hold Sensor is unique in that it measures the distance the aircraft has moved relative to the initial position. This is different than the normal absolute measurement in that bias errors do not affect the solution.

	TOTAL	NAV	FLIGHT CONTROL
Horizontal	1.0	0.84	0.55
Vertical	0.3	0.25	0.17

(Meters RMS after 3 minute hover)

Table I. Hover Hold Error Budget for the LHX.

The LHX requirement in Table I has both a horizontal and a vertical component. Although GPS provides vertical position, the accuracy of the vertical measurement was not capable of meeting the requirements of this demonstration. This demonstration, therefore, only considered the horizontal component. It is expected that a Radar Altimeter could be used to provide the vertical measurement.

Although AVRADA's demonstration program was directed toward the LHX requirement, there are a large number of uses for a Hover Hold System, for example search and rescue, airlift of equipment, etc.

Sensors:

The choice of GPS as one of the Hover sensors was made because of its highly accurate, all-weather and (eventual) worldwide coverage. GPS will provide the sensor system with continuous, highly accurate measurement with a one second update rate.

Using GPS, an externally referenced system, has an additional quality for hover in that special alignments are not necessary. While self-contained sensors have high drift rates and require special calibration, GPS does not have any such characteristics.

The Hover Hold Sensor must provide an output data rate sufficient to support the flight control system. For this reason, an Inertial Navigation System (INS) was chosen to compliment the GPS. Because of the complementary error characteristics, an optimal combination of the two sensors will provide the Hover Hold Sensor System with the short term stability of the INS and the long term stability of the GPS.

In the early stages of the program, several GPS measurement considerations were made to determine if GPS would provide the accuracies necessary.

Because the Army's primary GPS receivers are 2 channel units, they were considered. Static tests performed with the 2 channel receivers found them to be unable to support the requirement because the 2 channel receiver has a greater amount of noise associated with its measurements. This is partially caused by the receiver sharing its two channels among the 4 satellites being tracked. This time-share technique causes the receiver to have a shorter dwell time for a measurement which, in turn, allows a greater amount of noise to be introduced. In addition, because of the constant switching, the 2 channel receiver must have a reliable reacquisition capability. This is accomplished by having a greater bandwidth which also contributes to a noisy measurement.

Subsequently, a 5 channel receiver was considered. The advantage of the 5 channel receiver was that four (4) of the channels could be used for continuous tracking of the four (4) satellites needed to form the solution. This leaves the last channel available for ancillary functions. Static tests performed found the 5 channel receiver's measurements to be capable of meeting the requirements.

Approach to Test:

Since this was a demonstration program for the sensor suite, AVRADA was only interested in the feasibility of meeting the Navigation error budget. For this reason, it was not necessary to simulate the complete Hover Hold System (i.e. closed loop navigation and flight control). Rather, it was only necessary to score the Hover Hold Sensor against the truth data. This post-processing approach was less costly and allowed the Hover Mode Kalman Filter to be optimized using actual sensor inputs. Figure 1 is an illustration of the real time/post-time relationship of the Hover Demonstration Program.

The Flight tests were conducted at the Airborne Electronics Research & Development Activity, Lakehurst, New Jersey using a UH-1 aircraft. The Hover Hold test range is as shown in figure 2.

The aircraft was equipped with a 5 channel Phase II GPS Receiver and a Standard Inertial Navigation System (AN/ASN-141). The GPS Receiver's data was passed over its Instrumentation Port (IP) and the Inertial System over its MIL-STD-1553 bus. The GPS Receiver also provided a once per second time mark pulse.

All the GPS and INS data as well as time mark data were recorded using an instrumentation program developed specifically for this application.

In order to determine exactly how much the aircraft had moved, an upward looking camera mounted on a tripod was placed directly below the hover point. The bottom of the aircraft had been prepared with reference marks. Using these marks, the actual horizontal movement of the aircraft could be determined. Although the aircraft was flown over the hover area, the only constraint was to keep the aircraft within the frame of the camera. By doing so, the Kalman Filter's solution could be scored against the actual movement of the helicopter as shown on the photographs.

In order to synchronize the sensor and truth data, an AM radio transmitter was used between the aircraft and the camera shutter. The radio transmitter was triggered using the GPS one second time mark pulse. The time-tag associated with the one second time mark pulse was recorded providing synchronization.

The tests were conducted by having the aircraft move into position over the hover area. At that point, the aircraft operator initiated the test by depressing a switch. The switch closure caused the following sequence of events to take place. First, the GPS receiver produced a Data Capture Block. This block has a time stamp indicating the time the switch was depressed. Second, the AM radio transmitter was enabled. Third, the path between the time mark pulse and the AM transmitter was enabled. In effect, synchronizing the photograph, after the data capture block, with the applicable time mark pulse.

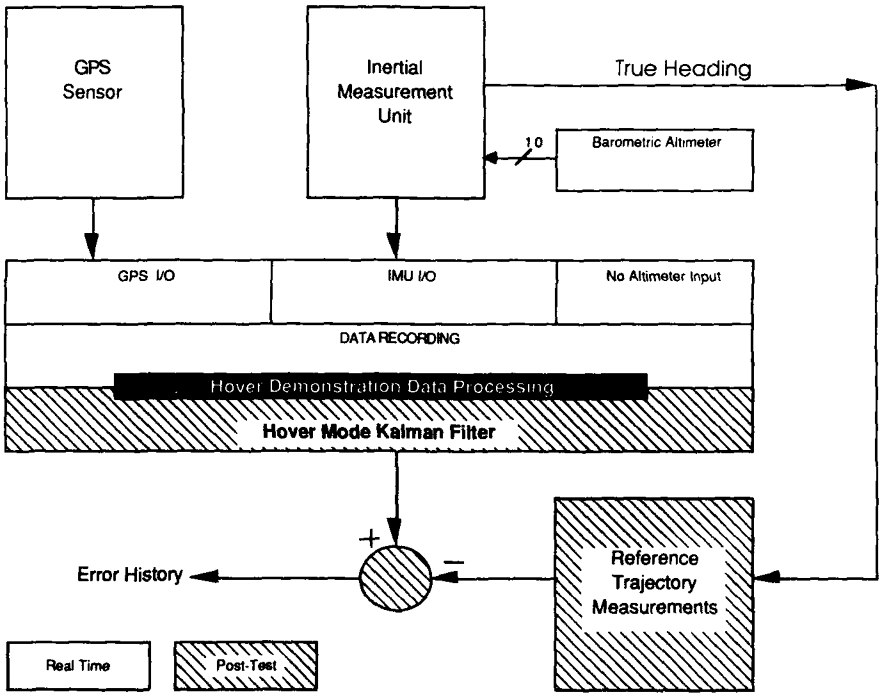

Figure 1. Hover Hold Demonstration System

Past experience had indicated that the camera shutter operation could skip causing a misalignment of the data. To avoid any skewing of the data, two methods were used to align the truth (photo) data with the Hover Sensor's data. The primary method used a special light emitting diode display which was mounted on the bottom of the aircraft. This counter was also driven by the GPS time mark pulse in much the same way as the AM transmitter link (i.e. allowing each pulse through once the Data Capture Block was produced). The LED display would count from 1 to 180 seconds. Backing up this method was a audio tape recorder which recorded the camera shutter operation (opening and closing). Using the two methods, data sets could be realigned prior to processing.

Once the hover was initiated and the camera shutter operation started, the ground crew, located at the camera location, would instruct the pilot to move as necessary to maintain the aircraft within the frame of the camera. As long as the aircraft remained in the frame of the camera, a truth measurement could be made and be used to score the Kalman Filter's solution.

The test range also included AVRADA's Navigation Van which served as a flight test control station providing communication and coordination for the test. The Van also served as a monitoring station which contained a GPS receiver concurrently tracking the four satellites used by the aircraft.

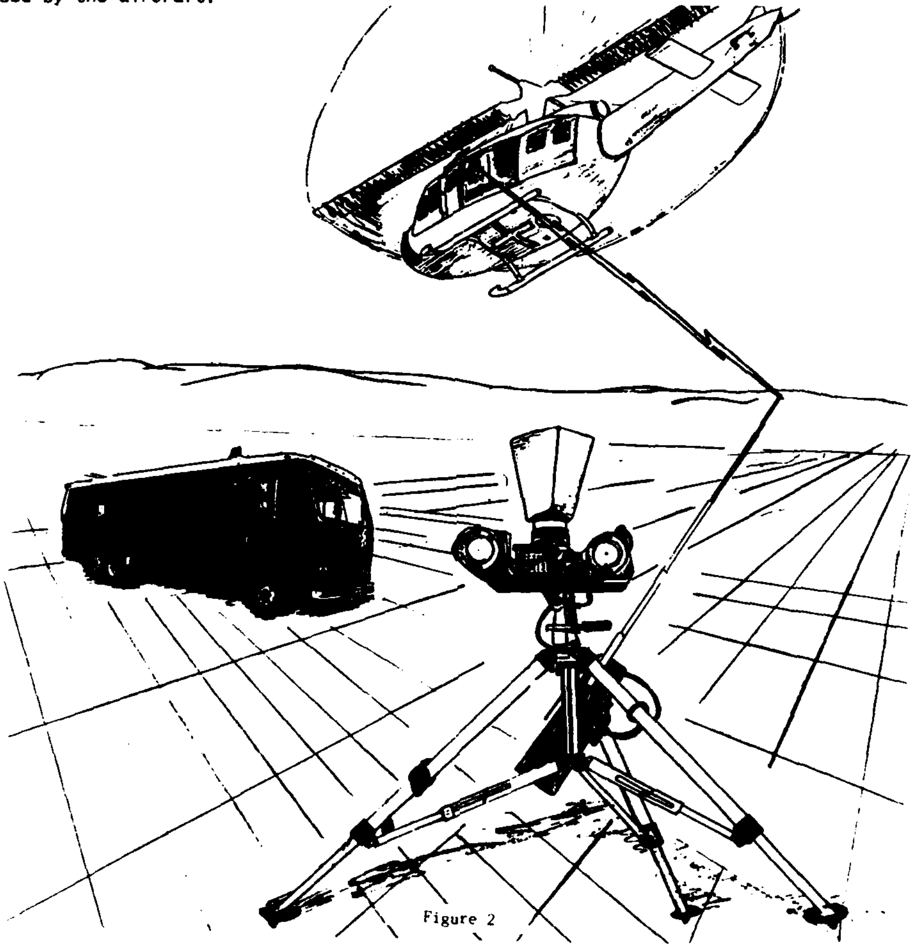

Figure 2

Receiver Management:

Although the 5 channel receiver could produce the accuracy for the LHX requirement, present receiver management would not support the hover mode of operation.

The most critical items relate to satellite switching during a hover. Normal receiver management seeks to optimize the geometric relationship between the receiver's antenna and the four satellites being tracked. As a better geometry becomes available, normal receiver operation would be to switch to the new constellation. Based on previous tests, this could cause up to an 8 to 10 meter shift in position. Therefore, satellite switching must be inhibited during a hover.

In addition to inhibiting the acquisition of a new satellite, the internal channel assignments must also be frozen for the duration of the hover. Although each channel has an associated bias error, the relative solution is unaffected by such an error. If the receiver would rearrange (i.e. shuffle) the assignment of channels during the hover, a new bias error would be introduced. The occurrence of this shuffling in some of the data sets showed a 0.1 meter step.

Although present receiver management does not provide for the two critical items shown above, we were able to force these conditions. This was accomplished by choosing certain constellations when a switch would not occur and, in the event that an internal rearrangement occurred, the data set was not processed.

The following items were not controlled during the flight tests but are recommended for optimization of accuracy during the Hover Mode. While these recommendations are important for the hover mode, the aircraft integrator will have to determine how the transient effects of entering and leaving the Hover Mode impact on normal en-route navigation.

Since the GPS receiver is being used to provide horizontal position, the receiver's constellation selection algorithm could be changed to optimize HDOP rather than GDOP.

Present receiver management uses the 5th channel to prepare for the transition to a new constellation and to make ionospheric measurements on the 4 satellites. Since satellite switching is inhibited, the 5th channel need not be used for the former purpose.

The ionospheric measurements take up the balance of the 5th channel's time. At present, the dwell time is equally divided among the satellites. In order to provide the greatest benefit, it is recommended that the 5th channel increase it's dwell time on the satellites which have the greatest ionospheric drift. During this demonstration, ramping effects were seen between 0 and 0.33 meters per minute. Using the 5th channel as described above should reduce this ramping effect.

Although the above recommendations alter present receiver management, AVRADA's Miniature GPS Unit's (MGU) Software Requirement Specification, SRS-MGU-001, contains functions that support such capabilities.

Post Processing:

After the flights were complete, the data was removed from the aircraft, sorted and aligned. During this process, a number of validity checks were made to determine the level of confidence in the data.

The validity checks included satellite switches, rearrangement of the receiver's channels, long periods where a measurement was not made on a particular channel and periods where two or more channel's measurements were not made. If any such cases were found, the data set was not considered. In addition to the above, a test was performed for every hover to verify that the receiver's tracking loops were working properly.

If the data set was found to have passed the validity checks, then the photo data was digitized. Once completed, both the aircraft data and the truth data were ready for the Kalman Filter processing and performance scoring.

Kalman Filtering:

The filter used was a conventional 11 state GPS/INS filter specially tailored for the Hover Mode of operation. The states are as follows: GPS Receiver Clock Bias, GPS Receiver Clock Rate, 3 INS Position Errors, 3 INS Velocity Errors, and 3 INS Platform Tilt Errors.

The uniqueness of the Hover Filter is that it produces relative solution rather than an absolute one. The initial conditions of the filter, therefore, are also unique in that at the start of hover the position is known exactly and the initial position error covariances can be set to zero.

In addition to the above, a hovering helicopter can be characterized by limited motion and minor accelerations. Both allow certain noise terms in the normal Kalman Filter error models to be reduced or eliminated.

Results:

Of the 32 hover flights conducted, 14 passed all validity checks and were processed. The majority of the discarded data sets exhibited GPS measurement effects attributable to receiver management, for example satellite switches and hardware channel reassignments. Some of the unprocessed data sets contained intervals where a satellite was masked for a considerable portion of the hover duration.

Table II shows the probable error (50th percentile) and the RMS error for each of the 14 hovers. The horizontal probable error is identical to the familiar CEP statistic. It can be seen in the table that the worst case CEP was 0.524 meters, while the worst case RMS error was 0.558 meters over the 3 minute hover period.

It is important to note that the flight tests were conducted with the limited constellation of satellites available in the May-June, 1989 time frame. The results shown in Table II reflect the performance at the upper limit of acceptable geometry, with a GDOP of about 6. The actual range of GDOP experienced was 4.5 to 6.6, however, for the majority of the flights it was between 5.5 and 6.0.

A typical horizontal error history is shown in figure 3. The most prominent feature of this plot is the upward ramp of the error as time increases. Each of the 14 hovers exhibited such an error ramping effect. As indicated earlier, this is most likely caused by the uncompensated ionospheric error drift. In order to further illustrate this general characteristic, an ensemble error and standard deviation history was generated from the 14 individual hovers. The standard deviation history, shown in figure 4, shows that the Hover Sensor System uncertainty grows essentially monotonically with time.

A more detailed discussion of the experiment and the results can be found in the "GPS Hover Hold Study and Demonstration Final Report" currently being prepared by Intermetrics.

	Probable Error			RMS		
Identifier	East	North	Horizontal	East	North	Horizontal
052389.H3	0.140	0.155	0.241	0.209	0.278	0.348
052389.H5	0.249	0.247	0.350	0.310	0.313	0.441
052689.H1	0.156	0.170	0.264	0.224	0.226	0.319
052689.H2	0.178	0.219	0.331	0.302	0.369	0.447
052689.H3	0.283	0.144	0.367	0.437	0.253	0.505
052689.H4	0.324	0.135	0.399	0.341	0.249	0.422
052689.H6	0.263	0.409	0.524	0.305	0.468	0.558
060189.H1	0.119	0.376	0.434	0.152	0.451	0.476
060189.H2	0.215	0.066	0.278	0.307	0.109	0.326
060189.H4	0.179	0.212	0.317	0.256	0.328	0.416
060289.H2	0.079	0.119	0.164	0.132	0.354	0.378
060289.H3	0.074	0.266	0.277	0.134	0.309	0.337
060389.H1	0.138	0.204	0.314	0.168	0.513	0.540
060389.H8	0.328	0.147	0.406	0.471	0.200	0.512
Ensemble Statistics of Experimental Results						
Mean	0.195	0.205	0.333	0.268	0.316	0.430
Standard Deviation	0.084	0.096	0.090	0.106	0.111	0.081

(table values in meters)

Table II. Summary of Hover System Error Statistics.

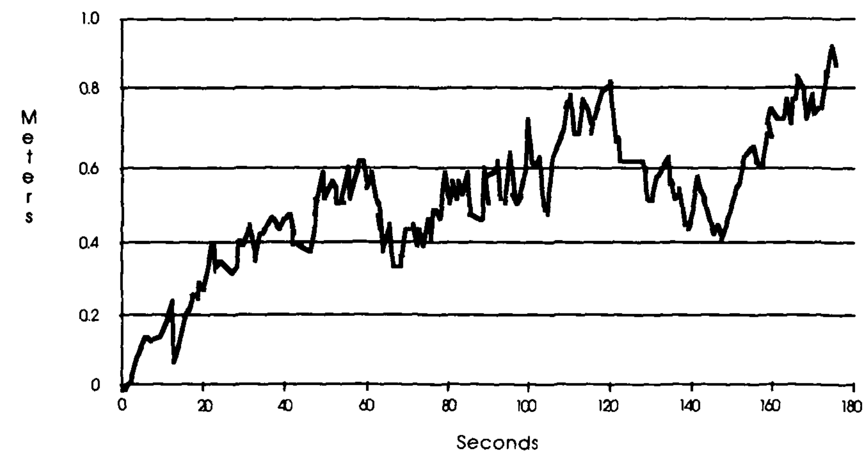

Figure 3. Horizontal Hover Error for 052689.H6

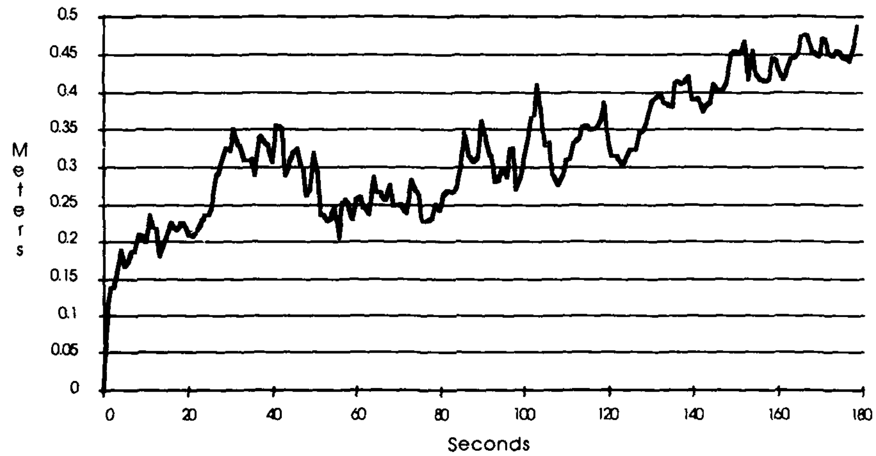

Figure 4. Ensemble Standard Deviation History for 14 Hover Flights

Conclusions:

The demonstration and study did not address application specific issues, for example, the transition effects of entering and leaving hover mode, nor were satellite masking and jamming effects considered. The results of the demonstration do, however, clearly indicate that with proper GPS receiver management and Kalman Filtering, the LHX desired hover stability is achievable with a hybrid GPS/INS navigation system. The results were obtained for a typical GDOP of 6. Even better performance can be expected as the NAVSTAR constellation fills and GDOPs improve.

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POTENTIAL NEW TACTICAL APPLICATIONS OF THE GLOBAL POSITIONING SYSTEM (GPS)

by

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The Global Positioning System (GPS) is an all weather global navigation satellite system deployed by the United States Department of Defense primarily for achieving force enhancements for the United States and NATO military forces. The major objective of the GPS is to provide highly accurate positioning capability to tactical weapon platforms. The GPS will eventually have 21 to 24 operational satellites continuously transmitting navigation signals to users around the globe.

The objective of this paper is to investigate possibilities of using GPS to disseminate critical information in time of conflict to tactical forces. This type of information distribution can be accomplished without any space vehicle hardware modifications on the GPS Block II vehicles by the use of spare bits in the navigation message data frames. With minimum hardware changes on the next generation GPS Block IIR space vehicles, a continuous communication channel can be made available. This paper provides various system engineering issues and applications related to the communication capability of GPS.

1. Introduction

GPS will be operational in the early 1990's and will provide extremely accurate three dimensional position and velocity information to properly equipped users. It is a Joint Service Program managed by the United States Air Force. An overview of the GPS concept is provided in Parkinson (1976) and Parkinson and Gilbert (1983).

The basic elements of the GPS are: the Space Segment, the Operational Control Segment (OCS), and the User Segment. A GPS special monograph of the Institute of Navigation (1980) contains several publications which give some of the specific details of these segments. A very brief account is given here.

The Space Segment consists of a constellation of 21 to 24 GPS satellites. Each satellite radiates ranging signals modulated with satellite ephemeris and clock information. The OCS consists of a master control station, monitor stations, and ground antennas. It tracks the radiometric data from the satellites, estimates accurate ephemeris and clock data, and uploads these estimates to the satellites for broadcast to the users. At present, these uploads occur about three times per day. The User Segment consists of an antenna and a receiver with signal and data processing capabilities. The user measures the time difference (scaled by the speed of light) between satellite signal transmission and user signal receipt. These measurements, along with the transmitted ephemeris and clock data from each of four satellites, allow the user state vector (position, velocity, time) to be computed.

2. Overview of Block II and Block IIR Satellites

The satellite radiates two spread spectrum pseudo-random noise (PRN) radio signals. The signal consists of a C/A (coarse acquisition) code at 1.023 MHz and P (precision) code at 10.23 MHz bandwidths. The signals are transmitted at two frequencies: L(1) (1575 MHz) and L(2) (1227 MHz). Both are coherently derived from highly stable onboard atomic clocks. Both C/A and P-codes are transmitted on the L(1) frequency, whereas either C/A or P-code is transmitted on the L(2) frequency. The selection is determined by ground command. The L(2) frequency is utilized primarily to correct the error in range measurements due to ionospheric effects.

