AGARD-AR-322

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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT 322

TacSats for NATO

(Les Satellites Tactiques pour l'OTAN)

This Advisory Report has been prepared at the request of the Avionics Panel of AGARD.

NORTH ATLANTIC TREATY ORGANIZATION

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

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- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
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Preface

Tactical satellites, called TacSats, have the potential to offer significant advantages to a theatre commander. The use of strategic satellites during Operation "Desert Storm" clearly showed the utility that space can bring to the conduct of theatre military operations. However, strategic satellites are quite expensive, are limited in number, and, most importantly, were designed to meet strategic rather than tactical needs. The purpose of this Advisory Report is to demonstrate that TacSats possess the potential to enhance and enlarge the essential information needed by a theatre commander.

TacSats must be affordable, flexible, and responsible to the requirements of the theatre commander. Affordability limits the weight of TacSats — generally to less than 750 kg. It is also achieved by allowing the commander to obtain the needed space assets in smaller incremental quantities than if he must use expensive and large strategic satellites. Flexibility is demonstrated in this Report by showing TacSats can meet at least six important mission needs: battlefield surveillance, communications, missile warning and assessment, regional maritime surveillance and environmental observations, weather, and navigation. Responsiveness is accomplished by shorter revisit times permitted by a greater number of satellites, since they are affordable, in optimized orbits. In addition to these capabilities TacSats can be used synergistically with strategic satellites as supplements or complements to the strategic missions when not needed by a theatre commander. The Report strongly recommends more detailed studies of how TacSats can meet specific NATO military operational needs.

AGARD's Avionics Panel established Working Group 16 to study the utility of TacSats for NATO. The Working Group was comprised of individuals, from six NATO nations, with extensive experience in space systems. They relied not only on their own knowledge and that of colleagues, but on the information provided at a classified AGARD symposium entitled "TacSats for Surveillance, Verification and C3I" held in Brussels, Belgium from 19th-22nd October 1992. The unclassified portions of this symposium have been published as AGARD Conference Proceedings 522 (February 1993). Working Group 16 formally met four times and also had extensive telephone, fax and mail interchanges. During these formal meetings and at many other times, many individuals, too numerous to mention, aided the members of the Working Group in their task. These contributions are gratefully acknowledged. It is hoped this Report will meet its primary purpose of having NATO conduct a detailed study of the ability of TacSats to meet its tactical military operations requirements.

Préface

Potentiellement, les satellites tactiques, ou TacSats, offrent des avantages appréciables au commandant du théâtre d'opérations. La mise en oeuvre des satellites stratégiques lors des opérations "tempête du désert" a montré très clairement l'utilité des moyens spatiaux pour la conduite des opérations militaires du théâtre. Cependant, les satellites stratégiques sont relativement coûteux, limités en nombre, et, surtout, destinés à des fins stratégiques plutôt que tactiques. L'objet du présent rapport consultatif est de prouver que les TacSats ont le potentiel pour affiner et amplifier les informations essentielles demandées par les commandants du théâtre.

Les TacSats doivent être polyvalents et d'un coût acceptable budgétairement. Ils doivent répondre aux attentes du commandant du théâtre. La faisabilité budgétaire impose certaines contraintes au niveau de la masse des appareils — généralement moins de 750 kg par unité, mais cette option permet au commandant du théâtre d'acquérir les moyens spatiaux qui lui sont nécessaires par incréments graduels, au lieu d'utiliser les gros satellites stratégiques dispendieux.

La flexibilité est soulignée dans ce rapport, qui illustre la capacité des TacSats de répondre à au moins six besoins opérationnels: la surveillance du champ de bataille, les télécommunications, l'alerte aux missiles et leur évaluation, la surveillance maritime régionale, les observations de l'environnement ainsi que la météo et la navigation. Une meilleure réponse peut être obtenue grâce aux intervalles d'observation plus courts résultant du plus grand nombre de ces satellites, puisque moins coûteux, évoluant en orbite optimisée.

En plus de ces capacités, les TacSats peuvent être utilisés synergiquement avec des satellites stratégiques en supplément ou en complément des missions stratégiques moyennant leur mise à disposition par un commandant du théâtre. Les auteurs du rapport recommandent vivement la réalisation d'études plus détaillées sur l'adéquation des TacSats aux besoins militaires opérationnelles spécifiques de l'OTAN.

Le Panel AGARD d'avionique a créé le groupe de travail No. 16 pour évaluer l'intérêt des TacSats pour l'OTAN. Le groupe était composé de membres originaires de six pays de l'OTAN, ayant une grande expérience des systèmes spatiaux. Les auteurs ont puisé non seulement dans leurs propres connaissances et dans celles de leurs collègues, mais aussi dans les informations fournies par un symposium AGARD classifié intitulé "Les TacSats pour la surveillance, la vérification et la C3I" organisé à Bruxelles, en Belgique, du 19 au 22 octobre 1992. Les communications non-classifiées présentées lors de ce symposium ont été publiées sous la référence Compte rendu de conférence AGARD No. 522 (février 1993). Le groupe de travail No. 16 s'est réuni officiellement quatre fois, en plus des nombreux échanges qui ont eu lieu par téléphone, par fax et par courrier.

Plusieurs personnes, dont le nombre serait trop grand pour permettre de détailler, ont également aidé les membres du groupe de travail lors de ces réunions officielles ainsi qu'à de nombreuses autres occasions. C'est avec plaisir que nous reconnaissons la valeur de ces contributions. Nous espérons que ce rapport atteindra son objectif principal, qui est de présenter une étude détaillée de l'adéquation des TacSats aux besoins des opérations militaires tactiques.

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In addition to the contributions of the Working Group members listed above, important contributions were also made by Dr Ron MacPherson, National Defence Headquarters, Canada, and Christian Seeholzer, GSOC-DLR, Germany. Special thanks are also due to Dr Franz Schlude, GSOC-DLR, Germany, for hosting a Working Group meeting at DLR and to the French members of the Working Group for sponsoring and arranging a meeting room for our Paris Working Group. While the Working Group's activities were ongoing the group was assisted by many individuals, including the staff of AGARD Headquarters, especially Martine Tessier, Secretary to the Avionics Panel and Colonels Chris Sautter and Raffaele Cariglia, Avionics Panel Executives.

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* retired
† deceased
** Presently at Thomson-CSF

Contents

List of Acronyms

AFB	Air Force Base
AGARD	Advisory Group for Aerospace Research and Development (NATO)
AH	Ampere Hour
AJ	Anti-Jam
AKM	Apogee Kick Motor
ARPA	Advanced Research Projects Agency (formerly DARPA)
ARS	Adaptive Random Search
ASAT	Anti-Satellite
ASW	Anti-Submarine Warfare
ATO	Air Tasking Order
ATR	Automatic Target Recognition
AVHRR	Advanced Very High Resolution Radiometer
AZ	Azimuth
BDA	Battle (or Bomb) Damage Assessment
C&DH	Communications and Data Handling
CFRP	Carbon Fiber Reinforced Plastic
C3I	Command, Control, Communications, Intelligence
COMSAT	Communications Satellite
DAMA	Demand-Assigned Multiple-Access
DARPA	Defence Advanced Research Projects Agency
D/L	Down Link
DMSP	Defence Meteorological Support Program
DOD	Depth of Discharge
DSCS	Defence Satellite Communications System
DSP	Defence Support Program
EC	Earth Coverage
ECCM	Electronics Counter Counter Measures
EHF	Extreme High Frequency
EIRP	Effective Isotropic Radiated Power
EL	Elevation
ELINT	Electronics Intelligence
ELS	Eastern Launch Site (Cape Canaveral AFB)
E-O	Electro-optical
EOL	End of Life
ERS-1	Earth Resources Satellite - 1
ESM	Electronic Support Measures
GDOP	Geometric Dilution of Precision
GMTI	Ground Moving Target Indicator
GN&C	Guidance, Navigation and Control
GPS	Global Positioning Satellite
GSO	Geo-Stationary Orbit
GTO	Geostationary Transfer Orbit
HEO	Highly Elliptical Orbit
HPA	High Power Array
ID	Identification
IUS	Inertial Upper Stage
LDR	Low Data Rate
LEO	Low Earth Orbit
LEOPS	Launch and Early Operations
LHS	Left Hand Side
LPE	Low Probability of Exploitation
LPI	Low Probability of Intercept
MBA	Multiple Beam Antenna
MDR	Medium Data Rate
MEO	Medium Earth Orbit
MTI	Moving Target Indicators
MULB	Multiple Path, Beyond Line of Sight
NACISA	NATO Communications and Information Systems Agency
NATO	North Atlantic Treaty Organization
NUS	No Upper Stage
OSC	Orbital Sciences Corporation
R&D	Research and Development
RCS	Radar Cross Section
RF	Radio Frequency
RHS	Right Hand Side
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communications System
SAW	Surface Acoustic Wave
S/C	Spacecraft
SCSG	SatCom Sub Group
SHAPE	Supreme Headquarters Allied Powers, Europe
SHF	Super High Frequency
SLAR	Side Looking Aperture Radar
STC	SHAPE Technical Center
STRATSAT	Strategic Satellite
T/R	Transmit/Receive
TACSAT	Tactical Satellite
TBM	Theatre Ballistic Missile
TECH. INTEL.	Technical Intelligence
TOPEX	Topographic Experimental (Satellite)
TT&C	Telemetry, Tracking and Control
UHF	Ultra High Frequency
UK	United Kingdom
U/L	Up Link
W.G. 16	Working Group 16, Avionics Panel, AGARD (authors of this report)
WLS	Western Launch Site (Vandenberg AFB)

CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

Today, the military has an overwhelming need to know precisely where potential enemy forces are located, what their strength is, where they are going, and to be able to communicate, navigate, and predict the environmental conditions in potential battle areas that may be beyond the NATO national boundaries. Additionally, many future operations will be regional and in constrained, but denied (to NATO forces) areas. Space systems offer an effective, and perhaps the only, means of performing these functions. A unique class of space systems called TACSATs may offer an affordable way to counter an ever changing threat, in an environment of reduced budgets, through increased effectiveness of existing NATO forces.

1.2 CURRENT SPACE DEFICIENCIES

With the passage of time, it has become an accepted belief that space will be a dominant factor in any future conflict. However, the recent shift in emphasis from GLOBAL STRATEGIC warfare to REGIONAL THEATRE TACTICAL warfare raises the question – "are the current space systems adequate?" The adequacy of space systems is further challenged by the change from a bi-polar world (EAST vs. WEST) to one that is multi-dimensional, where weapons are proliferating and threats to NATO interests can and are materializing from all "points of the compass." Space systems that were optimized to the previous strategic world must now either accommodate the new situation, have a change in emphasis and investment while accepting the introduction of more tactically oriented space capabilities, and/or be totally replaced with systems optimized to the new world situation.

A recent test of space systems adequacy occurred in the United Nations operation Desert Storm. The "report card" on the performance of these systems was as follows:[1]

> Communication – not enough, not mobile enough, and the ground terminals were inadequate.
>
> Weather – good information, but the data dissemination was poor.
>
> Navigation – great, but not enough receivers.
>
> Imagery – a controversial subject. While there was not enough surveillance, it was also viewed as a failure because of dissemination problems.

This "report card" was made in an environment where the NATO defense community had not yet experienced the severe financial cutbacks and force reductions that are being addressed today. In the future, NATO military forces will be reduced in size, will be based on a rapid deployment approach, and will have a wider mix of capabilities depending on the multi-national contributions to any hostilities. In addition, targeting and support systems such as space-based systems may experience changes in deployment and have quantities that are "bare minimum" for peacetime operations.

1.3 IMPLICATIONS

In the above context, any future space capabilities must not only accommodate potential strategic needs (although somewhat reduced), but also the new tactical needs. It is in this latter case that space systems must adopt the characteristics of affordability; sufficient low cost pipelines of ready systems; interoperability; and flexibility to match levels of terrestrial force deployments (large and small), and to provide optimized support in the region of conflict. Not only do these characteristics call for a new approach to spacecraft design and deployment, they also call for launch and control systems that are responsive and can be operated from various locations to ensure the optimum operation of the space system relative to the region of hostilities.

One important aspect of future space systems will be their ability to match the needs of the terrestrial forces without an overcommitment of space resources. In the past, it was acceptable to maintain an on-orbit capability for any situation; thus, spacecraft and booster designs were optimized for the most capability per kilogram. This situation, while reducing the satellite and booster cost per kilogram, also resulted in a major investment step-function when added capability was required. In this future cost constrained environment, there will be less attention to cost per kilogram and more to smaller incremental cost steps for added capability.

The most *critical aspects* of future space systems will be their responsiveness to theatre operations and the needs of the commander. In most eventualities, space systems will have to reconfigure themselves to operational demands in near real-time. First, space systems will be required to transition from a minimum capability to a full up capability. The two build-up concerns that must be addressed are the levels in capability needed with respect to the scenario and the amount of time available to meet the level of capability. Second, space systems must be dedicated to the demands of the theatre without interference from other users. This

[1]AGARD Conference Proceedings 522, "TACSATs for Surveillance, Verification and C3I," BGen Dickman, USAF Space Command, 19 October 1992, Brussels, Belgium (published Feb. 1993).

requires an optimization toward theatre operations in the form of support availability and tasking.

1.4 TACSAT DEFINITION

The TACSAT concept is based on meeting the theatre commander's requirements in terms of local/regional applications, frequent revisit opportunities, fast information delivery, and a comparably fast build-up rate. It also calls for simplified control and data dissemination with direct ties to the theatre. These requirements are also associated with limited costs, dictated by reduced defence budgets, that lead to smaller satellites.

This approach is in contrast to complex and heavy strategic satellites that are focused on meeting national requirements. TACSATs are considered as complementary to strategic satellites and not as competitors–they are not intended to fulfill the same requirements.

It should be emphasized that TACSATs are not "small, smart, cheap lightsats." The TACSAT size, cost, and performance are possible because military operations requirements concentrate on basic theatre needs. Concepts that adopted high risk design and reliability approaches to fit the TACSAT definition were not considered as appropriate (see Chapter 6 on Costs for further discussions).

1.5 SYNERGY BETWEEN TACTICAL AND STRATEGIC SPACE SYSTEMS

There are two mission areas where strategic and tactical space systems are easily distinguished–surveillance and communications. It is here that TACSATs fill specific needs that may most easily be kept separate from strategic systems. Figure 1.1 describes the synergy between strategic and tactical surveillance satellites.

Essentially, Figure 1.1 calls for strategic system support of theatre operations to maintain and improve the data base for future military operations and the tactical systems to use that data base as a reference for targeting and obtaining needed information about the battle.

In communications the distinction is between strategic systems support to theatre operations being in the form of extra-theatre communications during a crisis for global interactions and preparations for theatre actions. Tactical systems will provide concentrated theatre communications to the region and connectivity to supporting elements that are external to the region.

While there are distinct differences between TACSATs and STRATSATs, they can perform complementary functions with respect to each other as can be inferred from the above discussions, including during times other than military operations. In this sense some of the costs of TACSATs could be amortized as contributory to the STRATSAT mission.

1.6 USE OF CONCEPTS

Several concepts of specific TACSAT systems are provided in this report, particularly with respect to electro-optical and radar payloads. These concepts have been taken from the AGARD Avionics Panel TACSAT Symposium[1] or from national studies made available to the Working Group. They should not be taken as preferred concepts to meet requirements of specific mission areas; nor should it be assumed that all member nations on the Working Group endorse such concepts. Rather, they are presented to show that, in several cases, detailed studies have been carried out and that the authors of these concepts believe them to be feasible for the weights and funding quoted.

SATELLITE	MISSION	THEATER OPERATIONS	SPATIAL RESOLUTION	REVISIT AND RESPONSE TIME
STRATSAT	CRISIS PREVENTION AND MONITORING	PREPARATION FOR ACTION (Intelligence/ Data Base, Indices of Activity/Tension)	HIGH	LONG
TACSAT	MILITARY OPERATIONS	SUPPORT TO ACTION (Detection, Targeting, BDA...)	MODERATE	SHORT

Figure 1.1 Synergy between Tactical and Strategic Surveillance Satellites

[1]"TACSATs for Surveillance, Verification and C3I," AGARD Conference Proceedings 522, Feb. 1933.

CHAPTER 2

MISSION OPPORTUNITIES AND PERFORMANCE NEEDS

2.1 INTRODUCTION

Classically, new capabilities are justified through a process that starts with requirements, an examination of system solutions, followed by the selection of an approach. With respect to TACSATs for NATO, it was the belief of the Working Group that the first two steps had been accomplished, although not in the classical sense. The rationale is as follows:

- There are numerous documented cases of requirements for the capabilities addressed in this report for the mission areas of tactical battlefield surveillance, missile warning and assessment, communications, regional maritime surveillance and environmental observation, navigation, and weather. Some would argue these requirements are not specifically for space systems; they are partially correct. Requirements should not be system specific but should be generic in form.

- The capability of space systems to satisfy specific requirements better than the competing ground, air, and sea based alternatives, particularly in denied areas, has been proven in actual operations as was the case in Desert Storm. From a NATO perspective, the space systems employed to date, except for the NATO communications satellites, have been systems owned by member nations which may not be available to NATO on all occasions.

The question that is addressed in this report is: if space systems are to be critical elements of future NATO military operations, is there an affordable approach that NATO could pursue? It is well understood that the space systems currently flying are not only very capable but also very expensive. Over the years, many studies and technologies have been pursued in the general TACSAT arena that claim to provide an approach that can serve as a lower cost alternative to these large systems and still maintain reasonable capabilities. This report will address such claims in a form that will allow NATO to determine if further actions with regard to additional consideration of these systems are warranted.

2.2 ATTRIBUTES

The basic operating premise for TACSATs is: all system elements should be consistent with the operating, maintenance, and design philosophies used for terrestrial military forces. This premise cannot be fulfilled in all details by the current approach to space systems where they are assembled by highly trained specialists, are comprehensively tested and have limited responsiveness to rapidly unfolding tactical situations.

To satisfy this premise, the following operational and design attributes should be paramount.

2.2.1 Operational Attributes

- All TACSAT systems must be responsive to the theatre commander.

  - This attribute is the prime driver for all other attributes; however, it does not necessarily call for operational control being exercised from within the theatre of military operations.

- The systems must be capable of being rapidly brought into play in any regional area of conflict at support levels commensurate with terrestrial needs for deployment and engagement strategies.

  - This attribute dictates a system operating and design approach that emphasizes regional support rather than global support which, in turn, may affect such things as orbit selection and data dissemination techniques.

  - Timely responsiveness is a critical aspect of this attribute. Where possible, TACSATs should provide early basic support to military operations during the build-up phase, followed by incremental increases in capability consistent with the build-up rate of the terrestrial forces. This attribute probably dictates a timing requirement of certainly no more than 30 days from a "launch call" (or orbital space activation) to on-orbit operation, with a goal of seven days.

- The systems must be able to support operations in one theatre of operations that is generally defined as 2000 km x 2000 km or smaller.

  - This attribute will be a prime driver for low earth orbit satellite duty cycles.

- The systems should allow for increasing operational support at reasonable increments of capability and cost.

  - The purpose of this attribute is to provide the theatre commander with deployment options that do not involve massive financial investments. For example, for a military situation that calls for 5 additional channels of communications, the deployment decision would be easier if the option for a 5 channel TACSAT at $50M each is available, as opposed to an option for a single satellite that provides 100 channels at a cost of $300M.

- Ground support systems for TACSATs should:
  - Provide on-demand, direct, and timely support.
  - Be operationally transparent to the user, except for the user interface.
  - Allow for easy data access, processing, and use.
  - Complement and/or enhance current capabilities.
  - Produce fusion-compatible information.
  - Not require peculiar communications support.
  - Be available throughout the cycle of theatre operations and allow for "training the way we fight."
- Launch systems should:
  - Provide for build-up rates consistent with theatre needs (does not apply to store-on-orbit deployment strategies).
  - Should not impose orbit insertion constraints on the spacecraft that limit regional coverage capabilities or that create extraordinary spacecraft design and constellation constraints.

2.2.2 **Design Attributes**

- TACSATs designed specifically for tactical theatre support will generally weigh less than 750 kg.
- Total system designs must provide for flexibility, responsiveness, on-demand support, and short revisit times.
- TACSATs must generate a field useable product.
- Any new TACSAT must be designed so that its data and telemetry, tracking and command (TT&C) communications are compatible with current terminals and allow for realistic training.
- Affordability must be paramount and hence should lead to considerations of such items as: commonality, a common bus approach, using items off-the-shelf when feasible, and strict control of requirements. A general target cost is about $50M per satellite.
- TACSAT designs do not necessarily have to be for launch-on-demand; they can also be for store-on-orbit in a dormant or low-level state ready for rapid activation and repositioning.
- There must be a provision for rapid change out of payloads during launch preparations, although this may be difficult if attempting to change out different classes of payloads (e.g., communications for surveillance).
- TACSATs must require minimum infrastructure and maintenance needs.

2.2.3 **General Attributes**

- TACSATs should be used in tandem with strategic systems by: increasing mission area responsiveness, selecting orbits to match the threat, concentrating on a specific geographic area, and filling in for a failed strategic system satellite when necessary.
- Large strategic systems can be used as TACSATs if data dissemination and payload tasking can be made to be more responsive to tactical military operations. However, care must be taken when looking across all missions. For example, in surveillance the following simple comparison can be made as shown in Table 2.1.

Table 2.1 Surveillance Comparisons

STRATEGIC REQUIREMENTS CALL FOR:	TACTICAL REQUIREMENTS CALL FOR:
– High resolution	– Moderate resolution
– Narrower field of view	– Wide field of view
– Limited search	– Extensive search
– Costlier	– Less costly
– Heavier	– Less heavy
– Longer processing time	– Simpler processing
– Long revisit time	– Short revisit time
– One or two satellites	– Multiple satellites

The point is, that to force a strategic surveillance system to do the tactical job will take a large number of very expensive satellites. The reason is that the strategic system design is incompatible with the tactical requirement and that a high cost, brute force approach would be necessary if such a system were to be used for tactical purposes.

2.3 ISSUES

The issues presented in the following discussion must be addressed in follow-on TACSAT efforts. However, the remaining chapters will address various sides of some of these issues and will also highlight where any of the issues no longer apply because of conceptual constraints. Additionally, all of these issues can be viewed parametrically. If all of the TACSAT concepts can be developed to accommodate the issues, then the question becomes one of the needs of the user and what is affordable.

One of the primary issues is in the area of mission deployment. A number of questions must ultimately be answered concerning the options of single-event mission deployment (one satellite at a time) vs. multiple-event mission deployment (several satellites at a time)–see Table 2.2.

In addition to the satellite deployment issue, the issues of satellite control and cost must be dealt with. One of the control issues is whether or not the satellites should be controlled by the theatre commander either directly or indirectly from the theatre. Another addresses the question of whether or not the TACSATs, if controlled indirectly, should use a relay satellite, which might also be used for data transmission. Finally, there is the question of whether the constellation should be operated by a military staff (perhaps using knowledge-based computer systems) or by technical experts. In either case the choice must be made between in theatre, or remote, command and control.

TACSAT cost issues basically address the conflict between simplicity, requirements and risk. Specific cost issues include the use of "military-quality" standard parts, limitations that might be placed on requirements growth, and the substantial costs imposed by the launch vehicle. Particular attention must be paid to reliability since, for a TACSAT system to be useful, the troops must be able to rely upon it; i.e., it must have no infant mortality–it must work the first time.

2.4 MISSION NEEDS

TACSATs can play a vital role in theatre conflict. They can make critical contributions in areas such as battlefield surveillance, communications, missile warning and assessment, maritime surveillance and observation, navigation, and weather.

2.4.1 Battlefield Surveillance

Tactical battlefield surveillance capabilities are required during escalating crises or in military operations. The requisite capabilities are oriented more to military functions such as threat assessment, theatre targeting, short-term movement of troops, etc. These functions create requirements for a tactical reconnaissance satellite that are not levied on strategic systems. They are rapid accessibility, near-real time information, short revisit time, short feedback delay and accurate localization, all in a limited theatre of operations.

A prime requirement of a satellite system for tactical observation is that the end user receive imagery as quickly as possible. In other words, a good tactical system should provide the end user with an image, even if in a limited resolution, quick-look form, within one to six hours from request. Clearly, such a system is the most efficient when it approaches a capability for continuous monitoring. Data relay satellites, positioned in space and linked to the small terminals of operating units, may be useful to meet these needs.

Table 2.2 Mission Deployment

Option Area	Single-Event Deployment	Multiple-Event Deployment
Launch	(Launch-on-demand)	(Tandem launch with a major payload or Launch of multi-TACSATs by a larger booster)
Satellite storage	On ground	On-orbit
Bus design	Relatively small	Unconstrained
Constellation construction	Many separate launch events	Single launch event with many satellites
Training	Periodic launches needed	Use existing satellites already on station

The need for short revisit times which may be met, in part, by means of mechanical and electronic steering of the sensor, may also be effectively satisfied through the proliferation of on-orbit sensors. This is exactly the function that may be performed by TACSATs launched on demand. However, large systems, whose operation often requires long setup times, may also be used to improve resolution, as well as to create the necessary reference databases for prompt and accurate identification of objects.

When considering strategic satellites for these purposes, one finds they generally are not well matched to the needs of tactical missions: they do well with technical requirements but do not offer near real time or short delay services. Typical feedback delays for providing data to the theatre commander can be as long as 24 to 36 hours. Programming and processing time could be reduced by support structure improvements (data relay satellite, additional TT&C stations), but even with these improvements, strategic satellite systems are unlikely to meet all the requirements for tactical purposes.

The above discussion leads to the issue of how to define the requirements for resolution and timeliness of battlefield surveillance data against which any proposed system concepts can be measured. Any such definition must relate to military objectives. For the purposes of this analysis, the Working Group adopted the following criteria.

RESOLUTION
Resolution is associated with the ability of a given system to perform the following INTERPRETATION TASKS:

DETECTION:
- Location of a class of units, object, or activity of military interest.

GENERAL IDENTIFICATION:
- Determination of general target type.

PRECISE IDENTIFICATION:
- Discrimination within target type of known types.

DESCRIPTION:
- Size/dimension, configuration, layout, components-construction, count of equipment, etc.

A sample of target types that fall within these interpretation tasks is represented in Figure 2.1 which refers to visible electro-optical observations.

In a general sense, these interpretation tasks can be represented as shown in Figure 2.2.

TACSATs whose resolution falls in the 1 to 5 meter range can satisfy most of the military operational requirements. While a strategic system could also satisfy these requirements, the cost necessary to make it conform to the military revisit and timeliness requirements would be excessive. *The key function a strategic system can play in the military arena is to provide a precise data base for the target sets that then allows a TACSAT to concentrate on the interpretation tasks of detection and general identification.*

TIMELINESS
For this report, the Working Group divided military surveillance tasks into seven utility categories:

- Targeting
- Keying other assets
- Ocean surveillance
- Battle Damage Assessment (BDA)
- Technical intelligence
- Verification
- Terrain mapping

These categories can be compared according to timeliness versus resolution. Such a comparison is presented in Figure 2.3.