The C/A code is available to all users, however, the P-code may be available to only authorized users because of the anti-spoof (AS) feature. Therefore, an unauthorized user will have access to C/A code only on the L(1) frequency because, generally, only the P-code is transmitted on the L(2) frequency. In addition to the PRN range codes, 50-bps navigation message data, which consists of ephemeris and clock parameters (Van Dierendock, at al., 1987), are modulated onto the PRN sequence on both L(1) C/A and P codes. By ground command, the navigation message may be modulated on L(2) frequency. Figures 1, 2 and 3 illustrate the navigation message format.

The current baseline configuration for the operational phase of GPS consists of 21 satellites in 55 degree inclined circular 12 hour orbits. Five-satellite global coverage, Green, at al., (1989), is provided by placing the satellite in six orbit planes which are 60 degrees apart in longitude. Expansion to a 24-satellite constellation is planned.

The first ten Block II satellites will continue to function without any ground contact for a period of about 45 days. Satellites 11 through 28, known as Block IIA satellites, are designed to function without any ground contact for a period of 180 days. However, if any subsystem element fails, redundant systems can only be switched on by ground command. There exists no autonomous redundancy management system in the Block II satellite design.

The GPS program is currently in the process of procuring replenishment satellites for the GPS Block II. The replenishment satellites are known as Block IIR. The primary objectives of the Block IIR satellites are to provide improved navigation accuracy and increased autonomy and survivability. Major emphasis will be placed on reducing satellite dependence on ground support. The objective is to provide full system accuracy for a period of 6 months without any ground support. Block IIR will achieve this objective by use of an autonomous navigation system.

Ananda, at al. (1984), describes an autonomous navigation system wherein the Block IIR GPS satellites would make crosslink ranging measurements to each other and exchange data via a crosslink communication system. Each satellite would use onboard processors to compute satellite ephemeris and clock parameters, using the crosslink range measurements. Study results show that such a system could operate for a period of 6 months without ground contact and achieve system accuracies comparable to operating the system with the Control Segment.

The crosslink ranging system is based on a time division multiple access (TDMA) scheme. Each satellite has a specific time slot during which the satellite transmits a pseudo-random noise ranging code similar to the C/A or P code, which can be received by satellites that are within the viewing geometry. Each satellite will be able to exchange ranging data with 12 to 14 other Block IRI satellites. The Block IIR design has 24 time slots and each slot time period is 1.5 sec; a complete ranging frame would take 36 sec. The ranging measurements are then exchanged during the next crosslink frame. By processing the crosslink range measurements, each satellite will be able to update its pre-stored reference navigation message. The update scheme would be totally transparent to the navigation user.

3. GPS as an Information Dissemination System

The intent of the GPS is to provide accurate navigation capability to military and civilian systems. This architecture provides continuous worldwide visibility of four or more satellites which are transmitting radio signals continuously. This architecture also can be used as a global tactical information distribution system (GTIDS). Although the navigation function requires a minimum of four GPS satellites properly located with respect to the user, information distribution requires only one satellite. It is, however, possible to validate the information by comparing data from more than one satellite.

GPS cannot be used as a two way communication satellite system without significant modifications to the space system. However, the current Block II satellites, without any modifications, can provide some limited capability for data dissemination. With Block IIR satellites, which can still be modified, the full system capability for information dissemination can be achieved. There are three basic approaches.

The Block II satellites can disseminate information by using unassigned or unused portions of the 50 bps navigation data message. The data format is shown in Figures 1, 2 and 3.

The OCS uplinks the data using ground antennas and stores the data in specifically allocated memory on the satellite. The onboard system takes the data from the memory and downlinks it at the 50 bps data rate. The data format and the contents are determined by the OCS. The onboard memory can be considered as a buffer for temporary data storage. No data processing is performed by the onboard system.

With the current design, identical navigation messages are transmitted on all three L-Band Links (L1P, L1C, L2P or L2C). It is possible, with minor satellite modifications, to transmit different messages on the various data links. With additional modifications, a dedicated information dissemination system can be added. Sections 4, 5 and 6 discuss these three approaches.

4. Use of the GPS Navigation Message

The content of the navigation message and the data format are shown in Figures 1, 2 and 3. The navigation message utilizes a basic format consisting of a 1500-bit long frame made up of five subframes, each subframe being 300 bits long. Subframes 4 and 5 are subcommuted 25 times each, so that a complete data message requires a transmission of 25 full frames. Subframe 1 contains the clock parameters and subframes 2 and 3 contain the ephemeris parameters. Subframes 1, 2 and 3 are repeated every 30 seconds. Since subframes 4 and 5 each have 25 pages, these subframes are repeated only once in every 12.5 minutes.

There exist several bits in subframes 4 and 5 which are not currently used and are classified as spare bits. It is possible to use the spare bits to achieve a limited capability of information dissemination. These data can be preencrypted by the OCS such that only those who have a separate key can decrypt the information. It is also possible to have different information distributed using different satellites. If a particular message is transmitted through a particular satellite, then the time delay between the uplinking of the message data and the reception of the data will depend on the relative geometry of ground status satellite and recipient.

For example, if the same information is transmitted through all 21 satellites in the constellation, using all three remote ground antennas plus one in the CONUS to upload the message, then a user anywhere in the world can receive the information without any significant delay following upload. The maximum delay then would be 12.5 minutes, which represents the repetition period of the information frames, plus the required upload time.

If, however, each satellite is uplinked as it comes into view of a single ground antenna in the CONUS, then the maximum delay in contacting a user anywhere in the world would be about 5.5 hours. The Figure 4 shows contour lines of contact times for various locations. A large percentage of the earth can be contacted instantaneously. However, a very small area as shown in the figure can only be contacted after 5.5 hours.

In the worst case, if one uploaded only a single satellite from the CONUS station, then the maximum delay in contacting a users would be about 17.5 hours. Figure 5 gives the contour lines of contact times. Note that much of the northern hemisphere region still can be contacted instantaneously. However, in the southern hemisphere the contact time varies from 4 hours to 17.5 hours. The case illustrated here assumes that the CONUS is distributing a message to Western Europe. Obviously, if a message was destined for South America, a satellite in view of that location could be chosen.

If two of the satellites in the constellation are uplinked from the CONUS, then the maximum delay in contacting a user anywhere in the world is about 6.0 hours. Figure 6 shows these contour lines of contact times. Much of the southern hemisphere region can be contacted in less than 4 hours. However, a small region can only be contacted after 6 hours. If one uplinks three or more satellites from the CONUS, the maximum delay in contacting a user would be about 5.5 hours. A summary of the various cases is shown in Table 1.

In summary, if one uses the existing spare bits for information distribution, then the current Block II satellite can be utilized without any changes. Current user equipment would require modification in order to receive the message data. Some modification to the Operational Control Segment software would be required to properly uplink the information message.

5. Use of C/A Code and P-Code on L(2)

As stated earlier, L(1) frequency carries both C/A code and P-code whereas the L(2) frequency carries only C/P code or P-code, as determined by the OCS. Most of the time, P-code is transmitted on L(2) frequency. Identical navigation messages can be transmitted on both the L(1) and on L(2) frequencies. The data modulated on L(2) frequency could be used for GTIDS purposes. However, certain users take advantage of the potential redundancy to improve the user performance. Therefore, it may be more beneficial to modify the system such that the L(2) frequency carries both C/A code and P-code simultaneously, as in the case of the L(1) frequency.

When L(2) frequency has both C/A code and P-code, the data modulated on the C/A code can be used for either navigation data or GTIDS. For military applications, the data message on the C/A code on L(2) frequency can be formatted quite differently from the normal navigation message. There are other advantages for having C/A code on L(2) frequency as well, primarily to correct the ionospheric effects. Currently the C/A code user cannot use the two-frequency ionospheric correction method, but must depend on the ionosphere model transmitted by the satellite, which is only accurate to about fifty percent.

This approach requires hardware changes to the satellite. These changes can be incorporated in the Block IIR design. However, they are not currently in the baseline Block IIR design. If the changes are made prior to the Critical Design Review (CDR) in the summer of 1990, the impact to the satellite and the cost associated with the changes would be minimum. If, however, the changes are made after the various payload boxes are designed and manufactured, the cost would be significantly higher.

Figure 7 shows a simplified block diagram depicting the changes required to implement both C/A code and P-code on the L(2) frequency. Some software changes are required in telemetry tracking and control (TT&C) to accept the new upload of message data. The mission data unit (MDU) needs both software and hardware changes. The software changes are primarily to store, process and retrieve message data. Additional software changes may be required to include encryption, parity check and synchronization functions. The hardware changes are required to simultaneously transmit P-code and C/A code on L(2) signal. If it is decided that the C/A code on L(2) does not need to be continuous, a hardware change is required to add an on/off function for C/A code on L(2). Additional hardware changes are also required to substitute GTIDS data for navigation data on the C/A code on L(2).

The L-Band subsystem (LBS) needs to be modified to add QPSK modulation on the L(2) signal. Also, hardware changes are required to increase L(2) HPA output. There may be some other additional hardware and software changes, but these changes are rather minimal and can be accomplished with relatively little cost impact if the design changes are carried out early in the design phase.

The user equipment will have to be modified appropriately to receive the message data from C/A code on L(2). The user equipment currently in use may have some impact when the L(2) signal transmits both C/A code and P-code. It is advisable to use an encryption key for message data that is independent of the key to be used by an authorized navigation user.

The Block IIR in its current design supports the exchange of autonomous navigation data via satellite-to-satellite crosslinks. If the GTIDS message data can be crosslinked as well, then the contact time can be reduced to one or two crosslink TDMA frames, which is 36 to 72 seconds, even when only one satellite is uplinked from the CONUS. The Block IIR current design has most of the subsystem functions necessary to accomplish the transmission of message data using the crosslink. However, one may have to study further to determine what additional changes are required.

6. Use of a Dedicated Information Distribution Channel (IDC)

The example of L(2) can be further extended by incorporating a dedicated GTIDS downlink. This approach would permit data rates much higher than 50 bps. The GTIDS IDC could be either a part of L(2) or a separate L-Band frequency. In addition, it could utilize the crosslink for dissemination. Based upon the crosslink architecture, a data reach of 11 Kbps could be sustained. Either one message could be continually transmitted, or multiple short messages could be sequentially transmitted via an L-Band version of the crosslink TDMA strategy. The IDC could be designed so that all downlinks simultaneously transmit the same message, thereby ensuring spatial diversity of the message in disturbed environments.

The satellites would require modifications similar to those in Section 5 for simply adding a 50 bps data message to L(2). Specialized user equipment would be required, if an 11 Kbps data rate were adopted. Figure 8 illustrates than an antenna gain of 20 to 40 dB would be required, depending on received signal strength. As always, OCS software changes are required to implement the message data uploads.

7. Summary and Conclusion

It has been shown that, without any modification to the existing Block II satellites, GPS can be enhanced to achieve information distribution to users all over the world. With modest modifications to the Block IIR satellites, the information distribution capability can be increased significantly by adding a simultaneous C/A code on the L(2) frequency. The transmission of the GTIDS message data on the crosslink makes it possible to distribute the data worldwide and nearly instantaneously to all users with a single upload to a single satellite from the CONUS. With additional modifications to the Block IIR satellites, an IDC link can be used to distribute data at a higher data rate.

Such enhancements can only be achieved in a cost effective way if design changes to the Block IIR satellites are incorporated prior to the Critical Design Review of the Block IIR satellites. If this opportunity is missed, the cost to develop and field such an information distribution system might be prohibitive.

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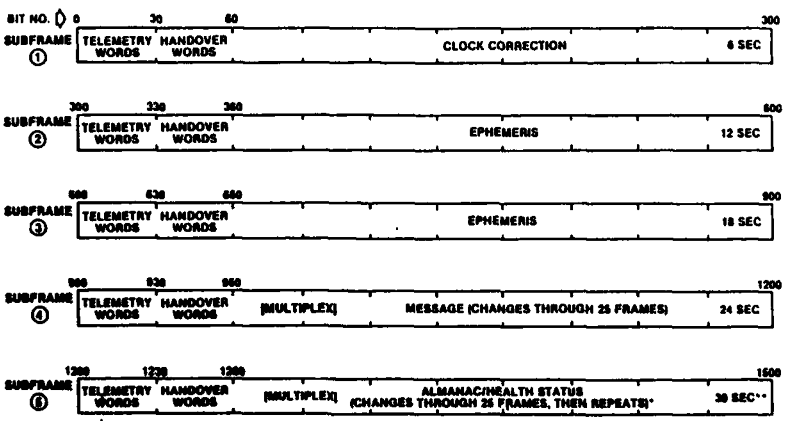
TABLE 1

WORLDWIDE CONTACT TIMES

UPLOAD STRATEGY (NO. OF SVs/SITE)	MAXIMUM USER CONTACT TIME, HRS	CS WORKLOAD IMPACT
1/CONUS	17.5	LOW
2/CONUS	6.0	MEDIUM
ALL IN VIEW/CONUS	5.5	HIGH
1/CONUS + 1/SINGLE GA	6.0	MEDIUM
1/CONUS + 1 EA/THREE GAs	1.2	MEDIUM
ALL IN VIEW/CONUS + THREE GAs	NEGLIGIBLE	HIGH
1/CONUS + CROSSLINK DISTRIBUTION	NEGLIGIBLE	LOW

CONTENT OF THE GPS NAVIGATION MESSAGE



*FORMAT OF FRAME TWENTY-FIVE CHANGES.
**12.5 MINUTES BEFORE THE ENTIRE MESSAGE REPEATS.

FIGURE 1

SATELLITE DATA FRAME

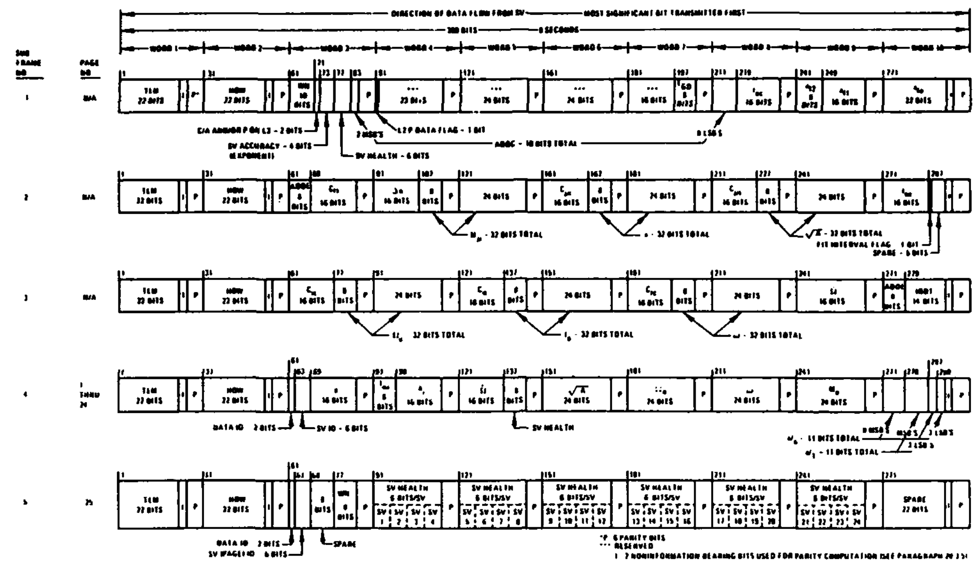


FIGURE 2

SATELLITE DATA FRAME (CONTINUED)

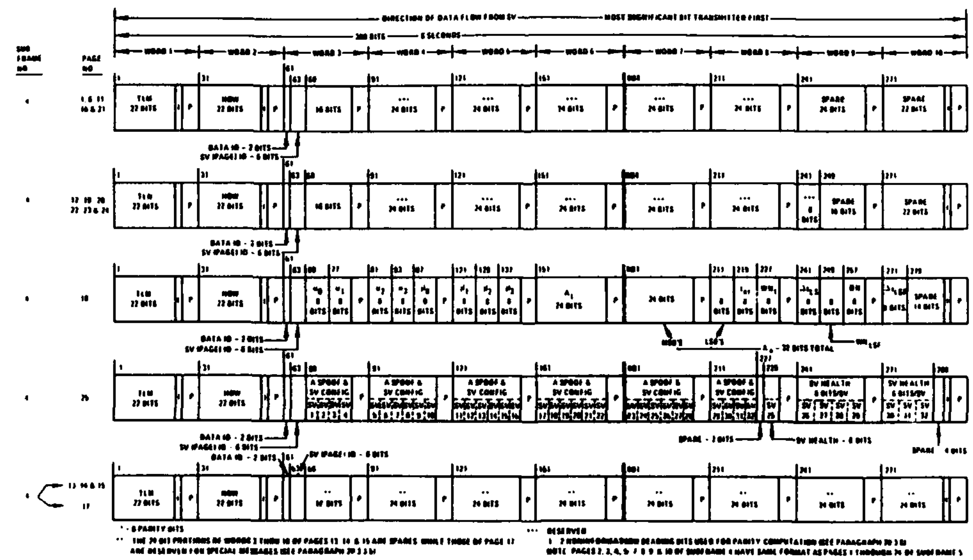


FIGURE 3

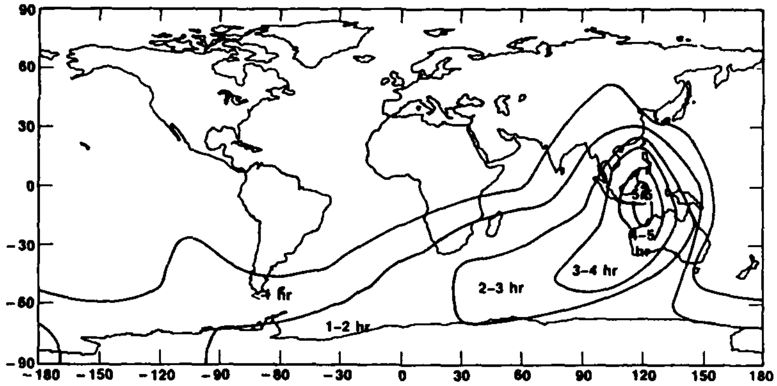


FIGURE 4

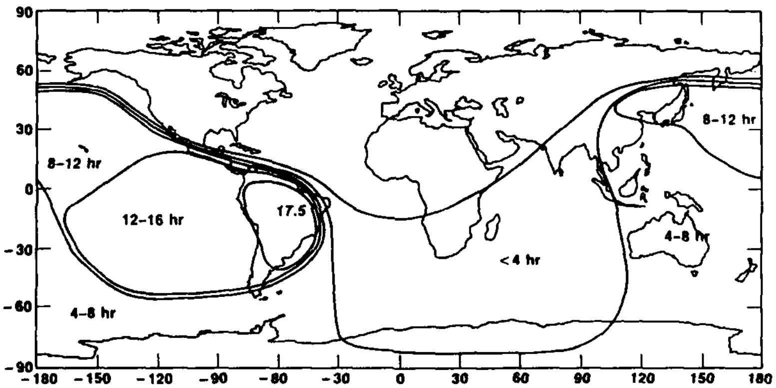


FIGURE 5

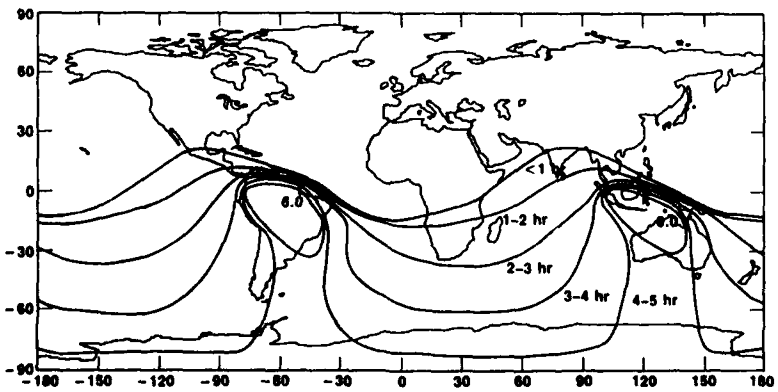
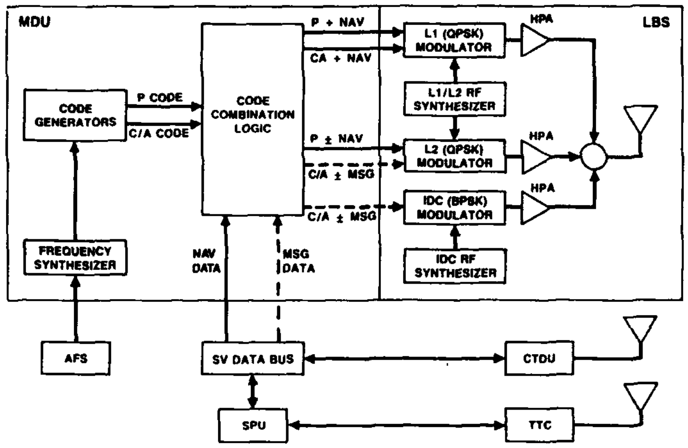


FIGURE 6



SIMPLIFIED BLOCK DIAGRAM

FIGURE 7

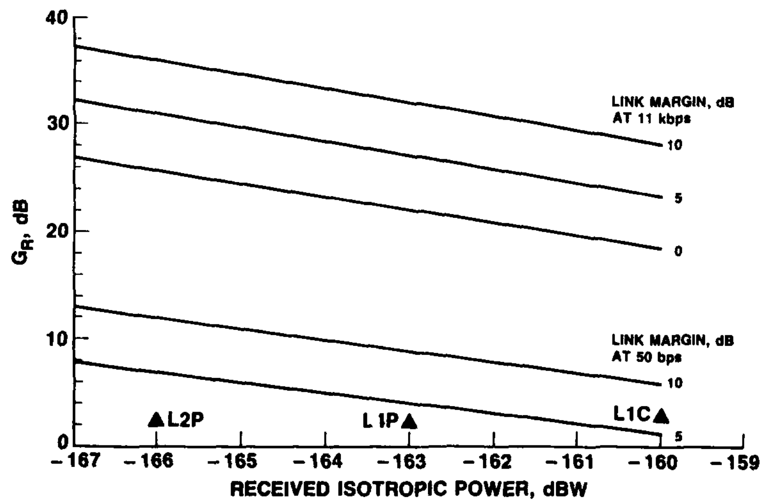


FIGURE 8

DISCUSSION

QUESTION E. B. Davies

What is the relationship between the minimum response times for the additional data services being considered for GPS Block IIR satellites (30-60 sec.) and the FAA integrity requirement of <10sec. for flying air lanes with military aircraft?

ANSWER

The existing and proposed architecture cannot address the FAA 10-second rule. The 36 to 72 seconds discussed in the presentation includes only the time to distribute an uplinked data message to the entire constellation. The complete delay in receiving a message is the sum of (1) the time to upload one satellite (about 30 to 60 minutes), (2) the distribution time to place a satellite in view of all ground points (36 to 72 seconds utilizing crosslinks), and (3) the transmission time (up to 12.5 minutes at 50 bps).

In contrast, the FAA requirement includes (1) anomaly detection, (2) message preparation, (3) message upload, (4) message transmission, and (5) user reception and reaction. Clearly, the present GPS architecture cannot perform these functions within 10 seconds.

TACTICAL USES OF THE DSCS III COMMUNICATIONS SYSTEM

by

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INTRODUCTION

Originally conceived and designed in the late 1970's, the DSCS III Communications System was primarily oriented toward long haul, point-to-point service for strategic users who desired a high degree of antijam capability combined with physical survivability. The satellite portion of the system was designed under the auspices of the United States Air Force Space Systems Division. Overall responsibility for the DSCS system rests with the Defense Communications Agency (DCA), which has developed much of the tactical philosophy discussed in subsequent paragraphs. (In particular, Reference 1 was a significant source of information on tactical concepts.) Although primarily conceived as a strategic support system, a significant portion of the total resource was allocated to tactical uses. In subsequent paragraphs, some of the tactical concepts that evolved for the present design, as well as some new ideas concerning possible tactical uses for the system, will be described.

SYSTEM DESIGN

Figure 1 illustrates the DSCS III satellite. It contains super high frequency (SHF) and ultra high frequency (UHF) command systems that are completely redundant in function. Figure 1 also illustrates the array of communication antennas that are on the earth facing side of the vehicle. Nuclear hardening and antijam protection are also major features of the design. In order to meet the stringent pointing requirements of the DSCS mission, the satellite contains adequate propellant to maintain its orbit inclination to within 0.1 deg for 10 years, which is the estimated design life for an individual satellite.

SUPER HIGH FREQUENCY TRANSPONDER DESIGN

The DSCS SHF transponder design is shown in Figure 2. The transponder contains six communications channels, and each has a high power amplifying device: either a traveling wave tube amplifier or a solid-state amplifier. As shown, the transponder provides in excess of 10 separate communications paths when connected with the array of antennas that are available. These antennas are capable of providing a range of patterns from earth coverage to very high gain narrow beams. This permits the use of the DSCS satellite for a wide variety of uses, both strategic and tactical. Also, each channel has individual commandable gain control that provides a measure of flexibility for system users. Another feature that promotes versatility is the "bent pipe" nature of the overall transponder design. Other than frequency translation, there is no processing in the transponder; this simplifies access to the satellite for users.

SYSTEM CHARACTERISTICS

The basic configuration of the DSCS System consists of satellites in five primary operating positions with two spares. Figure 3 shows a typical constellation of primary satellites. Management of the DSCS communications network is provided by the DCA Operations Center (DCAOC). The center directs all of the communications activities of DSCS satellites by supervising the DSCS Operational Centers (DSCSOC's), which, in turn, perform real-time control over satellites in a particular geographic area. All of the housekeeping functions required to support the satellites can be performed from the Consolidated Space Operations Center at Colorado Springs, Colorado and the Consolidated Satellite Test Center at Sunnyvale, California.

TACTICAL USES OF THE DSCS SYSTEM

Provisions were made early in the operational design process to facilitate the use of the DSCS System for tactical applications. These include support for deployments of Army, Navy, Air Force, and Marine Corps elements, as well as tactical support of Joint Task Force units. Such support would be provided using a "gateway terminal" concept in which the gateway would serve as an interconnect between tactical users and the main elements of the Defense Communications System. This system of gateway terminals, together with the tactical users, has been designated as the DSCS Ground Mobile Segment (GMS). The gateway terminals employed in the GMS are DSCS operational terminals that have been modified to contain gateway interface equipment. These terminals provide interoperability between tactical users and the Defense Communications System.

TYPICAL OPERATIONAL SCENARIOS

A variety of deployment configurations can be accommodated within the structure of the DSCS-GMS. They include hub-spoke, gateway, and ship-to-shore communications. Figure 4 provides an illustration of such interconnections that would be used by the Ground Mobile Forces (GMF) which comprise the United States Army element of the GMS. (It should be noted that the United States Army is the executive agency responsible for development and procurement of all GMF type terminals for the Army, Air Force, and Marine Corps.) Deployment concepts for the theater operations and task force operations are shown in Figure 5. Figure 5 depicts a theater operation that is supported at the brigade level with connections to Division Headquarters and a subsequent connection to the DCS through a gateway terminal. Another scenario is illustrated wherein communications are maintained between Tactical Air Center and control and reporting posts. Tactical support for a Marine Air Ground Task Force is also shown in this figure. Finally, the figure shows an application where all of the elements are joined in support of a Joint Task Force.

SYSTEM MANAGEMENT

The highest level of near-real-time management for the DSCS-GMS is the DCAOC. As is the case during other DCS operations, it will be the responsibility of the DCAOC to maintain and adjust the satellite payload as required for network integrity. Just as the DSCS is divided into geographic areas of responsibility, so the GMS also has a local GMS manager in each of the designated areas. These managers will be responsible for coordinating the allocation of resources, not only for Army Ground Mobile Forces, but also for other DSCS-GMS elements. Ground Mobile Segment managers will each be assigned three areas each, which are: Central, Pacific, and Europe. Figure 6 shows the relationship between various major communication nodes, the DSCS-GMS and the DCAOC.

TERMINAL EQUIPMENT

There are two types of terminals that are most commonly employed in the DSCS-GMS. These are the AN/TSC-85A and the AN/TSC-93. The AN/TSC-85A terminal would most commonly be deployed as a hub and can support up to four spokes. It can use a 20-ft quick reaction antenna or an 8-ft antenna. The terminal will be housed in a transportable shelter and transported on a 2-1/2-ton vehicle. The AN/TSC-93 is commonly used as a spoke terminal. It will usually employ an 8-ft antenna and can be transported on a 1-1/2-ton vehicle. Other types of terminals have also been developed for the GMS; for example, the LST-8000 is a man-portable terminal that uses a 6-ft foldup antenna.

OTHER TACTICAL ARCHITECTURES

We have previously discussed tactical uses of DSCS within the boundaries of the GMS. The GMS was designed to provide maximum flexibility for a variety of users, but it requires working within the framework of the DCS and competing for resources with other DSCS users. Concern has been expressed that the demand for "warfighting" communications within individual strategic and tactical commands may exceed the capability that can be allocated within a five satellite DSCS constellation. In this regard, alternative methods have been suggested for satisfying these additional requirements, including proliferated systems consisting of large numbers of small satellites orbiting at medium altitude. Other concepts would feature relatively lightweight, but low-cost satellites operating at synchronous altitude.

TACTICAL ALTERNATIVES USING DSCS

In addition to the capability which it offers within the GMS, DSCS presents other opportunities for satisfying tactical requirements. Presently, 10 additional SHF satellites are planned to be launched as part of the DSCS. These satellites will be launched in the 1990's and will fulfill DSCS SHF requirements beyond the year 2000. Whereas the next few launches will occur in rapid succession to fill out the DSCS constellation, several options exist for scheduling the remaining launches. A conventional approach would be to store the satellites on the ground and launch them as needs dictate. Another approach would be to launch satellites on a fixed schedule, thereby storing them on orbit. Studies have shown that, for DSCS, the cost of ground storage exceeds, or is at least equal to that of storage on orbit, even when one considers the cost of premature wear-out due to launching before the satellites are actually required to fill prime positions in the constellation.

Even if there were no cost advantage between early launch and ground storage, then another potential advantage of early launch suggests itself. Satellites that were launched early and which would otherwise be on a standby or spare status, could be deployed to meet the requirements of theater or other tactical users who could take advantage of the large available bandwidth of a DSCS satellite. Control of a satellite operating in this mode could be achieved by emplacing an SCCE terminal that would be dedicated to performing payload control of the satellite asset.

A possible plan for launch of the remaining 10 DSCS IIIB satellites is described in Figure 7. Figure 7 also illustrates the results of a simple deterministic analysis of satellite population size on orbit assuming that each satellite will have a useful life of approximately 7 years. Even after modifying the numbers downward to account for launch failure, it is apparent that a substantial spare channel capability will be available after the mid-1990's to provide tactical "warfighting" support. Of course, this capability is also required to provide spare capability for the primary DSCS constellation.

Several studies are also in process to define possible enhancements to DSCS SHF capabilities for the 1990's. *One such change is illustrated in Figure 8, which shows* the addition of a seventh communication channel (heavy outline) and another gimballed dish antenna. These particular additions would further enhance the capability of DSCS to meet additional requirements such as those from operational commands.

There are, of course, issues regarding frequency assignment and other matters which would have to be examined in order to achieve this additional tactical capability with DSCS satellites. It would not appear, however, that these problems would be less amenable to solution using the DSCS spare capability than they would be if a totally new system were created to meet these requirements. It should also be noted that another source of "spare" capability could be made available if we consider the use of satellites that have been relegated to a standby status because their channel capacity, while still considerable, has dropped below the level required to fill a primary position in the orbital constellation. Such satellites could conceivably have the potential for several years of useful service.

REFERENCE

1. The Defense Satellite Communications System Ground Mobile Segment (Draft) The Defense Communications Agency, September 1986.

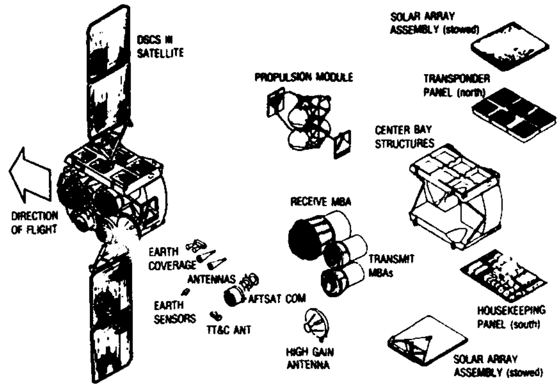

Figure 1. DSCS III Satellite

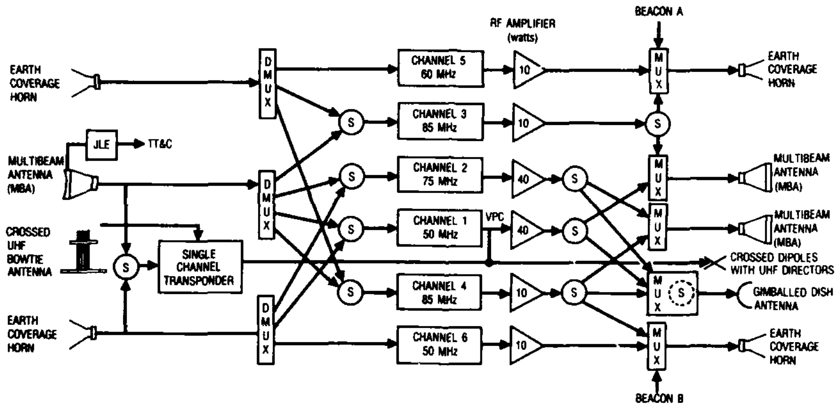

Figure 2. DSCS Payload

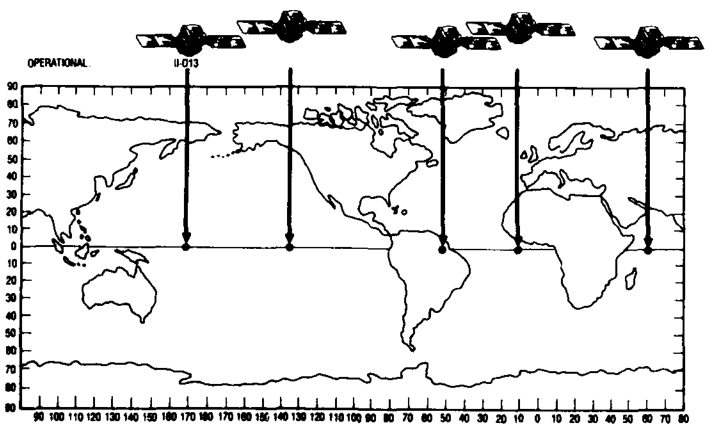

Figure 3. DSCS Orbital Deployment

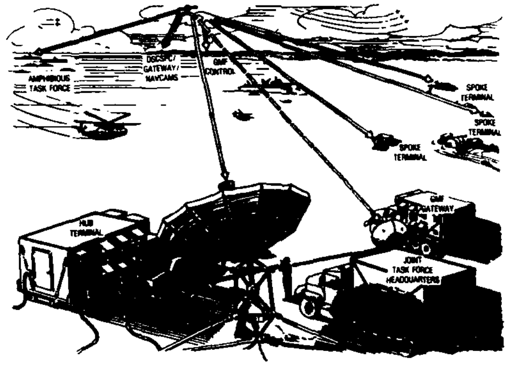

Figure 4. DSCS-GMS Deployment with Hub-Spoke, Gateway, Control,and Ship-to-Shore Satellite Communications

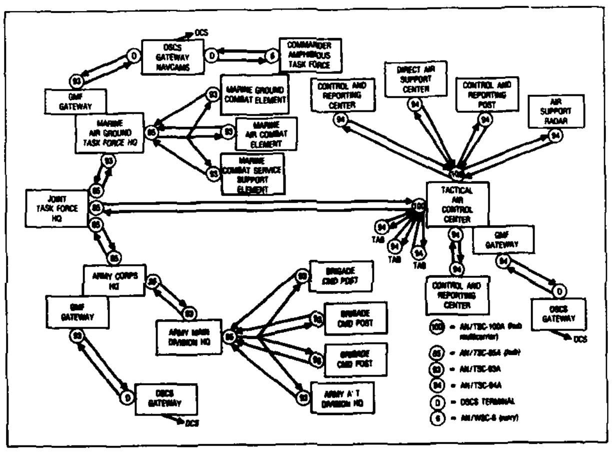

Figure 5. Example of Triservice DSCS-GMS Deployment

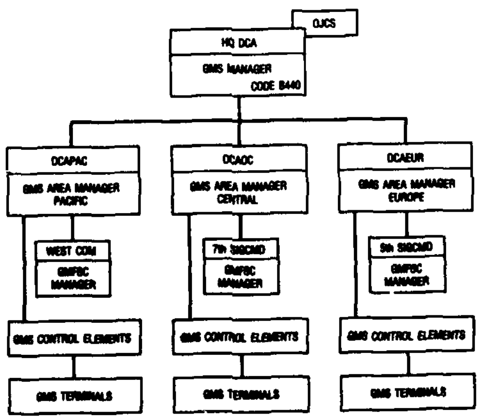

Figure 6. DSCS-GMS and GMFSC Management Structures

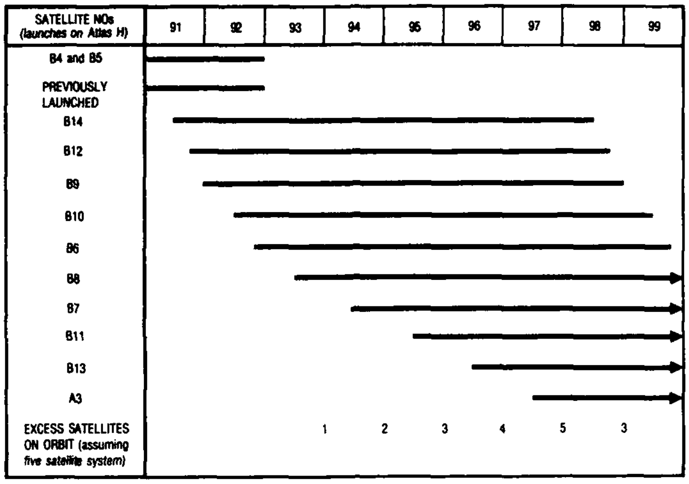

Figure 7. Possible DSCS Launch Scenario for the 1990's

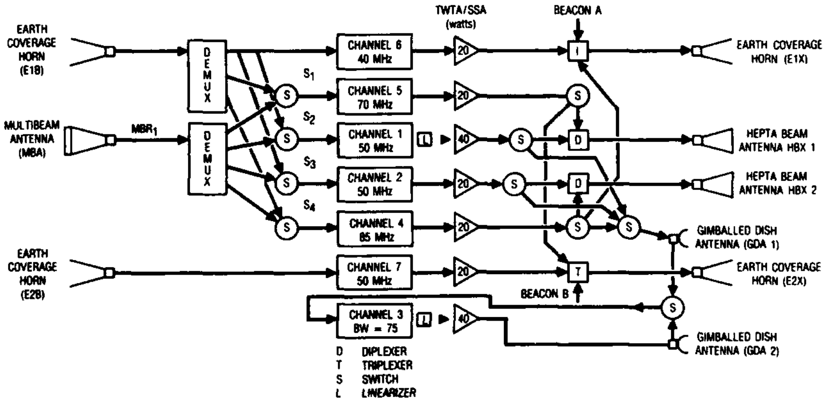

Figure 8. DSCS Communications Subsystem with 7th Channel (7th Channel, Second GDA, 20W-SSA)

DISCUSSION

QUESTION E. B. Davies

Are intersatellite links being considered for future developments on DSCS, and, if so, for what benefits?

ANSWER

There are EHF packages being considered for a follow-on DSCS spacecraft. Several of these design considerations would feature a k-band crosslink.

QUESTION D. P. Haworth

Have you considered the burden on command and control authorities if a large number of DSCS III Spacecraft are used to actively support tactical operations?

ANSWER

If space DSCS III satellites were used in a particular theater, the control system for that utilization would have to operate on a non-interference basis with the normal DCA control system. One way to accomplish this objective would be to put an additional x=band control terminal in place for the theater support mission.

QUESTION D. L. Andrews

What resistance does the uplink have to electronic counter measures (ECM)? Where does a jammer have to be in relation to the uplink transmitter to cause problems, i.e. what is the jammer power/distance relationship at which problems occur?

ANSWER

The uplink (at UHF) is Earth coverage; therefore there is no discrimination between user and jammer. There is no significant resistance to ECM at UHF.

TACTICAL APPLICATIONS OF THE UHF SATELLITE COMMUNICATIONS SYSTEM

by

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Summary:

The intent of this paper is to provide information on how the US Navy uses the UHF Communications Satellite Systems to support its tactical operations. It identifies shortfalls associated with the existing UHF SATCOM System and shows how these shortfalls are overcome. It presents methods which are used to "operationally" increase the number of satellite accesses available by implementing FDM and TDM techniques. New space communications initiatives are also discussed.

The authors of this paper are assigned to the staff of the Commander, Naval Space Command in Dahlgren, VA. COMNAVSPACECOM is the operational manager of the Navy's FLTSATCOM system and thus, this paper is presented from an operational, not technical point of view.

Since their introduction in the late 1960's, the UHF satellite communications (SATCOM) systems have revolutionized the way our Naval forces communicate. The names of these systems have been unusual, like LES or TACSAT in the early days; GAPFILLER, FLTSAT or LEASAT more recently; and UFO in the future. What is not unusual about these systems is the reliable communications links they provide.

The principles which make UHF the frequency range of choice for line of sight communications apply likewise to satellite communication systems. By placing a bent pipe UHF transponder aboard a geo-synchronous satellite, man's line of sight, for communications purposes, is extended to an area that covers one third of the earth's surface. Messages can be passed thousands of miles in milliseconds using inexpensive, compact, user friendly terminals.

These qualities of cost, size and simplicity are paramount when planning the communications requirements of the large number of tactical users who routinely use the UHF Fleet Satellite Communications (FLTSATCOM) communications systems. UHF SATCOM radios are inexpensive, costing a fraction of what is spent on equipment suites to operate in the higher frequency bands. In the size and weight areas, UHF terminals are small, light and highly mobile. They can be rack mounted or carried on the back of a man. They don't require elaborate site preparations or facilities support for normal operations. Operators must simply point their antenna in the direction of the satellite, hook up the power and communicate.

For all their obvious benefits, UHF communications satellite systems have some drawbacks, all of which are well documented. The one that is most often cited is the ease with which UHF communications satellites can be degraded through RFI. One only has to look at the morning message traffic to see that this is true. We are routinely our own worst enemy, and it's generally operator error that causes the problem. I will concede that this is a problem, but we can often locate and remove the source of the interference by implementing administrative or operational procedures. Along this line, we must also remember that this is a tactical, not strategic, system. We recognize that it is not survivable through all levels of conflict, and we plan for its use accordingly. The bottom line here is that UHF SATCOM provides reliable communications links to support tactical, crisis and contingency operations, nothing more, nothing less. We can live with it's drawbacks.

Another shortfall associated with the UHF SATCOM system is the small number of available channels, relatively speaking. The UHF frequency band is very busy, and the portion of the spectrum assigned for military satellite communications is small. In many cases satellite receive channels share frequencies with civilian, terrestrial, line of sight networks. This sharing of frequencies is, in most instances, not a problem to either user. The signal level on the satellite receive frequency is extremely small, much too small to cause interference to the ground based primary user of the frequency, but it is sufficiently strong to "close the link" to the sensitive antennas and receivers which are the ears of the satellite communications ground terminals.

This second drawback represents what I consider to be the greatest short fall we must consider, the number of channels in the UHF frequency spectrum available for military use. The spectrum is fixed so we can't place additional transponders on orbit to improve the situation. The answer can only be realized by making better use of what we have, by being smart in how we use it.

To this end, from the very early days, we have been trying to do things operationally which will allow us to squeeze out additional accesses and accommodate more users.

In the early days frequency division multiplexing (FDM) techniques were employed to allow us to assign multiple users to the 500 kHz transponders that were the mainstay of the first UHF satellites. To do this we had to contend with two potential problem areas, one being downlink power management and the other the generation of inter-modulation products (IMPs). By controlling the number and uplink power of assigned users we can guarantee that each user will have a sufficient share of the downlink power to satisfy the link requirements of his particular system. Thus, we can provide satellite access to eight or more users with a single transponder. The more complex problems of IMPs is minimized by a combination of user power and bandwidth control and the careful selection of the frequencies within the 500 kHz band which are assigned to the eight users. Because this method of channel multiplication is very dependent on user discipline, monitoring equipment is installed at each of the major Naval communications nodes, to detect, isolate and correct violations.