There are two messages in Figure 2.3:

- Strategic systems are best suited for establishing the data base that will be used by the TACSATs during military operations.

- While strategic systems have the resolution to cover the TACSAT area of interest, their complexity and cost to duplicate the TACSAT timeliness (and broad area coverage) will be prohibitive.

2.4.2 Tactical Communications

As forward bases on foreign soil continue to be closed, the ability to project joint forces combat power from the home country will be increasingly important. Such forces will require the ability to move great distances with little advance notice. They will require reliable telecommunications both en route and in the theatre of operations. Tactical satellite communications, provided by spacecraft already in-orbit or launched on demand, can provide this service, or augment existing satellite service.

In the past, in the interest of economy, satellite communications systems have been designed to provide a nominal capacity. This is less than the peak demand during a war. Desert Storm was the first "information war" with telephone traffic reaching 700,000 calls per day and message (hard copy) traffic at 152,000 per day. To support this demand, satellites were re-positioned to augment the coverage normally available, leaving some other areas, such as the West Pacific, without normal coverage. In future theatre conflicts, TACSATs could be used to meet the peak demand.

(IN METERS)

OBJECT	DETECTION	GENERAL IDENTITY	PRECISE IDENTITY	DESCRIPTION
Bridge	6	4.5	1.5	1
Communications Radar	3	1	0.3	0.15
Supply Dump	1.5-3	0.6	0.3	0.03
Troop Units	6	2	1.2	0.3
Airfield Facilities	6	4.5	3	0.3
Rockets and Artillery	1	0.6	0.15	0.05
Aircraft	4.5	1.5	1	0.15
Command & Control HQ	3	1.5	0.9	0.15
Missile Sites (SSM, SAM)	3	1.5	0.6	0.3
Surface Ships	7.6-15	4.5	0.6	0.3
Nuclear Weapons Components	2.4	1.5	0.3	0.03
Vehicles	1.5	0.6	0.3	0.05
Land Minefields	3-9	6	1	0.03
Ports and Harbors	30	15	6	3
Coasts & Landing Beaches	30	4.6	3	1.5
Railroad Yards & Shops	15-30	15	6	1.5
Roads	6-9	6	1.8	0.6
Urban Area	60	30	3	3
Terrain	-	90	4.5	1.5

Figure 2.1 Target Resolution Required for Interpretation Tasks[1]

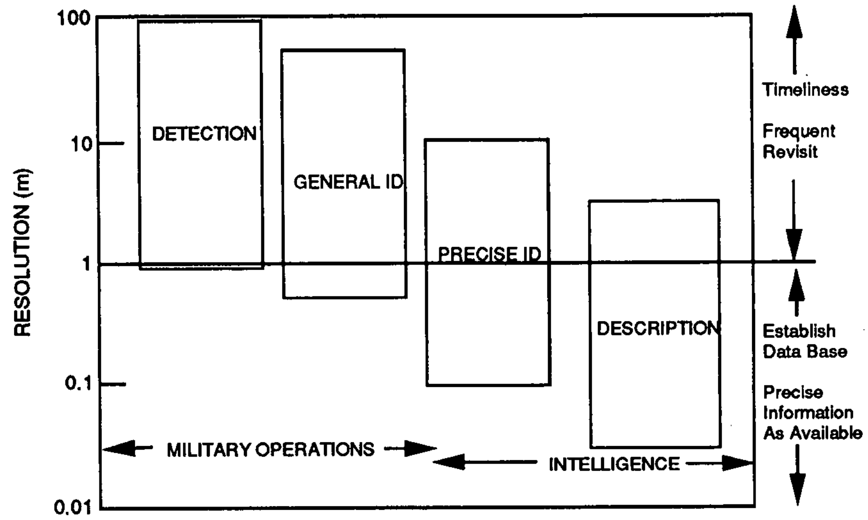


Figure 2.2 Target Resolution for Interpretation Tasks

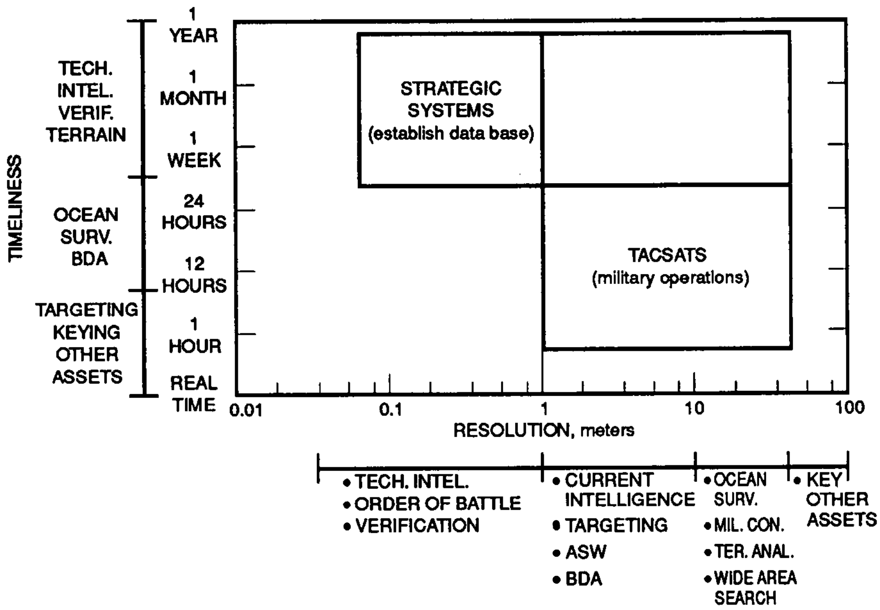


Figure 2.3 Timeliness vs. Resolution

[1]Ann M. Florini, "The Opening Skies" Third-Party Imaging Satellites and U.S. Security, International Security, Vol. 13, number 2 (Fall 1988).

There are two main mission opportunities for theatre satellite communications:

a) Communications between the theatre and the home country: this is a primary requirement for theatre operations, particularly in areas which do not have a fully-developed communications infrastructure. Mobility is not the primary concern and so, given some Electronic Counter Counter Measures (ECCM) upgrading, this wide-band requirement can be well-satisfied by the current SHF (8/7 GHz) systems, typically using ground station antennas of 2.5m diameter or larger.

b) Tactical communications within the theatre: this is the application which is evolving rapidly as a result of Desert Shield/Storm and consequently is the main focus of this review. For air/land operations, the main requirement is for beyond line-of-sight range extension for the tactical commander, where mobility is a primary concern. For naval forces, mobility is inherent and vessels are usually large enough to support both UHF and SHF terminals.

2.4.2.1 **Air/Land Operations Needs**

Future combined air, sea and land operations will not be joined before enemy forces have been significantly weakened by precision bombing and deep-fire weapons. Forces will operate in a highly-mobile situation, requiring communications to be available at all times and at beyond line-of-sight distances. Such operations will require high availability, secure, tactical communications systems with good ECCM protection.

a) Land Forces

Because, initially, only key pieces of terrain are expected to be seized and held, conventional combat net radio, linked by hill-top repeaters, cannot guarantee the required connectivity, while tropo-scatter links do not have the required mobility. At the same time, the two currently-deployed satellite systems, UHF and SHF, are not ideally suited to this scenario.

UHF (275–400 MHz) manpack terminals were used extensively in Operation Desert Storm. While UHF is potentially the most suited to highly-mobile operations, it offers virtually no protection against jamming. The great advantage of the low cost of UHF radios also means that jamming technology is cheap and readily available. Also, in most tactical situations, low probability of exploitation (LPE) is a concern. UHF satcom radios are more easily detectable because of the lack of spectrum-spreading and broader antenna beamwidths.

The SHF (8/7 GHz) systems typically use at least 2.5m diameter dishes and are deployed at the Corps and Division level. These ground terminals are not mobile enough for the tactical commander. Some prototype SHF manpack terminals have been developed and demonstrated (e.g., by the UK) but have not come into general use, partially because they require the use of a separate, dedicated, transponder channel.

Soon-to-be-deployed EHF (44/20 GHz) systems will overcome some of the disadvantages of the current systems, for those tactical situations where mobility with good anti-jam (AJ) and low probability of intercept (LPI) characteristics are essential.

b) Air Forces

Satellite communications links are required to connect the theatre tactical air control center to remote air/ground transmit/receive sites. Typical intra-theatre communications requirements are for:

Airspace management
Tactical secure telephone
Scramble circuits
Air tasking order circuits

2.4.2.2 **Maritime Forces Needs**

The ability to project joint forces combat power to a distant theatre depends, in the most likely scenarios, on the navy. Over 90 percent of the material necessary to sustain battle must go by sea. The required communications capacity for this important force will be supplied by many alternative paths, but the backbone will be SHF satellite communications. The UK and France already have surface ships and submarines equipped with SHF terminals. Current spacecraft include a minimum of five US DSCS-III satellites, the UK's three Skynet 4s, France's Syracuse I and II and the NATO IVA satellite.

The shortfalls of the SHF system, as it is presently implemented, are:

1. No coverage of the northern circumpolar region required by NATO.

2. Incompatibility between national systems handicaps international operations.

3. SHF requires large and heavy shipborne terminals.

4. SHF transmitters saturate the radar electronic support measures (ESM) receivers used to detect incoming missiles, requiring extra sophistication in the ESM system.

5. There is concern about saturation of regional capacity in the event of a theatre war such as Desert Storm.

Many alliance navies are interested in the future EHF systems because of their superior low probability of intercept, anti-jam characteristics, and small ship-terminal size.

2.4.2.3 Requirements Summary

Table 2.3 provides a summary of the requirements of the armed forces for each of the satellite communications technologies.

2.4.2.4 Role of the TACSAT Concept for Communications

Because enemy counter-measures have not been used, e.g., in Desert Storm, many of these requirements have been met by existing UHF and SHF systems, re-configured by re-locating satellites to augment capacity in the theatre area. TACSAT concepts should concentrate on SHF approaches that ensure the availability of counter-measures and on next-generation EHF systems that have the potential to solve some of the problems related to mobility, AJ and LPI. However, it must be noted that EHF has some disadvantages which include the large propagation margin that may be required, the difficulty in acquiring the satellite with a narrow ground-terminal beamwidth, the large Doppler shift due to satellite motion and restrictions on the type of orbit that can be accommodated by the data link standard.

While these technical requirements do not mandate TACSAT type systems, they do bring up the issue of what military systems may be in place in the future. In today's fiscal environment, the chances of maintaining the full spectrum of national military space-based communications is diminishing rapidly.

Desert Storm demonstrated the effectiveness of a coordinated and cooperative international operation. This trend is likely to continue into the future, because of the severe military spending cuts that are facing individual nations, thus leading to a desire for international cooperation in the procurement of space assets, as evidenced by the EUMILSAT and INMILSAT initiatives.

What the TACSAT concept offers is smaller increments of communications capacity that allow for smaller commitments in funding. It also allows for storage options on the ground, with rapid deployment when required, in order to augment or restore capacity on-orbit, in the appropriate area. *If a degree of commonality and interchangeability can be achieved, for example through the adoption of a common design for a TACSAT bus, the TACSAT concept could become very attractive.*

2.4.3 Tactical Missile Warning and Assessment

The tactical missile threat must be included in any theatre operations. To do so, a missile attack must be detected as soon as possible and tracked through its flight profile. A ground defence system like the PATRIOT is limited in detection capability and thus detects the missile later than a satellite system. A satellite like DSP (Defence Support Program) is designed to detect long range ballistic missiles and therefore has a limited capability against a short range ballistic missile, especially if the missile has a depressed trajectory. In summary, there are very limited capabilities available from today's resources.

TACSAT can be a player in this mission area primarily because of the need to observe only a small region of the earth, thus making it possible to detect dim targets with small aperture sensors and thus light weight satellites. To impose the dim target requirement on full earth coverage satellites drives the system complexity and weight to unacceptable levels.

The needs for TACSAT missile warning and assessment systems fall into three categories:

Table 2.3 Military Satcom Requirements

	UHF	SHF	EHF
Land Forces	Used for manpack terminals, in peacetime or against an unsophisticated enemy. Poor AJ and LPI.	Backbone comms. range extension method for distances over 200 km. Remote terminals are typically 2.5m diam. Greater mobility desirable.	Next-generation system, providing greater AJ, LPI and mobility. Initial capacity low. Low data rate terminals likely 0.6m diam.
Air Forces	AFSATCOM: Specialized use for command and control of nuclear forces. Will be phased out.	Backbone comms. long-range extension method for air/ground radio network.	Replacement for UHF. Potential replacement for SHF in critical applications.
Maritime Forces	Extensive use; low capacity, poor AJ (except broadcast mode), poor LPI.	Backbone system for most alliance navies. High capacity, moderate AJ and LPI.	Will complement SHF where good AJ and LPI are priorities. Initial capacity low.

- Active defence
- Passive defence
- Counterfire

Active defence calls for the precise location of the launch event and early tracking of the missile. This information must be accurate enough to achieve three objectives: (1) identify the attacker by geographic location, (2) provide launch location for follow-up negation by NATO forces, and (3) track the missile so that weapons can be cued to intercept the missile during the boost phase.

Passive defence involves the identification of the area under attack so that passive measures, such as making use of gas masks, can be implemented. Depending on the passive measure, time can be a critical element of this activity.

For those counterfire systems that have limited terminal surveillance capabilities, a TACSAT missile surveillance system can perform the critical cueing function of intercept zone determination. This action allows the counterfire system to point its surveillance system for maximum effect.

2.4.4 Regional Maritime Surveillance and Environmental Observation

If necessary, part of the naval forces of the NATO member states could be deployed under a unified authority in order to:

- insure a NATO presence on the high seas,
- conduct naval actions including blockades and embargoes,
- support specific actions on land (power projection).

In such cases, the NATO naval forces should be sized to provide the optimum response to the threat, after integration into an adequate C3I system. Considering the huge surface areas, the hostility and the emptiness of the oceanic areas, C3I satellites are a very attractive alternative to more conventional means of C3I (e.g., aircraft).

Every naval unit, from submarines to surface ships and aircraft carriers, can benefit from satellite services to satisfy its specific needs in terms of:

- communication,
- position location,
- naval intelligence (discussed below),
- environmental knowledge (discussed below).

Two types of naval intelligence data can be distinguished and characterized by significantly different values for data refresh time and accuracy: they correspond to "strategic" (sparse, precise) and "tactical" (frequent, limited) needs.

While the capability of recognizing and identifying a fleet already located at sea, or isolated vessels in a harbor/arsenal can easily be provided by current and future observation satellites, the problem of ocean surveillance requires specific considerations of detectability and tracking of mobile sea surface targets. In particular, the revisit time for a given target (ship) is strongly dependent on the swath of the instrument on-board each satellite, on the orbits and number of the satellites, and on the location and the size of the theatre. As for detectability matters, primary concern is directed toward relatively large vessels (e.g., greater than Aviso type), but greater sensitivity for the detection of smaller ships should also be considered in the far-term for its own sake and to take into account foreseeable progress in the development of stealth capability.

Given this capability, the NATO authority for the Navy should then have at its disposal updated maps of surface maritime traffic in the theatre of interest, with tracks of designated targets as well as means of correlating this information with other data sources (e.g., measurements of in-situ acoustic signals).

Knowledge of the marine environment classically involves the atmosphere, for meteorological forecasting, as well as the sea surface and the deep ocean for hydro-oceanographical needs, mainly for anti-submarine warfare (ASW) activities. The modelling of these complex physical phenomena requires the measurements of many meteo-oceanographical parameters (e.g., speed and direction of sea surface wind, wave height, vortices, sea currents, thermocline depth, sea surface temperature, vertical profiles of salinity, pressure, temperature, etc.) with global and homogeneous sampling, both in time and space, which are particularly well performed by LEO satellites.

2.4.5 Navigation

The US GPS Navstar system will use 21 satellites (plus 3 spares in orbit), placed in 6 circular orbital planes, all at 55° inclination and at about 20000 km of altitude, to deliver a global positioning service. This satellite constellation has potential service degradations in particular geographic areas on a daily basis caused by the geometrical alignment of the satellites as seen by the users.

The system has been conceived to present the users, wherever they may be located, a view of at least four satellites; however, there are times when two satellites are almost aligned. In this situation, the coupled satellites are identified as one, generating an increase in localization error. The same type of degradation can occur when one satellite fails or when the user is shadowed from one satellite.

The error caused by this geometric effect, the most relevant in the total error chain, is evaluated by the parameter called "Geometric Dilution of Precision" (GDOP). The GDOP mainly depends on the angular separation through which the user sees the four satellites which is then used to accomplish the distance measurement: Consequently, it depends on the user's position and time. In some particular areas, at a certain time period (when some or all the satellites are in the same orbital plane), the GDOP is particularly high.

The scope of a complementary TACSAT navigation system would be to decrease as much as possible the GDOP value in a particular geographical area (as wide as the Mediterranean region) without affecting the Navstar user segment (the receivers), permitting also the evolution of the TACSAT system toward an autonomous one by the progressive injection of other satellites.

2.4.6 Weather

The potential applications of meteorological tactical satellites can be seen from Figure 2.4. This figure shows that cloud motion monitoring and short term weather predictions, as may be required for tactical mission planning and management, require a spatial resolution in the 100 m to 10 km range and a temporal resolution from 1/2 to 3 hours. These requirements, in general, are more severe than commercial needs and would consequently call for dedicated military capabilities.

The required temporal resolution can be achieved with small satellite constellations only, possibly flown in orbits tailored to the theatre latitude. The average spatial resolution requirement is quite modest, considering the low altitude of LEO spacecraft, and is compatible with the use of low resolution optical sensors. Most probably, the required sensors will not justify, or require, dedicated satellites but rather they can be fitted on small satellites nominally designed to meet more stringent mission requirements, such as battlefield surveillance. Nevertheless, the use of minisats is also possible, flown in larger quantities, to substantially decrease the revisit interval, thus improving the temporal resolution.

The smoke due to the oil wells set afire during the Gulf war was a serious problem: the availability of a tool to predict the spread of the smoke trails due to winds could have considerably improved the situation. In a tactical scenario, the near term availability of cloud cover predictions through cloud motion monitoring would considerably enhance the effectiveness of medium range bombing missions. Local surface wind and sandstorm predictions, via cloud motion monitoring, can help conduct in-depth attacks by ground forces, thus reducing losses. A better knowledge of near term cloud cover forecast can also improve the effectiveness of the deployment of other tools (airplanes, satellites) equipped with optical sensors for intelligence and surveillance missions.

In conclusion, there is a definite role and scope for tactical meteorological satellites. The needed sensors do not necessarily require dedicated spacecraft, but can share a platform already designed for more ambitious tactical purposes, in particular for battlefield surveillance.

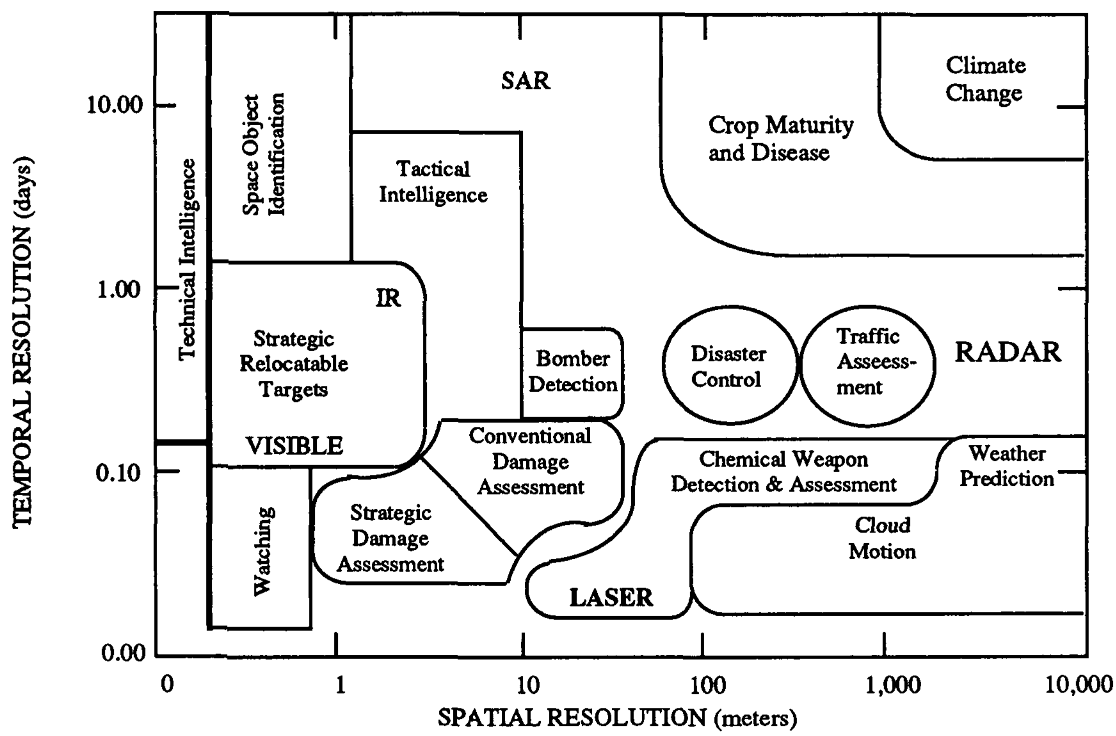


Figure 2.4 Applications of Meteorological Tactical Satellites

CHAPTER 3

TACSAT SYSTEM CONCEPTS

3.1 OVERVIEW

In this chapter the Working Group addressed six mission areas and one special topic (ELINT systems were not addressed because of security classification issues):

- Battlefield Surveillance
  - Electro-optical
  - Radar
- Communications
  - UHF
  - SHF
  - EHF
- Tactical Missile Warning and Assessment
- Regional Maritime Surveillance and Environmental Observations
- Weather
- Navigation
- Special Topic: Orbit Selection

The key to the following discussion is the identification of viable TACSAT concepts that conform to the needs identified in Chapter 2. At the outset, it can be said that in all areas there were concepts with solid military utility. However, for radar battlefield surveillance there was some discussion over whether the technology is currently available to build a satellite that falls in the TACSAT weight regime and can be constrained to a cost of approximately $50M.

In each mission area, the discussion format covers the areas of concepts and operating characteristics (orbits, control). It should be noted that there were classified concepts, not discussed in this document, provided to the Working Group that further validated the TACSAT concept.

3.2 BATTLEFIELD SURVEILLANCE

3.2.1 Electro-Optical (E-O)

TACSAT optical systems are useful in crisis situations and/or conflicts. Optical systems differ from other systems, when considering performance, in that they have better geometric resolution capability; but high resolution may not be necessary in a crisis or conflict where the primary objective is force detection and position location.

One of the requirements at the start of hostilities is to know the precise characteristics of forces involved. During peace time there will be many opportunities, using strategic satellites and other means, to observe forces in countries which might become potential enemies. One has sufficient time to perform high resolution observations which include precise identification and description. In just such a case, optical systems are very useful as a result of their high resolution. Cloud coverage in areas of interest, in such situations, is only a secondary drawback because the time needed to carry out the observation typically is not priority limited and such an observation may be made on a subsequent orbital pass over the target area. Thus, when a crisis occurs the original deployment and strength of adverse forces should be well known. What is important then is the determination of the adversary's subsequent movements as quickly as possible.

Optical systems suffer in this respect because of potentially interfering meteorological conditions; however, they have a significant advantage over other approaches. Namely, it is possible to design, at a relatively low cost, small and simple satellites.

The nature of the information obtained is one more advantage for optical systems. The exploitation of an image taken from an optical instrument is usually straightforward because it presents an image as we are used to seeing it. This is not the case for images coming from radar instruments: a visible image of the same area, preferably taken simultaneously, may be useful for a better interpretation of a radar image.

If for TACSATs with electro-optical payloads, one limits oneself to simple instruments but on numerous satellites, there will be no difficulty in the design of such satellites. A TACSAT optical satellite project can start immediately without additional research if funding is available. Its properties might be:

- geometrical resolution:
  5 m (visible)
  5 to 20 m (mid IR)
  10 to 30 m (thermal IR)
- useful optics diameter:
  10 to 70 cm
- spectral bands:

  visible (0.45 to 0.7 μm)

near IR (0.8 to 1.1 μm)
mid IR (3.5 to 5 μm)
thermal IR (8 to 12 μm).

It is feasible to implement several spectral bands on the same TACSAT or to divide one spectral band into several smaller bands. The choice depends on the use the end user is expecting from the images. Obviously, the more spectral bands used the more complex the instrument and its on-board processing electronics.

A cooling system will be needed for mid and thermal IR band sensors. One can use either passive or active cooling systems, but passive systems are generally very large. Active systems can be used, although, at present, they may generate troublesome vibrations as well as being of limited life.

3.2.1.1 Orbital Trades

Orbital type

It is important to distinguish between the orbital requirements of visible and infrared satellite systems. In the first case, favorable earth illumination conditions are required to achieve good image quality. That imposes the use of sun-synchronous orbits where the ascending (or descending) node is positioned near noon. In the second case, with IR, such a condition is not required because thermal-IR sensors utilize self-emission of radiation rather than reflection of sunlight.

Orbit altitude

The geometrical resolution for an E-O system is a function of the orbit altitude: the lower the satellite, the better the resolution can be. However, one cannot decrease the altitude indefinitely because under a certain altitude (say 200 km) strong atmospheric drag will lead to a very short satellite lifetime.

Phasing

If one tactical satellite is dedicated to a given theatre, one can choose its orbit in order to increase its frequency over the area of interest. For instance, it is possible to choose an orbit which will be over the theatre each day (it is called a "one day phased orbit"). Such an orbit can be either circular or elliptic. Elliptic sun-synchronous orbits can be very interesting: they can be one day phased, have their perigee located over the zone of interest and, thus, allow a good resolution with a long lifetime due to the high altitude of the apogee. The drawback is that the perigee will move (due to the earth's gravity field) and, as a consequence, the resolution will become poorer. This type of orbit can be used for limited mission duration, or if one accepts a decrease in resolution. The solution to keeping good resolution for a long period of time is to use several satellites in sequence (generally 3 satellites are enough).

3.2.1.2 E-O Concept A

One of the national studies considered an electro-optical satellite with high resolution for tactical purposes as well as for crisis monitoring and management tasks.

The selected constellation included four to six equi-spaced satellites at an altitude of 570 km in a single sun-synchronous, non-resonant, near-noon orbital plane providing continuous earth coverage, up to high earth latitudes, for continuous monitoring and surveillance tasks over multiple theatres scattered throughout the world. This system configuration could allow daily revisits and has the advantage of constituting a ready-to-use permanent asset in space. Optical image retrieval could be done by transportable ground receiving stations deployed inside the theatres.