More recently, FDM operations, on a much smaller scale, have been accomplished on the FLTSAT and LEASAT 25 kHz bent pipe transponders. The first application would be the way we back up the Anti-Jam (AJ) SHF Fleet Broadcast (FLTBCST) subsystem. To satisfy the back up requirement, adjacent NAVCAMS uplink a simulcast of their normal FLTBCST on the same channel, one transmitting 11 kHz above and the other 11 kHz below the center frequency. Power levels are tightly controlled by each station to assure that normal operations are maintained. Another application assigns a second, relatively static, broadcast type network to a channel which normally supports a secure voice network. The secure voice network is selected because it can better tolerate the link fluctuations that may be caused by the second user. The power level authorized for the second user is also kept lower than that of the primary user to insure that mutual interference does not occur. Data rates up to 2400 bits per second (bps) are possible on the second channel.

While FDM is one way of operationally making better use of what we have, not having to contend with power sharing and IMP problems is still desirable. In our second major generation of UHF satellites we included individual 5 and 25 kHz channels, in addition to the 500 kHz wideband transponders. While several of these channels are operated in a shared mode, as discussed above, they are for the most part operated in a single carrier per transponder (SCPT) mode of operation. This mode of operation protects the users from the pitfalls associated with power sharing and provides cleaner channels with greater link margins to the operational users.

You may think that SCPT operation is not making efficient use of our available capacity, and you would be correct if we did not couple this with advances in the way we structure and implement the networks which are assigned to these SCPT channels. Because of the high quality service which is available on these SCPT channels we are able to operate processor controlled information exchange subsystems (IXS) which address the requirements of hundreds of users on a single channel. Placing this many eggs in one basket would not be possible were it not for the high confidence we are able to place in the service provided by these SCPT channels.

The operational concept that applies to the IXS is relatively simple and is used by several different networks. Each IXS is made up of a link controller and multiple users, with each terminal transmitting in turn, according to the pre-arranged, time interleaved network protocol. When one subscriber finishes, the next in line starts. This type of network is very efficient with data transfer speeds of 2400-4800 bps nominal.

The real value of the IXS concept is that it allows users with similar interests to share, or exchange information, allowing every station on the net to see what the other stations are seeing. In the Anti-Surface Warfare (ASUW) war fighting area, where the Over-the-Horizon Targeting (OTHT) problem is difficult under the best of conditions, the Navy has found IXS to be very useful. Similar benefits can be realized when these networks are integrated into the planning process for other war fighting areas such as Anti-Submarine or Anti-Air Warfare.

With the advent of long-range anti-ship missiles like HARPOON and TOMAHAWK the reach of the ship's weapons far exceeds that of its sensors, which are normally limited to the ships horizon. Help is needed to correct this situation and it is received in the form of the all-source information which is available from many sensors. The network which delivers this information is called the Officer-in-Tactical-Command Information Exchange Subsystem (OTCIXS). On this circuit, the cruise missile shooters and the operational intelligence fusion centers are all subscribers, exchanging the vital bits of information that are passed computer to computer and then correlated into a common, cohesive picture. Only in this manner can a coordinated anti-ship cruise missile attack be successfully accomplished. With all shooters sharing the same tactical picture, orders from the OTC become more precise, producing better results.

The key here is that IXS operates computer to computer, producing a tactical network of inter-operational battle management systems, whether they are local networks, operating within a battle group, or fleet wide, encompassing an entire ocean area.

A similar system in use is TADIXS, or the Tactical Data Information Exchange Subsystem. Using the same scheme described above, ships and shore stations exchange tactical information at high data rates. Because this information is not necessarily related to the OTHT problem, other platforms, besides the cruise missile shooters and CV/CVNs will be subscribers.

While many of the channels on satellites are dedicated to special uses, like OTCIXS and TADIXS described above, some channels serve the entire user community. An example of how the Navy satisfies its service-wide communications, by taking advantage of the IXS concept, can be seen by examining the way general service (GENSER) message traffic is passed between Naval activities. Shore originated hard copy messages enter the system via AUTODIN (Automatic Digital Information Network) and the NAVCOMPARS (Naval Communications Processing and Routing System), which sorts the traffic and forwards it to the appropriate SATCOM gateway facility for transmission to the fleet. Afloat users receive the traffic via FLTBCST, which in turn feeds it to the Naval Modular Automated Communications Subsystem (NAVMACS) for further processing or distribution. Return traffic to the shore is also processed by NAVMACS. Certain "special users", with requirements for high volumes of traffic, will participate in the Common User Digital Information Exchange Subsystem, or CUDIXS where they can both transmit and receive record traffic. Once the messages are received ashore they are routed to the intended user via the NAVCOMPARS and AUTODIN. In all, five independent message processing and distribution systems come into play to satisfy the Navy's GENSER traffic requirements with as few as two satellite channels in each ocean area.

Having discussed our use of FDM and utilization of IXS networks I would like to go one step further and talk about Time Division Multiplexing, or TDM. In the early 80's the Navy placed its version of "Demand-Assigned-Multiple-Access" (DAMA) into operation. While the Navy DAMA is not operated as a true demand- assigned subsystem it does take advantage of the TDM techniques which are the heart of any true DAMA system. TDM allows multiple networks, operating at different baseband date rates, to share a single satellite channel. The beauty of this system is that each user appears to have sole use of the channel. The DAMA network is typically composed of three or four 2400 bps user time slots with up to 13 additional time slots available for point to point TTY circuits. The DAMA system operated by the Navy today needs only the addition of a central network processor, at a master control site, to fully automate the system and provide true DAMA operation. Provisions for the development of the automatic call processor are contained in the production contract for Mini-DAMA, the Navy's second generation DAMA multiplexer, which is under contract today.

When we take the communications techniques we have just discussed, and tie them together with DAMA and the FLTBCST package that flies on the newer components of the FLTSATCOM system, we have a broadcast communications capability that has the AJ protection of the FLTBCST subsystem and can support the many multi-user networks that can be processed via DAMA. This is simply done by inserting the burst data stream from the DAMA multiplexer into the FLTBCST modulator-demodulator. The end result is that networks which are operated on the DAMA now have an AJ uplink to the satellite. The ability to provide AJ protection to these additional networks provides the Fleet Commander with an AJ link to all his deployed forces which is not available on any other space systems.

The Navy is currently under contract for the next generation of UHF communications satellites, UHF Follow-On or UFO for short. UFO will provide "more of the same" UHF satellite service to the thousands of military users who have grown to rely on the communications links which are provided by the UHF FLTSATCOM constellation. UFO will replace the aging satellites of our existing constellation to assure the availability of UHF SATCOM links well into the next century. While the UFO procurement is on track for a first launch in mid 1992, we are all holding our breath that the existing FLTSATs and LEASATs will remain healthy until they can be replaced by UFOs.

In developing UFO the Navy has gone entirely to independent transponders but there is not the increase in number of channels that some had expected. The spectrum, as discussed above, just won't support it. Improvements are being made to the broadcast channel which will embed a multiplex-demultiplex capability into that system, but that is the only improvement expected. From the operator's point of view it will be business as usual when UFO comes on line.

Speaking as the operator of the Navy's FLTSATCOM system, I do not see anything short of a new R&D effort that will increase the number of UHF satellite channels over the number that is on orbit today. Given time and money, I'm sure that anything is possible, but don't expect much help in the near term.

The real challenge is ours. We must continue to find new or better ways to optimize what we have today.

DISCUSSION

QUESTION A. Waltho

Has there been any consideration of providing Link 11 via UHF satellite communications, using a UHF bent pipe on existing or future UHF satellites?

ANSWER

Use of Link 11 over UHF satellites has been considered, but there are no known on-going efforts to provide this capability.

QUESTION A. C. Smith

1. Users of UHF satellite communications must be well-drilled in the use of their equipment. If one user increases his EIRP in a misguided attempt to achieve better link quality, he would likely disrupt the communications of other users. How is this situation avoided?

2. Is there a danger that the US Navy proliferation of UHF satellite communications for peacetime use will impact wartime operations when UHF will not be available?

ANSWER

1. For the most part, high value networks are assigned to individual transponders where the power sharing issues are not a problem. Discipline is the key in wideband operations and users are actively controlled to prevent problems.

2. The use of UHF satellite communications is not proliferating, but the US Navy is taking good advantage of what works. A good communicator will get the traffic through. If UHF satellite communications is not available, alternatives will be found.

QUESTION D. P. Haworth

Rumors abound about flying an EHF payload UHF Follow-on. What can be said about the status of this payload?

ANSWER

EHF is being considered for the UHF Follow-on; however, options are still being explored as to the best way to do it. Since it is currently not defined, it was purposely excluded from this presentation. It probably will be there, and it will be compatible with the EHF terminals the US services are developing today.

DISCUSSION

QUESTION P. J. Scarlett

The Navy is presently involved with the MILSTAR program through NESP terminals. Will this capability grow and eventually supercede UHF? Since UHF is not survivable, is it considered a non-essential resource that can only be used for housekeeping and allowed to fail under stress? Isn't there some danger of such a convenient system being used extensively during peacetime and thereby becoming essential for efficient operations?

ANSWER

1. MILSTAR will not have sufficient capacity to support the day-to-day communications requirements of the Navy. UHF will be around for years to come.

2. UHF will be used until it drops off the air, and then will be used again when it comes back.

3. Although there is heavy reliance on UHF satellite communications, its disruption will not interfere with the ability to perform essential operations. Since it is known that it can go away, planning and training proceed accordingly.

THE POST-2000 MILSATCOM ARCHITECTURE

by

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(U) SUMMARY

(U) Military satellite communications (MILSATCOM) systems presently in use and those under development will provide service to a variety of users until the end of the 20th century. What MILSATCOM systems should be fielded for the post-2000 time frame is the subject of an intense study called The Alternative MILSATCOM Architectures (TAMA). This paper examines the present MILSATCOM architecture, including those systems scheduled to begin operation in the early 1990's; discusses how the TAMA study was conducted; and presents insights as to what the 2010 MILSATCOM Architecture should look like.

(U) INTRODUCTION

(U) The Military Satellite Communications (MILSATCOM) Systems Office, generally known as the MSO, was established October 1973. The primary reason for creating this office within the Defense Communications Agency was to coordinate the inter-Service and inter-Agency planning and budgeting for all MILSATCOM Systems and to provide architectural guidance for the evolution of next-generation systems. This broad charter provides the MSO with the responsibility to collect users' satellite communications requirements, and to recommend MILSATCOM system developments that are responsive to users' communications and operational needs. In turn, these acquisitions must be balanced against our estimate of enemy threats, and consistent with state-of-the-art technology, available resources, policies and guidance. Presently fielded MILSATCOM systems, plus those in the process of being fielded, will provide service until the late 1990's and very early 2000's. What our future systems will look like, specifically the post-2000 MILSATCOM Objective Architecture, is a subject under intense study by all agencies in the MILSATCOM business.

(U) BASELINE MILSATCOM ARCHITECTURE

(U) Figure 1 depicts the baseline MILSATCOM Architecture of current and planned systems, and general categories of users who are being supported.

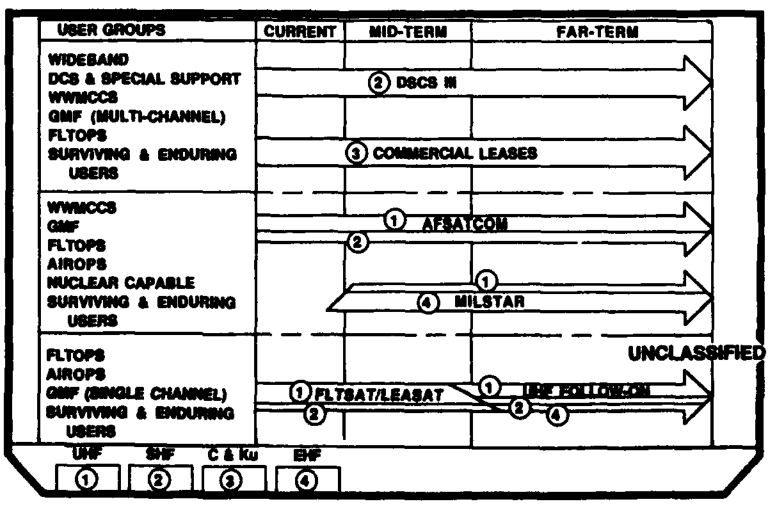

Figure 1. (U) Baseline MILSATCOM Architecture

(U) The Fleet Satellite Communications (FLTSATCOM) system, made up of government-owned FLTSATCOM satellites and augmented by leased, contractor-owned satellites (LEASAT), provides low-capacity, worldwide command and control in the Ultra High Frequency (UHF) band to a large community of customers using small, mobile terminals. Also in the UHF band, the Air Force Satellite Communications (AFSATCOM) system provides the specialized command and control capabilities required by U.S. nuclear forces via communications packages placed on the the FLTSATCOM satellites and other host satellites. AFSATCOM users are also served by the Single Channel Transponder (SCT) packages which provide better capabilities in stressed environments. These SCT packages are currently carried aboard the Defense Satellite Communications System (DSCS) satellites in selected regions. In the Super High Frequency (SHF) band, DSCS provides the backbone of high capacity command and control, intelligence, and multi-channel communications service to a widely diverse group of strategic, tactical, and non-DOD customers. This service is provided by DSCS-II satellites and newer, more capable DSCS-III satellites. Additional communications are provided through leased circuits on commercial C (6/4 GHz) and Ku (14/11 GHz) band satellites. Commercial systems augment military systems in two ways: they provide additional communications channels for routine day-to-day service, and offer an alternative transmission paths in case of loss or disruption of links over military systems.

(U) Two major new systems are under full scale development to enhance our MILSATCOM capabilities: Milstar and UHF Follow-on (UFO). Milstar is a multichannel, Extremely High Frequency (EHF) satellite communications system that will provide survivable, enduring, jam-resistant, and scintillation-resistant secure voice or data communications for the President, Joint Chiefs of Staff, and Commander-in-Chiefs of the Unified and Specified Commands. It will be used for the worldwide command and control of U.S. strategic and tactical forces in all levels of conflict. The UFO system will replace the FLTSATCOM and LEASAT systems and will continue to support communications to large numbers of small terminals in peacetime and crisis situations. A Demand-Assigned Multiple Access (DAMA) system is being developed to allow a substantial increase in the number of users that can be served over the the present UHF system. UFO systems will no longer carry AFSATCOM packages; those critical users presently being served will transition to the Milstar system.

(U) <u>THE NEXT GENERATION - POST 2000</u>

(U) What's on the horizon for 21st century MILSATCOM systems? Studies have already been conducted towards the goal of defining concepts for an upgraded capability for the DSCS system, looking at ways to offer improved service, particulary in a severely stressed operational environment. But that's only one part of the overall architecture. What comes after Milstar and UFO? How big of a role should commercial satellites play in the overall structure? What types of service (and how much) do the operational users of MILSATCOM need to support them into the 21st century? To answer these and other questions, the Assistant Secretary of Defense for Command, Control, Communications, and Intelligence (ASD/C3I) tasked the MSO in November 1988 to develop objective MILSATCOM architectures that will be responsive to user requirements and postulated threats, using projected technology for the post-2000 era. As a result, The Alternative MILSATCOM Architectures (TAMA) study group was initiated. Although MSO was responsible for the overall TAMA effort, this study brought in experts from all aspects of the MILSATCOM field -- experts from the service staffs, space agencies, various defense agencies, government contractors, research facilities, and industry representatives -- all working as a team to provide the best answers to those difficult questions above. The scope of the study included an evaluation of current MILSATCOM deficiencies, present and planned systems, threat analysis, technology, mission requirements, and costs associated with both the space and ground segments (including terminals and control) needed for the time period 2005-2010. The study also looked at various transition issues that would be involved if we implement these objective MILSATCOM architectures. Although the study is ongoing, some interesting insights as to what our future MILSATCOM architecture should look like have already surfaced. It should be emphasized here that TAMA is a process, a method of studying future MILSATCOM systems, and the insights we gain are not absolute nor are they locked in concrete. The TAMA study offers a variety of solutions on how we can meet the operational needs of the future. As we continue this process, new ideas or guidance may surface that may change the way we view future system implementations.

(U) <u>GENERAL CONSIDERATIONS</u>

(U) Factors influencing the development of any MILSATCOM architecture are shown in Figure 2. Several of these key areas are addressed below.

(U) <u>Requirements</u>.

(U) Probably the most difficult task, especially in the far term is determining, and understanding requirements. Several studies were conducted simultaneously to project requirements for the post-2000 era. The first effort addressed requirements as was done in the past, by grouping requirements into user communities: Intelligence, Worldwide Military Command and Control System (WWMCCS), the Defense Communications System (DCS), Ground Mobile Forces (GMF), Nuclear Capable Forces (NCF), Fleet Operations (Flt Ops), Air Operations and Special Support.

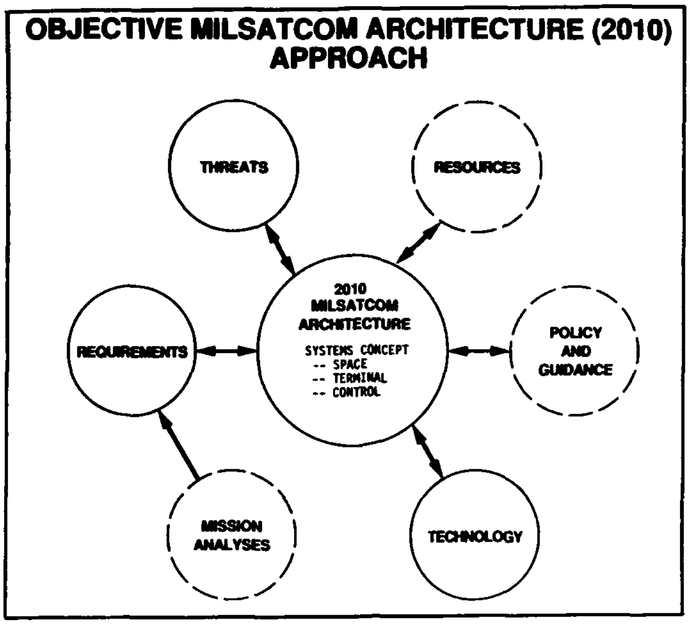

Figure 2. (U) Objective MILSATCOM Architecture Approach

(U) User communities' requirements vary from a low number of very high data rate links, to some who need a high volume of low data rate links. One thing that is apparent -- MILSATCOM requirements are increasing at an alarming rate, as is the need for higher data rates with jamming and scintillation protection. A second requirements study was also conducted that was somewhat different than past studies. By developing a wartime scenario, requirements were looked at during different levels of conflict, by regions, and by mission areas being supported (e.g, land combat, theater Command & Control, theater intelligence, etc.). MILSATCOM planners are able to better design system concepts that will be responsive to the users' needs by understanding the results of these requirements studies.

(U) Threats

(U) Three general categories of threats were considered in the development of the objective MILSATCOM Architectures: electronic threats, nuclear effects on the propogation medium, and physical threats. The principal electronic threats are jamming and interception, which are expected to be significant at all current and planned MILSATCOM frequencies in the 2010-era. The threat of a nuclear detonation during heightened levels of conflict is expected to continue through the 2010-era. A nuclear detonation may cause severe disruption of MILSATCOM communications links due to scintillation and absorption of signals. The third threat category is physical threat. Although this category may include physical threats to both the space and ground segments of the MILSATCOM architecture, physical threats to the space segment were emphasized. Of particular concern in the 2010-era is the development of anti-satellite (ASAT) weapons, such as direct-ascent ASATs, plus ground and space-based lasers (or other directed energy weapons).

(U) Technology.

(U) As with the development with any new system, there must be a corresponding effort to develop the needed technology for those systems to be effective, especially looking out 15 - 20 years. Since UHF and SHF are more mature technologies, minimal new technology development will be required for the post-2000 era. EHF technology is less mature than UHF and SHF. EHF has been demonstrated for low data rates and is under current reseach and development for higher data rates. These technologies are expected to be ready for the post-2000 architecture. As planners looked to future applications of EHF payloads in the Objective MILSATCOM Architecture, they see the need for advancements in many other technologies that permit development of lightweight components. Specifically, improvements are needed in receiver frequency synthesizers, downlink transmitters, cross-link components, advanced antenna and beamforming technology, radiation hardness, and onboard processing components. There is sufficient time to make these necessary improvements for the post-2000 era but a conscious effort, with corresponding funding to support it, must be made for this technology development.

(U) OBJECTIVE MILSATCOM ARCHITECTURE (2010)

(U) Figure 3 depicts the Objective MILSATCOM architecture components which are being proposed at this point in the TAMA study.

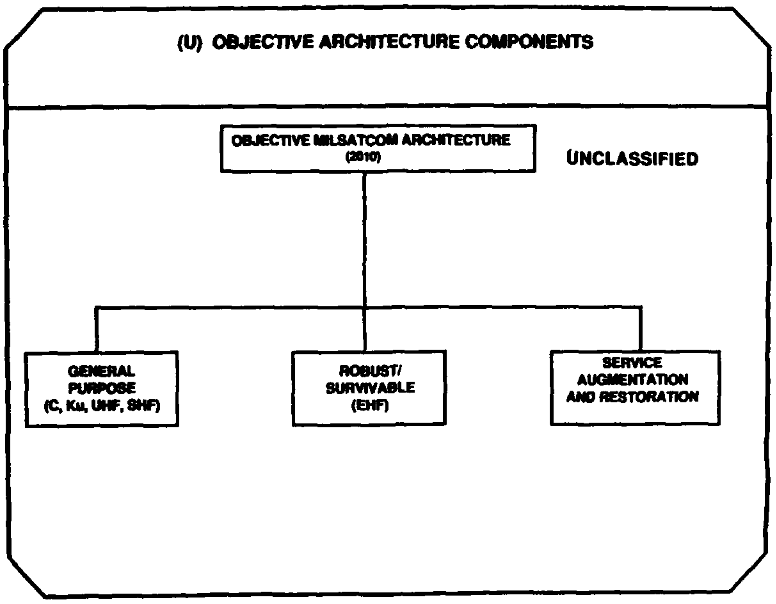

Figure 3. (U) Objective MILSATCOM Architecture

The General Purpose component, primarily consisting of satellites in geostationary orbits, provides service to users who have needs in a peacetime or crisis situation and require only low-level or nuisance jamming protection. Second, the Robust/Survivable component serves users who require communications in high threat environments such as jamming, nuclear scintillation, and physical attack. This component permits communications at all levels of conflict. The third component, Service Augmentation and Restoration, consists of payloads for responsive launch either to augment MILSATCOM service or to restore lost MILSATCOM service. Characteristics of these components will be described in the following paragraphs.

(U) General Purpose Component

(U) The General Purpose component of the Objective MILSATCOM architecture is composed of three types of service. The first type, commercial service, would augment MILSATCOM much as it does today but could also serve as a host for MILSATCOM packages for communications. Fundamental issues related to using commercial service for satisfying MILSATCOM requirements include the cost of commercial service relative to dedicated MILSATCOM systems, and the coordination and approval for use of domestic satellites (DOMSATs) and international services such as INTELSAT and INMARSAT. The second type of service, UHF service in the 225 to 400 MHz band, consists of 5- and 25-KHz transponded channels (similar to the UFO system), fully exploiting ground-based Demand Assignment Multiple Access (DAMA) to provide greater bandwidth/power efficiency. General Purpose UHF will serve the community of small, mobile, and transportable terminals but will offer no electromagnetic survivability (i.e., jamming and scintillation protection). Those users at UHF today that need that type of protection should transition to either SHF or EHF systems in the architecture. The third type of service, SHF service in the 8/7 GHz up/downlink frequency band, consists of transponding satellites. Jamming protection is provided by the terminal modem, while adaptive nulling is provided by the satellite uplink antenna. The SHF service also permits continued compatibility between the U.S. and its allies. Although a processing capability at SHF could be developed, it is not advocated at this time. It is more cost effective (performance-wise) to process at EHF, and this capability will be included in the Robust/Survivable segment.

(U) Robust/Survivable Component

(U) A tremendous amount of study has gone into this area on how best to satisfy those missions operating in a wartime environment. The toughest issue is how to satisfy a growing number of requirements in the face of a growing threat. The electronic and scintillation threats can best be overcome by a processing satellite at EHF. The present concept is to use operating frequencies in the 44/20 GHz uplink/downlink bands, however other frequency bands are possible, such as 30/20 GHz. This Robust/Survivable component will be compatible with the existing low data rate EHF waveform standards, and those evolving for the medium and high data rates. Satellite-to-satellite crosslinks will be employed, using a 60 GHz crosslink to satisfy requirements as we understand them. Laser crosslinks are still an option, especially if the data rate requirements go beyond 100 Mbps. Cost-performance tradeoffs in this area continue.

(U) Other Features. When we defined the concepts of "robust" and "survivable", there were certain features inherent in both and certain differences as well. As far as their capabilities in the areas of jamming protection, scintillation protection, crosslinks, and the ability to handle data rates up to 1.544 Mbps, the robust and survivable systems are very similar in capability. The robust service would provide geostationary coverage and would offer high data rate (above 1.544 Mbps) capability, while the survivable service would provide worldwide coverage and would not include the capability for high data rates. The major difference between robust and survivable service is in the area of physical surivabilility. While the robust satellite is recommended for collateral hardening only, the survivable constellation would either be a small number of hardened and maneuverable satellites, or a large number of relatively small, less hardened satellites that are proliferated. Given the basic features needed in "robust" and "survivable" service, numerous concepts were explored on how best to provide that service. Some of the concepts explored are listed below:

a. (U) Concept 1: A combined robust/survivable satellite, capable of all data rates, worldwide coverage, hardened and maneuverable, approximately 10 satellites in orbits similar to Milstar.

b. (U) Concept 2: A combined robust/survivable satellite as in Concept 1 above, plus a smaller survivable satellite to cover the polar regions. Approximately 6 of the combined satellites would be in geostationary or low inclined orbits (LIO). Approximately four of the smaller survivable satellites would be placed in polar orbits. These smaller, survivable satellites would handle only low and medium data rates (up to 1.544 Mbps).

c. (U) Concept 3: Separate robust and survivable satellites. Approximately six robust satellites would be placed in geostationary (or LIO) orbits, capable of handling all data rates, hardened only to the collateral level and no maneuvering. Approximately 10 survivable satellites, capable of only low and medium data rates, would be employed in orbits similar to Milstar, and would be hardened and maneuverable.

d. (U) Concept 4. Separate robust and survivable satellites, introducing the concept of proliferation. The robust segment would be the same as described in Concept 3 above. The survivable segment would consist of at least 24 satellites in circular orbits (10 hour, 9340 NM, 53 degrees inclination), arranged in four planes. These satellites would provide low and medium data rates, and would only be collaterally hardened. Survivability is achieved by proliferation.

e. (U) Concept 5. A totally proliferated system consisting of a combined robust and survivable satellite, capable of handling all data rates. Approximately 32 satellites would be in circular orbits (11 hour, 10,500 nm, 53 degrees inclination), four planes of eight satellites each. These satellites would be much smaller than the combined satellites in concept 1, and would be hardened only to the collateral level.

f. (U) Other Concepts: For the far term, there are certainly other concepts that may serve the robust and survivable communities very well. The concepts above were studied in detail to gain an appreciation of how well they could satisfy requirements, what the impacts to the terminal and control communities would be, and types of satellites designs and technology that would be needed in the future. From these studies other concepts have spawned, looking at ways to possibly reduce cost or tailoring satellites to large user groups such as Intelligence and Ground Mobile Forces. TAMA has generated a process to generate and analyze these future MILSATCOM architectural concepts.

(U) Service Augmentation and Restoration.

(U) The purpose of the third objective MILSATCOM Architecture component, Service Augmentation and Restoration (SA&R), is to reduce dependency on large, fixed-station launch facilities. Fixed launch facilities are characterized by protracted launch preparation periods and high vulnerability to physical destruction during any level of conflict. SA&R capabilities augment existing MILSATCOM service by providing additional capacity and coverage in regions with unforeseen growth requirements. SA&R also permits restoration of service in regions experiencing a satellite loss or failure. Potential advantages of SA&R are increased survivability, responsive launch, and lower cost. Since we have not in the past included a SA&R component in the MILSATCOM architecture, a great deal of research needs to be done in the areas of launch control, operational and control concepts, and initial platform checkout and control.

(U) CONCLUSION

(U) The post-2000 MILSATCOM Architecture must be a very flexible architecture able to meet the diverse and growing needs of operational commanders and government agencies. Satellite systems should be tailored to the needs of the customer -- one size won't fit all. The costs and complexity associated with satellite systems designed to operate in increasingly hostile threat environments make it prohibitive to give that service to everyone. The TAMA study explored alternatives for future MILSATCOM service. The General Purpose component would offer service in the UHF, SHF, and commercial bands in a similar manner as it is being handled in today's architecture. As the need for higher data rate service and protected service grows, customers who need that type of service should transition to the Robust/Survivable segment of the architecture. The TAMA study has explored various options to implement this robust and survivable service, using concepts ranging from a few dedicated satellites all the way to concepts that incorporate smaller satellites that are proliferated. And for the first time, the idea of having small satellites with a responsive launch capability is incorporated into the MILSATCOM Architecture through the proposal of the Service Augmentation and Restoration component. The TAMA process continues to explore new concepts for our future MILSATCOM systems. The ability to better define the post-2000 architecture, and insights gained from the TAMA study, will help the Department of Defense and Congress make critical decisions concerning the future of MILSATCOM systems.

DISCUSSION

QUESTION N. A. Ince

1. Are the communication needs of submarines included in your plans?

2. Do systems utilizing smaller satellites necessarily cost less to meet a given set of requirements?

ANSWER

1. There are plans for EHF communications with submarines for the future.

2. No. However, by having smaller satellites in the architecture, it may be possible to reduce the overall capacity of the bigger satellites (and hence reduce their cost). The net cost to satisfy requirements may be about the same; however, there will be a great deal more flexibility and enhanced ability to more efficiently satisfy requirements.

LIGHTWEIGHT EHF COMMUNICATIONS SATELLITES

by

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ABSTRACT

Current and planned Military Satellite Communications (MILSATCOM) systems, which typically employ a few, large satellites operating in synchronous altitude circular orbits, provide good fundamental service. However, there are concerns among some users regarding the potential for localized capacity shortfalls, particularly for anti-jam tactical service. Due to the large size of the currently planned satellites, there is no capability to rapidly augment capacity through timely and survivable launches of additional space assets. Small EHF satellites can significantly complement the anti-jam service of basic MILSATCOM space segments. Mobile/survivable launch vehicles with rapid launch preparations can be utilized to deploy these satellites into high altitude elliptical or circular orbits. In these orbits, only a few satellites are needed for high duty cycle coverage of critical areas. Through the use of standard EHF waveforms, the complementary satellites will be compatible with existing EHF terminals. Advanced technology allows the development of the highly capable, lightweight payloads required for this role. Some of the key technologies for these complementary satellites include high speed, low power digital signal processing subsystems, lightweight frequency hopping synthesizers, and efficient solid-state transmitters. These same technologies are also applicable in reducing the size of the large, fundamental-service space segments or in implementing highly capable secondary EHF payloads.

INTRODUCTION

The trend in communications satellites over the past years has been to larger satellites. This trend has continued as satellite communications have evolved into the EHF bands (44 GHz uplinks and 20 GHz downlinks) in order to provide robust and survivable MILSATCOM service. As a result, the development and deployment of large EHF satellites is a lengthy process and the final systems provide limited flexibility for supplementing capacity as requirements change. An EHF augmentation satellite which can be launched with a small, mobile rocket into a high altitude orbit will provide a significant enhancement to the overall system architecture by providing several desirable features [1]. The motivation for this type of lightweight communications satellite will be described. Then, the system concept for the lightweight EHF augmentation satellites will be discussed next. Finally, some of the critical technologies needed to implement high capability payloads with low weight and power impacts will be identified, and examples of the savings possible with these technologies will be presented.

MOTIVATION FOR LIGHTWEIGHT COMMUNICATIONS SATELLITES

Currently, MILSATCOM systems support user requirements utilizing UHF and SHF satellites as shown in Fig. 1. Planned MILSATCOM systems transition users to the EHF bands in order to provide better anti-jam (AJ) performance. However, both the current and planned MILSATCOM systems employ a few (<10), large (>2500 lbs) satellites operating in synchronous altitude, circular orbits. As a result, large launch vehicles are required to deploy the satellites. Only a few appropriate launch sites exist and the preparations for a launch are lengthy. The planned systems provide good fundamental service. However, due to the characteristics associated with the large satellite size of these systems, concerns are expressed by some of the MILSATCOM users. Since relatively few of the large, expensive satellites are deployed, there may be localized capacity shortfalls in the available AJ service. There are also questions about the survivability of a small number of satellites. Due to the lengthy construction and launch sequence for the planned satellites, on-orbit resources cannot be rapidly increased for a theater of operation. Therefore, tactical users (for example) may experience an AJ capacity shortfall, and new satellites cannot be launched in a timely or survivable manner to augment or restore service.

The use of lightweight communications satellites can significantly mitigate these user concerns. These satellites can augment the basic robust MILSATCOM service by providing operation at EHF utilizing the standard transmission formats (MIL-STD-1582). Thus, these augmentation satellites will be compatible with the current and planned EHF terminals being developed by the Services. The small augmentation satellites will also provide flexibility in meeting user requirements by providing a responsive launch capability using small, mobile/survivable launch vehicles and by allowing deployment of service in smaller increments. This incremental deployment flexibility is illustrated in Fig. 2 where the number of Low Data Rate (LDR; < 20 kbps per channel) EHF channels is shown versus the total satellite weight. The band of large satellites represents the class of EHF satellites currently planned. They are large, multi-mission satellites with anywhere from a few to many EHF LDR channels. The augmentation/restoration satellites are single mission satellites which span a region of interest covering a few tens of channels with satellite weights of several hundred pounds. As an example, suppose a particular region of the world required another 20 channels of AJ service. With large satellites, coverage of this region could eventually be obtained by deploying one or more satellites depending on the number of channels supported on each satellite. However, this approach will require considerable time and expense to implement and will provide an excess of capability that might well be wasted (thus perhaps leading to a decision to provide no service for these additional 20 required channels). With the service augmentation satellites, one or more (depending on the orbit achieved with the launch vehicle used) 32 channel satellites weighing about 300 lb could be deployed to provide this capability. Since these satellites are small and their launch costs are low, the cost of providing this increment in required service is much lower than with the much larger satellites.

The significance of this role for lightweight satellites is reflected in their inclusion in the architecture studies recently lead by DCA/MSO (i.e., The Alternative MILSATCOM Architecture (TAMA) studies). Earlier studies also identified this approach to addressing the user concerns discussed earlier. A study performed by Lincoln Laboratory for DARPA in the summer of 1988 investigated the utility of lightweight communications satellites [1]. The study considered a number of factors including frequency bands, transmission formats, service capabilities, launch vehicles, deployment options, and critical technologies required to implement the concept. The study concluded that lightweight EHF satellites can provide significant complementary service to the larger, fundamental service EHF systems. A Defense Science Board study on the assured military use of space (also done in the summer of 1988) identified needs in the area of tactical communications: connectivity within tactical forces, AJ capacity, and polar coverage. They recommended an EHF communication adjunct providing AJ service, mobile/survivable launches to orbits capable of providing polar coverage, and proliferation of smaller, lighter satellites for wartime functions.

SYSTEM CONCEPT

The system concept for the augmentation satellites is illustrated in Fig. 3. Service in critical areas can be enhanced by an EHF satellite using the standard waveforms and responsively launched into a high altitude orbit. Advanced technologies will be critical for achieving the capabilities needed in a lightweight, low power configuration.

The launch vehicle for the small satellite should be a small, potentially mobile rocket. Figure 4 shows the estimated launch capabilities for some representative boosters. The spacecraft weight placed into orbit is plotted versus the net launch velocity required for the mission. Several typical orbits are indicated on the top axis. The general region of interest (spacecraft weights of several hundred pounds) for the augmentation satellites (see Fig. 4) is within the capabilities of several of the example boosters as the desired orbit ranges from about a 6 hour Molniya-type orbit to a 24 hour circular orbit. These include the Pegasus air-launched booster in the lower portion of the region of interest and the Taurus standard small launch vehicle (SSLV) in the upper portion of the region. Launch vehicles typically used for geosynchronous satellites (i.e., the Delta and Atlas) exceed the capabilities required for the small satellites.

With high altitude orbits, good coverage of an area can be obtained with only a few satellites as shown in Fig. 5. A 1500 kilometer area is shown centered on Bonn, West Germany. The percentage of time this area is covered (with a 20-degree minimum terminal elevation angle) as a function of the number of satellites deployed into a particular type of orbit is shown in the first graph. The second graph shows the availability of a long baseline link out of the area (in this case to Washington D.C.). A single geosynchronous altitude satellite with a low inclination orbit provides 100 percent service to this area. Two satellites in Molniya-type orbits of from 6 to 12 hours provide good coverage of the area (about 75 percent to almost 100 percent coverage) and fair availability of the link to CONUS. The satellites in Molniya-type orbits also provide coverage to the polar regions and to other areas of the world.

An example small EHF payload is illustrated in Fig. 6. This payload has a 5-deg spot beam and an Earth coverage beam to provide uplink (44 GHz) and downlink (20 GHz) coverage. A total of 32 communications channels and 8 acquisition channels are processed by the payload (half from each beam). An on-board access controller provides resource assignment and reconfiguration services in response to requests from terminals. A 2 W solid-state amplifier provides the transmission power for the single time division multiplexed downlink stream. Using the type of technology (early 1980's) which is currently on-orbit for LDR EHF communications, this payload would require about 230 lb and 200 W. Utilizing technologies which will be available in a year or two, the payload can be reduced to 80 lb and 100 W. Further reductions in the weight and power are possible in the far term as indicated.

There are several alternative launch vehicles available for deploying a small payload of this type. In the first deployment option (see Fig. 7), the near term (80 lb, 100 W) payload is coupled with a small, 200 lb (on-orbit weight) satellite bus and a fourth stage (on the order of 500 lb). Using the three stage Pegasus air-launched space booster, this small satellite can be launched into a 6-hr Molniya-type orbit. In the second deployment option (see Fig. 8), the 280 lb small satellite with a fifth stage (apogee kick motor) is launched by the Taurus SSLV into a 24-hr (synchronous altitude), low inclination circular orbit. Thus, depending on the launch vehicle selected, the example small EHF satellite can be launched into any of the desired orbits for providing good area coverage service with one or two satellites.

CRITICAL TECHNOLOGIES

An EHF communications payload can benefit significantly from advanced signal generation and signal processing techniques. The simplified block diagram of a LDR EHF payload shown in Fig. 9 highlights several of the areas in which such technology can make significant contributions in a lightweight satellite. Each of the areas illustrated will be discussed in this section: the lightweight frequency generators, the high speed signal processing, and the high efficiency solid-state power amplifiers.

With near term technology, significant reductions can be made in the weight and power required to implement the uplink and downlink frequency hopping synthesizer circuits and the associated local oscillator frequency generation circuitry. As shown in Fig. 10, current on-orbit versions of these subsystems were implemented with early 1980's technology for about 33 lb and 40 W. In the near term, using high speed, low power direct digital synthesizers and hybridized RF circuitry results in a subsystem requiring only about 4 lb and 12 W. This is a savings by factors of more than 8 in weight and 3 in power over the earlier technology.

In the area of high speed signal processing, Fig. 11 shows some comparisons between near-term and far-term Fast Fourier Transform (FFT) demodulators for processing the M-ary FSK LDR waveform. In the near term, using VLSI circuitry and application specific ICs (ASICs), the FFTs needed for handling 32 communications channels and 8 acquisition channels (such as in the example small EHF payload) could be implemented for about 12 lb and 30 W. In the far-term, the use of wafer scale integration will allow twice as many communications channels and the same number of acquisition channels to be demodulated for half the weight and two-thirds the power.

The 2 W, 20 GHz transmitter in the example small EHF payload could be implemented in a lightweight, low power configuration using either FETs or permeable base transistors (PBTs) as shown in Fig. 12. By circuit combining the output powers of several devices, output powers with the desired 2 W level can be achieved. The FET transmitter requires fewer active devices, but also requires more DC input power than the near-term PBT amplifier. The power output levels and the device efficiencies of the PBTs are expected to show the greater improvements in the far-term. As can be seen in Fig. 12, a 5 W PBT transmitter is expected to require less DC input power than a near-term FET transmitter generating 2 W.

Advanced packaging concepts are also required to obtain a lightweight EHF payload. Figure 13 shows a possible configuration for the example small EHF payload. The 5 deg uplink and downlink antennas dominate the volume required. The RF electronics are mounted on the antenna structure. The digital electronics are mounted on the payload platform as illustrated. These digital boxes are thin (accommodating a single board), and the thermal control paths are integrated with the box structure. By providing large circuit board areas, the number of interboard connections (and the associated harness weight) is reduced.

The technologies which are used in making a highly capable, small satellite for augmenting MILSATCOM service can also be applied to other communications payloads. For example, using the advances in technology, the basic service satellites could either be implemented as smaller satellites for the same level of service, or they could be configured with additional capabilities in the same weight and power envelope. The small payloads developed with these advanced technologies could also be highly capable secondary payloads on host satellites.

SUMMARY

Lightweight EHF communications satellites can play a significant role in augmenting the service provided by fundamental EHF MILSATCOM systems. These satellites can provide extra capacity for critical areas, can be launched responsively by several types of mobile or survivable launch vehicles, and can achieve lower incremental costs for providing augmentation capacity. The system concept incorporates small satellites utilizing the standard EHF transmission formats and user control provisions. These satellites can be launched into high altitude elliptical or circular orbits by small launch vehicles. Several critical technologies have been identified which can significantly reduce the weight and power of the EHF payload. These include high speed signal processing, lightweight frequency generators, and efficient solid-state transmitters.

REFERENCES

[1] D. P. Kolba, L. L. Jeromin, D. R. McElroy, and L. N. Weiner, MIT Lincoln Laboratory, "Complementary Robust MILSATCOM Service: A Significant Role for Lightweight Spacecraft," 1 March 1989, Project Report SC-79.