Two E-O panchromatic sensors of different telescope diameters were considered (respectively 30 and 50 cm) thus giving different resolutions and imaging performances (see Table 3-1).

The 30 cm diameter E-O sensor will be able to take discrete pictures of ground targets about 12 by 12 km wide, but is unsuitable for continuous ground strip imaging. This operational limitation is offset by the relatively low data rates required (see Table 3-1). Repointing of the optical telescope to access ground target areas inside the access angle of ± 30° with respect to the nadir is done by spacecraft tilting about the roll axis at a rate of 2°/sec thanks to the small mass and inertia of the satellite.

The higher performance 50 cm diameter E-O sensor is conceived for continuous strip imaging of about 12 km in width, which may be important for certain tactical surveillance tasks: but the system output data rate increases significantly (see Table 3-1).

Both sensor types can be accommodated inside a spacecraft weighing less than 500 kg, at launch, including propellant for orbit keeping throughout the longest mission duration.

3.2.1.3 E-O Concept B

This concept involves the use of a single satellite design to perform two different surveillance missions - *theatre surveillance and tactical missile tracking*. While the latter mission is the subject of a separate discussion in this chapter, it will be discussed here in this application for completeness.

Although these missions have different requirements, it will be shown that by selecting the proper orbits, both missions can be met with a common payload design. Theatre surveillance involves looking at relatively small target areas in order to do target location and

Table 3.1 E-O Sensor Concept A - Summary Performance

• telescope diameter	30 cm	50 cm
• full f.o.v.	1.2°	1.14°
• swath from 570 km height:	12 km	11.2 km
• active detectors	5600	7600
• resolution from 570 km height	2.1 m	1.5 m
• integration time	1.3 msec (min)	0.14 msec
• digital resolution	11 bits	11 bits
• output data rate	< 50 Mbit/sec	640 Mbit/sec
• sensor mass	25 kg	40 kg

then bomb damage assessment. These parameters are also required to allow the user to monitor the battlefield in order to determine deployment and strategies. To do this with reasonable size optics requires that the satellite be flown at relatively low altitude. A 500 km circular orbit was chosen for this application. Tactical missile tracking, on the other hand, requires coverage over a larger area and the ability to detect and track missile launches from the infrared signature given off by the rocket plumes. For this application, satellites in geostationary orbits were postulated.

The *theatre surveillance system* uses an electro-optical payload in the visible region for imaging of selected target areas. At 500 km altitude, the payload would be able to acquire targets within an area of 2000 km in track and 1000 km cross track. Within this acquisition area, the payload would be directly commanded by the user to image target areas up to 9 x 9 km. The data taken by the satellite would be transmitted directly back to the user who would have the capability to do data exploitation in near real time. It is envisioned that the entire process from tasking of the satellite, acquisition of the data and downlinking to the user would take a minimum of 15 minutes. The maximum timeline is governed by the revisit time and is a function of the number of satellites in the constellation and the orbit inclination. The *theatre missile tracking system,* deployed in a geostationary orbit, uses a scanning infrared sensor to detect tactical missiles and afterburning aircraft in a 2000 x 2000 km area. Within that target area, the system is capable of processing up to 1000 potential targets and, after processing, tracking up to 100 real targets simultaneously. For ballistic missiles, both launch and impact points can be predicted. These predictions could then be used to initiate a counterforce strike or cue defensive systems.

A *single sensor* that could do both the theatre surveillance and tactical missile tracking missions was conceived and is shown in Figure 3.1.

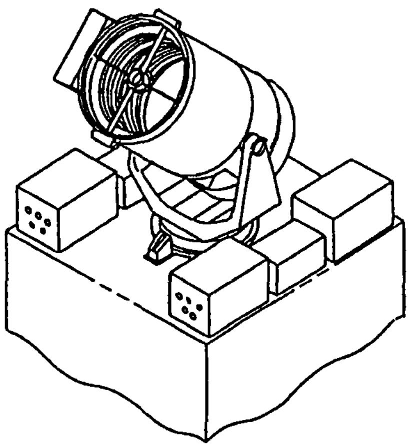
The sensor has common optics for both missions and a dual focal plane array to accommodate both the wide field of view and the high resolution requirements. The payload is compact in design and weighs approximately 100 kg. It is now possible to satisfy the affordability attribute; a single satellite that could do more than one mission depending upon the orbit into which the satellite was deployed. This spacecraft and its payload were examined to determine whether they could do missions other than those for which they were designed. Figure 3.2 shows that the missions of multispectral imaging and space object surveillance could also be done from a satellite in a 500 km orbit and that the mission of cloud and ocean imaging could be done from geosynchronous altitude.

The imaging missions would utilize both the IR and visible spectrum at the discretion of the user depending upon the operational and environmental conditions at the time. The surveillance of space objects from space would be done solely in the visible band.

3.2.2 Synthetic Aperture Radar (SAR)

SAR sensors with good performance, in terms of ground resolution and short revisit intervals, can be implemented onboard small satellites for tactical purposes, thanks to several factors peculiar to the TACSAT application. These factors are:

- very low operating duty cycles on the order of ≤1 to 5% of the orbital period;
- elimination, or strong reduction, of spacecraft redundancies, thanks to the adoption of the constellation concept;
- orbital lifetime in the 3 to 5 year range;
- injecting satellites in low altitude orbits, say between 450 and 600 km, thus reducing the peak and average power requirements during periods of sensor activation.
- high ground resolutions, in the 1 to 3 m range, as required for the majority of the tactical battlefield surveillance tasks, imply short SAR antennas in the 2 to 6 m range, thus making them inherently suitable for being accommodated on small satellites.



Optics	**• 45 cm aperture**
Focal Plane Arrays	**• Visible and IR** **• Wide FOV focal plane** **– 3° x 0.5°** **– F/7 off-axis** **• High resolution focal plane** **– 0.16° x 0.16°** **– F/15 on-axis**
Pointing and Scanning	**• Reactionless drives** **• ±45° conical field of regard** **• Wide area coverage in 3° swaths**
Envelope	**• 70 x 100 x 100 cm**
Weight	**• 112 kg**
Power	**• 370 W (600 W peak)**
Downlink Data Rate	**• 0.03 – 308 Mb/s (mission dependent)**

Figure 3.1 A Single Sensor for Both Theatre Surveillance and Tactical Missile Tracking

Mission	Theatre Surveillance	Multi-spectral sensing	Space Object Surveillance	Cloud/ Ocean Imaging	Tactical Missile Tracking
Orbit, km	500	500	500	35750	35750
Spectral Bands, µm	0.45-0.90	Various Commandable 0.4-10.0	0.45-0.90	Various Commandable 0.45-10.0	2.7
Field of view/ scan rate, data rate	1.5° x 1.6° 274 Mbps	3° x 0.1° swath 2.5°/sec 274 Mbps	360° swath 1.9°/sec 20Kbps	18° x 18° 8°/sec 70 Mbps	3° x 3° 8°/sec 20Kbps
Re-visit	12 Hours for one satellite (but up to 24 hours between daylight passes)		–	Continuous over Area of Interest	2 sec

Figure 3.2 Potential Missions for the Sensor in Figure 3.1

Starting from these considerations, several national studies have verified the feasibility of small SAR satellites for tactical surveillance. The studies differ in the complexity and performance offered but, in general, all point to the fact that such satellites will have launch masses in the range of 500 to 700 kg. They should fly in constellations of 4 to 8 spacecraft to ensure short average revisit intervals; and they can offer ground resolutions in the 1 to 5 m range and instantaneous swaths of the order of 10 to 60 km, depending on the achieved ground resolution.

3.2.2.1 **Orbital Selections**

A substantial advantage of SAR sensors is that they do not depend on solar illumination and are not adversely affected by weather conditions. The choice for satellite orbits can take advantage of this fact to fulfill the observation requirements over specific theatres, in which case reference is generally made to "tailored orbits"; orbits that have an inclination close to the latitude of the theatre which may allow for several viewing opportunities per day. An approach to the dynamic threat environment is, therefore, the use of "tailored orbits" (discussed later) that are specifically selected at the time of launch for optimized coverage of the crisis area. Of course, the setting up of such a constellation is mandatory to achieve revisit intervals of the order of a few hours. The main limitations of the "tailored orbits" are the following:

a) The average revisit interval increases rapidly at latitudes below that of the orbit inclination;

b) No coverage is provided for latitudes above the orbit inclination.

Therefore, additional constellations would be needed if new crisis areas appeared outside the latitude belt covered by the original constellation, or if the new crisis areas are situated at latitudes well below that of the original constellation orbital inclination.

Cost considerations might then limit the setting up of constellations that can provide tactical surveillance services to as many simultaneous theatres as possible (distributed in the politically unstable areas). Such "near global coverage" can be implemented using different orbit types, but the sun-synchronous ones have proved to be both adequate and capable of leading to very significant satellite simplifications, owing to solar panel illumination, especially if the satellites are injected in sun-synchronous dawn-dusk orbits. These design simplifications include a reduction in the number of batteries because of minimum energy storage requirements and the use of batteries that do not have to accommodate the depth of discharge and charge cycle needs of other orbital configurations.

Obviously, to achieve greater coverage compared to that achievable with "tailored orbits," the price to be paid is an increase in the number of satellites in the constellation to provide nearly the same average revisit interval over the sites of interest. Another obvious point is that the excellent revisit interval performance achievable from a constellation in "tailored orbits" in the vicinity of latitudes corresponding to the orbit plane inclination cannot be matched by a constellation of satellites in sun-synchronous orbit, unless the number of satellites in the latter is increased very substantially.

3.2.2.2 SAR Satellite Concept A

One concept for a SAR satellite constellation is presented here. The high resolution SAR sensor operates in X-band and is characterized by a non-moving antenna with electronic scanning in the elevation plane only. Both Stripmap and Scansar operating modes are envisaged for battlefield surveillance. In the SAR Stripmap mode a continuous, uninterrupted, earth strip (having a width equal to the SAR instantaneous swath) can be pre-positioned within the SAR field of regard by scanning the antenna beam in the cross-track plane and keeping it fixed for the duration of the image formation. In the SAR Scansar mode the antenna beam is sequentially scanned in the cross-track plane, and the echo returns from each sub-swath are integrated for a fraction of the time normally allocated to image taking in the stripmap mode. Therefore, the mapped area increases, but at the expense of a decrease in the ground resolution due to the decrease of the integration time allocated to each portion of the image. Ground resolutions and swath widths of 2.5 m and 28 km in the Stripmap mode and of 5 m and 60 km in the Scansar mode are feasible. Access to both fields of regard between 20° and 50° off nadir is done by the spacecraft tilting in roll; instantaneous swath orientation inside the field of regard is done by SAR antenna beam electronic steering in the cross-track direction.

The spacecraft dimensions are compatible with a launch vehicle of the Taurus/Scout class. The deployed SAR antenna dimensions are 5 by 1.4 m; during launch it is folded in two panels onto which the redundant high power arrays (HPAs) are also integrated.

The satellite will be flown at rather low altitudes, in the 450 to 600 km range, either in sun-synchronous dawn-dusk orbits or in low to medium inclination prograde orbits. The satellite launch mass is in the 600 kg range, including fuel for a 5 year lifetime in its nominal orbit.

The same basic spacecraft configuration can fit both orbit types, with minor changes to a few subsystems and operating modes. The main differences concern spacecraft electrical energy management. When the satellites are flown in sun-synchronous orbits, the SAR energy supply, when active, is partly from the solar array, for which a 4 meter squared area is projected, and partly from onboard batteries, with a capacity in the 20 to 30 Ah range. The better sun illumination, in the sun-synchronous orbit, allows an increase of the SAR operating duty from a few percent up to 20 to 25% of the orbit period. This increases the average system throughput and allows serving multiple theatres simultaneously.

In medium inclination orbits, however, the different and changing sun illumination conditions imply that the SAR electrical energy must be supplied from the batteries, which are recharged during periods of sun illumination and no SAR operation. This inherently reduces the feasible operating duty cycle to a few percent of the orbital period, which nevertheless may be more than adequate for the majority of tactical battlefield scenarios.

The SAR satellite will transmit data to ground at about 200 Mbit/sec via a directed, steerable, antenna pointed towards the data receiving station, which is assumed to be deployed inside the theatre. The ground terminal antenna diameter is less than 2.5 m, thus being easily transportable and ensuring reception of satellite data from within a circle of about 2500 km radius around the terminal site.

Four to six such satellites can be injected into a dawn-dusk, sun-synchronous orbit, providing two viewing opportunities per day for sites inside an 80° North to 80° South latitude belt. Alternatively, 6 satellites in medium inclination orbits, say 45° to 55°, can provide much shorter revisit intervals, of the order of 3 hours, on average, at latitudes corresponding to the orbit plane inclination: but the revisit intervals increase rapidly going towards the equator, and there is no coverage at all for sites at latitudes above the orbit plane inclination.

3.2.2.3 SAR Satellite Concept B

The TACSAT mission is one associated with a theatre conflict where the theatre is defined as being a region measuring some 2000 km by 2000 km and the duration of the conflict is anticipated as being relatively short, typically of months, rather than years. Although areas of political and military risk can lie at any latitude, the ending of the Cold War suggests that if there were to be such a theatre conflict, then its occurrence in the lower latitude regions, rather than the more northerly latitudes, seems more likely.

The mission envisaged for a TACSAT SAR is to provide the theatre commander with a dedicated service yielding surveillance data only over the crisis area. The dedicated nature of the TACSAT mission is taken to mean that the theatre commander has total control over the satellite so that the satellite will not be made available to provide surveillance over any region other than this crisis area. Depending on the particular operational philosophy, satellite control might be exercised either directly from within the theatre, or remotely, using global control systems but under the primary control of the theatre commander.

Finally, the dedicated nature of the service proposed for the TACSAT SAR therefore facilitates some interesting departures from the system thinking associated with global space surveillance concepts. These departures influence the choice of orbit, the spacecraft bus design, and the basic sensor design.

For this SAR concept, the orbit is selected using the following rationale. The expectation of a theatre location away from the high northern latitudes invites consideration of orbits of a lower inclination than the polar sun-synchronous orbit that is characteristic of civil remote sensing missions. In particular, if the chosen operating philosophy for the TACSAT SAR is one of launch-on-demand in time of crisis, then the orbit inclination can be chosen to maximize viewing opportunities over the crisis area. If, however, the philosopy is one of in-orbit storage, then an earlier decision must be made about inclination because of the large fuel overhead involved in effecting changes in orbit inclination. However, even in this latter case, it may well be appropriate to set the inclination of the storage orbit so that coverage is optimized for the lower latitude regions. The absence of sun-synchronism, a consequence of the low orbit inclination, will not present a particular problem to the radar sensor which is capable of operating as well by night as by day.

In addition, the relatively short duration envisaged for a theatre conflict allows serious consideration to be given to orbits significantly lower than those used for long duration remote sensing missions: these lower orbits, perhaps as low as 250 km, would be suited to a philosophy of launch-on-demand. However, although particularly low orbits are less attractive for the case of in-orbit storage because of the short life time which results from atmospheric drag, it is possible to conceive of two distinct and attractive patterns for TACSATs using the philosophy of on-orbit storage. During the storage period, the TACSAT could be stored in a higher orbit and could be used for training purposes as well as for secondary surveillance service, although at coarser sensitivity. In the event of crisis, the potential would exist to reduce the orbit altitude in order to improve sensitivity over the operational theatre. It is important to note however, that such a reduction in altitude will not bring significant advantages in improved spatial resolution, and the coverage access available to the satellite on any one pass over the theatre will be more limited than that achievable from a higher orbit.

The dedicated nature of theatre surveillance means that the periods during which satellite service is required is of short duration. Typically a satellite in the low earth orbit (LEO) will take only 5 minutes to traverse a theatre measuring 2000 km on the side, and with only 2 such passes likely per day, SAR payload power demands will readily be met from batteries. The advantage to the platform design is that relatively small solar arrays can then be used to collect electrical power and trickle-charge the batteries during the prolonged periods of payload inactivity.

The design goals for this sensor concept are shown in Table 3.2.

A major difficulty in realizing a radar design of this sophistication is the achievement of high resolution and in the implementation of a phased array antenna able to

Table 3.2 Design Goals for SAR Concept B

PARAMETER	VALUE	UNITS	COMMENTS
operating frequency	9.6	GHz	X-band
spatial resolution	10 1 20-50	m m m	Steered Spotlight Ground Moving Target Indicator (GMTI)
minimum detectable RCS	10	m^2	
minimum detectable velocity	6.5	knots	Radial velocity
P_{fa}	10^{-6}	–	
polarization	–	–	Scattering matrix preferred

operate over such wide instantaneous bandwidths. Overall it is felt that a resolution of 1 m at X band is feasible at a 30° grazing angle. All options are based on an assumed antenna area of 6 m^2. This area is derived from considerations of viable payloads for implementation onto a toroidal platform within the TACSAT mass goal of < 700 kg.

The operating geometry for a TACSAT SAR is shown in Figure 3.3 in order to identify the principal parameters.

In order to perform a useful reconnaissance role, the SAR must be capable of providing images of specific target zones such as airfields, harbours, choke points and railway installations at the finest possible resolution. This task calls for Spotlight operation in order to provide adequate resolution in the along-track (azimuth) direction and the provision of this capability is a major driver in the design of the antenna.

For the TACSAT SAR mission considered here, target imaging requirements fall into the following two main categories:

- detection and classification of hard targets, e.g., military vehicles, tanks, grounded aircraft, ships, etc.
- monitoring and change detection for distributed targets, e.g., airfields, military camps and installations, harbours, railway yards, choke points, etc.

In the former cases, the targets of interest generally have large radar cross sections relative to the background scene. As a result, the ability to detect and subsequently classify such targets depends primarily on the spatial resolution of the imagery, the system radiometric performance being relatively unimportant. A spatial resolution of at least 3 m, and ideally less than 1 m, will be necessary.

In the latter case, however, the features of interest are generally no brighter than other features in the scene; the key requirement for discrimination and recognition of such targets is, then, good radiometric resolution (best SAR speckle reduction). This may be achieved by multi-looking. The spatial resolution requirement for these types of targets is considered less exacting than for "hard" targets at around 5–6 m. However, the fact that multi-looking is required implies that the inherent single-look capability be similar to that for hard target detection (i.e., around 1–3 m).

It can be seen from the preceding discussion that the TACSAT antenna requires electronic steering in azimuth in order to provide the Spotlight mode and that

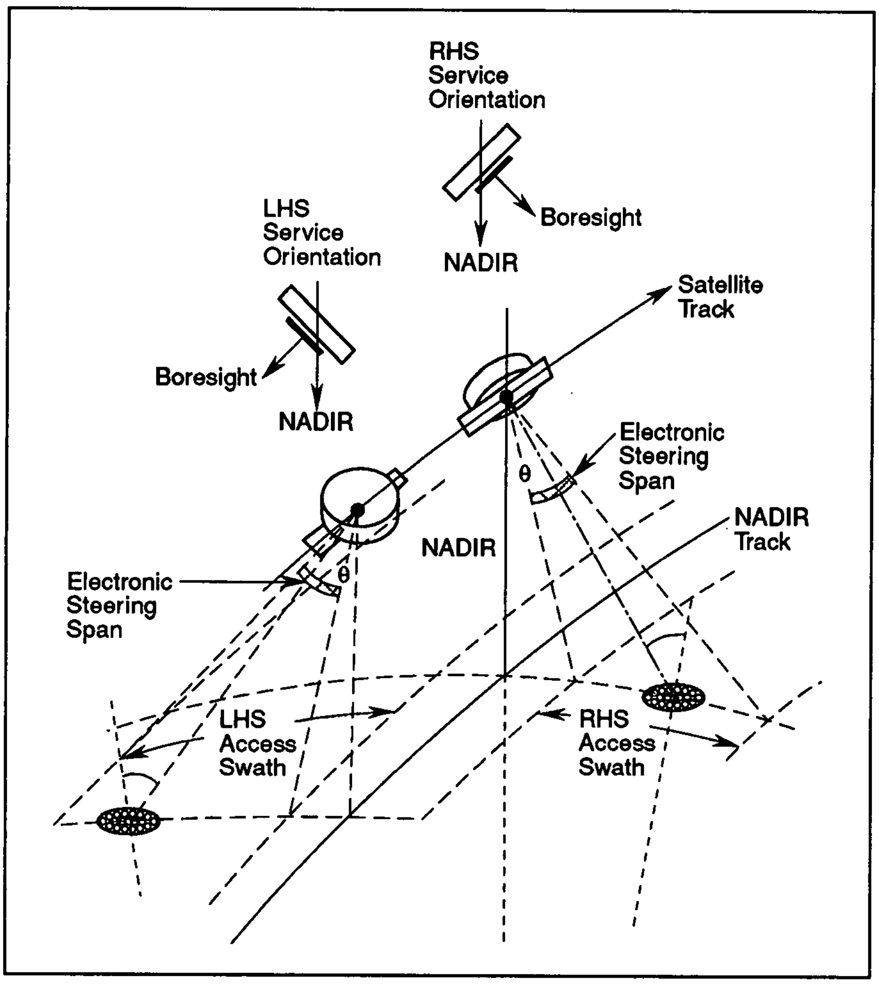


Figure 3.3 Operating Geometry for a TACSAT SAR

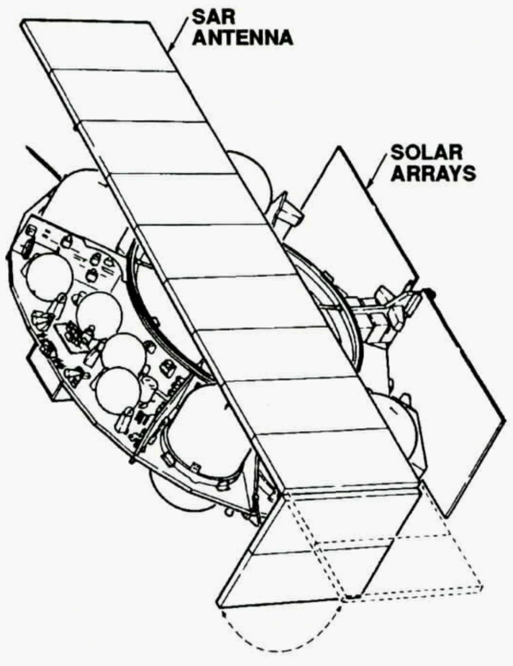


Figure 3.4 A Possible SAR Spacecraft Configuration

a similar capability in the elevation direction is highly desirable in order to facilitate the imaging, during a single pass, of different zones located at different elevation bearings relative to the satellite.

Thus, the case for electronic steering in both azimuth and elevation directions appears to be strong and leads to the need for a fully active phased array solution for the envisaged TACSAT mission.

The particular aspect ratio assumed for the antenna is based on the need to accommodate the toroidal bus, the 6 m^2 overall area being required to provide the unambiguous access. Two distinct cases were examined, one at C-band, the other at X-band. In both cases, the antenna was built from 11 panels which were assembled onto the bus as indicated in Figure 3.4.

In the C-band case, each panel was populated with 32 T/R modules and measured some 1300x418 mm whereas in the X-band case, each panel was populated with 64 T/R modules and measured some 1400x388 mm. Thus, the aspect ratio of the antenna was similar in both cases being 4.6 m(az) by 1.3 m(el) in the C-band case, and 4.27 m(az) by 1.4 m(el) in the X-band case. It is important to note that despite their intended major role as Spotlight imaging sensors, both of these SARs would be capable of providing better than 3 m resolution in conventional Steered SAR mode.

Different data rates can be associated with the SAR depending on whether range compression is conducted on-board or on the ground. With the long duty cycles envisaged for use in Spotlight mode, there is a need to receive radar returns, not only for the duration of the time delay from near to far sides of the image region, but also for the duration of the transmit pulse.

It is possible to limit the data rate to values as small as 130 Mbit/s for operations at C-band where the SAR chirp bandwidth is limited to 100 MHz, and to 400 Mbit/s for operations at X-band where the chirp bandwidth is limited to 300 MHz. Data links with these bandwidths exist but the problems of handling these quantities and rates of data will require further examination.

There has been much discussion about the possible lifetime of a TACSAT mission. Depending on the mission concept, the intended lifetimes can vary from several weeks–associated with launch on demand, through months–associated with launch in anticipation of a crisis, to years–associated with pre-deployment of the satellite(s) and storage in space.

The particular needs which might be envisaged for a TACSAT SAR are that it be capable of viewing the designated theatre at very regular intervals. For instance, a full system may be required to provide viewing opportunities at 8-hourly intervals: such a revisit rate would call for the service of a constellation of 3 satellites.

The toroidal bus design selected here facilitates the launch of a mini-constellation of 4 or 5 satellites on a dedicated launch using either Ariane-4 or Titan. System reliability can, in this case, be improved by the redundancy which results from using the multiple satellite launch, i.e., by using one of the 4 or 5 satellites as a spare.

In summary, a SAR operating at X-band would be capable of providing single-look imagery at 1 m spatial resolution and a noise floor of better than–20dB when flown in a circular orbit at 500 km altitude. The total mass of a satellite carrying this SAR has been estimated at around 600 to 700 kg. While it is quite within the bounds of technology to conceive of integration of both the SARs discussed here on a platform suited to individual launches, it is specifically the absence of such dedicated launch vehicles which is the driver towards a toroidal bus structure. This structure is well suited to a multiple launch.

The adoption of such a philosophy provides the opportunity of getting single satellites into orbit economically, but not with a rapid turn-around. In addition, the toroidal bus structure provides the possibility of deployment of a complete constellation, using a single launcher. In this way, it will be possible to amortize the cost of the larger launcher against the corresponding cost of several individual launchers using smaller vehicles.