FIGURE 1

CHARACTERISTICS OF CURRENT/PLANNED MILSATCOM SYSTEMS

CURRENT

- FEW (<10) LARGE (>2500 lbs) SATELLITES
- SYNC. ALTITUDE CIRCULAR ORBITS
- MODEST AJ

PLANNED

- SIMILAR SPACECRAFT NUMBERS, SIZES, DEPLOYMENTS
- EXCELLENT AJ

LARGE LAUNCH VEHICLES REQUIRED
- FEW APPROPRIATE SITES
- LENGTHY PREPARATIONS

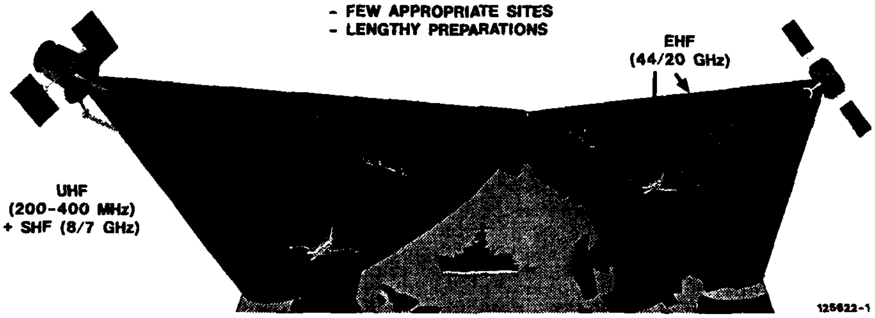

FIGURE 2

EHF DEPLOYMENT OPTIONS

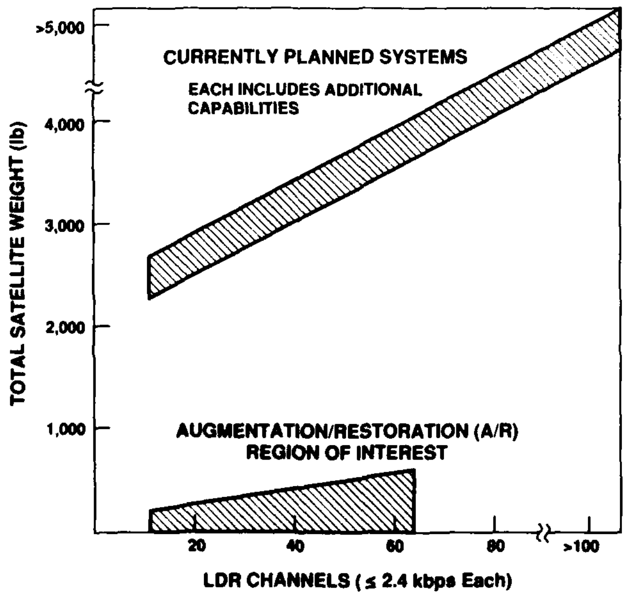

FIGURE 3

SMALL SATELLITE SYSTEM CONCEPT

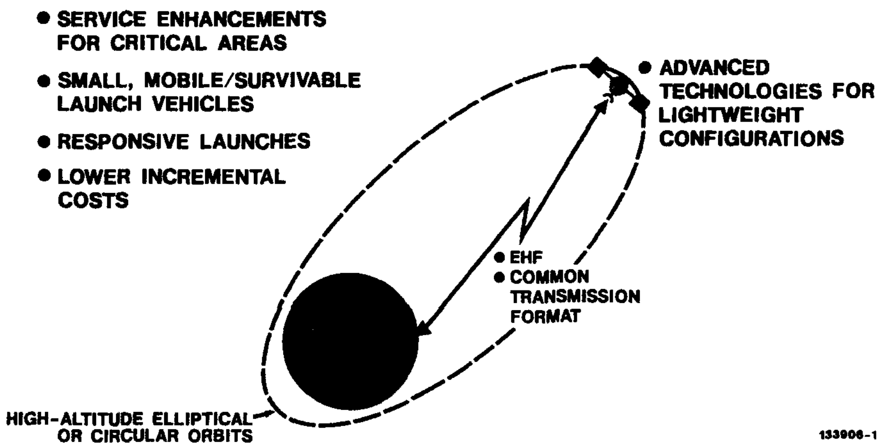

FIGURE 4

LAUNCH VEHICLE CAPABILITIES

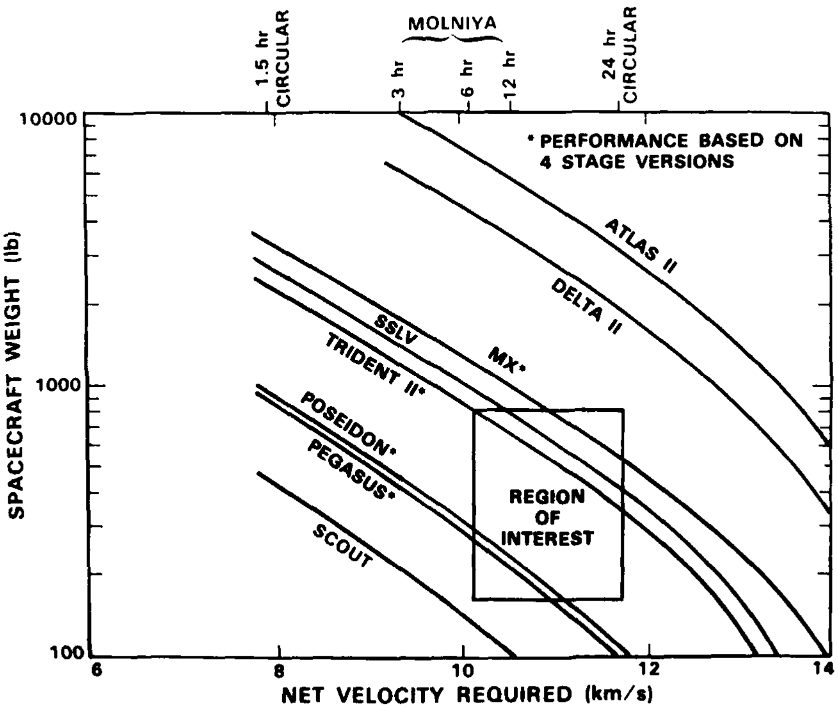

FIGURE 5

EXAMPLE AREA COVERAGE

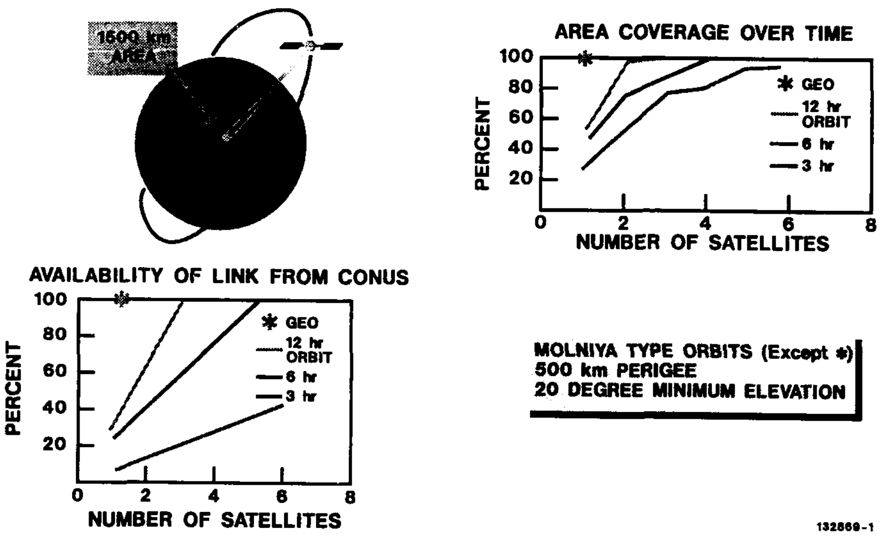

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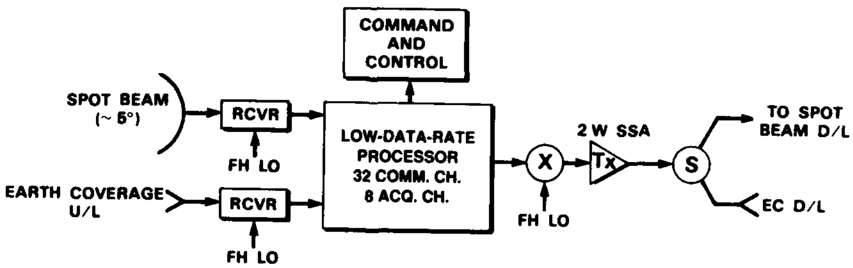
FIGURE 6

EXAMPLE SMALL EHF PAYLOAD



	CURRENT ON-ORBIT TECHNOLOGY (Early 1980's)	NEAR-TERM TECHNOLOGY (0-3 yr)	FAR-TERM TECHNOLOGY (> 5 yr)
WEIGHT (lb)	230	80	55
POWER (W)	200	100	70

FIGURE 7

LIGHTWEIGHT EHF SATELLITE DEPLOYMENT

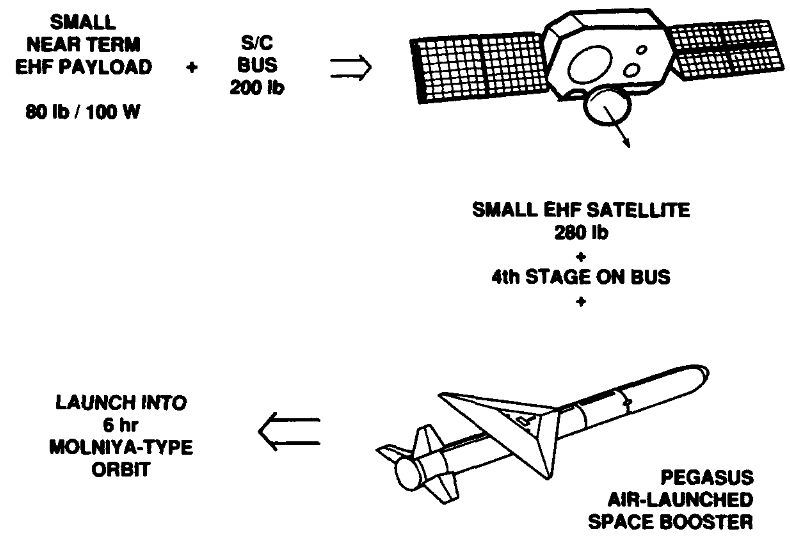


FIGURE 8

LIGHTWEIGHT EHF SATELLITE DEPLOYMENT

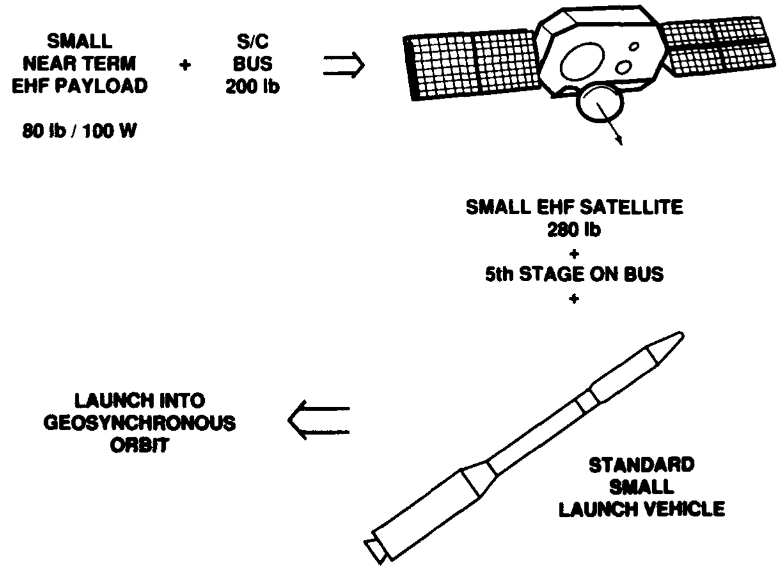


FIGURE 9

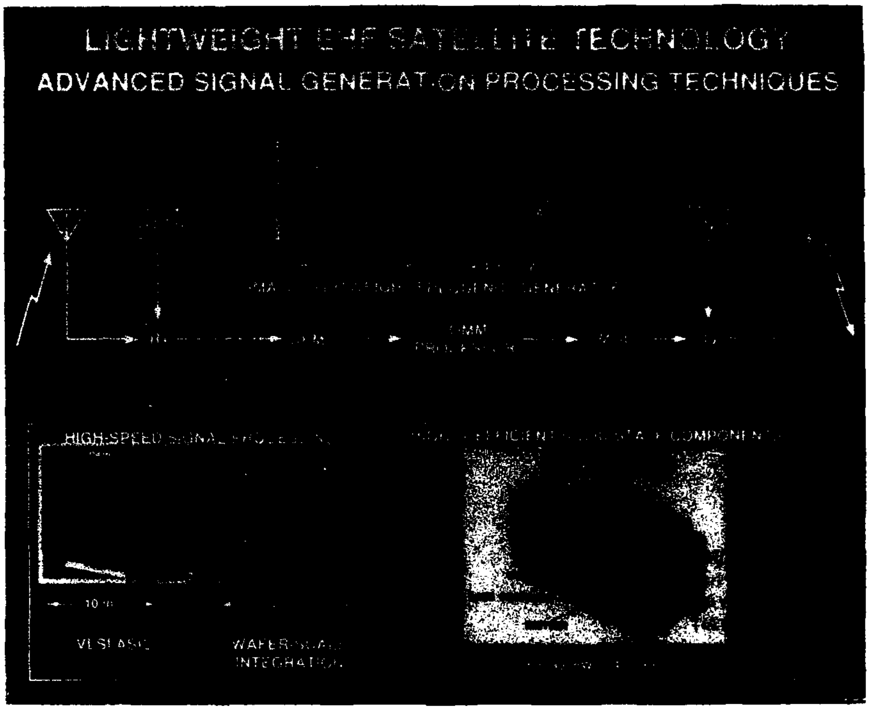


FIGURE 10

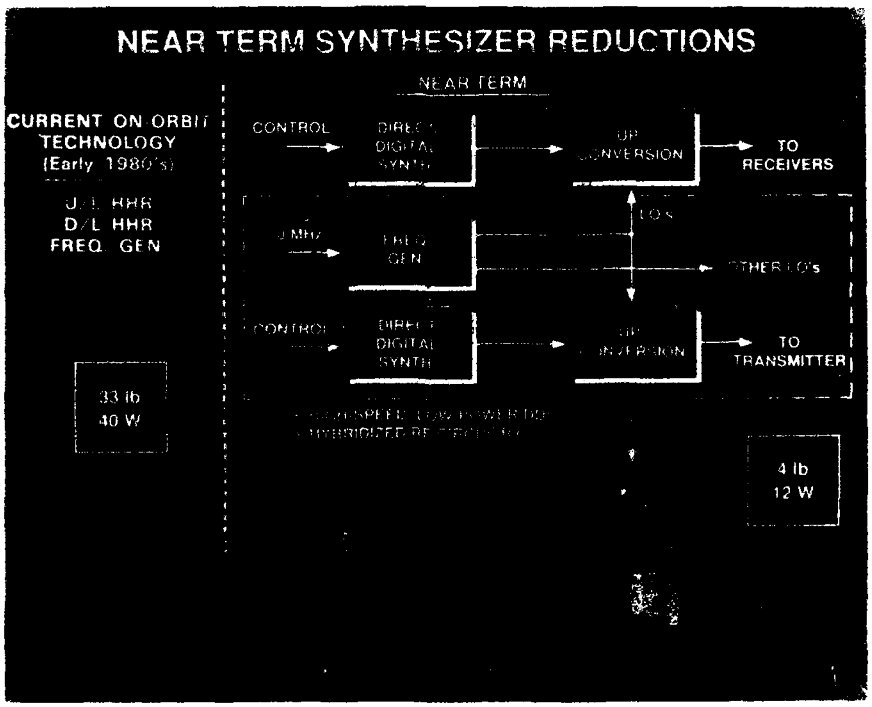


FIGURE 11

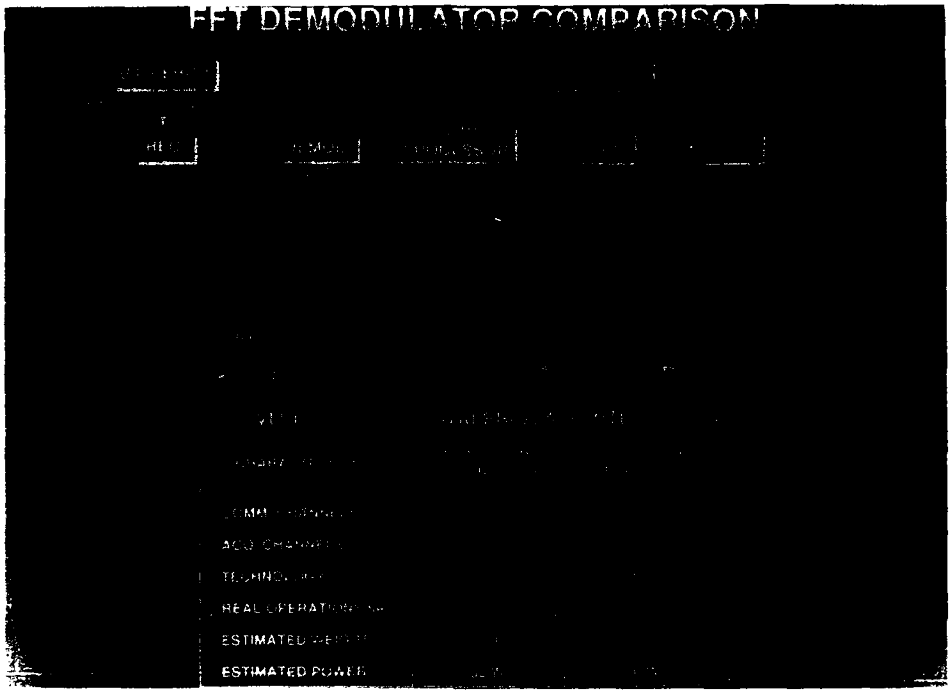


FIGURE 12

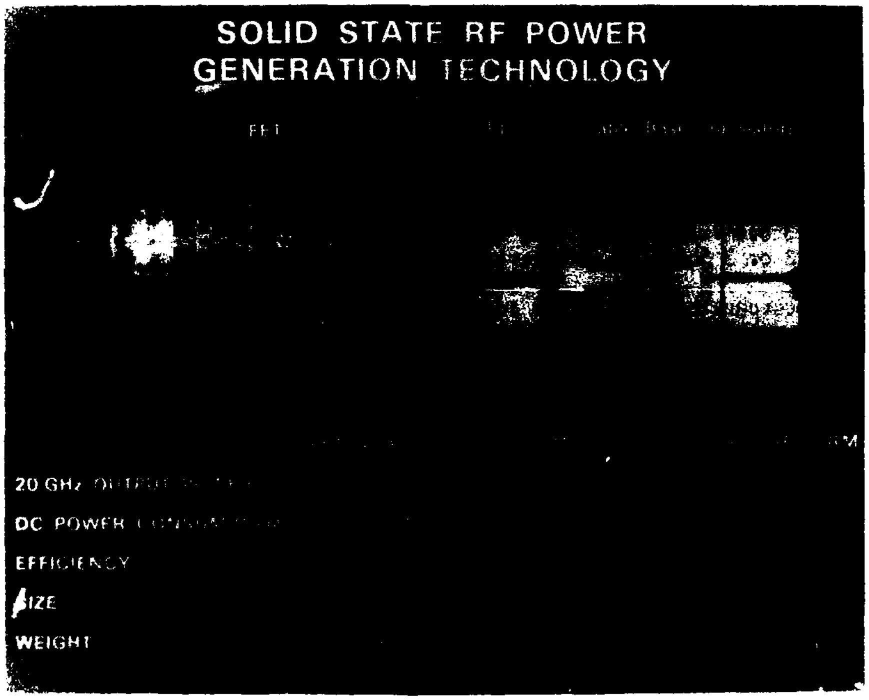
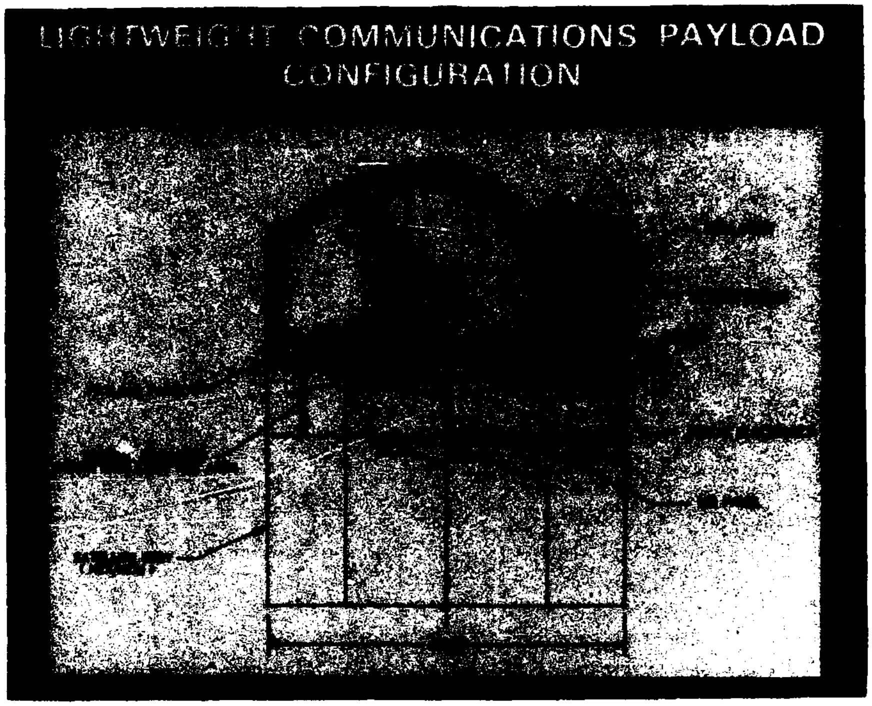


FIGURE 13



DISCUSSION

QUESTION P. Scarlett

Could a small amount of adaptability, such as

(1) 3 beam mainbeam nulling in theater applications
(2) 2 or 3 low gain auxiliaries for side lobe cancellation

be incorporated with little additional weight, volume, and power? This could greatly improve survivability for a reasonable cost.

ANSWER

Yes, the lightweight EHF payload which was described has significant anti-jam capabilities through spread-spectrum and on-board signal processing techniques as well as side lobe discrimination against interference sources outside of the field-of-view of the spot beam antenna. By adding a multiple-beam feed, amplitude and phase weighting circuitry, and additional processing to this spot-beam subsystem, the payload would have autonomous, adaptive capabilities to further discriminate against interference sources, including those within the spot-beam footprint. Such a capability would probably increase the indicated payload weight/power estimates by approximately 20%.

TACTICAL EHF SATELLITE COMMUNICATIONS FOR NATO EMPLOYING NON-GEOSTATIONARY ORBITS

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SUMMARY

Most of the world's satellite communications employ satellites in the geostationary orbit, for ease of tracking by the ground stations, and the ability to realize coverage of the populated regions of the globe with a set of three satellites. Geostationary satellites, however, afford poor visibility and degraded performance in the northern zones. This area is extensive and it is of strategic military importance. Satellites in the non-geostationary orbits can provide the required coverage in the north. The object of this paper is to examine the use of non-geostationary satellites for tactical communication for NATO, their orbits, and implications for on-board processing.

PREFACE

Requirements of Tactical Satellite Communication

Military communications, for NATO areas of responsibility, encompass large areas, including the north. For tactical reasons, there is a need for communication that is available continuously, is secure, has low probability of intercept (LPI), has nuclear survivability, is immune to EMP, and has anti-jam (AJ) features. In addition, communication is required between the various elements of the forces; that is a network comprised of a switch as well as a variety of earth terminals (land-mobile, fixed, transportable, manpack, shipborne, submarine, airborne) is needed.

For secure communication use of spread-spectrum frequency-hopping is the preferred technique, with the degree of protection being determined by the "spreading bandwidth." At EHF sufficient bandwidth is available. The move to extremely high frequency (EHF; 30-300 GHz) is also desirable for a variety of other reasons; the antenna size (and weight, volume etc.) is small for a given gain, the user discrimination is better, the effect of nuclear scintillation fading is less, and advanced antenna techniques (antenna nulling, beam hopping, etc.) become feasible[1-23].

Non-Geostationary Orbits

Examples of suitable orbits are polar orbits, inclined circular orbits (e.g. circular inclined synchronous), inclined elliptical orbit (e.g. Molniya and Tundra). The selection of an orbit for a constellation of satellites to provide communication in NATO countries is described. Orbital elements and the ephemeris model to compute the results are presented. These will include satellite ground track, elevation, azimuth, doppler shift, and range variations.

Finally some implications for the Payload of using non-geostationary orbits, regarding hand-over of information from one satellite to another in the constellation, and switching of information for use within the field-of-view (FOV) of the satellite are presented.