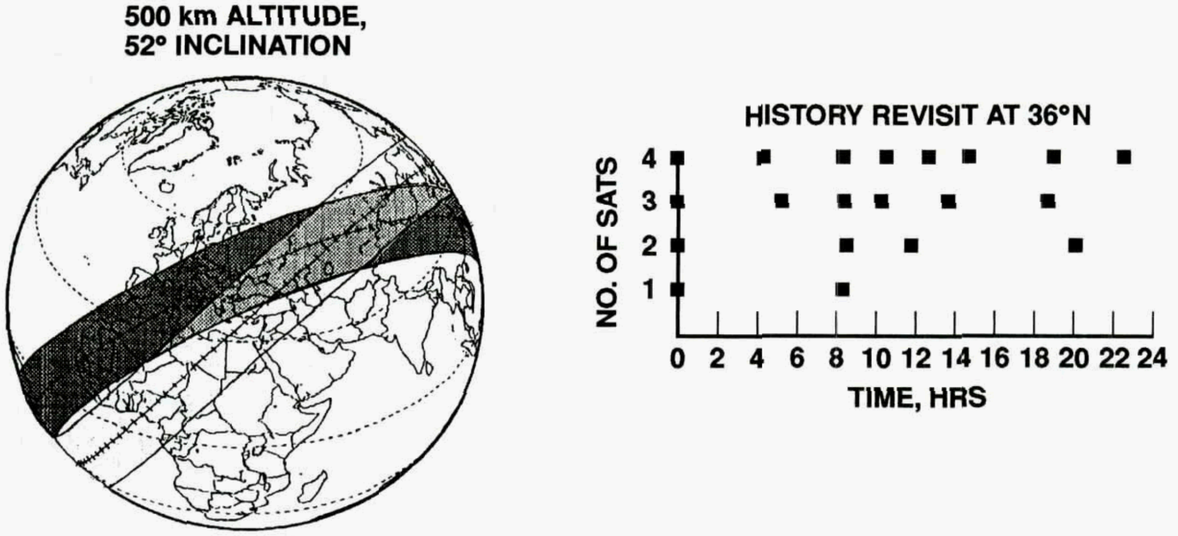


Figure 3.5 Tailored Orbit with Revisit History

3.2.2.4 The Tailored Orbit for Tactical Surveillance

An orbital approach that may be more oriented to the dynamic threat environment is the use of tailored orbits that are specifically selected at the time of launch for optimized coverage of the crisis area. Figure 3.5 is an example of such a tailored orbit.

For this example, the basic orbit of 52° inclination was selected because it offers coverage of most of the potential conflict locations. A given point in a tactical operations area of 100 km by 100 km at a latitude of 36° North (e.g., Iraq) will be revisited by a four satellite constellation eight times during a 24 hour period. At the 52° latitude such a point will be revisited twelve times per day, of which eight will be in the daylight during summer.

Assuming an area of interest of 100 km by 100 km a desired pixel foot print of 0.5 m and 50 percent time allowance for slewing from target to target, settling time, and image motion compensation, between 40 and 50 spots of 10 km by 10 km, or equivalent strips, can be accessed by a visible payload, or 15 to 20 spots by a SAR payload on each pass. The imaged area per pass decreases as the distance between the terminal and the specific area of interest (the ground trace) increases; this distance can be as much as 1000 km. If the data throughput capacity were to double, which is quite feasible, then the area covered per pass could double.

In an extended conflict, two to four standby satellites could be launched into inclinations approximating the latitude of greatest interest, thus easily fulfilling the desire of two to four hour revisit times each day.

Another example of orbit selection can be seen in the following: For Iraq, one can place five satellites at an altitude of 243 km with an inclination of 33° and obtain a revisit time of 90 minutes for daylight coverage. This coverage can be achieved, for a rapid launch strategy, by launching the satellites every eight days.

3.3 COMMUNICATION TACSATS

In order for communications TACSATs to be able to fill the gap between demand and supply, they will need to fulfill a number of criteria. The first and most essential of these is affordability. In this era of reduced defence spending, the ability to acquire increased capacity at a low incremental cost is highly attractive. One way of achieving affordability is through commonality. For example, a common bus and bus subsystems could be promoted, which could be used for different missions. Also, TACSAT systems could be designed to use the same ground terminals as systems already deployed. Cost could also be reduced by accepting a shorter lifetime and less survivability against hostile action.

Another important consideration is responsiveness, the essence of the TACSAT concept. This could be achieved either through storage on the ground, with launch-on-demand, or through storage on-orbit, with repositioning as required. This is particularly suitable for satellites in the geostationary orbit.

There are two ways of approaching TACSAT communications concepts. One could develop a common bus with interchangeable payloads for each of the three frequency regimes (UHF, SHF and EHF) or one could consider a satellite operating at all three frequencies. However, this latter option would be very complex and heavy and would thus violate the TACSAT concept. The following concept examples were considered appropriate.

XPNDRS	ANTENNA		PAYLOAD		SATELLITE	
	U/L	D/L	WEIGHT (kg)	POWER (W)	WEIGHT (kg)	COST ($M)
5 x 20W	EC	MBA	90	704	545	55
4 x 20W	EC	MBA	80	583	525	53
3 x 20W	EC	MBA	45	462	510	50
2 x 40W	EC, SPOT	EC, SPOT	55	261	360	23
2 x 20W	MBA	EC, SPOT	80	245	445	37
2 x 20W	MBA	EC, SPOT	85	226	280	31
2 x 20W	EC	MBA	65	341	475	48
1 x 20W	EC	MBA	55	220	455	46

Figure 3.6 SHF Concepts

3.3.1 UHF TACSAT

Two small multiple-access communications satellites, known as MACSATS, were developed under DARPA sponsorship in the USA. They were deployed in a near-circular polar orbit in May, 1990, and were used during Operation Desert Storm to provide open and encrypted store-and-forward communications. They have an on-board storage capacity of 2.4MB. Users have a ten-minute window in which to uplink data to the visible satellite. The concept complies with the low-cost criterion in that the only non-standard UHF satellite terminal components a user needs are a frame formatter and some special connecting cables. However, store-and-forward communications has a very limited use in military operations because of the non-real time aspect of such systems.

Envisioned as providing a quick-reaction capability for expeditionary units, use of the UHF band by the MACSATS still leaves open the questions about the poor AJ and LPI characteristics of this band.

3.3.2 SHF TACSAT

An opportunity for SHF TACSATs exists as a means of augmenting system capacity in theatre conflicts, without re-locating existing geostationary-orbit (GSO) satellites, and thereby leaving other regions without adequate coverage. A payload concept for a lightweight TACSAT was reported in paper 3 of the AGARD TACSAT conference.[1] In summary, the payload concept weighs 84 kg, and uses 225 watts of power. It includes two 80 MHz transponder channels, for mission flexibility. For example, one channel could be used in high-gain mode and dedicated to use by manpack terminals. The other would then be available for the standard 2.5 m antennas currently used for air/land operations. The spacecraft antennas include AJ nulling capability, with spot beams and earth-coverage beams. The estimated spacecraft weight, including 45 kg of extra propellant for re-positioning, is 460 kg (exclusive of apogee kick motor).

The difficulty in selecting an SHF configuration for a TACSAT is the broad array of options available in this weight regime. Such options result from various mixes of communication channels and satellite antenna configurations. Figure 3.6 is an example of different satellite configurations, their weights, and their costs.

3.3.3 EHF TACSAT

An opportunity exists for EHF TACSATs to augment the rather low capacity of the initial Milstar system. The Milstar Polar Adjunct program could also provide a flight opportunity for such a payload. The northern coverage requirement offers an opportunity to develop a system where the requirements of one country in the polar region may not be sufficient to justify a national system, but the combined requirements of NATO and various alliance members may be sufficient.

An EHF payload concept for a TACSAT was reported in paper 3 of the AGARD TACSAT conference.[1] It was designed to support EHF man-portable terminals. It includes 32 low-data-rate (MIL-STD 1582C compatible) communications channels. The sample payload has a 61-beam multiple-beam antenna (MBA) with a nulling processor on the uplink. The downlink includes a 19-element MBA, a spot-beam antenna and an earth-coverage (EC) horn. Assuming one user per terminal and an average call duration of four minutes, teletraffic engineering methods can be used to calculate the number of terminals which can be supported. For a

[1]AGARD Conference Proceedings 522, "TACSATs for Surveillance, Verification and C3I," BGen Dickman, USAF Space Command, 19 October 1992, Brussels, Belgium (published Feb. 1993).

CHANNELS	ANTENNA			PAYLOAD	SATELLITE	
	U/L	D/L	WEIGHT (kg)	POWER (W)	WEIGHT (kg)	COST ($M)
3 MDR, 48 LDR	EC, SPOT	EC, SPOT	85	221	280	37
36 LDR	EC, SPOT MBA	EC, SPOT MBA	115	113	475	30
36 LDR	MBA	SPOT	120	228	435	48
32 LDR	EC, SPOT	EC, SPOT	40	107	210	35
20 LDR	EC, SPOT	EC, SPOT	90	272	500	52
18 LDR	EC	EC	71	227	470	49
4 LDR	MBA	SPOT	105	173	381	43

Figure 3.7 EHF Concepts

5% probability of blocking or a 20% probability of short delay, approximately 400 to 500 user terminals could be supported. The system uses demand assignment of channels. The payload is estimated to weigh 120 kg and to use 245 watts of power. The total spacecraft weight (exclusive of AKM) is estimated at 500 kg.

As was the case for SHF, EHF also has a broad array of TACSAT options. These options are reflected in Figure 3.7.

3.3.4 Orbit Selection for Communications Satellites

3.3.4.1 Use of the Geostationary Orbit

The geostationary orbit has traditionally been of most value for communications. It avoids the need for sophisticated tracking ground-station antennas and makes satellite acquisition in the field, using prediction tables and sun-angle methods, a relatively easy matter. One drawback is that it is a relatively high-energy orbit, and requires the inclusion of an apogee kick motor in the spacecraft to circularize the transfer orbit. Other problems are the annoying propagation delay for voice links, the large propagation loss and the inability to provide coverage of the northern circumpolar region. Nonetheless, the advantages are likely to outweigh the drawbacks for most tactical applications.

3.3.4.2 Use of Non-Geostationary Orbits

Lightweight satellites could be deployed in non-geostationary orbits to provide northern coverage not available with the current geostationary-orbit (GSO) systems. Service augmentation for high-traffic theatre conflicts could also be performed by satellites in alternative orbits. Also, low earth orbits could make the use of low-powered manpack terminals more practical.

For EHF systems, it should be noted that the waveform standard, MIL-STD 1582C, is specified for low-inclination geostationary orbits only. Its use for other orbits has not been verified. Inclined highly-elliptical orbits may present a different problem, because of higher levels of Doppler shift.

a) *Low Earth Orbit (LEO) Systems*
The attraction of LEO systems is that they make the use of easily-transportable or truly mobile systems practical, due to the large reduction in propagation loss compared with geo-stationary orbit (GSO) systems. One drawback with these systems is the large number of satellites which may be needed depending upon the service availability requirement. Some commercial system proposals have involved up to 77 satellites in order to provide global coverage, 100% of the time. LEO systems are more vulnerable to anti-satellite weapons; however, they may have an advantage because of their highly proliferated nature.

A UHF system would enable the use of a low-gain ground-terminal antenna, providing the greatest operational convenience. At least two demonstrations are in progress. However, such a system would be even easier to jam than the current GSO UHF systems because of the close proximity to the jammer, and may be of reduced value in a war fighting situation.

LEO systems operations at SHF or EHF would require tracking ground station antennas and would be subject to a service interruption at handover from the setting to the rising satellite.

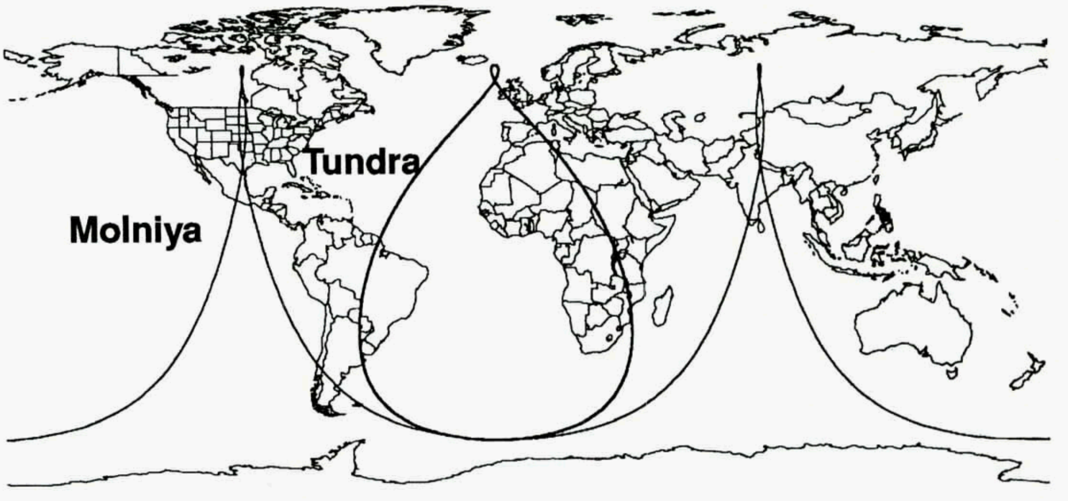


Figure 3.8 Molniya and Tundra Ground Tracks

b) *Medium Earth Orbit (MEO) Systems*
Circular orbits at about 9,000-12,000 km altitude can take advantage of the relatively low-particle-concentration "slot" between the Van Allen high-energy proton and electron belts. The advantage of this type of orbit over LEO systems is that fewer spacecraft are needed for a given service availability. One commercial proposal, for example, uses twelve satellites to provide continuous, essentially global, coverage.

c) *Inclined Highly-Elliptical Orbit (HEO) Systems*
The Molniya and Tundra orbits are useful to provide high-latitude coverage for a particular theatre, with high elevation angle. These orbits are inclined at 63.4 degrees to the equatorial plane, in order to maintain the apogee in the desired part of the orbit without undue expenditure of fuel. Along with highly-inclined or polar circular orbits, they are another option to provide the northern coverage that NATO may require.

The Molniya orbit, for example, is a 12-hour highly-elliptical orbit. The satellite can be used for an eight-hour period around apogee, during which time a high satellite look-angle is maintained from the service area. To give continuous coverage of the service area, three satellites are required in three similar orbits, equally spaced around the earth, but with each satellite displaced in its orbit by eight hours. Given this arrangement, each satellite traces out the same ground track, but displaced in time by eight hours, thereby providing continuous coverage.

The Tundra orbit coverage duration is more than twelve hours per satellite, and so continuous coverage can be provided by only two satellites. The disadvantages of the Tundra orbit are a greater range at apogee (52,000 km, Tundra; 40,000 km, Molniya) and a higher launch energy requirement. Other trade-offs are Doppler Shift, range variation and angular tracking rate.

Figure 3.8 shows typical ground tracks for these two orbits (loci of the sub-satellite points).

d) *Eight Hour Orbits*
The eight hour highly inclined (63.4°) elliptical orbit has very attractive properties.

First, its three-fold groundtrack (see Figure 3.9) is nearly optimum for Regional coverage: during the day, the satellite will in fact be at the apogee above three zones angularly displaced by 120°, in Earth coordinates. Such zones can correspond to Europe, North America and Central Asia/Russia.

This improves the utilization efficiency of each satellite whose communication capacity can be exploited in time sharing by three different geographic areas. A limited constellation of three to six satellites, depending upon the geographical areas to be optimally served, can thus provide continuous services for tactical communications throughout two to three main regions. In particular, with four satellites spaced 90° apart, continuous coverage of a site in the

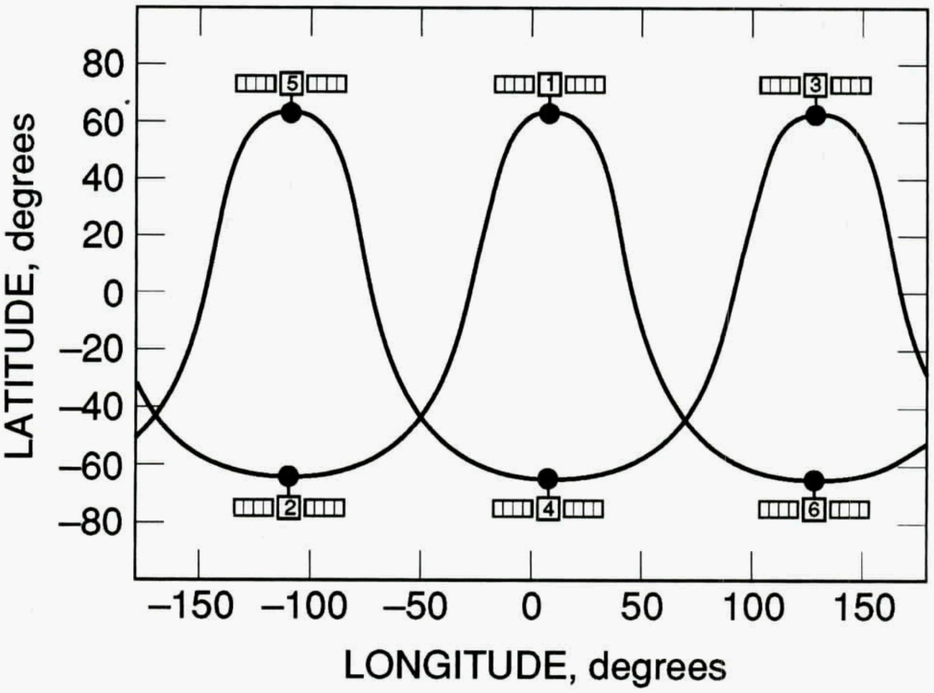


Figure 3.9 Ground Tracks of Eight Hour Orbits

medium-high latitude belt, can be achieved. Second, the lower period, with respect to the Molniya and Tundra orbits, implies a lower orbit energy and, correspondingly, a reduced cost for orbit injection or transfer from a lower circular parking orbit. Third, the lower apogee with respect to the Molniya and Tundra orbits, implies smaller delays in two-way voice communications. Fourth, the orbital parameters can be chosen in such a way that Doppler, range variation and angular tracking rates can be made competitive with those achievable with the Molniya and Tundra orbits even if the orbital period is shorter.

In summary, a limited constellation of small satellites in inclined eight-hour orbits may prove extremely attractive to implement a permanent tactical communication system. Besides the communication applications, it is worth mentioning the possibility of using these satellites for extending the meteorology observations to high latitudes, poorly served by geostationary satellites, thanks to the high orbital inclination and the multiple, daily, pseudo-stationary aspects of the satellites at their apogees.

3.4 TACTICAL MISSILE WARNING AND ASSESSMENT

With the proliferation of short range theatre ballistic missiles, the threat to NATO populations and military centers is now a distinct possibility. The question that will soon face NATO is should it press for use of proposed advanced U.S. capabilities that are global in nature or develop a TACSAT payload that is oriented to NATO theatres of interest. One concept that was reviewed by the Working Group is described below.

3.4.1 Theatre Ballistic Missile Warning TACSAT

In section 3.1, a multi-mission sensor was described that could accommodate both the theatre missile warning and battlefield surveillance missions. The selected mission was determined by which orbit the user selected (geostationary or low earth orbit, respectively). If some of the battlefield surveillance features are excluded from the sensor design, the total spacecraft weight could be reduced by 10%; however, this reduction would be used for added propellant to allow for rapid repositioning of the spacecraft to cover different theatre of operation. The following is a description of the multi-mission system as it would be for the tactical ballistic missile tracking mode.

3.4.1.1 Tactical Ballistic Missile Tracking Concept

The theatre ballistic missile tracking system would be deployed in a geostationary orbit and would use a scanning infrared sensor to detect tactical missiles and after-burning aircraft. It could scan a 2000 x 2000 km area and detect targets within that area with a 1 km spatial resolution. It could process up to 1000 such targets and, after processing, track up to 100 real targets simultaneously. For ballistic missiles, both the launch and impact points could be predicted and these predictions could be used to take either passive, defensive or offensive actions.

The focal plane would operate in the IR region of the spectrum. The sensor package itself could be relatively small with a weight of about 110 kg and with a power consumption of less than 400 watts. Total spacecraft weight, including manoeuver propellant, is not expected to exceed 700 kg.

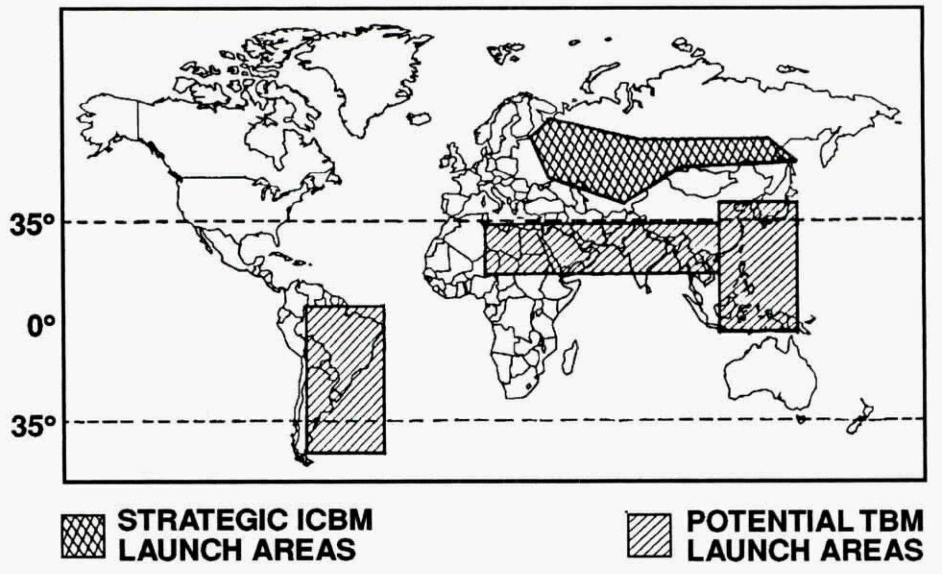


Figure 3.10 Shift in NATO Missile Threat

3.4.1.2 **Orbit Selection**

A theatre ballistic missile warning TACSAT is ideally suited for the geostationary orbit. With the breakup of the Soviet Union and the Warsaw Pact, the threat to NATO interests has moved toward the equator and in all likelihood will fall between 35°N and 35°S as presented in Figure 3.10.

The concept of TACSAT has generally been associated with rapid launch-on-demand. For existing medium lift launch vehicles, it nominally takes 10 to 24 days from the time the spacecraft is mated to the launch vehicle until launch. Studies have shown that improvements could be made to reduce this time to between 5 and 7 days. Whether that will be achievable remains to be seen. In any case when one adds the travel time to orbit and spacecraft checkout time once the spacecraft is in orbit, it is not clear whether the GSO-based satellites can be responsive enough to consider launching them on demand using medium lift launch vehicles.

Instead of trying to launch GSO-tactical warning satellites responsively, it seems to make more sense to launch such TACSATs on a routine basis and store them in GSO or near GSO orbits until needed. As the need arises, these satellites can be turned on and repositioned to the area of interest. This kind of repositioning was done with U.S. communications satellites during Desert Storm. Defence Satellite Communications System (DSCS) satellites were moved into the Persian Gulf area at a rate of about 2 degrees per day. This low shift rate was used to conserve fuel since that same fuel is used for station keeping and therefore affects satellite lifetime. For the tactical warning TACSAT system, 45 kg of propellant has been included that can be dedicated to manoeuvering. This would allow a 600 to 700 kg satellite to be shifted up to 30 degrees per day although it is doubtful that it would ever be necessary to move that quickly since crises and conflicts generally develop rather slowly. A shift rate of 5 degrees per day seems more reasonable. Under those conditions, the 45 kg of propellant would allow for 4 to 5 such manoeuvers without affecting the effective life of the satellite.

3.5 REGIONAL MARITIME SURVEILLANCE AND ENVIRONMENTAL OBSERVATION

The maritime and environmental regions are those in the general area of a given theatre of operation and therefore fit the area (2000 km x 2000 km) definition for TACSAT operation.

3.5.1 Ocean Surveillance

A constellation of Side-Looking Aperture Radar (SLAR) tactical satellites can provide the required spatial and temporal coverage in order to detect, locate and track surface ships.

For instance, one example of such a system is a satellite flying at a 600 km altitude and an inclination of 60 degrees that will optimize the revisit time over NATO oceanic areas of interest. Two satellites of 800 kg, equipped with two antennas each (left and right looking), can insure a satisfactory mean revisit time of 6 h. With only one antenna, the satellite weight is only 550 kg but four satellites are then required to achieve the same revisit performance. The mass budgets are given for a four year lifetime. The characteristics of the payload are given below.

Ships with a radar cross section (RCS) greater than 30 dBm^2 can be detected in a sea state of 5, with a detection probability of 0.9 and a false alarm rate of 10^{-6} (i.e., only one false alarm on the Mediterranean Sea).

Moreover, smaller ships can be detected when the sea state is relatively calm.

The localization accuracy is less than a few nautical miles. The data rate is low and compatible with a direct transmission to a naval unit: 5,000 ships can be detected every orbit by each satellite.

An example Side-Looking Aperture Radar (SLAR) can operate in X-band with a repeat frequency of 60 Hz, a bandwidth of 10 MHz and a pulse width of 500 µs. The peak power is 2.6 kW with an average power of 75 W. The proposed set of incidence angles, ranging from 75 to 87 degrees, will result in a 900 km swath width at 600 km height for one antenna (dimensions are 10 m x 1.5 m). The mass/power consumption budget for a payload with one antenna and two antennae becomes respectively 250 kg/400 W and 400 kg/600 W.

Eavesdropping (Elint) techniques, while of great interest for ocean surveillance, are not addressed in this report.

3.5.2 Marine Environment

An altimetric satellite system and a wind scatterometer satellite system are considered separately here, but both payloads could be combined on the same platform while remaining in the TACSAT weight range. An altimetric mission not only requires a radar altimeter to measure height profiles of the ocean surface but also secondary instruments such as a precise positioning system with preferably two frequencies to cope with ionospheric propagation delays and a three frequency radiometer to cope with tropospheric propagation delays. Considering the spatial and temporal scales of the oceanic phenomena, it is sufficient to operate simultaneously with optimized repeat cycles above the typical oceanic areas of interest for NATO (e.g., 150 to 200 km and 40 to 10 days for the Atlantic Ocean).

For operational purposes, altimetric data must be provided to an operational center of analysis and oceanic forecasting which has the duty to regularly provide naval users with updated maps of bathy-celerimetry, wave heights and wind speed maps, vortices and current locations, etc.

The accuracy of an altimetric measurement should be 2 cm. It is noteworthy that additional information can be extracted from the waveform echoes from the nadir, such as wave heights and wind intensity with respective accuracy of ± 2% (m) and ± 0.3 m/s. Such an altimetric satellite should weigh less than 220 kg without redundancy and about 260 kg with redundancy. It is thus compatible with a Pegasus launcher type. The on-board memory is sized at about 10 Mbits, with a data rate of 12 Kbit/s for the downlink. A constellation of 2 or 3 satellites equally phased in a common orbit (polar or inclined) could meet the operational goals on a permanent basis. A wind scatterometer is probably the best instrument to measure the speed and the direction of the wind at the ocean surface, since it is very sensitive to the radar reflectivity variations due to the small wind-driven surface waves. Wind speed can be measured between 4 and 24 m/s with an accuracy better than ± 2 m/s (or 10%) and ± 20 deg on 50 km x 50 km pixels.

Such an instrument will weigh less than 130 kg, which corresponds to a satellite of 300 kg. The data rate is about 90 Kbit/s and the on-board memory is sized to 4 Gbit for a 12 h storage duration. One operational wind scatterometer flying on a circular polar orbit at 800 km altitude is considered as a satisfactory minimum, even though a constellation of two satellites would provide better sampling. Because of the size of its five antennas (0.5 m x 4 m each), a wind scatterometer satellite is not compatible with a Pegasus launch, but can be launched by an Ariane DLA-P.

Altimetric Payload

A proposed altimetric payload combining a monofrequency radar altimeter (e.g., Poseidon), a bi-frequency precise positioning system (e.g., Doris at 400 MHz and 2 GHz) and a three-frequency radiometer (e.g., modified ATSR on ERS-1 at 18, 21 and 36 GHz) leads to a mass of less than 70 kg without redundancy. The radar altimeter operates at 13.65 GHz with a tunable repeat frequency around 1700 Hz. Using a solid state amplifier, the emitted power is 5 W. The pulse lengths before and after compression by surface acoustic wave (SAW) dispersive lines are respectively 105 µs and 3,125 ns. Owing to these choices, the radar altimeter that is currently flying aboard the Topex satellite is very compact (43 l), light (23 kg) and with low power consumption (49 W). It can be considered as an off-the-shelf instrument, like Doris and GPS or, to a lesser extent, since a channel has to be added, like ATSR (7-1/2 kg/35 W).

Wind Scatterometer Payload

A proposed wind scatterometer operates at 5.3 GHz with a VV polarization and a repeat frequency of 30 Hz. The pulse length ranges from 5.8 ms to 8.5 ms. The emitted bandwidth ranges from 30 to 120 kHz. The emitted peak power is 20 W and is compatible with solid state technologies. The antennas are waveguide slot antennas.

3.6 WEATHER

The military has defined needed meteorological support in terms of a number of critical issues:

- Timeliness: Delivery time from observation to user
- Refresh: Interval between observations of a given area

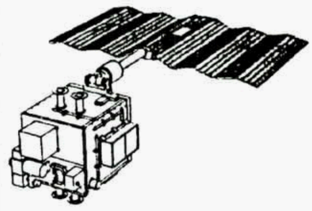
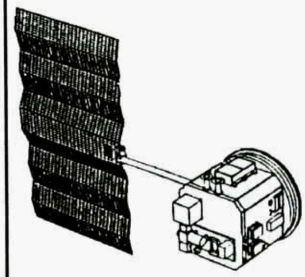
Spacecraft Family Carrying Typical Payload	SCOUT CLASS	PEGASUS CLASS
		
Solar array	Deployed/Articulated	Deployed/Articulated
Design life/goal (months)	6/12	12/36
Stabilization	Three-axis	Three-axis
Pointing accuracy/knowledge (deg)	0.1/0.1	0.1/0.1
Mass at separation (kg)	148	389
Array power (BOL, W)	542	588
Downlink rate, maximum (Kbps)	1,000	1,000
Payload mass, maximum (kg)	50 to 100	170
Payload volume, maximum (m^3)	0.25	1.0
Payload power, orbit average (W)	50 to 100	100

Figure 3.11 Examples of Spacecraft Configuration for the Weather Mission

- Ocean fronts: Improved observations of fronts and eddies
- Cloud type: Distinguish cloud types

The current Defence Meteorological Support Program (DMSP) provides the primary weather support to the U.S. military. It is a capable system with direct downlinks to selected tactical users. However, since only two spacecraft are maintained on orbit, military guidelines for timeliness and refresh are not being satisfied by this system alone. Also, the DMSP sensors are not adequate to support the ocean front observation requirements. The Navy currently relies upon a five-band Advanced Very High Resolution Radiometer (AVHRR) on NOAA's TIROS satellites. These data are key to many naval operations including anti-submarine warfare (ASW). The TIROS data are unencrypted and have been used by the Soviets; in time of conflict the AVHRR will most likely be turned off. Finally, as a low altitude satellite, DMSP is subject to conventional laser, and nuclear ASAT attack. It is not rapidly reconstitutable. Its loss would severely impact the war fighting capabilities of nearly all tactical commanders.

3.6.1 Weather Concept A

Essential meteorological data can be obtained by a single instrument, specifically the five-band AVHRR. It is a relatively small instrument weighing approximately 35 kg. It can be easily carried by small spacecraft and provide direct downlinks to tactical users. The concept is to add small satellites to the DMSP constellation improving the systems timeliness and refresh capabilities. These satellites would mimic the DMSP downlink thus ensuring interoperability with existing ground and sea-based receiving stations. Information vital to naval operations would be provided by military spacecraft with encrypted downlinks. Rapid reconstitution by small boosters is both feasible and affordable.

An example of the spacecraft configuration for this mission is shown in Figure 3.11.

3.6.2 Weather Concept B

As with the theatre ballistic missile surveillance mission, the multi-mission system at GSO described in paragraph 3.1, could also be used for cloud imagery. Such a system would weigh 500 to 600 kg. The sensor configuration would be as follows:

Spectral bands (μm)	Commandable from 0.45 to 10.0
Field of view	18° x 18°
Scan rate	8° /sec
Data rate	70 Mbps
Re-visit	Continuous over theatre

The ideal orbit for this system is geostationary.

3.7 NAVIGATION

When the Global Positioning System is fully deployed, the question will be "is there justification for a dedicated NATO system?" Clearly, the answer to this question will depend on the cost of the system and how it might solve the GPS deficiencies discussed in Chapter 2. If a TACSAT system is fielded by NATO based on system commonalities across many mission areas, such a navigation supplement to GPS may be practical.

Table 3.3 Specifications for Navigation Concept B Satellite Orbits

Sat. n.		Apogee (km)	Perigee (km)	Inclin. (degree)	RAAN (degree)	Perigee argum. (degree)	True anom. (degree)
1	GEO	35786	35786	0	0	0	330
2	GEO	35786	35786	0	0	0	15
3	GEO	35786	35786	0	0	0	60
4	TUNDRA	47105	24470	63.4	105	270	0
5	TUNDRA	47105	24470	63.4	185	270	180

3.7.1 Navigation Concept A

The main capabilities of the GPS (Global Positioning System) are well known and its fields of application are numerous for military as well as civil users. It is also clear that such performance (almost permanent world-wide coverage) requires a large number of sophisticated satellites.

This (Concept A) navigation system concept uses the same principle as that of GPS but provides permanent coverage of the whole of Europe while using a small number of satellites.

The search for convenient constellations was conducted using a numerical optimisation technique based on the Adaptive Random Search (ARS) method. In order to provide a permanent coverage of a limited area of the Earth, only orbits with a 24 hour period were taken into account. Several interesting constellations using various number of satellites were considered. An interesting concept needs only four satellites: one geostationary and three others on low inclination, low eccentricity orbits at the geosynchronous altitude. (It is important to note that the minimum number of satellites needed for GPS-type navigation is four.) This constellation provides coverage of Europe, the Middle East and Africa.

Moreover, it is possible to use rather simple and cheap satellites. All satellites are always visible from the same point on the earth, making it possible to place on the ground (versus space) the ultra stable oscillator used to provide the time reference for satellite-user range measurement.

The station keeping is of particular concern. In this regard, the influence of natural perturbations (Earth gravity field, Moon and Solar gravitation, Solar radiation pressure) on the constellation performances was of particular concern. It was determined that station keeping manoeuvers were necessary every 8th week in order to maintain a good European coverage. The annual cost of these station keeping manoeuvers over 7 years, in terms of "delta v," is approximately of 85 m/s (50 m/s for a geostationary satellite).

3.7.2 Navigation Concept B

This concept addresses another architecture for a NATO navigation satellite system that is a mix of geostationary and elliptical satellites. In order to keep the GDOP (see 2.4.5) value under 6, at least 3 geostationary satellites and two elliptical satellites will be required. For the latter satellites, the choice between Molniya and Tundra orbits favors the Tundra for better GDOP and reduced satellite complexity, since the Molniya orbit periodically crosses the heart of the Van Allen belts.

The specification for the five satellites is provided in Table 3.3.

With an antenna gain of about 22 dBi, resulting in an RF transmission power for the navigation signal of about 50 W, the EIRP will be 30/35 dBW which will enable the user to operate an omnidirectional antenna (minimum gain about -5 dBi). The satellite's receiver can be in C (or Ku) band. The overall payload mass in the L/C band will be 40 kg, but two antennas must be added operating in L band to interface with the users and in C-band to interface with the earth stations. Table 3.4 is a preliminary indication of mass and power budgets.

3.7.2.1 Orbit Selection

One of the most significant system issues is that of the orbital maintenance strategy for the Tundra orbit in order to minimize the propellant consumption and therefore the launch mass. For the geostationary satellite, the problem is less crucial and of the same order as that of a typical communication satellite.

For the Tundra satellite some manoeuver strategies were investigated, in particular, a very promising strategy is based on leaving the longitudinal drift in the range of ± 5 degrees and completely freeing the synchronous time (in the range of ± 5 degrees at a maximum of 26 minutes). This analysis shows that it is possible to reduce the delta "v" value to 3 meter/sec/year.

Table 3.4 Mass and Power Budgets for Navigation Concept B

	kg	Watt
Navigation payload	35	150
Antenna and power amplifier	36	300
Additional structure	12	—
Total payload	83	450
Dry bus	390	300
Total satellite	473	750

CHAPTER 4

TECHNOLOGY OPPORTUNITIES FOR TACSATS

4.1 INTRODUCTION

It must be emphasized that we can build very capable TACSATs today. The technology discussions presented here are directed at increasing that capability and significantly reducing system costs. In addition to the many successes of the Allied Forces in space, there have also been shortfalls: SCUDs could not be located and destroyed before they were launched, nor could timely and accurate battle damage assessments to optimize sortie missions be obtained. The solution to these shortfalls will require space systems better attuned to the needs of a theatre commander. However, we can hardly afford the space systems we have now. TACSATs offer a possible solution to this dilemma.

In the present economic climate, it appears certain there will be significant cutbacks in most areas of NATO member nations' defence budgets, including military space systems. However, the defence industry will be expected to design and field more advanced and more efficient space systems. The dilemma will be that these newer systems must make even more use of miniaturized, high technology components than are incorporated in our current stable of satellites, while at the same time being more affordable.

While technology is developing on a schedule of 2-1/2 to 3 years, our satellites are still being developed on 10-year or greater cycles. By the time we launch our assets, their technology is already obsolete by several generations and we often cannot buy the parts to replicate the satellite, even if we wanted to! We must find a better way to do business in space. TACSATs, incorporating new technology, and produced on accelerated time scales offer one technique that is deserving of investigation.

4.2 BATTLEFIELD SURVEILLANCE

4.2.1 Electro-Optic Payloads

Several optical payloads are available for tactical satellites. Additionally, several optical payloads with sensors responding in different wavelength regimes can be implemented on the same satellite bus. This is because of the relatively small dimensions of the optical instruments that can be used for tactical needs.

As geometrical resolution is directly linked to the useful diameter of a telescope and the satellite altitude (for a given spectral band), the solution to obtaining high resolution with a small instrument is to reduce the altitude. A limit also exists, dictated primarily by atmospheric diffraction (it is not possible to achieve resolution below about 10 cm) and secondarily by the satellite lifetime (orbital altitudes must be above 200 km).

Today, most optical instruments use electro-optical detectors instead of film for both visible and infrared bands. The new technologies in electro-optics allow the use of arrays of pixel elements in place of two dimensional mechanical scanning or even push-broom scanning. This technique is particularly useful for high resolution when the photon intensity from the source is insufficient with the push-broom technique.

Optical instruments do not levy special requirements on the spacecraft except for stability when high resolution is desired. For that case, it is necessary that equipment on the spacecraft does not generate significant vibrations.

Electro-optical systems designed for spacecraft are well in hand and no essential modifications are needed to meet general needs. However, improvements for far term electro-optical TACSATs can be envisaged in at least three ways:

- lightening of optical instruments,
- larger scale integration of electronic signal preprocessing directly on the detectors,
- very high speed electronics with large scale integration.

The primary mirror is generally the most massive piece of a space telescope. Several techniques have been employed to reduce this mass. These include:

- holes drilled in a glass mirror; this technique is now well understood and allows lightening of up to 70% of the original mass,
- metallic mirrors deposited on a beryllium or SiC (Silicon Carbide) substrate,
- thin and flexible mirrors controlled by an active optics control system. This technology offers the extra advantage of allowing the modification of the mirror surface in order to nullify the in-flight perturbations such as thermal-elastic deformations. This action can be performed during the lifetime of the satellite either automatically or by using remote control. The use of this technology will only be

effective if it does not increase the weight of the actuators and their stable support. The use of this technique for TACSATs, even in the far term, remains questionable.

Studies continue to be conducted to try to integrate simple electronic computations directly on the detector chip. This preprocessing then could be used to equalize the pixel-element's response, to improve the contrast response, to simplify the detector interface, to limit the data flow, etc.

High speed, large scale integration electronics will permit implementation of all the functions with a reduction in weight as well as power consumption. Using such electronics, test procedures will be simplified because of the significantly smaller number of interfaces.

These improvements will allow either for a decrease in the satellite mass or, for the same mass, a significant enhancement of capabilities: e.g., more spectral bands, more observation modes, more coverage capacity (increase of the buffer memory size and of the data writing rate).

For infrared sensors, imaging focal plane materials can use Indium Antimonide, requiring operating temperatures of 77K. Sterling cycle cryogenic coolers are available for these temperatures, with lifetime demonstrations approaching several years. Power requirements are still high, causing some weight concerns. Mercury Cadmium Telluride focal plane material technology is progressing rapidly, so that it is reasonable to expect required cooling temperatures to rise over 100K, which in turn would reduce the concern about weight.

4.2.2 Synthetic Aperture Radar (SAR)

The SAR payload design to meet a Taurus-like launch vehicle constraint is aggressive, but recent advances in antenna design and signal processing should allow for the introduction of such SAR satellites. What needs to be shown is that a Taurus-like launch vehicle can be ready by 1996, that it will be capable of lifting the required payload, and that an existing ground station can be modified to accommodate a SAR data stream.

The major limiting aspect of this concept is the communication bandwidth required to transmit SAR imagery to the ground. Technology advances in imagery processing and data compression would greatly increase the area coverage throughput of the system. In particular BAQ (Binary Adaptive Quantizer) techniques appear very promising to both reduce the data rates and to match the SAR output data flow to the features of the target area to be observed, especially when implementing on-board programmable or commandable variable resolution SAR sensors. Automatic Target Recognition (ATR), Moving Target Indicators (MTI), and Optical Data Processing techniques would all enhance the utility of the system to the theatre commander. Advances in these areas are currently taking place, so that significant upgrades in a ten year time frame are feasible.

Future R&D efforts on radar techniques should be focused on sensor capacity improvement rather than payload miniaturization. The following concepts should be implemented, e.g., wide instantaneous bandwidth, multi-frequency waveform, low frequency waveform, advanced ECCM, etc.

In the future, other longer range improvements might be achievable:

- cluster of satellites. A cluster of microsatellites, each with a single radiating and receiving element, when synchronized, could form a large phased array radar.

- space based antenna. In this concept, the satellite carries only a phased array antenna; all the other radar equipment remains ground-based. For theatre operations, this concept holds great promise and should be investigated.

4.3 COMMUNICATIONS

Technology opportunities arise partly from the perceived shortfalls in currently-deployed systems. These include:

- low capacity and poor AJ and LPI properties of UHF

- poor mobility and difficulty of camouflaging of 2.5 m SHF forward-base terminals used by land and air forces

- need for better AJ protection for SHF systems

- need for international inter-operability of SHF systems

- capture of radar electronic support measures (ESM) receivers by satcom transmitters

- need for service augmentation in theatre war conflicts without leaving other areas underserved due to re-deployment of space assets

- lack of coverage of the northern circumpolar region

- immense cost of national systems with multiband payloads

4.3.1 UHF Systems

UHF does not have the throughput that the Air/Land battle doctrine requires. The problem of low capacity is being addressed to the extent practical by the introduction of demand-assigned multiple-access (DAMA). With so little bandwidth available, there is not much opportunity for the introduction of significant AJ protection. Similarly, any improvement in LPI characteristics is constrained by the low bandwidth and wide ground terminal antenna beamwidths. Use of UHF is risky in the theatre against a sophisticated enemy, except perhaps in its fleet broadcast mode.

During Desert Storm, UHF was used, particularly by the US Navy, practically to the saturation point. Although Iraqi forces had at least four Soviet-made UHF jammers, which could have shut down the FLTSATCOM and AFSATCOM systems, they were not used. Control of the skies by coalition forces equipped with radiation-seeking missiles discouraged such usage.

Technology opportunities for TACSATs in this band are very limited; however, a concept is being examined called the Multiple Path, Beyond Line-of-Sight (MUBL) Communication effort. MUBL is aimed at providing interference-resistant voice communications among affordable, handheld UHF terminals having approximately 5 watts of RF output. The concept provides a single-hop capability and may be thought of as an amplifying ionosphere. No satellite crosslinking is contemplated. When more than one satellite is in view of the communicating terminal pair, there are multiple propagation paths. The modulation and coding system is designed to support this and resists interference from other satellites.

4.3.2 SHF Systems

SHF is the backbone satellite communications technology for the armed forces of alliance members. Investment in this area continues to increase, particularly by the US Navy. Under the Quicksat program, 42 ships will be equipped for SHF by the year 2000. Eventually, 200 ships could be so equipped.

To improve the ECCM situation, an SHF anti-jam modem, called the "universal modem," is under development as part of a US/UK/France initiative. This will give a significant amount of protection. The universal modem will be developed to a waveform standard which is the subject of a NATO STANAG, and will therefore help promote national inter-operability.

SHF transponders may, however, still be subject to capture by a large land or ship-based jammer, making the use of spacecraft receiving antennas with variable gain or a null-steering capability of interest. The DSCS III satellites have multi-beam antennas with some of this capability. Research on these antennas continues in several countries. *This type of antenna should be included in any TACSAT concept.*

4.3.3 EHF Systems

Future EHF (44/20 GHz) systems have the potential to provide the mobility which SHF currently lacks, because of the small ground-terminal antenna size. The system concept also includes excellent AJ and LPI characteristics. The drawbacks include the high cost, due to the developmental nature of millimeter-wave technology, the overhead in providing up- and down-link ECCM, the large propagation margin, and the sophistication required in the terminal to acquire and track the satellite with a narrow beamwidth. Doppler shift due to satellite motion also becomes very significant. Despite these drawbacks, there is a definite trend to EHF in various defence organizations, as follows:

a) NATO: in April 1991 the NATO Satcom Sub-Group (SCSG) tasked the NATO Communications and Information Systems Agency (NACISA) to convene an ad-hoc panel of experts (from STC, international staff, and Major NATO Commanders) to identify options for NATO satcom in the post-2000 era. The target date for submission of final results to the nations is the fourth quarter of 1993. Provision of EHF will certainly be a consideration.

b) The USA: the US Congress has re-directed the Milstar EHF program to provide support to the tactical commander. Although the initial Milstar 1 spacecraft (to be launched late-1993) will only support low data-rate (LDR) communications, suitable for services such as voice, FAX, etc., later Milstar 2 versions, to be launched starting in 1999, will also support medium data-rate (MDR) to 1.544 Mb/s. The Milstar system may be augmented by lightweight satellites (lightsats) in polar orbit (the "Milstar Polar Adjunct") to provide communications in northern latitudes. The Advanced Research Projects Agency (ARPA) will develop a number of options which will be reviewed by the Defence Acquisition Board in late 1993.

c) Other nations are also developing EHF technology, although it is probable that SHF will continue as the backbone system. The UK's Skynet 4 carries an EHF receiver which is cross-strapped to the SHF transmitter. Canada is developing a prototype EHF satellite payload and ground terminal. Italy's SICRAL satellite will carry an EHF payload. Italsat has a 30/20 GHz transponder. Other systems involving international cooperation are under discussion; e.g., EUMILSAT, INMILSAT.

As regards international compatibility, Canada is leading the development of a NATO EHF waveform standard (based on US MIL-STD 1582C) in a manner similar to the USA/UK/France SHF initiative.

The Milstar Polar Adjunct program could provide a flight opportunity for an EHF TACSAT payload. The northern coverage requirement offers an opportunity to develop a system where the requirements of one country in the polar region may not be sufficient to justify a national system, but the combined requirements of NATO and various alliance members may be sufficient. Another opportunity for EHF TACSATs is augmentation of the rather low initial capacity of the next-generation EHF systems.

4.4 TACTICAL MISSILE WARNING AND ASSESSMENT

The basic technologies necessary to carry out this function are presently available, but some improvement could be realized by new technology.

4.5 REGIONAL MARITIME SURVEILLANCE AND ENVIRONMENTAL OBSERVATION

4.5.1 Ocean Surveillance

With respect to the near-term TACSAT constellation of SLAR satellites, one can expect that the far-term will carry improvement in spacecraft mass, volume and power consumption for a given performance of detection, but this should be compensated by a foreseeable increasing need to detect "smaller" ships (e.g., stealth and/or new threats).

Yet, the availability of new spacecraft propulsion systems (e.g., electric propulsion) could permit the significant lowering of the satellite altitude in order to increase the radar sensitivity (e.g., 300 km), but the number of satellites will also increase (e.g., constellations of up to six satellites).

An alternative to a pure SLAR instrument for detection is to envisage an additional ELINT payload which should be designed for the marine mission, dedicated to radar emissions by ships (e.g., navigation radar). The complementarity of the two types of data is attractive in terms of target detection, identification and tracking, and should then be optimized through a suitable data fusion process. A constellation of two satellites combining radar and ELINT instruments on the same platform would certainly be the best solution for ocean surveillance with a TACSAT.

4.5.2 Marine Environment

With respect to a near-term TACSAT system for operational altimetry, no significant progress is expected in terms of allowing a smaller number of satellites since ocean phenomena are very changeable, complex, and difficult to model, and thus require continuous and homogeneous measurements. The most significant progress is to be made in modeling techniques and assimilation of altimetric measurements, especially at the basin scale for the Pacific Ocean. It would be attractive to add a wind scatterometer payload aboard future altimetric satellites since their measurements are very complementary.

4.6 NAVIGATION

The basic technologies necessary to carry out this function are presently available, but some improvement could be realized by new technology.

4.7 WEATHER

The basic technologies necessary to carry out this function are presently available, but some improvement could be realized by new technology.

4.8 SPACECRAFT TECHNOLOGY

In principle, most of the platform subsystems can be implemented using available technologies. There are, nevertheless, a few topics that require special attention and technology development.

The first critical technology concerns low power ion thrusters to implement long lifetime (>5 years) electrical propulsion for drag compensation and limited manoeuvering in orbit. While ion propulsion technology is well established and is continuing to be improved, nevertheless the achievement of an operating lifetime of the order of 20,000 hours, as may be required for drag compensation in typical worst cases, has to be demonstrated on the ground and in orbit.

The second critical technology concerns on-board batteries capable of repeated charge/discharge cycles (order of 30,000) with a high depth of discharge (DOD) for long lifetime missions (order of 5 years). At present, the best available batteries are capable of limited DOD for a much smaller number of cycles. Therefore, technology developments are needed to substantially improve the present situation; in the meanwhile a characterization of the best batteries for extended cycles would be desirable.

The third critical technology concerns mass reduction; mainly the utilization of Carbon Fiber Reinforced Plastic (CFRP) truss type structures using important payload components as integral and reinforcing elements of the structure itself.

Another important technology is a miniaturized, low-power parallel processor. This technology will reduce, by an order of magnitude, on-board processor size, weight and power consumption for space-based sensor systems. Such a processor must employ massively parallel architectures with large numbers of processing elements in order to achieve the high throughputs required (up to tens of billions of operations per second or more). The approach for achieving this goal is to use three-dimensional, hybrid wafer scale interconnect and packaging technology. In this concept, individual modules with multiple, unpackaged semiconductor chips are compactly interconnected into a high density package with substantial weight and power savings over existing packaging approaches.

4.9 LAUNCH SYSTEMS

The next major milestone relating to TACSAT will be the demonstration of the Taurus launch vehicle. Taurus will have significantly more payload capability than Pegasus and is scheduled to demonstrate the ability to set up an entire launch base within five days of arrival at an austere location. The entire launch base will be transportable. Once the base is established, the launch system must demonstrate the ability to integrate satellite payloads, perform launch vehicle system checks and launch within 72 hours of notice. On its first launch, Taurus will be used as a means to place into space two technically-sophisticated small satellites: the 450 kg Air Force TAOS satellite and the 200

CHAPTER 5

TACSAT IMPLEMENTATION

5.1 INTRODUCTION

This chapter looks at currently available methods for TACSAT implementation, such as spacecraft buses, ground operations systems, launch vehicles, reliability, and approaches to data transmission. These methods must be consistent with the TACSAT concept in the form of:

- reduced unit cost (but not necessarily mission cost)
- smaller cost step functions for added capability,
- repeatability of orbital passes,
- flexibility in the choice of the orbit parameters,
- sharing the risk of failure across several spacecraft while lowering vulnerability of the overall system,
- flexibility in using the system. This means that on-orbit the satellites are matched to the level of crisis within a continuum ranging from strategic use to tactical use,
- dedicated satellites for a given mission,
- satellite programming and use decentralized to the field theatre users.

The eventual outcome is, at a reduced cost, to increase operational flexibility and responsiveness to the needs of the theatre commander by concentrating on the basic space capabilities needed in the individual mission areas.

If the above list is to be realized, then the implementation of the TACSAT in areas common to all missions must receive special attention. The following, plus the discussion in Chapter 6, will address the problems and the solutions in meeting this objective.

5.2 NATO SPACE FORCE STRUCTURE

Before any discussion of how the TACSAT concept might be implemented, one must have a vision of what the collective space force structure could evolve to for all NATO member nations. While NATO itself will not control such a force structure, it could provide influence over future procurements. An example of such a space force structure is presented below. Budgetary constraints and changes in the terrestrial forces could call for a realignment of individual national space programs to a mix of heavier class satellites and TACSATs. This realignment would have three important aspects.

- Some large national assets would be maintained for strategic purposes and for their value in maintaining the data bases for tactical missions.
- In some areas, TACSATs would be procured as dedicated national assets by individual NATO countries.
- Whether deployed jointly or individually, the TACSATs would be common for all nations in each mission area.

Figure 5.1 is a notional representation of how a future space force structure might evolve collectively for NATO member nations given the joint development of a TACSAT. It is assumed that the national space assets of individual countries are a part of NATO operations but, of course, are not owned by NATO. Figure 5.1 calls for EHF communications to change to TACSATs exclusively; missile warning and battlefield surveillance missions would be covered by both strategic satellites and TACSATs; navigation would remain as structured; and weather would be divided between civil/commercial systems and TACSATs. For UHF and SHF, in the near term TACSATs would absorb the functions now performed by national assets allowing for transition to commercial systems at a later time. For this example space force structure, TACSATs are most viable because they can be pursued across all mission areas.