LIST OF SYMBOLS

a	Semi-major axis of the orbit
a_{12}	Semi-major axis of the orbit for two revolutions per day ("12 hour" period)
a_{24}	Semi-major axis of the orbit for one revolution per day ("24 hour" period)
ae	Distance from Center to Focus of the elliptical orbit
AJ	Anti-jamming
CIS	Circular Inclined Synchronous

EMP	Electromagnetic pulse
ENKE	First N-body orbit determination algorithm widely used, developed by Enke
GPS	Global Positioning System
km	kilometer
LPI	Low probability of intercept
Mol12	Molniya 12 Hour
Mol24	Molniya 24 Hour
NASA	National Aeronautics and Space Administration
NORAD	North American Air Defence
SDP	Deep space orbit prediction algorithm
SGP	First and simplest of the NASA orbit prediction algorithms based on a Keppler 2-body solution
T	The period of a satellite in an elliptic or circular orbit around the earth
TUNDR	Tundra
μ	The gravitational parameter

1 INTRODUCTION

The purpose of this paper is to identify non-geostaionary orbits that are suitable for tactical communication by NATO, provide characteristics for these orbits, and present the spatial, frequency and time tracking requirements for the ground terminals. To this end, various non-geostationary orbits are examined, an estimate is made of the coverage area requirements, the criteria for selection of the satellite orbits are given, the orbit parameters for the various orbits are presented, and finally results are provided in graphical form.

2 REQUIREMENTS AND ORBIT SELECTION

2.1 Requirements

The requirements of satellite coverage are as follows:

- 24 Hour coverage
- Coverage of NATO's area of responsibility

Some of the non-geostationary orbits suitable for NATO coverage are listed below:

- Circular Inclined Synchronous
- Molniya 12 Hour
- Molniya 24 Hour
- Tundra
- GPS (Global Positioning System)

2.2 Criteria for Selection of Parameters

The criteria used for the selection of the orbit parameter values were the above stated requirements as well as the considerations listed below:

- Ideally coverage in the area bounded from 25° N Latitude to the North Pole and from 45° E and 170° W Longitude, i.e. area including the NATO member countries of Belgium, Canada, Denmark, France, Greece, Iceland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Turkey, the United Kingdom, the United States and West Germany
- Ease of tracking
- Tolerable range (with regard to transmit/receive power requirements)
- Tolerable Doppler shift (with regard to synchronization, and feasibility of hardware design)
- Tolerable elevation angles, >10° (with regard to transmit/receive power requirements, and antenna tracking)
- Small number of satellites in the constellation (to minimize cost)
- Low launch costs
- Negligible atmospheric drag
- Little exposure to radiation from the Van Allen belt
- Security (physical security of the satellites)

2.3 Models

In order to specify the size and shape of an inclined orbit and its orientation relative to earth and the position of a satellite in its orbit, 6 orbital parameters are required. For the five orbits listed above, namely *Circular Inclined Synchronous (CIS), Global Positioning System (GPS), Molniya 12 Hour (Mol12), Molniya 24 Hour (Mol24), and the Tundra (Tundr)* orbital parameters are given in Table 1. In Fig. 1 various orbits are shown, and as an example the Tundra orbit is shown in Fig. 2.

TABLE 1

ORBITAL PARAMETERS

Parameters	Values for Circular Inclined Synchronous Orbit	Values for GPS-012 Orbit	Values for Molniya 12 Orbit	Values for Molniya 24 Orbit	Values for Tundra Orbit
Catalog Number	cis	gps-012	mol12	mol24	tundr
Epoch Time	78/06/20 21:36:00 UTC	89/02/25 01:41:49 UTC	78/06/20 21:36:00 UTC	78/06/20 21:36:00 UTC	78/06/20 21:36:00 UTC
Element Set	1	2	3	4	5
Inclination	40.0°	55.1294°	63.4°	63.4°	63.4°
RA of Node	345°	216.2430°	275°	65°	20°
Eccentricity (e)	0.0	0.0090905	0.73	0.73	0.374
Arg of Perigee	-90°	180.3094°	-90°	-90°	-90°
Mean Anomaly	0.0°	179.6527°	0.0°	0.0°	0.0°
Mean Motion *(Rev/Day)*	One	2.01388764	Two	One	One
Decay Rate, Drag, *(Rev/Day²)*	0.0e+00	1.500e-07	0.0e+00	0.0e+00	0.0e+00
Epoch Rev	One	17	One	One	One
Semi-Major Axis (a)	42164 km	26487.80 km	26561.789 km	42164 km	42164 km
Beacon	10000 MHz	10000 MHz	10000 MHz	10000 MHz	10000 MHz
Distance from Center to Focus (ae)	0 km	265 km	19390 km	30780 km	15769 km
Semi-Minor Axis (b)	42164 km	26559 km	18154 km	28817 km	39104 km

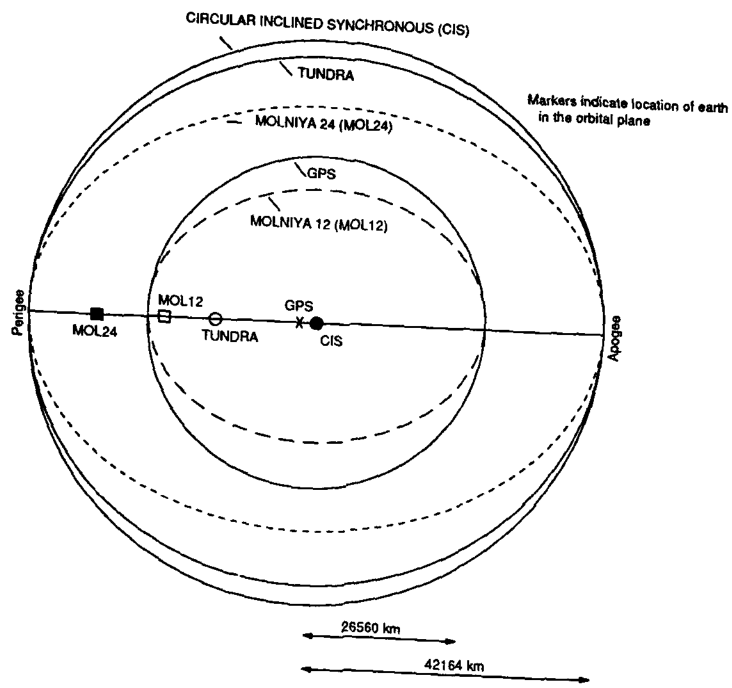

Fig. 1. Various non-geostationary orbits (ignoring inclination and scaling)

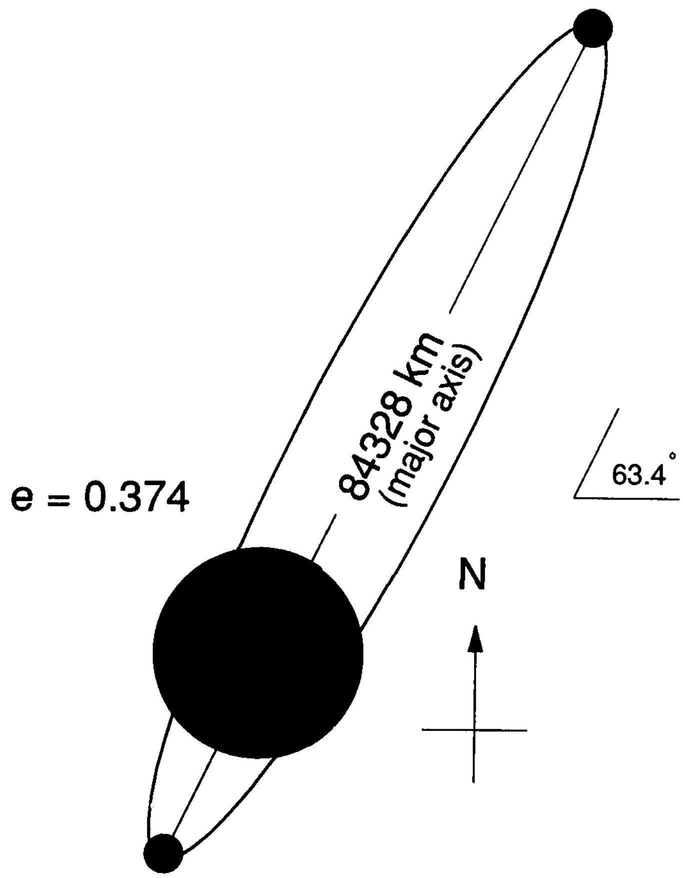

Fig. 2. The Tundra orbit.

The calculations of semi-major axis values given in Table 1 are presented here. The period T of a satellite in an elliptic or circular orbit around the earth is given by[24]:

$$T = 2\,\pi\, a^{1.5}\mu^{-0.5} \text{ sec mean solar time}$$

where

a is the semi-major axis
μ is the gravitational parameter.

$$\mu = (73.594762)^3\,\text{km}^3\,\text{sec}^{-2}$$

Sidereal day is the time for earth to rotate around its axis relative to the stars; and it is equal to 86164 sec

Thus, a_{12} for two revolutions per day ("12 hour" period), and a_{24} for one revolution per day ("24 hour" period) are given by:

$$a_{12} = 26562 \text{ km}$$

$$a_{24} = 42164 \text{ km}$$

A computer program called "*Orbit*" was used to carry out computations for azimuth, elevation, range, Doppler shift, etc. at 4 locations of the coverage area for each of the 5 non-geostationary orbits. "*Orbit*" is a non-geostationary satellite tracking program based on the NASA/NORAD near space (SGP) model. The original program[15] was modified to work under 4.3 BSD and the Microsoft C-Compiler to allow user input of the observer (earth station) location. "*Orbit*" calculates the satellite sub-point, range, tracking antenna azimuth and elevation, and doppler shift for a given beacon frequency.

3 RESULTS

3.1 General Comments

In order to completely determine the satellite visibility for acquisition and tracking in the coverage area, for a given orbit azimuth-, elevation-, range- and doppler-variation should be plotted for the corners and centroid of the coverage sector. This, however, requires extensive effort, particularly if a large number of orbits are examined. Here, only the results from the approximate centroid, i.e. Reykjavik, Iceland are presented. To complete the work azimuth variation, etc. should be examined from the perspective of important locations such as Washington, Ottawa, the North Pole, London, Oslo, Brussels, Paris, and Ankara.

Satellite ground tracks during the satellite visibility from Reykjavik, Iceland for the five non-geostationary orbits are shown in Fig. 3.

For each of the above 5 non-geostationary orbits the following graphs are included for Reykjavik; (Figs. 4 through 7 for Circular Inclined Synchronous), (Figs. 8 through 11 for GPS), (Figs. 12 through 15 for Molniya 12 Hour), (Figs. 16 through 19 for Molniya 24 Hour), and (Fig. 20 through 23 for Tundra).

- Azimuth and elevation variation over 12 hour period
- Elevation variation over 24 hour period
- Range variation over 12 hour period
- Doppler shift at 10 GHz over 12 hour period

3.2 Circular Inclined Synchronous

Azimuth and elevation variations at Reykjavik are shown in Figs. 4. Both the azimuth and the elevation vary smoothly without any sharp transitions. Even at the satellite switch-over, the change in azimuth and elevation is of the order of a few degrees and is not drastic. The tracking of a satellite in the CIS orbit should be feasible. The elevation is greater than 15° for 12 hours,

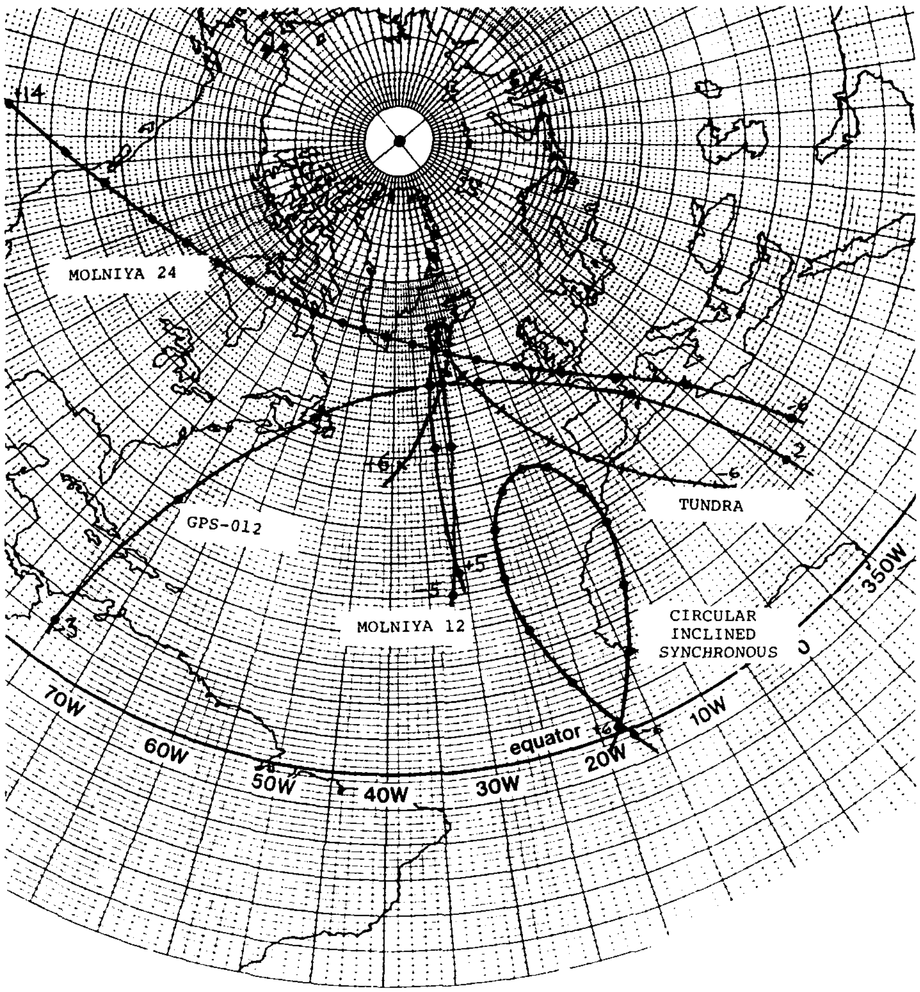

Fig. 3. Satellite ground tracks for various orbits.

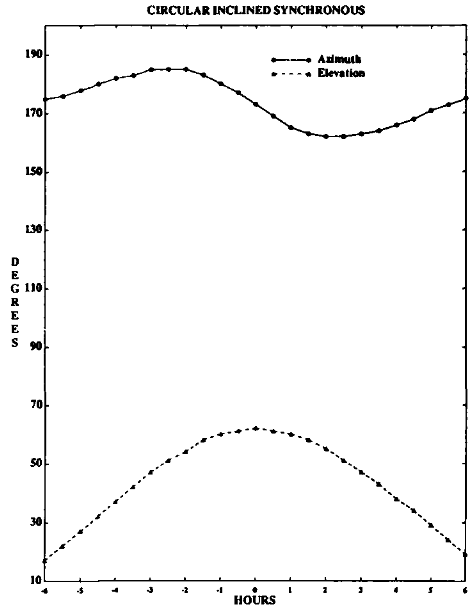

Fig. 4. Azimuth and elevation variation for CIS orbit

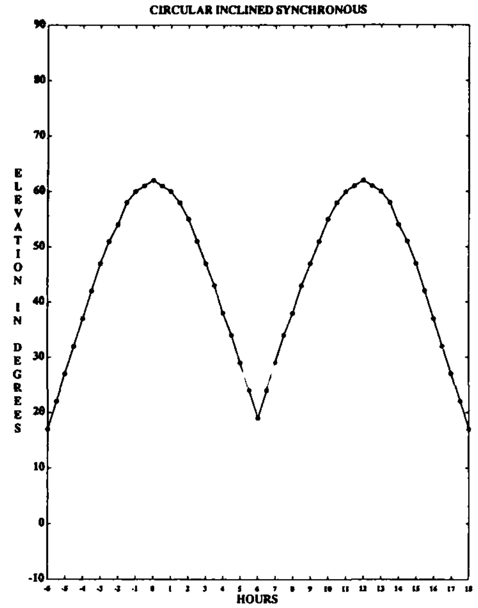

Fig. 5. Elevation variation with two CIS orbit satellites

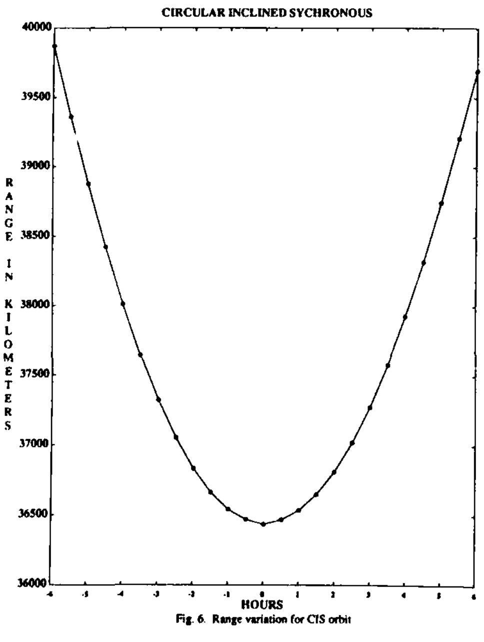

Fig. 6. Range variation for CIS orbit

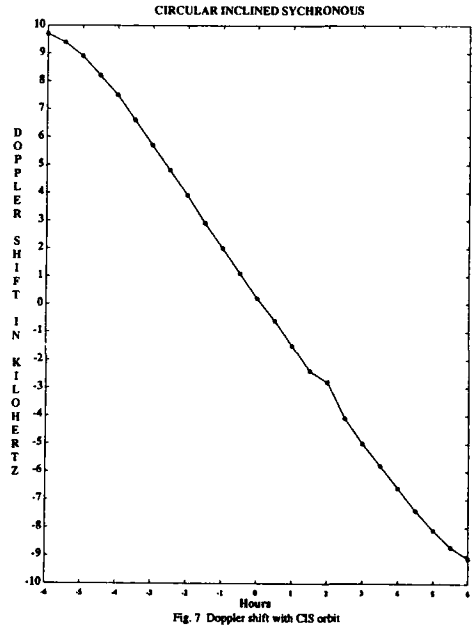

Fig. 7 Doppler shift with CIS orbit

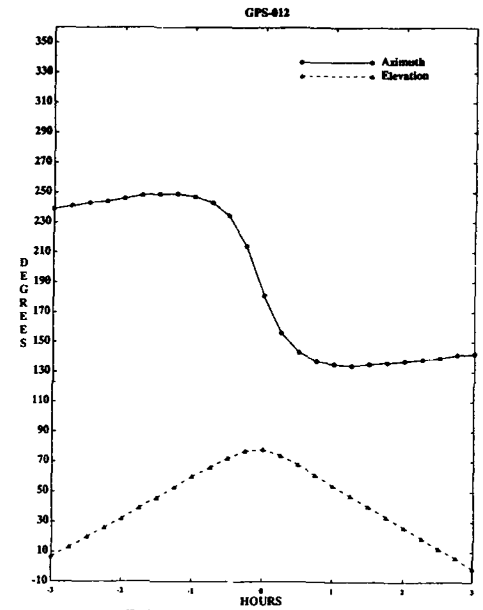

Fig. 8. Azimuth and elevation variation for GPS-012 orbit

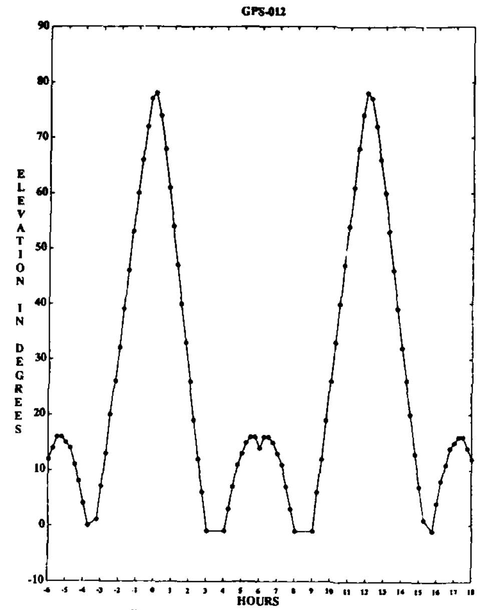

Fig. 9. Elevation variation with two GPS-012 satellites

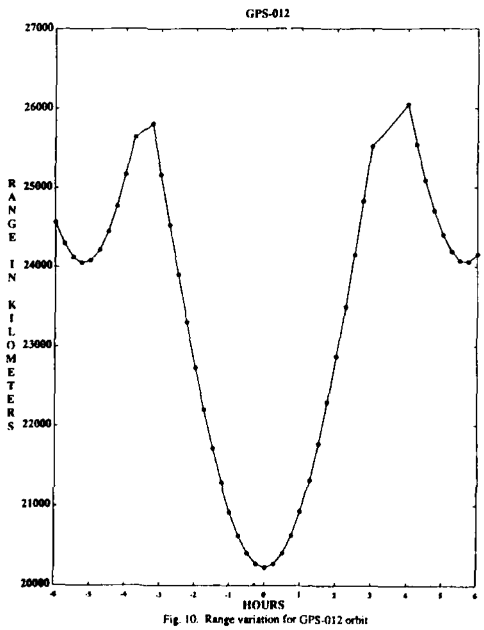

Fig. 10. Range variation for GPS-012 orbit

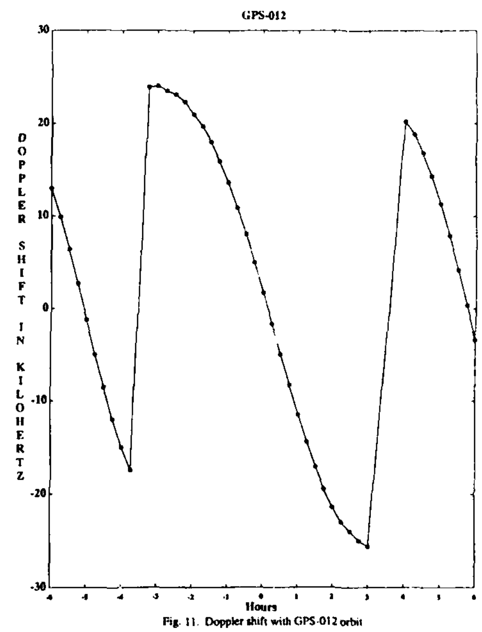

Fig. 11. Doppler shift with GPS-012 orbit

therefore a minimum of 2 satellites are required in a constellation to obtain 24 hour coverage. Of course using 3 satellites will increase the elevation and reduce the change in azimuth and elevation at switch-over between satellites. The Doppler shift is 0.48 Hz/s at 10 GHz.

3.3 GPS

Note that Global Position System uses a network of 24 NAVSTAR satellites in three orbital planes at an inclination of 63°. Each plane contains 8 equally spaced satellites and the ascending nodes of each orbital plane are separated by 120°. The coverage duration varies from 2 hours to about 6 hours depending upon the location.