5.3 SPACECRAFT BUS

In general, the technology necessary for designing an appropriate spacecraft bus is in hand. However, affordability must be addressed "head-on" in this area.

One method of achieving affordability is to maximize design commonality across the spectrum of missions to be performed. Optimally, one would desire to have a single satellite design capable of performing any mission. This, of course, is not possible. A second level of commonality would be to have a common bus and common bus subsystems such as power, attitude control, and thermal protection. In this concept, the payloads would be different for each mission. The least

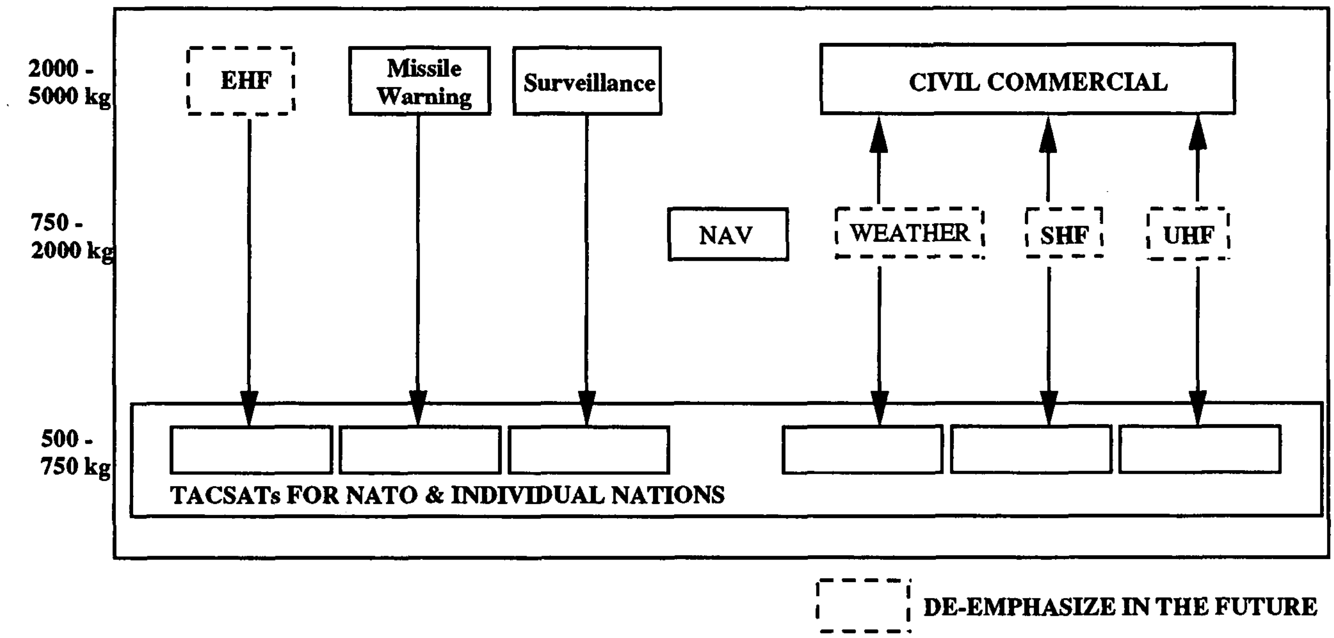


Figure 5.1 Example of a Possible NATO Space Force Structure

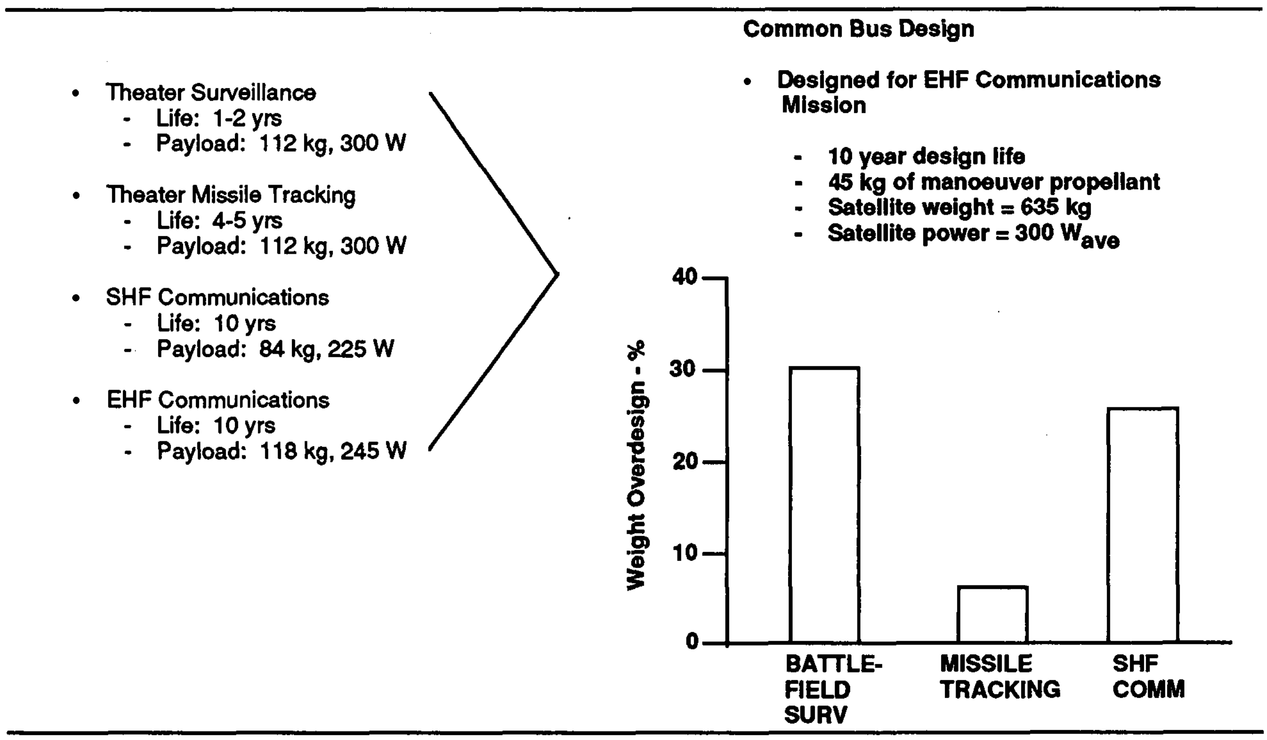


Figure 5.2 Common Bus Concept

degree of commonality would be achieved by having a common bus with subsystems and payloads tailored to the individual mission. Any amount of commonality will result in a larger unit buy, thereby amortizing the RDT&E costs over a larger base and taking advantage of the production learning curve to reduce the unit cost.

5.3.1 Common Bus Concept

One national effort examined a TACSAT approach that involved three interchangeable payloads that used a common bus. These payloads were:

- single E-O surveillance sensor (for battlefield surveillance from LEO and missile tracking from GSO),
- SHF communications,
- EHF communications.

Payload weights ranged from 84 kg to 118 kg and the power requirements were from 225 watts to 300 watts. If we now try to design a common bus, one that accommodates any of the three payloads, we find that the payload governing the design is that of EHF communications. It is the heaviest payload, has near maximum power requirements, desires a 10 year life and requires 45 kg of maneouver propellant (the reason for which will be discussed later). The resultant spacecraft weight, including payload, is 635 kg. In comparison with a unique spacecraft designed for each specific mission, the common bus spacecraft represents approximately a 30% weight overdesign for the theatre surveillance mission and a 7 to 8% overdesign for the theatre missile tracking mission (reference Figure 5.2).

This overdesign basically comes about from the differences in satellite design life which governs the amount of propellant that must be carried for station keeping. In addition, the theatre surveillance mission is conducted from lower orbit and does not require the 45 kg of manoeuver propellant. In comparison to a satellite specifically designed for the SHF communications mission, the common bus design represents a 27% increase in weight. This is mostly due to the lighter SHF payload weight and reduced power requirement. Penalties of this order of magnitude must be accepted to take advantage of a common bus design with its overall lower costs.

Not only does commonality achieve cost reductions as a result of an increased production buy and corresponding learning curve leverage, but it promotes the use of standard test procedures and test equipment. Payloads can be handled as black boxes and, thereby, integration and test times can be reduced. It is clear, however, that the more the payload weights and mission parameters diverge, the larger the penalty that must be paid by using a common bus.

The surveillance and communications missions were used to define the more complete set of bus design parameters shown in Figure 5.3.

ORBITS	LOW–MEDIUM EARTH ORBITS		GEOSYNCHRONOUS ORBITS	
MISSIONS/ PAYLOAD TYPE	ELECTRO OPTICAL (<1600 km)	OTHER COMM (17,600 km)	ELECTRO OPTICAL	COMM
Bus Parameters		Navigation		
GN & C				
Stabilization	3-axis	3-axis	3-axis	3-axis, dual spin
S/C Pointing (deg)	.5 to .01	.5 to .1	.2 to .01	.5 to .02
S/C Jitter (deg)	.1 to .001	.5 to .02	.1 to .0001	.5 to .03
Slewing (deg/sec)	3.0	None	None	None
COMMUNICATIONS				
Frequency Band	S,X,SHF,EHF	S,L,UHF	X,SHF,EHF	S,X,SHF,EHF
Downlink Rate	up to 274 Mbps	4 Kbps	up to 274 Mbps	10 Mbps
Downlink BER	$<10^{-6}$	$<10^{-6}$	$<10^{-6}$	$<10^{-6}$
Contact with grd	2 to 12 x/day	Intermittent	Continuous	Continuous
C & DH				
Bulk Storage	2 Gigabits	No	No	No
Processing				
Autonomy		180 days	1-3 Months	90 days
PROPULSION				
Stationkeeping	No	Yes (± .10 deg)	Yes (± .10 deg)	Yes (± .10 deg)
Alt Adjustment	Yes (± 25mm)	No	No	No
Orbit Reconstitution	Yes	No	Yes	Yes
Momentum Mngmt	Yes	Yes	Yes	Yes
POWER				
EOL Ave Watts	600	<1000	<1300	<1000
Eclipses	Frequent (>50000 cycles)	Frequent	Infrequent (~3000 cycles)	Infrequent (~3000 cycles)
ENVIRONMENTAL				
Rad Dose-Rad(Si)	<500/yr	5000/yr	2000/yr	2000/yr
Thermal Req's	Stressing	Mod to low	Low	Low
Outgassing	<50 PPM	<50 PPM	<50 PPM	<50 PPM

Figure 5.3 Bus Parameters for Surveillance and Communications Missions

As expected, these parameters vary both as a function of mission and orbital parameters. In the area of Guidance, Navigation and Control (GN&C) the most stringent requirements (pointing and jitter) are dictated by the electro-optical mission from GSO. This mission also has the largest communications data rate demand. The requirement for autonomy falls under the general heading of Command and Data Handling (C&DH) and can be up to 180 days. To achieve this, it is thought that connectivity with the Global Positioning System (GPS) would be required to provide ephemeris updates. The propulsion requirements are driven by the need for orbit reconstitution (on-orbit manoeuvering). Finally, the bus will need to be protected from the natural space environment at a minimum. It is recognized that a truly common bus design may compromise these requirements but the determination of the extent of such a compromise will require more detailed study.

While the above results in suboptimizing several of the mission bus designs, there are potential savings in non-recurring and recurring costs, in addition to efficiencies in logistics, launch operations, and on-orbit operations.

For *nonrecurring development,* it has been found that, on the average, 20% of the satellite nonrecurring development costs are attributable to the spacecraft bus. However, it has also been found that the bus commonality between mission areas will not exceed 75% of the subsystems. One is then led to the conclusion that a 15% cost savings in development for each mission area is possible. Such a figure can be significant when multiplied across several mission areas.

For *recurring production,* the cost savings opportunity may be even greater. In the production world, there is the 20% rule which says that every time the production of a unit doubles, the unit cost drops by 20%. So, if the basic production for a spacecraft was four units, and the production was increased to 24 units, the unit cost could be reduced by up to 44%. This was demonstrated by the US Agena D program.

Of course, the degree of commonality that should be pursued should be determined by the tradeoffs of cost versus functionality and performance, which are inherent in commonality.

Not discussed here is the potential for reducing manpower for satellite ground control because of common operations and improvements in launch operations and booster interfacing with the satellite.

5.4 GROUND OPERATIONS

Ground operations are one of the more difficult aspects of any space capability. For TACSAT, they may be particularly challenging because of the responsiveness demands of the theatre combat command. For this discussion, TACSAT ground operations are divided according to those areas shown in Figure 5.4.

Not all of the areas apply to each mission area; for example, communications satellites do not produce data to be disseminated; however, communication systems are a distributor of data generated by other systems.

Shown under each area are the primary issues that must be resolved by the user.

In order for any TACSAT ground operations approach to be successful, it must satisfy the following requirements:

- Be responsive to the theatre combat command
  - On demand, direct, and timely support
- Operationally transparent to the user except for the user interface
- Complement and/or enhance current capabilities

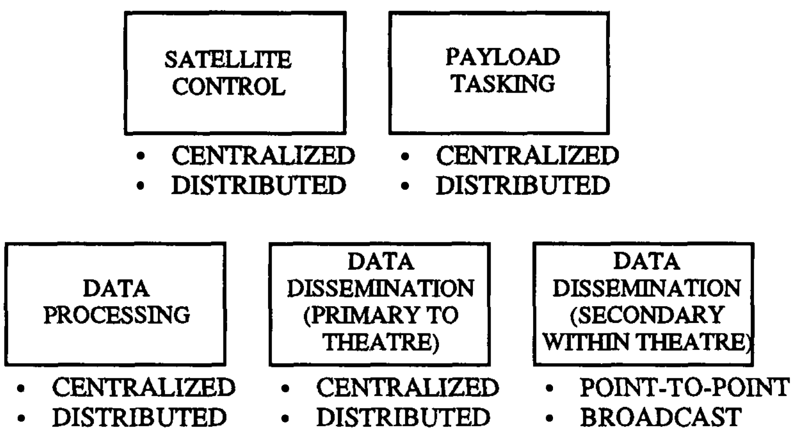


Figure 5.4 Standard Ground System Architecture Elements

- Be cost-effective
- Fusion compatible information
- Should not limit communications
- Be available throughout the cycle of operation
- Train the way you fight.

5.4.1 Overall Concept

During the full TACSAT mission, there will be the following, distinctly different, phases of operations.

5.4.1.1 Launch Preparation Phase

It is possible that there will be a choice of Launch Vehicle configurations. For each, there will be a complex trade-off between orbit parameters (especially orbit inclination) payload mass (or functionality) and target area revisit periodicity. There will also be a complex trade-off for the phasing of any particular orbit between spacecraft constraints (e.g., sun angle at injection), operational coverage requirements and spacecraft fuel consumption during orbital manoeuvers. There may be a military requirement to deceive a sophisticated enemy, able to identify and track TACSAT launches, as to the nature of the intended tactical support, especially phasing over the target area. Finally, there may be a requirement to defend the TACSAT system against jamming.

The trade-offs must be resolved and the launcher/spacecraft configuration finalized (including programming of on-board computers) early in the tactical deployment when the tactical staff will have many other pressures to finalize deployment plans and logistic support. However, since it cannot be assumed that these staff will be familiar with spacecraft operational constraints and speedy decision making may be of the essence, previous in-depth training in system operation will be a pre-requisite of successful TACSAT operations.

5.4.1.2 Launch and Early Operations (LEOPS) Phase

Launch services would be provided by a specialist supplier requiring minimum interaction with the tactical users. The booster ascent and spacecraft separation will be pre-programmed. However, determination of the initial orbit by ranging during first apogee will be necessary from appropriately located and equipped ground stations. Note that the spacecraft ranging transponders may well need to be protected by encrypters from ranging, and/or from jamming, by enemy ground stations; hence digital ranging, military staff and cypher distribution channels will be preferred. For accurate early orbit determination, these ranging stations would be on a long (>1000 km) baseline and must pass ranging data sets by communications links to a central control facility equipped to compute the initial orbit. It will be convenient to arrange for this center to also compute necessary manoeuvers, predict the subsequent orbit evolution and, most probably, execute the manoeuver sequence in a manner consistent with any requirement for payload deployment/activation/calibration. To effect the manoeuver/activation sequence, Tracking, Telemetry and Command (TT&C) access would have to be provided via several, well-distributed ground stations if this phase is to be completed with minimum delay. In short, this entire phase could be under the control of the launch site, provided with support from a network of appropriately equipped ground stations.

However, in view of the military sensitivity of TACSAT missions, it is more likely that all ranging, telemetry, manoeuver computation and telecommand functions would be exercised by a suitably equipped and military-staffed facility. For reasons of compatibility with launch site and back-up orbital support, TT&C functions could be conducted at S-band using the Space Ground Link System (SGLS) standard, but with encryption enabled shortly after successful injection into initial orbit. Ranging, telemetry and telecommand functions could be exercised by a 19 m S-Band Telemetry & Command Station (TCS), supplemented by relatively small (3 m) S-band terminals co-located with selected permanent ground stations. Alternatively, the entire TT&C support could be exercised within the X-band channel allocations for Milsatcom and Earth Resource Downlink channels. In either case, TT&C base band connectivity during the periods of TACSAT visibility must be provided, for example, via order wire channels within permanent communications accesses.

5.4.1.3 Data Transmission (Remote Sensing)

Data transmission is an important constituent of any of the remote sensing concepts and can be implemented in several ways. For tactical observation applications, data transmission concerns both housekeeping telemetry and satellite telecommands and remote sensing data proper. Several possibilities exist.

a) direct transmission to the ground of telemetry and sensing data and direct transmission from the ground of telecommands. In this case the satellite control station and the remote sensing data receiving station(s) are assumed to be sited inside the theatre;

b) use of a data relay satellite for spacecraft telemetry and command and direct transmission to the ground of sensors data. In this case the satellite control station(s) can be well outside the theatre, while the data receiving stations can be sited within the theatre. This configuration provides for more flexibility in mission planning and is particularly important in the case of small satellite constellations, while allowing an "in situ" management and handling of the sensor data;

c) use of a data relay satellite for relaying both telemetry and sensor data and spacecraft telecommands. With this configuration the reception of satellite observation data would also be done by receiving stations well outside the theatre, which would also be in charge of image processing and interpretation. The distribution of the interpreted images to tactical commanders would then require a separate communication channel or the utilization of other repeaters of the data relay satellite.

System trade-offs
There are advantages and drawbacks with any of these concepts.

The first puts the control and exploitation of the satellites entirely in the hands of the tactical commanders. However, the limited visibility time of each satellite, during overpasses, may unduly restrict the time necessary for reconfiguring dynamically the satellites to execute a specific observation mission. This is especially important when attempting to exploit the short revisit capabilities of the satellite constellations. Besides, controlling the satellites from inside the theatre is risky, in that the control station is exposed to physical threats, with the danger of completely losing access to the on-orbit resources.

The second concept removes the risk of physical threat to the control station. Moving the mission planning well outside the theatre allows a centralized management of the satellite constellation operation, which is particularly important if the constellation is intended to serve multiple theatres spread around the world. Besides, much better mission planning flexibility is achieved, since there are fewer restrictions on the access to the satellites for their reconfiguration to meet specific observation tasks. The disadvantage is the need to have continuous access from inside the theatre, concerning near-term observation mission needs, with the remote control center.

The third concept takes away the control and real-time exploitation of the satellite resources from the hands of the tactical commanders. They would still relay their short term observation needs to a remote control center via a data relay satellite (or other satellite communication systems) and would receive processed (and perhaps interpreted) images from a remote data processing center where the satellite observation data are sent in real time. The overall data traffic, in this configuration, may increase significantly since the relay satellite would have to handle all incoming data fluxes from the LEO satellites to the centralized data receiving station, and all return data flows from the processing center to the tactical theatre. This may well have a strong impact on the design of the relay satellite network. Besides, cutting-off the tactical commanders from the reception of raw data from the observation satellites for "in situ" processing and interpretation, may not be considered by some as the most effective way of meeting the tactical needs.

The problem is further compounded by the satellite launch approach, whether it is on-failure or on-need, or planned in advance. Satellite launches can be performed from outside the theatre, as probably will be the case for several practical reasons. Accordingly, there may be good reasons to decouple satellite operations, including constellation maintenance, orbit keeping and spacecraft health monitoring, from payload operations which are specific to satellite's resource utilization and mission needs. The former could be handled by the station(s) participating to the satellite launch and injection into their desired orbit. The latter could be handled either from stations inside the theatre, as per concept a), or outside the theatre, as per concepts b) and c).

Technical Aspects
There are clear differences concerning the technical aspects of data transmission either directly to the ground or via a data relay satellite, particularly in the transmission of high speed sensor data.

Direct Transmission to Ground
Direct transmission to the ground, even of high speed data, is a relatively simple technique. One national study pointed out the possibility of interconnecting a LEO observation satellite to a transportable terminal deployed in the theatre to establish links at 200 Mbit/sec, as required to relay data from SAR sensors with 2.5 m ground resolution and 25 km instantaneous swath, between the satellite and a data receiving station equipped with antennas of less than 2 m diameter. The satellite equipment would include a directional, mechanically repointable, small antenna and a 10 W transmitter. The mass and DC power of such equipment can be of the order of 15 kg and 70 W.

Links would be possible up to a 2500 km distance between the ground terminal and the satellite, considering a 3° to 5° minimum elevation angle above the horizon for the ground receiving antenna. The downlink frequency could be at X-band (7 GHz), although the 20 GHz band could be considered as well. The same equipment can serve the needs of direct data transmission to ground of medium-high resolution optical sensors.

Transmission via Data Relay Satellites
In the case of data relay via a relay satellite, the choice lies between the use of microwave or optical techniques. In the case of a microwave link, the use of 60 GHz helps keep the size of the terminal, especially the antenna, within reasonable limits. Optical techniques have been advanced in recent years, notably under ESA's SILEX program.

One study performed on microwave links shows the feasibility of relaying data rates of up to 200 Mb/s via a 60 GHz data relay satellite, using 50 cm diameter antennas and a 10 W transmitter onboard the small LEO satellite. The equipment mass and power consumption would be on the order of 15 kg and 100 W. Since the system operation would be discontinuous, and proportional to the sensor operational duty, data transmission would not significantly add to the payload power consumption. On board the data relay satellite, 60 GHz antennas of 2 m diameter would be required to support the high data rates involved, considering also the small sizes of the users' terminals.

A second study focused on optical inter-satellite links using AlGaAs laser diodes. Data rates targeted were 19.2 Kb/s for the forward command link and 100 Mb/s for the return data-transfer link, at an error rate of one in a million. The telescope diameter required was 136 mm for a total terminal mass of 30 kg. Power consumption was estimated at 80 W during acquisition mode and 50 W during normal operation. All components required are currently available.

5.4.1.4 COMSAT Control

Network Control is also required in the case of a TACSAT communications mission. It can be assumed that the communications transponder will be accessed only by in-theatre force elements, using locally-assigned cyphers. In order to provide communications services compatible with the needs of tactical end users, the way in which the network is managed and user access is granted and controlled must involve a minimum of "overhead" workload imposed on the end user. This can range from avoiding the need to point the antenna on the terminal precisely, to the simplicity of operation of the equipment, to a means of establishing user confidence in the integrity of the system, and to its ability to provide the services required.

Optimum use of the TACSAT capacity will be most easily achieved by a mixture of frequency assignment and timeline planning issued by the in-theatre signals staff. Some types of TACSAT store-and-forward communications missions will require quite complex space/ground protocols which must be transparent to the end user. Some classes of TACSAT will provide transponder configuration options that are selectable by ground command. The in-theatre specialist TACSAT operations staff will be best equipped to make the appropriate option selections, which could be implemented either by a local telecommand uplink or by a centralized control center. In the case of in-theatre jamming attacks, the former is likely to provide a far more successful ECCM response than the latter, provided it can counter any enemy jamming of the telecommand uplink.

5.5 LAUNCH SYSTEMS

5.5.1 Launch System Options

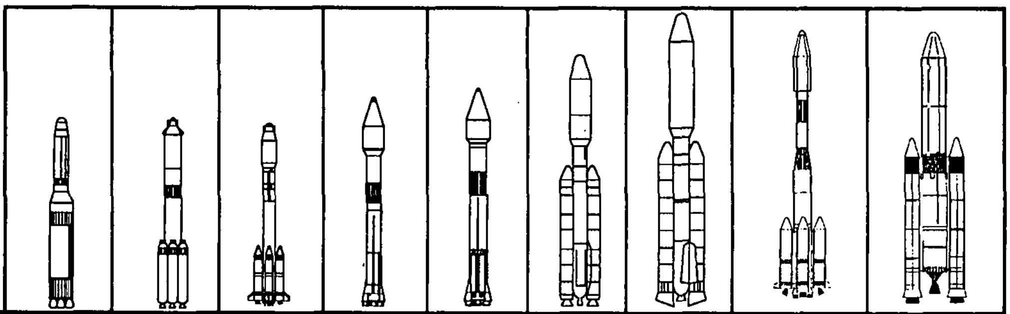
Within NATO, the member nations can provide a broad array of launch systems, some of which exist or are in hardware development (Figures 5.5 and 5.6), at varying costs and responsiveness. It is quite evident that no matter what the TACSAT deployment strategy might be, there is a booster option available within NATO.

5.5.2 Launch and Orbital Strategies

Two launch strategies have been considered for TACSAT application: launch on demand and launch on schedule. To understand the implications of these strategies, the launch vehicles available to the TACSAT must be examined. In the current fleet of launch vehicles (see Figures 5.5 and 5.6), the medium launch vehicle (MLV), i.e., Delta 7925, is the one that comes closest to satisfying the TACSAT weight requirements. With a solid propellant kick motor, it is capable of placing approximately 900 kg into a geosynchronous orbit. An Atlas class MLV will place approximately 1500 kg into GSO and Ariane 4 three times as much, allowing TACSATs to be launched two-at-a-time and possibly four-at-a-time, if such a launch strategy is deemed to be advantageous. For low altitude satellite deployment, the Pegasus lift capability is about 400 kg, somewhat low for the satellites discussed in this report. The Taurus, which is essentially a Pegasus on top of a Peacekeeper first stage, appears ideally suited to this application. This vehicle is, however, still in the development stage.

Responsiveness is a characteristic generally associated with TACSATs. The capability to rapidly deploy the satellite to the area in which it is needed is essential. When examining the responsiveness of our current launch fleets, however, the nominal time from the mating of the spacecraft to the launch vehicle until the launch can actually take place is 24 days for an Atlas II and 10 days for a Delta II. By streamlining the process, it may be possible to reduce this time down to 7 and 5 days respectively (see Figure 5.7).

Added to this is the travel time to orbit and the spacecraft checkout time once orbit has been achieved. It is not clear whether the GSO based satellites can be responsive enough using a launch on demand strategy to meet user requirements. On the other hand, for the low altitude satellites launched on a Taurus, it appears that, with judicious satellite designs, response times on the order of 24 to 48 hours may be possible. It should



LAUNCH VEHICLE	ATLAS E	TITAN II	DELTA II 7920/7925	ATLAS II	ATLAS IIAS	COMM'L TITAN III	TITAN IV (SRMU)	ARIANE 4	ARIANE 5
RESPONSIBLE AGENCY	USAF	USAF	USAF	USAF	COMM'L	COMM'L	USAF	ARIANESPACE	ARIANESPACE
PRIME CONTRACTOR	GD	MMC	MDC	GD	GD	GD	MMC	CNES	CNES
PERFORMANCE (kg)									
LEO POLAR	800	1,900	3,800	5,400	6,800	–	19,000	7,700	12,000
LEO DUE EAST[1]	–	–	5,000	6,400	8,400	14,500	22,000	9,600	18,000
GTO	–	–	1,800	2,700	3,500	4,300[2]	5,800[4]		6,800
GEO	–	–	950	1,400	1,850	1,350[3]	5,800[4]	–[2]	–[2]
RELIABILITY ~%	92.0	93.0	97.0	100.0	NOT FLOWN	93.0	93.0	87.5	N/A
PAYLOAD ACCOMMODATION									
PAYLOAD DIA ~m	2.1	2.8	2.8	2.9; 3.6	2.9; 3.6	3.6	4.6	3.6	4.6
CYLINDER LENGTH ~m	2.0	3.6; 5.2; 6.7	3.6/1.9	3.9; 4.2	3.9; 4.2	8.0	12.2	3.9; 4.9; 6.5	12.0
CONE LENGTH ~m	1.2	1.6	2.1	3.8; 5.5	3.8; 5.5	4.3	6.0	4.3	–
INITIAL LAUNCH CAPABILITY	1974	1988	1990	1991	1993	1989	1989	1989	1995
LAUNCH SITE	ELS	WLS	ELS/WLS	ELS	ELS	ELS	ELS/WLS	ELA-2 KOUROU	ELA-3 KOUROU
LAUNCH CAPABILITY (flts/yr)	N/A	3	12/6	9	9	6	6/2	12	TBD
RESPONSE TIME	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	V. HIGH	MED	MED
COST/FLT ~FY91 $M	49	43	47-52	74-84	116-126	130-150	154-227[4]	115-125	105-115

1) ~28.5°
2) WITH TRANSTAGE
3) With KICK MOTOR
4) CENTAUR UPPERSTAGE (other options: NUS; IUS)

Figure 5.5 NATO Mainline Expendable Launch Systems

LAUNCH VEHICLE	PEGASUS	PEGASUS XL	TAURUS	CONESTOGA IIA
RESPONSIBLE AGENCY	DARPA	USAF/NASA	DARPA	NASA
PRIME CONTRACTOR	OSC	OSC	OSC	EER
PERFORMANCE (kg)				
LEO DUE EAST				
185 km CIRC	335	425	1270	635
555 km CIRC	245	345	1135	570
LEO POLAR				
185 km CIRC	255	325	1045	545
555 km CIRC	175	260	865	475
GTO			280-500	
RELIABILITY - %	-	-	-	-
PAYLOAD ACCOMMODATION				
DIAMETER - m	1.15	1.15	1.5	1.25
CYLINDER LENGTH - m	0.91	1.19	2.44	2.71
CONE LENGTH - m	1.00	1.00	2.75	1.00
INITIAL LAUNCH CAPABILITY	1990	1993	1993	*20 mo FROM GO-AHEAD
COST/FLIGHT - $91 M	12	13-14	19+	10-12

*Conestoga I flew suborbital in 1980

Figure 5.6 Fixed/Relocatable/Mobile Launch Vehicles

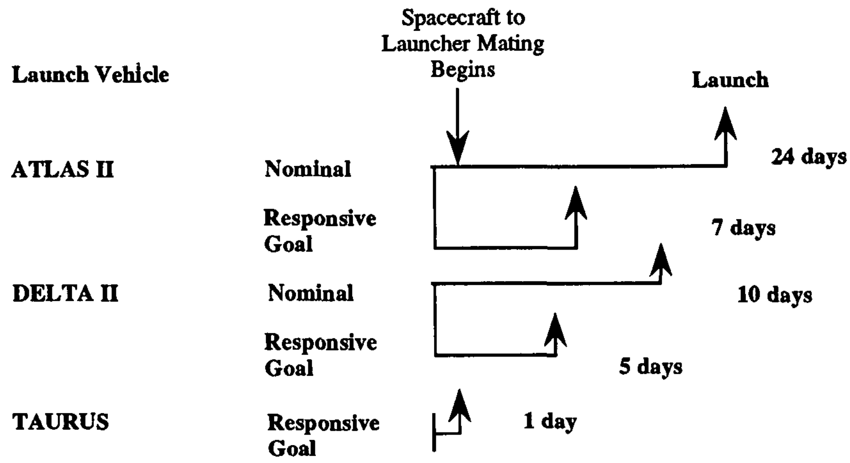


Figure 5.7 Launch Responsiveness

be noted that modifying the launch vehicle alone is not sufficient for rapid response. Today's spacecraft can require days or weeks of checkout after they achieve orbit. TACSATs can be ideally suited for solving this problem since they will be more oriented to simplicity than current systems. If surveillance data is to be obtained in the first orbit, for example, design features such as blowdown focal plane coolers and optics contamination avoidance systems must be incorporated.

For the GSO based satellites, there is an alternate means of providing responsiveness. In this strategy, the satellites would be launched when available or on some predetermined schedule and stored in orbit. The satellites could be stored in a dormant condition and activated when needed, thereby minimizing satellite life degradation. The satellites could be stored at a convenient point in the GSO belt and repositioned to the area of interest as the need arises. A 600 kg class satellite could be shifted up to 30° per day with the expenditure of no more than 45 kg of fuel. It is doubtful, however, that if several satellites are stored in this manner, there would be a requirement for this high rate of orbital shift. It seems more reasonable to anticipate manoeuvers on the order of 5° per day considering that crises or conflicts do not normally occur instantaneously but rather develop over some period of time. Under these conditions, the 45 kg of propellant could provide 4 to 5 such manoeuvers per satellite without affecting satellite life on orbit. However, in all probability some form of limited launch on need capability to launch single GSO TACSATs should be maintained.

Both of these possibilities, independent of their feasibility (because of launcher existence or non existence), have major advantages and drawbacks as summarized on the table below.

Essentially, TACSATs do not represent such a novelty that a new breed of launchers has to be developed. Some applications may favor on-orbit storage, others launch-on-demand (see Table 5.1). When store-on-orbit is appropriate, use of a larger booster carrying several TACSATs will be most cost effective. Future development of Pegasus and Taurus may lead to a modification of this observation, but a demonstration of their operational status is needed first.

5.5.3 Launch Responsiveness

Responsiveness becomes an issue only when the spacecraft are stored on the ground. Figure 5.8, while notional, makes the point that as the weight and cost of the spacecraft riding on the launch system and the unit price of the launch system itself increase, the care and time taken for launch will increase accordingly. This

Table 5.1 Comparison of Spacecraft Storage Options

	STORE ON ORBIT	LAUNCH ON NEED
Probability of satellite functioning	Excellent (back up satellite launched when needed)	Good but depending on launch success and satellite status
Delay before satellite operability	Very small if no orbital manoeuvers (quasi-instantaneous)	Small (few days)
Mission fulfillment when TACSAT aloft	Medium (non optimized orbit for non-GSO systems)	Excellent

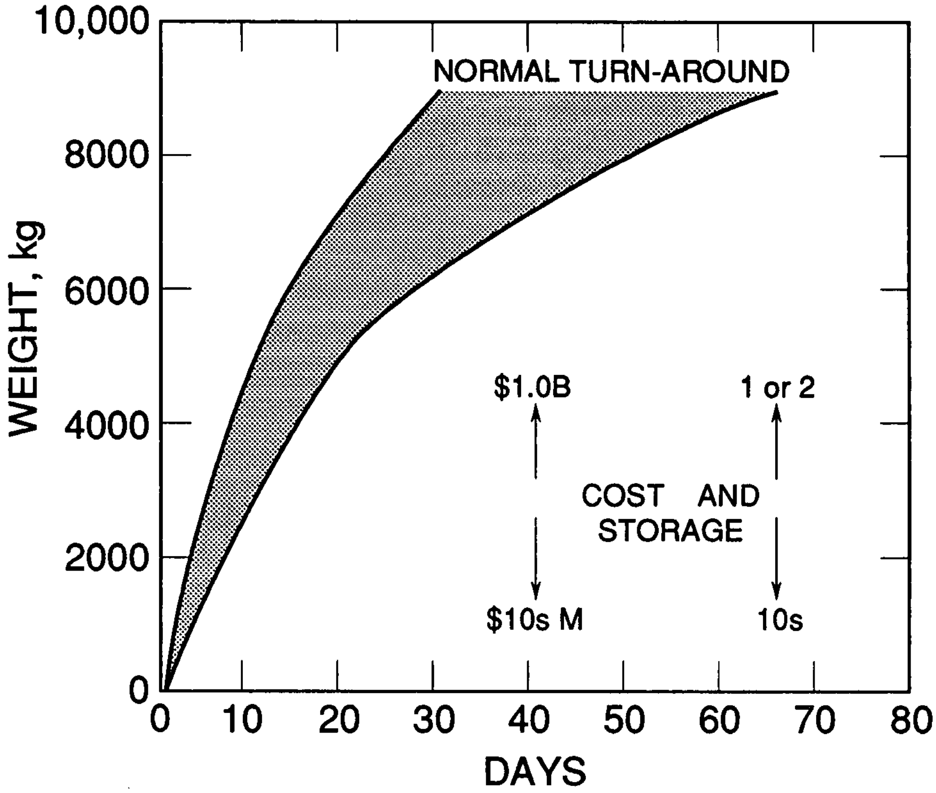


Figure 5.8 Notional Responsiveness (Weight vs. Turnaround Time)

point alone is one of the key drivers for the use of TACSATs.

It is impractical to consider the rapid launch of a large spacecraft whose cost may be $0.5B to $1.0B, particularly where the next spacecraft may be the last available and that its complexity will prohibit rapid checkout without a significant increase in risk. TACSATs are projected as the antithesis of this situation.

On the other hand, there is a similar argument for recovering from a launch failure. This argument is notionally represented in Figure 5.9.

If a ground based storage strategy is adopted for space systems, then a rapid launch strategy must be adopted. The primary driver will be to deploy space systems so their support is available in the theatre as NATO forces begin their deployment (or prior to deployment). This driver dictates that if a launch failure occurs, the system must be able to "fly through the failure." That is, a follow up launch must occur immediately using the assumption that the event was a random reliability failure, i.e., "the roll of the dice" came up negative. As expressed in Figure 5.9, "flying through a launch failure" is not practical for expensive spacecraft and launch systems primarily because the next spacecraft may be the last available.

5.6 RELIABILITY/REDUNDANCY

System reliability and availability are tightly connected to the launch policy and redundancy implementation. Several approaches can be considered, each with merits/demerits depending on mission and nominal constellation configurations.

For tactical applications, uninterrupted service availability is of paramount importance, in that on-orbit failures reducing the service availability over the theatre cannot be accepted. Nevertheless, small satellite constellations can be designed in such a way that any single satellite failure leads to a graceful performance degradation and not to a total service loss over a given area (the "theatre"). Therefore one must distinguish between a satellite system characterized by inherent graceful degradation and those that do not have such a feature.

5.6.1 Single Satellite Systems Without Graceful Degradation

Examples of such systems are single satellites launched on demand to provide a service, e.g., battlefield surveillance, over a specific theatre. Single satellites injected in a resonant orbit are just such an example. In this case the on-orbit failure of the satellite leads to a total, unacceptable service loss. Therefore such satellites should be launched at least in pairs, to have one operating and one on-orbit spare ready to substitute for the former in case of failure. Such satellite pairs would nominally have a limited lifetime, say on the order of 6 months, or perhaps one year. In fact, they would be limited to serve the specific needs of one theatre during military operations. Due to the limited design lifetime, satellite redundancies would play a lesser role in estab-

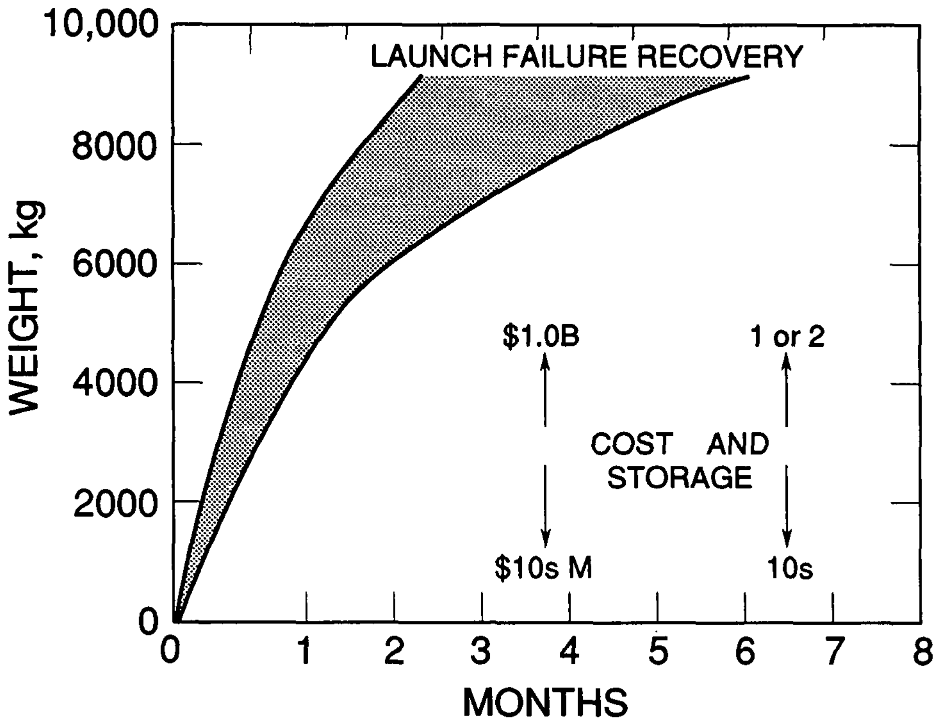


Figure 5.9 Notional Launch Failure Recovery (Weight vs. Recovery Time)

lishing the system success probability. Accordingly, redundancies can be eliminated, or at least minimized, positively impacting mass and the cost of the satellites.

5.6.2 Satellite Constellations

In setting up satellite constellations, there may be several approaches to guarantee service continuity and to implementing the required system reliability over the system lifetime. The replenishment strategy for failed, or aging satellites, impacts both the design, costs and operational aspects of the system and must be carefully considered.

5.6.2.1 Minimum Size Constellations

By this concept we mean a constellation having just the minimum number of satellites required to fulfill the service needs over the designated service area. Such a constellation has clearly the least initial cost and operational complexity, but any single spacecraft failure can seriously compromise the service availability. Under the assumption that no delay is acceptable, during military operations, to restore the constellation integrity, on-orbit spares should then be planned in advance. Nevertheless, the on-orbit spare satellites should be injected into the same orbit of the other satellites both to reduce the time required to bring them into their required orbital working position and to reduce the extra fuel for orbit altitude changes. Injecting the on-orbit spare satellites implies a greater initial cost, and controlling them while dormant puts a greater burden on the satellite control station. Besides, their lifetime may be affected by atmospheric drag even if kept dormant: this is an important factor, considering that the satellites of the constellation will probably be designed to support a nominal lifetime of 3 to 5 years.

5.6.2.2 Oversized Constellations

By this concept we mean a constellation with a number of satellites greater than the minimum required to provide the intended services over the service area, thus implementing a graceful degradation in performance. This can be an inherent feature of the constellation or can be implemented on purpose. In any case, any single spacecraft failure will not cause the total system to go down. Under this assumption, the constellation integrity can be restored by launching spares kept on ground, with one to two weeks delay from the occurrence of the on-orbit failure.

This approach has the following advantages:

- initial costs are less since launch costs are only incurred upon failures;

- the extra satellites initially launched, if necessary, to implement an oversized constellation, are always operating providing an inherent redundancy in the information gathering process when not failed;

- the spare satellites, when launched, are "new" and ready to provide the service for the nominal satellite lifetime;

- the satellite design, mass and costs are positively impacted since they need not cope with on-orbit storage requirements and operations.

The single greatest disadvantage of this approach is that in a cost constrained environment, the "extra" satellites in an oversized constellation will continuously be targets in any cost cutting exercise.

Concerning redundancies, the graceful degradation in performance available with an "oversized constellation" leads, again, to the possible elimination, or at least substantial reduction, of spacecraft redundancies; except perhaps a few single point failures. Clearly the mass and cost advantages of redundancy suppression increases with the number of satellites in the constellation and with the extra satellites making up the oversized constellation.

In this case, the system reliability model, from the viewpoint of guaranteeing the minimum required service, is that of M for N satellites with the further possibility of a spare on-ground substitution. An individual satellite success probability between 0.7 and 0.8 for 3 to 5 years is a reasonable objective for a spacecraft with very limited on-board redundancies. On these grounds, an M for N oversized constellation, with N of order 4 to 6 and M of order of N+2, can exhibit a system success probability in the 0.9 range, which is felt to be reasonable performance.

The implementation of an "oversized constellation" concept is relatively easy for battlefield surveillance, using optical or radar sensors, due to the modularity with which the satellite orbits can be designed. Besides, the overlap of the sensor's access areas generally helps in achieving the inherent redundancy, with the result that, in the case of any single failure, there can be a certain loss in performance, like the spread in the revisit intervals, without compromising the entire mission. However, the implementation of the "graceful degradation" characteristics with "oversized constellations" may be less trivial for other missions and ought to be more carefully evaluated.

5.7 TRAINING

5.7.1 Introduction

The staff operating TACSAT systems (Operators) must be fully familiar with the various modes of operation in order that the greatest benefit be gained from those systems during the theatre crises for which they are designed. Similarly, those using the systems (Users) must be fully capable of exploiting the type of information which those systems provide. This familiarity is particularly important when a TACSAT is provided to the theatre as part of the rapid build-up of dedicated theatre assets. The staff must not be faced with a rapid learning task at this time.

The following text calls for training to be a key feature of TACSAT systems, which in turn will have a significant impact at various design stages of both the system concept and of the operational concept.

5.7.2 Training Philosophy

Operators and Users will gain the experience necessary to use a TACSAT system in a number of educational stages which will include desk teaching and book work, system training gained using special-to-purpose TACSAT system simulation facilities, and field experience gained from the use of real TACSAT systems during military training exercises.

5.7.3 Discussion of TACSAT Operation Issues

The commitment of a TACSAT asset into the theatre represents a significant capital investment from which the maximum operational benefit will be sought. Inadequate training will seriously jeopardize the whole operation and deny the potential benefit which the investment is intended to bring. Therefore, adequate training is vital.

It is the opinion of the Working Group that training with real TACSAT systems is the only approach that will guarantee successful exploitation of the asset during a theatre crisis and that there is a consequent need to fly real TACSATs during training exercises.

5.7.4 Discussion of TACSAT Information Exploitation

The information brought by a TACSAT system will be similar to that brought by strategic systems but in the case of surveillance assets, it is likely to be made available much more rapidly, and in the case of communications assets, it is likely to facilitate closer contact with forces in the field.

The capabilities brought by a geostationary TACSAT to the communications user are likely to resemble the existing strategic communications assets and will likely not require much new training. However, a LEO TACSAT would require that the Operators become familiar with a new type of communications system requiring continuous tracking and, possibly, training in the use of store-and-forward communications.

The capabilities brought by the surveillance TACSAT are likely to be of coarser spatial resolution and its use will limit the capabilities of the image interpreters who, it is expected, will be deployed in the theatre as part of the TACSAT system. These staff will need to be able to operate under immediate pressure from a local User, with data which although good, is likely to suffer from distortions, noise, and moderate spatial resolution. These interpreters will need training and equipment in the field to best serve the needs of this local User. This would include the use of automatic feature extraction tools which will be available in the next few years.

5.7.5 Impact of Alternative Storage Options

Two alternative design philosophies exist for TACSAT systems, one based on "launch-on-demand," the other based on "on-orbit-storage." If the "launch-on-demand" philosophy is followed, then two further options become available for the satellite: it can be designed to have a short life suited to a crisis duration of months–and fly in very low earth orbit; alternatively it can be designed for longer life and fly in a somewhat higher orbit just like the "on-orbit-storage" satellite. Thus, the two real options are short life or longer life satellites.

If the basic TACSAT system design is based on short lifetime satellites, then field training exercises will require the dedicated launching of satellites to support the exercises. The exercises would therefore need to train operators in pre-launch, satellite acquisition, and on-orbit check out and commissioning activities, and would thus provide both Users and Operators with a fully representative TACSAT for their main-stream training and familiarization exercises.

If the long-life approach is adopted, then the TACSAT operation training activity can begin immediately with a fully commissioned satellite. In this case, the launch and commissioning activities will be undertaken by a different team, probably drawn from the existing satellite launch operation domain because there is no need for theatre experience in these aspects of system operation.

The cost impact of following the long-life approach is likely to be much more acceptable to the financial budget controller than the short-life approach which commits a real satellite to the training exercise. This impact of the training issue will require serious reviews of the two different satellite lifetime philosophies and of the consequent influence which the issue may exert on TACSAT system design concept.

CHAPTER 6

COSTS

6.1 INTRODUCTION

Cost will be one of the primary drivers for any TACSAT capability provided to NATO. While many national systems have very sophisticated multi-purpose capabilities in the mission areas addressed in this report, they are also very expensive. As a result, there is a spiral effect.

- Extensive planning is required which causes delays
- High reliability is paramount which dictates the use of low risk technology
- The combination of the above means that by the time the spacecraft are flown they are using obsolete components
- Large payloads are built to maximize the investment which in turn calls for large ground infrastructures
- Space systems become too big to be built by a single contractor which invokes a complex and expensive management structure making it difficult to optimize trade-offs between components because of rigid contractual boundaries.

The entire process feeds on itself. In general, TACSATs will be a break from this traditional approach in space system procurement and operation. This break in tradition is apparent when summarized as shown in Figure 6.1.

It must be emphasized that the cost-related observations in Figure 6.1 *do not* call for "smart, small, cheap, lightsats." Such a lightsat concept has been envisioned by many to mean constellations of numerous satellites limited in orbit life time and of low reliability which should, in theory, sharply reduce the recurring costs of the spacecraft. This concept has been reinforced (at the satellite level) by advances in technology in the fields of performance and miniaturization. However, the planner is faced with a dilemma. As the satellite recurring cost decreases and approaches the recurring launch

Modern TACSAT Characteristics	Cost-Related Observation
• Physical • Light (Mass) • Small (Volume)	Unit Cost of TACSAT < $50M
• Functional • Specialized Design • Dedicated Mission	Single User Requires Less Management Structure
• Procedure • Short Project Schedule • Reduced Documentation • Streamlined Organization	Avoid Costly Assessments of Many Options
• Developmental • Existing Components and Facilities • Micro Electronics/Software Advances	Use Non S-class Parts When Possible Reduce Testing/Qualification Costs
• Launch • Small Vehicle or Piggyback	Avoid Launch Date Slips, Stand-downs
• Ground Terminals • Simplified	Need Less Personnel

Figure 6.1 Modern TACSAT Characteristics

cost, it may be more cost effective to invest in the reliability and on-orbit life of the satellite to reduce the number of launches. It should be noted that advances in technology and miniaturization may enhance reliability substantially even without redundancy. The point is that "smart, small, cheap, lightsats" could have failure rates such that the launch costs will dominate and overwhelm any savings that may have been gained from current/low cost satellite design. It is not expected that launch costs will be reduced to a point where large risks can be taken in satellite design to the extent that frequent failures can be absorbed.

As a result of the above arguments, TACSAT concepts will, in all probability, be of moderate size, falling in the 500 to 750 kg end of the spectrum rather than being very lightweight. It will be essential that the satellite designer not forgo reliability in the "name" of cheapness.

6.2 TACSAT COST RELATIONSHIPS

In making the case for TACSATs (less than 750 kg in weight), one must go back to the rationale for TACSATs. First and foremost, TACSATs *MUST BE RESPONSIVE TO THE THEATRE COMMANDER* which, in varying degrees, large satellite systems have difficulty in meeting. But also of paramount importance, TACSATs must possess three main characteristics:

- *Flexibility*
- *Responsiveness*
- *Affordability*

One must avoid the syndrome of, "it is cheaper to add one more channel of communication to a large satellite than building a few smaller satellites," and thus ignore the above characteristics. Within this syndrome, one also forgets there are other needs and influences that must be accommodated which TACSATs can meet and large systems cannot. These are:

1. Multiple operations at different global locations: Large satellites cannot be split apart in order to transport unused capability to another operation.

2. Flexibility in the face of budget perturbations: one cannot cancel or delete 1/10 of a large satellite. The entire satellite is generally deleted with significant impacts on military capability.

3. Incremental cost and capability step functions: in today's defence world, the call for added capability as a conflict escalates may be in small steps and be very cost sensitive. Large satellites may cause governments to hold back on their commitment because of the significant funding required.

4. "Pipeline" problems: Because of the high cost of individual large satellites, there may be a limited number (or zero) ready to commit to launch. This situation makes the above argument, with respect to large satellites, worse.

5. Allow for flexibility as requirements change: TACSATs help avoid the situation of "over buying" capability, and they also allow for easier retrofits to match a changing threat.

Of course, there is the overall question of *affordability*. One important point is that TACSAT on-orbit life will generally be designed to fit the length of future theatre conflicts. For large satellites, as mentioned previously, they are so expensive that they must be designed to maximize on-orbit life. Herein lies a dilemma. When deploying a large satellite for a conflict that lasts only one year, and the next conflict does not occur for another 10 years, the politician will view the systems as 9 years of wasted investment.

From a cost point of view, the next point is quite significant. TACSATs, by their nature, will be designed to satisfy a minimum set of requirements. Thus, one must try to establish an "equal playing field" in making any cost comparisons between TACSATs and large satellites. The following discussions for battlefield surveillance and communications attempt to make this comparison.

Battlefield Surveillance

For tactical theatre support, the needs for battlefield surveillance are generally characterized as: moderate resolution, short revisit times, rapid dissemination, and affordability. Since high resolution strategic systems already exist, the question is, can these strategic systems fit the tactical characteristics without compromising the affordability criteria. A simple comparison is appropriate (see Figure 6.2).

The revisit requirements for tactical theatre operations may require six satellites. As a result, the cost for using strategic satellites for tactical battlefield missions could be an order of magnitude larger than using a TACSAT approach. This fact is even more significant if the TACSAT concept is used for other missions, thereby spreading the development costs.