Elevation and azimuth variations for the GPS-012 are shown in Figs. 8 and 9 respectively. Elevation varies rapidly but smoothly. The azimuth variation is quite rapid, at "0 hour." In the case of GPS the duration of visibility is brief (as little as 3 hours, see Fig. 9, therefore with multiple satellites pointing and acquisition are more frequent. Tracking in azimuth is affected in south-east and south-west corners of the coverage sector, in addition to that at Reykjavik. The Doppler shift is approximately 3.60 Hz/s at 10 GHz.

Concurrent NATO-wide coverage is not possible with a single satellite or even with a few satellites in the same orbital plane. Thus multiple satellites in more than one orbital plane have to be employed. This requires re-configuration of satellites from the ground, alternatively a complex network of inter-satellite communications is needed.

3.4 Molniya 12 Hour

Azimuth and elevation variations are shown in Figs. 12 and 13. Compared to the Circular Inclined Synchronous Orbit, there is reduced coverage provided by the Molniya 12 Hour Orbit of about 10 hours, *therefore a minimum of 3 satellites are required in a constellation to obtain 24 hour coverage.* Of course using 4 satellites will increase the elevation and reduce the change in azimuth and elevation at switch-over between satellites. Note the large Doppler shift, it is approximately 5.79 Hz/s at 10 GHz and represents the extreme case for the non-geostationary orbits considered here.

The elevation variation is smooth except at initial satellite visibility (see -5 hour region in Fig. 12 and 13) where it changes rapidly. Pointing and acquisition as well as tracking are affected. Azimuth variation is rapid near -1 hour region in Fig. 12, as a result pointing and acquisition as well as tracking are affected here.

3.5 Molniya 24 Hour

Azimuth and elevation variations are shown in Figs. 16 and 17. For the Molniya 24 Hour Orbit the coverage duration is about 12 hours per satellite. *Therefore 2 satellites in a constellation can provide 24 hour coverage.* Of course using 3 satellites will increase the elevation and reduce the change in azimuth and elevation at switch-over between satellites, which may be desirable because of the large change in elevation angles at switch-over. Note the Doppler shift, is approximately 2.64 Hz/s at 10 GHz.

The rate of change of azimuth is rapid at mid-point of satellite visibility (see 0 hour region in Fig. 16) which stresses acquisition as well as tracking. The elevation variation is smooth and slow.

3.6 Tundra

Azimuth and elevation variations are shown in Figs. 20 and 21. Unlike the Molniya 12 Hour Orbit, for the Tundra Orbit the coverage duration is more than 12 hours per satellite. *Therefore only 2 satellites in a constellation are sufficient to provide 24 hour coverage.* Of course using 3 satellites will increase the elevation and reduce the change in azimuth and elevation at switch-over between satellites, which may be desirable because of the large change in elevation angles at switch-over at the south-east and south-west corners of the coverage sector. Note the Doppler shift, is approximately 1.45 Hz/s at 10 GHz which is less than for any of the other four non-geostationary orbits.

The elevation variation is smooth. The azimuth variation is smooth except at "0 Hour" region in Fig. 20, consequently initial pointing and acquisition as well as tracking are affected. Effect on tracking depends on the location; it is extreme for the south-east and south-west corners of the coverage sector.

3.7 Summary of Orbit Results

A summary of the results is presented in Table 2. For purposes of comparison the parameter values listed in the table correspond to the indicated "Coverage Duration;"

- The CIS, Molniya 24 hour and Tundra orbits have the maximum "coverage duration" of more than 12 hours
- The elevation angle (> 40°) is the optimal with the Tundra orbit, for the indicated coverage duration

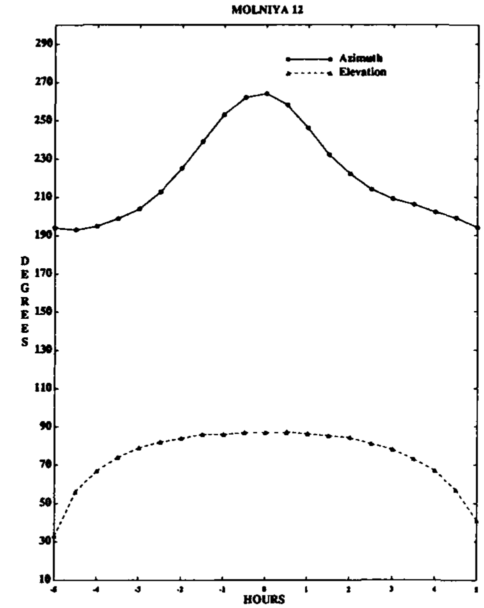

Fig. 12. Azimuth & elevation variation for Molniya 12 orbit

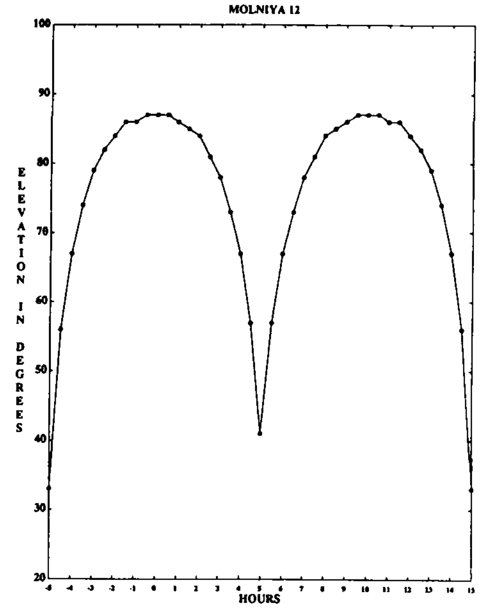

Fig. 13. Elevation variation with two Molniya 12 satellites

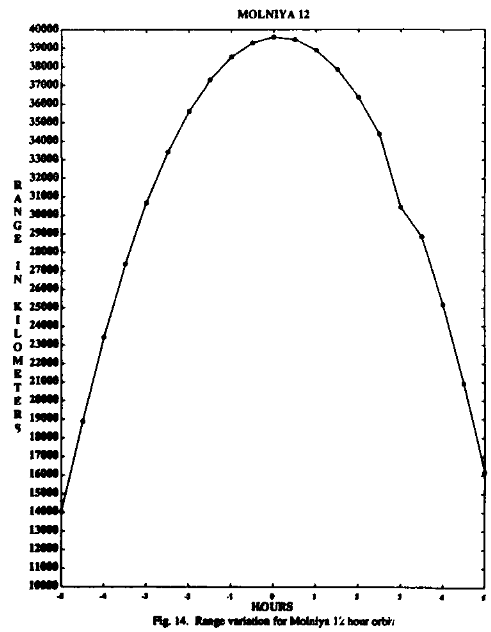

Fig. 14. Range variation for Molniya 12 hour orbit

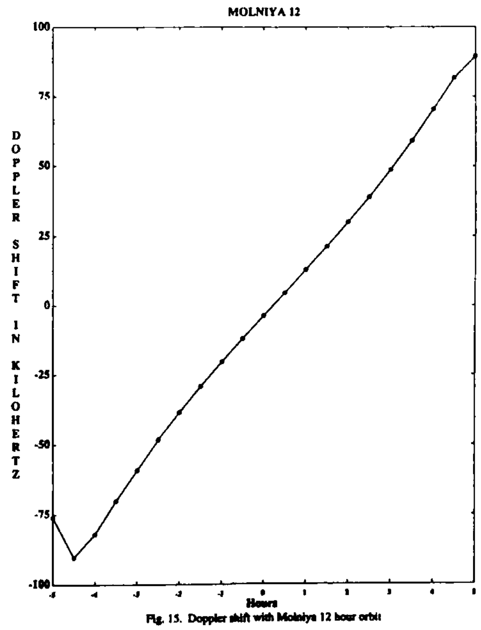

Fig. 15. Doppler shift with Molniya 12 hour orbit

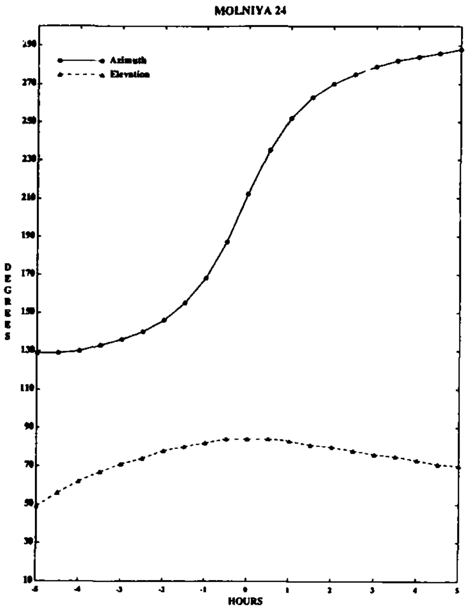

Fig. 16 Azimuth and Elevation variation for Molniya 24

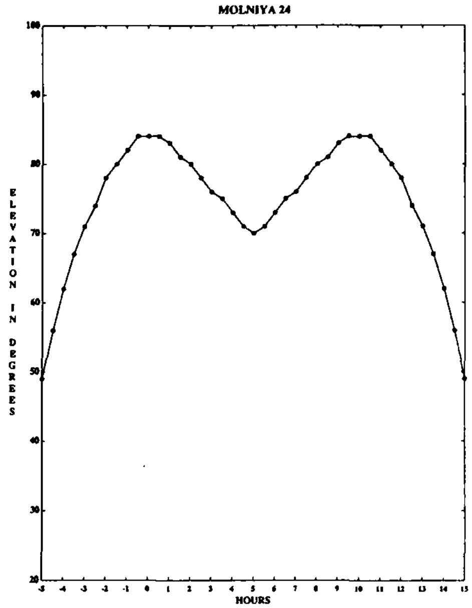

Fig. 17. Elevation variation with two Molniya 24

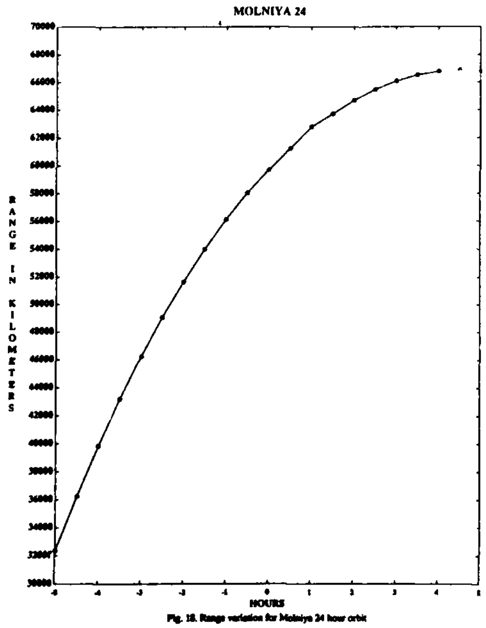

Fig. 18. Range variation for Molniya 24 hour orbit

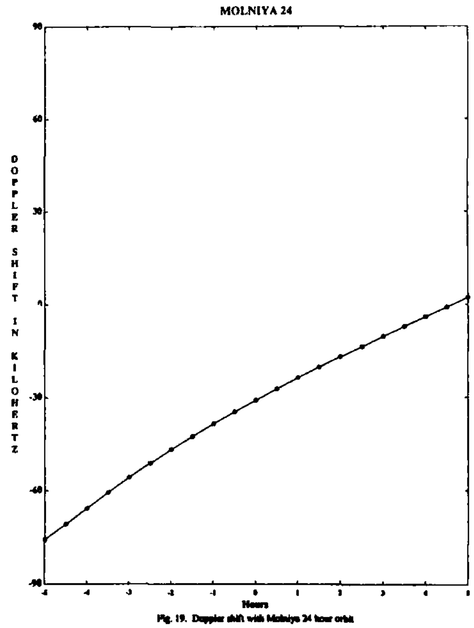

Fig. 19. Doppler shift with Molniya 24 hour orbit

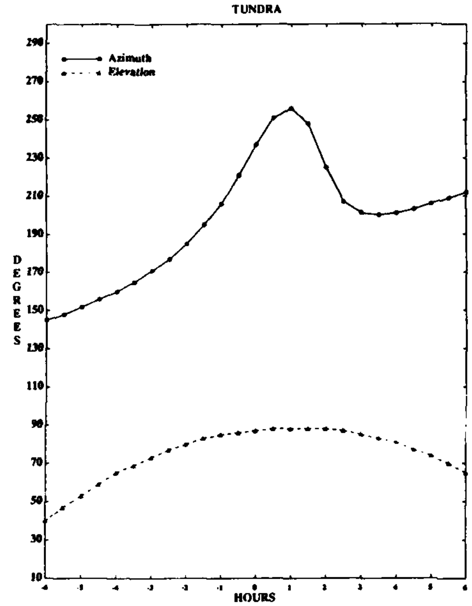

Fig. 20. Azimuth and elevation variation for Tundra orbit

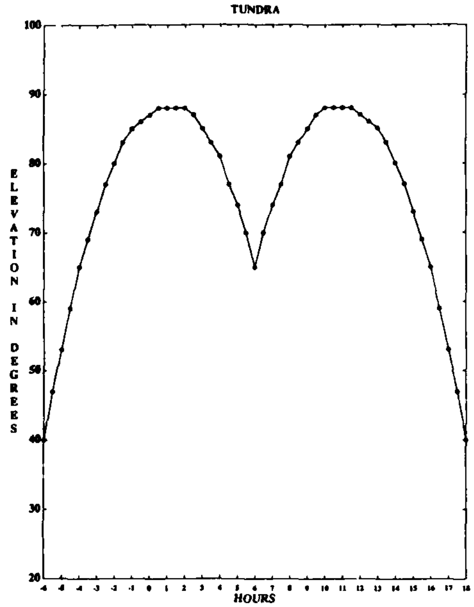

Fig. 21. Elevation variation for two Tundra satellites

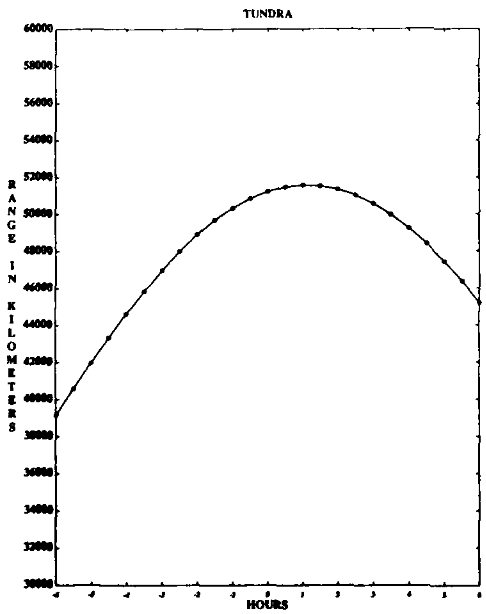

Fig. 22. Range variation for Tundra orbit

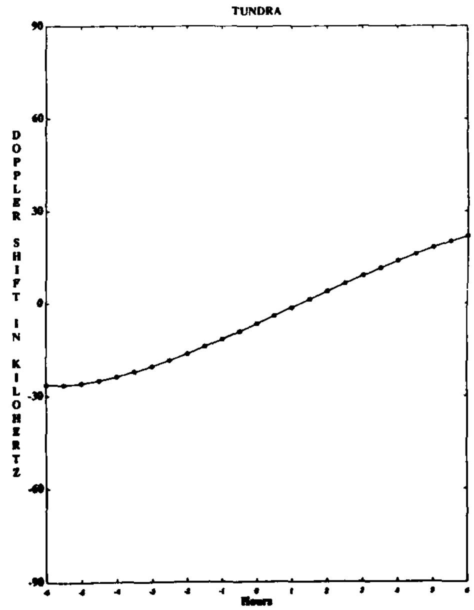

Fig. 23. Doppler shift with Tundra orbit

- Excluding switch-over, the worst case change in elevation is 0.93°/minute and it is for Molniya 12 hour orbit
- Excluding switch-over, the worst case change in azimuth is 2.20°/minute and it is for the GPS-012 orbit
- For communications the minimum range is 14,036 km (elevation angle 33°) for the Molniya 12 hour orbit, and the maximum range is 66,883 km (elevation angle 71°) for the Tundra orbit
- The minimum/maximum range doppler range is -90.3 kHz to +89.5 kHz at 10 GHz with the Molniya 12 hour orbit
- The maximum rate of change in doppler is 5.79 Hz/s at 10 GHz with the Molniya 12 Hour orbit

TABLE 2

SUMMARY OF RESULTS FOR THE ORBITS

Orbit	Coverage Duration (Hours)	Minimum Elevation (°)	Maximum Elevation Rate (°/min)	Maximum Azimuth Rate (°/min)	Range; Minimum - Maximum (1000's km)	Maximum Doppler Rate (Hz/s @ 10 GHz)	Doppler Variation during "Coverage Duration" (kHz @ 10 GHz)
CIS	12	17	0.53	0.53	36 - 40	0.48	18.8
GPS-012	6	6	0.38	2.20	20 - 25	3.60	49.1
Mol12	10	33	0.93	0.47	14 - 40	5.79	179.8
Mol24	12	28	0.67	0.87	24 - 67	2.64	87.5
Tundra	12	40	0.20	0.80	39 - 52	1.45	48.4

3.8 Implications of Using Non-geostationary Orbits on the Payload

3.8.1 On-Board Processing

The use of payload on-board processing can enhance the performance of satellite communication and mitigate the effect of jamming[17]. It does so by decoupling the up- and down-link design and performance. On-board processing of a digital bit stream also allows: spacecraft message routing, data relay (making up data streams from several uplinks and crosslinks). Furthermore, on-board processing permits signal and format changes from uplink to downlink for direct interconnectivity of different types of terminals. Four types of satellite processing have been identified for Frequency Hopping (FH) systems[26]; see Table 2:

1. *Bent pipe repeater*
2. *Dehop-Rehop transponder (DRT)*
3. *Symbol regenerative repeater*
4. *Full processing packet-switched satellite relay*

An additional type of processing is proposed here that can be used with the above on-board processing; this is ***On-board Message Store and Forward***. The feature of this technique is that messages are stored on-board the Payload, and forwarded at the appropriate time. This feature obviates the need for real-time connection between the two end users, and permits communication between users in different beams or who are geographically or temporally disparate. The ***On-board Message Store and Forward*** is particularly suitable for non-geostationary orbits where acquisition and tracking is complex, and the satellite foot-print does not encompass both ends of the circuit. Moreover, the satellite can be considered as a messenger transporting information from one part of the globe to another.

TABLE 3

COMPARISON OF TRANSPONDER TYPES

Transponder Type	Strengths	Limitations
Bent-Pipe Repeater	Simple, extensively used in current satellite systems	*Power Robbing*
Dehop-Rehop Transponder	On-board processing; only jamming within filter bandwidth is propagated; isolates the design and performance of up- and downlinks	More complex; dehop and rehop
Symbol-Regenerative Processor	On-board processing	Even more complex, and less flexible. Dehop, symbol demodulation, remodulation, and rehopping. Symbol detection errors are passed to downlink.
Full Processing Packet-Switched Satellite Relay	Coding with detection; isolation of uplink and downlink	
On-board Message Store and Forward	Obviates need for "Real-time" connection; simplifies acquisition and call set-up	Enhanced memory, complex connectivity maps, and processing required

3.8.2 Inter-satellite Links

The use of a non-geostationary orbit necessitates the use of more than one satellite in a constellation. This means that for tracking purposes the user has to contend with switch-over from one satellite to the next. The discontinuity in tracking is a function of the orbit and user location. The switch-over will result in a dead-period unless there are two antennae and receivers in the ground terminal and "make before break" feature is implemented. Even so, having more than one satellite means that the satellites have to communicate with each other and hand-over information through re-configuration of the payload/ network either from the ground or via inter-satellite links. For the non-geostationary satellites the inter-satellite links have to contend with continuously varying link vector.

3.8.3 Station-keeping

The ground terminals (fixed, transportable, manpack/teampack, shipborne, airborne, submarine) for acquisition and tracking with a non-geostationary orbit satellite require an accurate ephemeris algorithm and a computer. This feature can be used to reduce and if not eliminate the need for station-keeping, if the decay rate of the satellite orbit is incorporated into the ephemeris algorithm.

4 CONCLUSIONS

For the requirements and assumptions given above:

- The computed results and the graphs provide data for synchronization in general, and in particular, the range and elevation data to carry out link budget calculations, provide azimuth and elevation rate and acceleration for antenna tracking, and doppler frequency shift data for the hardware specifications (modems, synthesizers, etc.)
- To obtain 24 hour coverage a minimum of three satellites are required for the Molniya 12 hour, but only two satellites are required in the Circular Inclined Synchronous or Molniya 24 hour or Tundra orbit
- Several satellites in more than one orbital plane are required for the GPS orbit
- The Doppler frequency shift is largest (5.79 Hz per second at 10 GHz) for the Molniya 12 hour orbit

- Antenna pointing, spatial acquisition and tracking is challenging at initial satellite visibility, and at switch-over. The exact parameters are a function of satellite orbit, user location and time. This suggests that a feature of the field terminal should be to automatically display to the user a "preferred communication time," that has been computed by the terminal

- In a ground terminal, it would be desirable to have ephemeris algorithms for the moon and the sun to accurately calculate moon and sun look angles [Ash 1973]. The look angles can aid antenna pointing calibration by measuring the radio noise from the moon and sun.

- Based on the conclusions stated above, Molniya 24 hour and Tundra orbits are the preferred orbits and should be considered for detailed study and evaluation

- The proposed ***"On-board Message Store and Forward"*** technique: obviates the need for real-time connection between the two end users, and permits communication between users in different beams or who are geographically or temporally disparate; furthermore, it is particularly suitable for non-geostationary orbits

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14. Abstract

This Symposium was designed to bring together representatives of the industrial, government and scientific communities within NATO to discuss and explore Military User Operations and development problems associated with Tactical Applications of Space Systems.

The benefits, indeed the necessity of space systems to military operations have increased considerably in the past few years. Military communications satellites such as the NATO and SKYNET series as well as the US COMSATS have demonstrated their effectiveness as elements of military command and control systems. The various weather satellites are providing more accurate and timely weather forecasting and have become important to all military operations. The 18 satellite-Global Positioning System may revolutionize weapon systems navigation guidance over the next decade. New remote sensing systems such as the Space Based Radar and other systems are in study on various stages of development.

While the importance of space systems is becoming better appreciated by the leaders in the R & D community and by the military leaders in the NATO countries, the full potential of these systems has not been realized. The intent of this symposium was to bring into focus and to characterize the attributes of space systems which contribute to the effectiveness of tactical military operations.

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