Communications

For the purpose of this discussion, the communication satellites are SHF systems in geostationary orbits. From a cost standpoint, there will be two issues of concern to the field commander: (1) what level of capability should be in place at the start of any conflict, and (2) how much will it cost to incrementally add to that capability. Figures 6.3a, b, and c graphically bring out these issues.

COST	STRATEGIC SYSTEM	TACSAT
SATELLITE BOOSTER	$500M 200M(1)	$50M 20M(2)
TOTAL	$700M	$70M
CONSTELLATION (x 6 Sats)	$4200M(3)	$420M

(1) Titan IV
(2) Taurus
(3) Because of broad area search limitations, 8 satellites may be required, raising the total to $5600M.

Figure 6.2 Battlefield Surveillance Comparison

The systems used for comparison and their costs are described in Table 6.1.

In Figures 6.3a, b, and c, all concepts are normalized to the FULL SHF. The 30% and 40% concepts shown in Table 6.1 are somewhat subjective; however, for the purposes of this discussion they are fairly representative of small systems that, when combined, are competitive with the large system.

In Figure 6.3a, it is assumed that the FULL SHF constellation is 4 orbiting spacecraft. To build up to this level, either with spacecraft stored on the ground or stored on orbit, the cost step functions are $200M each. With this arrangement, the issues will be: (1) the funding commitment for added capability is large, (2) the addition of capabilities using a FULL SHF system may greatly exceed the needs of the scenario, and (3) the initial level of capability for peacetime and training may be more than is absolutely necessary.

The question is, are there small cost and capability options that can help resolve the above issues? Figure 6.3b uses an SHF spacecraft that has 40% the capability of the FULL SHF spacecraft, with a cost step function of $105M (curve B). This approach allows the commander to deploy an initial capability at a lower initial cost, and to add capability that can be more easily tailored to the needs of the scenario. By tailoring the constellation more closely to the scenario, the costs of military space support can be more cost effective. Of course, if one were to match the capability of a 4 spacecraft FULL SHF constellation with that of a constellation of 40% SHF spacecraft, the total cost would favor the FULL SHF approach. However, if a store-on-orbit deployment strategy were adopted, then the 40% system would be more cost competitive because two spacecraft could be launched on an Ariane or Atlas booster for an 80% capability with a cost step function of $186M (curve C).

In Figure 6.3c, the argument is the same as that for Figure 6.3b. However, a 30% system that matches the capability of the FULL SHF system appears to be more cost effective because of the ability to use a small, inexpensive booster. This situation may be an artifact of the way the 30% system was defined and should not be used to draw firm conclusions (curve D).

From the above, several generalizations can be made.

Table 6.1 SHF Cost vs. Capability

	FULL SHF	40% SHF (4)	30% SHF (4)
Transponders	2 x 40 W 4 x 10 W	4 x 20 W	2 x 20 W
Antenna	Up-link EC and MBA Down-link EC and Spot	Up-link EC Down-link MBA	Up-link MBA Down-link EC, Spot
Cost	Satellite $120M Booster(1) $ 80M TOTAL $200M	Satellite $ 53M Booster(2) $ 52M TOTAL $105M	Satellite $ 31M Booster(3) $ 20M TOTAL $ 51M

(1)ATLAS II
(2)DELTA II
(3)TAURUS
(4)From Figure 3.6

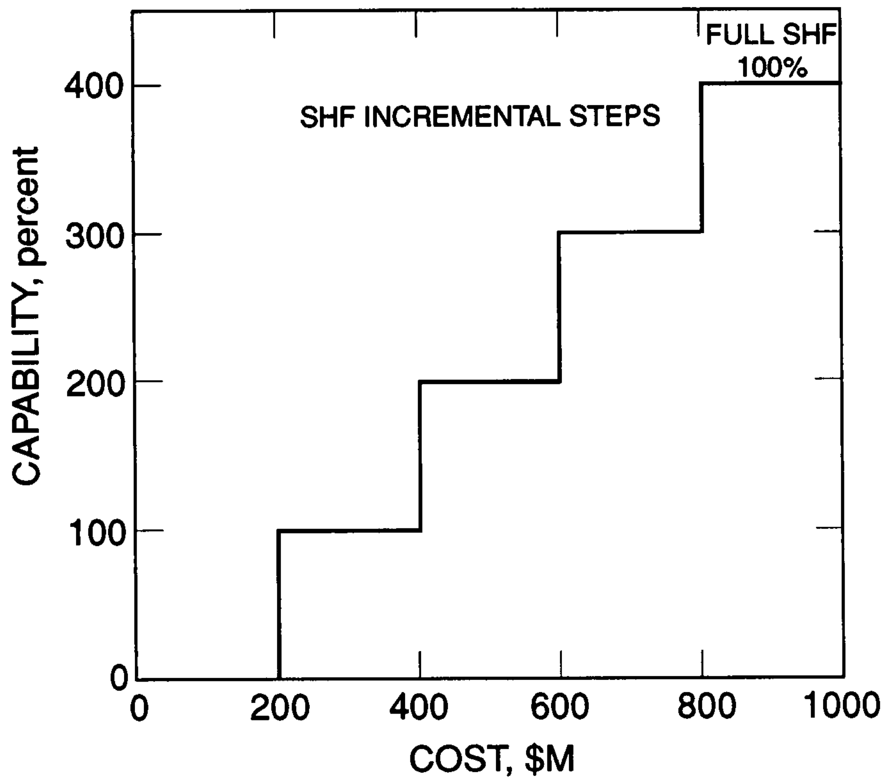


Figure 6.3a SHF Incremental Steps–100% SHF Capability

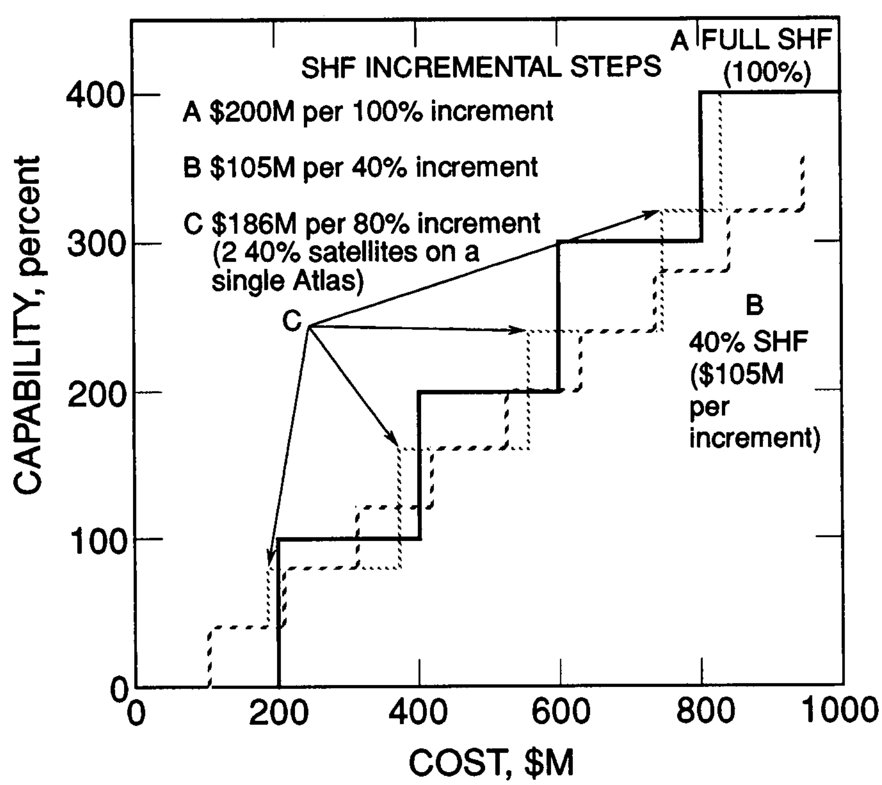


Figure 6.3b SHF Incremental Steps–40%, 80%, 100% SHF Capability

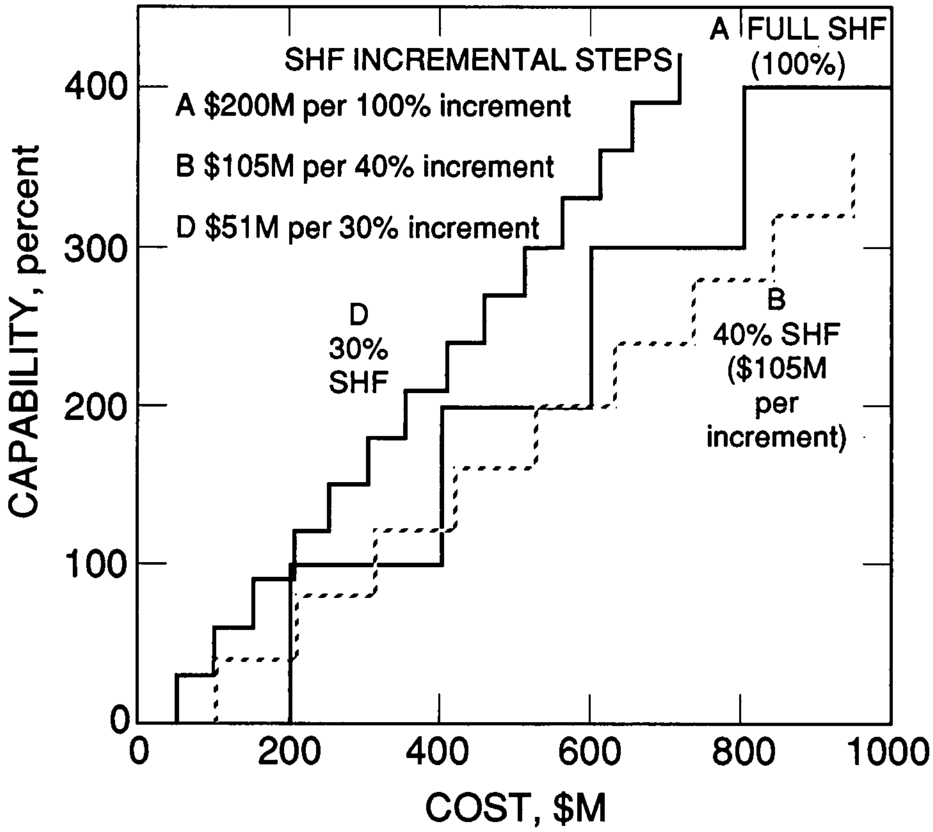


Figure 6.3c SHF Incremental Steps–30%, 40%, 100% SHF Capability

1. The use of TACSATs to achieve a similar capability to that of the large satellite will probably be reasonably close to cost equivalent. This is more evident when two 40% TACSATs are flown on one Atlas or Ariane. There may be some operational penalties associated with numerous TACSATs (for SHF there will be frequency interference problems but this will not be the case for EHF).

2. Using TACSATs to increase theatre capability can be done in smaller steps (sometimes resulting in fractional capabilities).

3. The cost for the initial capability at the start of a conflict can be significantly less.

Development of a curve for satellites using EHF would be similar and therefore was not constructed.

It should be noted that satellite overall life could become a factor if the conflict(s) are numerous and lengthy over a 10 year period. The premise here is that conflicts will be small in number and will not be protracted in time; otherwise the curves using current technologies may become skewed in favor of the large satellite. The ability of TACSATs to absorb enhancing technologies quickly suggests further analysis of this point may be needed in the future.

6.3 WORKING GROUP OBSERVATIONS

The Working Group acknowledges that a much greater depth of study than that undertaken by WG 16 is needed in order to define specific requirements for TACSAT missions. Nevertheless, at the conclusion of the Group's activities it has been proven that broad-brush estimates can be made of the primary cost centers that would characterize TACSAT programs.

The TACSAT concepts considered by WG 16 have shown that with careful control of requirements and specifications, the unit cost of these tactical space assets–in orbit–can be maintained within the price band $30M to $50M for communications and EO satellites, rising from $50M to certainly less than $100M for SAR satellites. These unit prices would be preceded by non-recurring development and demonstration costs in the region of $100M to $500M and would be divided across the range of TACSAT types, typically running at 2 to 3 times the unit cost.

The Working Group is also aware that historically, military space endeavors have been so closely identified with multi-billion dollar programs that the Working Group feels there may be a belief in the user community that costs for *all* such programs will be similar.

So radical is the advantageous impact of TACSAT on cost, that the Working Group has assembled a summary chart, presented in Figure 6.4. This chart shows the radical differences that exist between the global mission for which the current multi-billion dollar, strategic

MISSION	MISSION PRIORITY	DISCRIMINATOR	GLOBAL	THEATER
Battlefield Surveillance • Electro-optical • Radar	Primary	Revisit Time • Resolution • Coverage (duty cycle)	Not Time Constrained (strategic intelligence) • Large Optics (large S/C) • Horizon to Horizon (~ 20%)	Multiple Regional Viewing Opportunities per Day (military operations) Moderate Optics (TACSAT) Regional (~ 1%)
Communications	Primary	Cost Increments	Large Steps in Capacity and Cost	Smaller Steps in Capacity and Cost
Missile Surveillance	Primary	Terminal Mobility	Fixed & Large Mobiles	Transportable or Mobiles
		Coverage	Horizon to Horizon	Regional (< 2000 x 2000 km)
Navigation	Secondary	Assured Capability	GPS	Augmented GPS
Weather	Secondary	Assured Capability	Civil Systems	Augmented Civil Systems
Maritime	Secondary	Area Coverage	Broad Area Coverage (oceans/seas)	Selected Area Coverage (seas/coastal)

Figure 6.4 TACSAT Impact on Cost

satellites were built, and the theatre mission for which TACSATs are envisaged.

It is appropriate to consider the budget impact that will occur when the current fleet of strategic satellites come up for replacement. The military and intelligence communities rely heavily on these assets and on the exquisite support they provide. The Working Group anticipates that the national authorities who sponsor these assets may want to retain these capabilities. Thus, the sponsoring nation would have to fund the associated redevelopment.

Against this backdrop will be a bow wave of redevelopment/redeployment costs for strategic satellites. But the military users are now pushing for this exquisite information within the shortest possible revisit time. "Something has to give." However, in the future, budgeting constraints will probably restrict the availability of strategic satellites. In such a climate, the Working Group is of the opinion that TACSATs can be a useful, low cost complement to these reduced strategic assets. The Working Group envisages a scenario in which there will be a need to employ both strategic satellites as well as TACSATs to provide, at an affordable price, the balanced service which the Working Group envisages future missions are likely to require. Within this scenario, strategic reconnaissance satellites will still provide the very fine information needed for data base generation and other missions, but not necessarily with a rapid turnaround. Strategic communication satellites will satisfy the base-load for information transfer. TACSATs will provide surveillance information at coarser resolution than the strategic satellites, but with a more rapid turnaround; similarly, in the communications domain, TACSATs will be used to incrementally satisfy the increase in capacity which will be needed during a theatre crisis.

The Working Group anticipates that the ability of any particular nation to commit to either a TACSAT program or a combined TACSAT and Strategic satellite program will be significantly helped by international collaboration and the establishment of a collaborative program to develop the TACSAT units. In this situation, a particular nation's ability to fund the redevelopment of independent strategic systems will be significantly assisted by collaborative involvements in TACSAT programs that will be technically less challenging.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 OBSERVATIONS

The following observations are provided in order to establish the TACSAT baseline from which the conclusions and recommendations were drawn.

a. *TACSAT technology is available today and can be put in the field within the time cycle of current procurement systems.*

b. TACSATs are defined as space systems that are specifically designed to support theatre tactical operations. However, they may fulfill other missions not in direct support of military operations, i.e., as supplements or complements to STRATSATs.

c. TACSATs can be used for many missions. In this report the following missions have been addressed.

- battlefield surveillance (visible, IR, radar),
- communications (UHF, SHF, EHF),
- missile warning and assessment,
- regional maritime surveillance and environmental observations,
- weather,
- navigation.

d. The TACSATs missions are optimized to:

- limited area in size,
- fast zone accessibility,
- short revisit time,
- short information collection and dissemination time,
- accurate localization.

e. The TACSAT definition does not imply that the spacecraft must be small, however most of the TACSAT missions can be fulfilled with moderate size spacecraft (500 to 750 kg) of limited lifetime.

f. TACSATs for battlefield surveillance are complementary to strategic satellites whose mission is to collect accurate information on adverse force characteristics during peacetime. For this purpose, strategic satellites need very good spatial resolution, but need not adhere to strict timeliness constraints. TACSATs, on the other hand, are mainly used to quickly recognize and locate well known enemy forces which emphasizes the need for short revisit times.

g. Interoperability of TACSATs between NATO nations would be of great advantage.

h. Detailed definitions of the use of TACSATs, in concert with STRATSATs, are needed.

i. Cost could be lowered by using TACSATs with a low level of internal redundancy. However, costs may be increased when the number of these satellites is increased to cover a relatively long period of time with short individual satellite lifetimes, unless advanced technologies such as miniaturization and high functional integration leading to substantial parts count reduction are used in TACSAT subsystem electronics to enhance reliability and hence lifetimes.

j. Two different procedures may be followed to launch TACSATs:

- the satellite is put in a waiting orbit, and transferred, at the right moment, into the tactical orbit which will frequently fly over the zone of interest (for LEO systems) or dwell over the zone of interest (for GSO systems).

- the satellite is launched on request directly into the tactical orbit.

- The first solution requires some manoeuvering capability but does not set any constraint on the launcher. In addition, several TACSATs can be launched by the same launcher into the parking orbit, therefore, at low cost per satellite. The second solution needs both the launcher and the spacecraft ready at short notice, at any time, and abbreviated ground operations.

7.2 GENERAL CONCLUSIONS AND RECOMMENDATIONS

PREMISE: It is most likely that no single nation will individually develop TACSATs. As a result, such an effort can only succeed as a joint multi-national or, in the lower limit, as a bi- or tri-lateral undertaking. However, once development is complete, the procurement can allow one or more nations to draw from a supply of spacecraft and deploy them for their own purposes without inhibiting rules from other nations. This approach will influence how the systems are launched and controlled from the ground. The development of TACSATs make the national ownership of launch and control facilities and space assets more practical for those NATO nations that wish to carry out such a course.

With this premise in mind, the following are the general conclusions and recommendations of the Working Group.

a. TACSATs should have a major role in the NATO environment of smaller forces and the sudden evolution of old and new enemies. This role is seen as:

- Providing a significant force multiplier to the limited terrestrial forces at reduced cost.
- Providing denied area support, particularly in areas of limited NATO infrastructures, taking advantage of the high revisit attributes of TACSATs.
- Providing a significant advantage of NATO forces over any potential enemy.
- Providing dynamic space capabilities that can be varied in magnitude and geographic support as an inherent part of the system designs, with smaller cost increments.

b. There are major national space procurement decisions under consideration by several NATO member nations in the mission areas of: battlefield surveillance, missile warning and assessment, SHF follow-ons, EHF polar coverage and follow-on, weather and maritime support. As a result, TACSATs should be given emphasis at NATO so that these decisions can be influenced to treat TACSATs as an option to future national satellite procurements.

c. To ensure the above recommendation can be implemented without delay, the following actions should be taken under the leadership of a "space cell" formed within NATO:

- a requirements list be established for TACSATs from existing requirements in each mission area and other requirements that are in the review process,
- that system studies and technology studies be undertaken by an industrial group involving companies from NATO nations.
- that an agreement between NATO nations be reached on TACSAT policy,
- that a long term plan for TACSAT development and procurement be established,
- that the proposed long term plan incorporate and support early acquisition of dedicated TACSATs.

7.3 MISSION AREA RECOMMENDATIONS

7.3.1 Battlefield Surveillance

A demonstration program (both E-O and SAR) is needed by 1998.

The objective should be to demonstrate the operational concept using a smaller visible image camera, so that the entire spacecraft could be launched on a relatively inexpensive launch vehicle, which can carry 500 kilograms. An existing ground station should be enhanced to support mission planning. This demonstration could be ready for execution in 1996 at a cost of $100 million.

Later, the concept should be demonstrated and validated with a full size visible and infrared electro-optical payload using expendable cryogens on board. Also, a SAR configuration should be built for launch using a common spacecraft bus. The two satellites should be launched on Taurus-like launch vehicles. For this demonstration, an additional ground station should be purchased. The projected cost for this phase would be approximately $300 million with a launch date of 1998.

7.3.2 Communications

a. *TACSAT Working Group Recommendations*
A priority for future air/land operations is the development of highly-mobile, high-availability and secure tactical satellite communications systems with good ECCM protection. These systems are seen as the primary communications tools of the tactical commander, replacing hill-top repeaters and tropo-scatter links in the large and highly-dispersed battlefield of the future. TACSATs should be regarded as the ultimate "high ground" for radio relay.

For U.S. forces, a survivable capability will be provided by the EHF Milstar system. Milstar may be augmented in the near term with EHF satellites (similar to TACSATs) in polar orbit, to provide northern coverage not available from the GSO system. In the future, NATO should consider using EHF TACSATs for this purpose.

For the other NATO nations, it is likely that SHF will continue as the backbone system, due to the existing heavy investment in this area. EHF will likely be provided in next-generation systems for those users requiring mobility with high ECCM protection and compatibility with U.S. forces in international operations. A TACSAT approach is the most appropriate and should be pursued now.

The backbone of tactical satellite communications for many alliance navies will be the SHF/UHF systems. The present GSO satellites should be complemented with SHF TACSATs in alternative orbits, to provide northern coverage or to augment capacity where required.

The development of TACSATs will encourage a trend towards national ownership of space assets, including launch capabilities.

b. *Working Group 13 Recommendations*[1]
Avionics Panel Working Group 13 made recommendations on communications satellites. These recommendations are consistent with conclusions drawn by Working Group 16 in this report. A summary of the Working Group 13 study is presented below.

It is likely that cost will be the driving factor in determining the choice of a future SATCOM architecture and it is therefore appropriate to consider the three dominant cost factors, research and development (R&D), satellite replacement and launch costs, and indicate what steps could be taken to bring about cost reduction in each case:

1) Economy in R&D costs could be obtained through NATO/National collaboration and by adopting a modular approach to system diversification and evolution. An effective way of achieving the latter would be to develop at the outset separate SHF and EHF spacecraft and use them, in GSO and TUNDRA orbits alike, in a mix determined by the changing requirements.

2) The use of smaller spacecraft, even though more of them may be needed, could lead to lower system costs because of the economies of scale. Such economies of scale would be further enhanced if the same spacecraft types are used at all stages of system evolution over a period of, say, twenty years. They will also be enhanced if the same spacecraft types are bought for national as well as NATO use.

3) Launch costs can be minimized by reducing spacecraft mass, in particular through the exploitation of new technology. It is also important to maximize compatibility with the largest possible range of launch vehicles.

4) Interconnection of spacecraft increases system reliability and therefore tends to reduce the total number of spacecraft that need to be launched.

5) Finally, long-term planning is the key to achieving reductions in both R&D and recurring costs.

The NATO SATCOM systems so far acquired have been based on national developments adapted to NATO requirements and the continuity of service (not necessarily full service) has been obtained by sharing or borrowing capacity from national systems. The national systems, in turn, have relied for continuity of service on the availability of capacity on the NATO system. Each procurement has contained an important element of R&D costs and since successive systems have been developed almost independently of each other, R&D costs have been, like the replacement cost, also recurring.

There has been a minimum of joint national R&D and use of the system and each procurement has been preceded by lengthy negotiations on production sharing which has not, in general, satisfied at least some of the member countries. As a result of having independent NATO and national systems there have been considerable interoperability problems.

It is believed that this trend, based on successive jumps in spending and capability with a minimum degree of general national participation should be and can be changed to meet the needs of the coming decades which may be characterized by uncertainty and shrinking military budgets requiring affordable and flexible systems.

[1]AGARDOGRAPH 330, "Considerations for NATO Satellite Communications in the Post 2000 Era," published by AGARD - June 1991.

The member countries have adequate experience within NATO and Europe and know that under these circumstances it is necessary to resort to joint R&D, procurement and use of the system while ensuring effectiveness and competitiveness for keeping the costs down.

7.3.3 **Ballistic Missile Warning and Assessment**
This mission area is critical to survival of NATO forces and to carrying out appropriate response actions in the face of a theatre ballistic missile attack on NATO and member nation interests. There are two mutually dependent recommendations.

a. NATO and the individual member nations should develop experience in space-based missile warning techniques through the display of missile tracking data from the current DSP program anticipating NATO operation of TACSAT missile warning satellites.

b. Initiate a joint TACSAT design definition effort.

7.3.4 **Navigation**
This mission area is adequately supported with GPS. However, some deficiencies remain. A limited evaluation should be pursued of the concepts reviewed by the Working Group. Key constraints are that the evaluation team must take advantage of the other TACSAT concept work in order to significantly reduce costs and that the TACSAT navigation concepts should be compatible with existing satellite navigation systems.

7.3.5 **Weather**
NATO should assume that most support in this mission area will be provided by the civil systems of the member nations. In this context, an effort should be initiated to determine those military critical functions that will not be met by such systems. TACSAT options should be defined that will fill the deficiencies and that can benefit from TACSAT concepts developed in other mission areas.

7.3.6 **Maritime**
Some maritime applications such as environmental monitoring or surface ship surveillance appear to be well suited for TACSAT concepts sometimes with off-the-shelf instruments. However, NATO should define which maritime payloads are appropriate for their needs. Design definitions and preliminary costs should be developed.

7.4 ADDITIONAL RECOMMENDATIONS

7.4.1 **Common Bus**
One or two common spacecraft bus concepts will probably suffice to encompass the mission areas herein considered, bringing the potential for reducing overall TACSAT costs. Commonality also may have the benefit of providing a standardized system (bus, booster, and ground control) where significant development for future new missions need only concentrate on the payload, thus maximizing the impact of the investment. As a result, NATO should pursue investigations in this area that include applicable off-the-shelf concepts, and the design and costing of a joint dedicated system. The ultimate purpose should be to verify the cost effectiveness of such an approach.

7.4.2 **Launch Systems**
An early determination should be made of which launch systems are best suited for TACSAT use, both for dedicated rapid reaction launch, launch on schedule, and the launch of two or more spacecraft in a single event. Operational and design constraints should be identified early; for example, orbit inclination restrictions, mobility, spacecraft interface limitations, minimum turn-around times, etc. Included in this determination should be the accessibility of the launch vehicles to all NATO member nations.

7.4.3 **Ground Operations**
Options should be developed for the control of TACSATs in each mission area. These options should span the range of in-theatre to out-of-theatre architectures. Care must be taken to distinguish between on-orbit maintenance functions, and tasking and data dissemination during military operations. This effort should parallel the mission area investigation described above.

7.4.4 **Training**
Simulation facilities are likely to bring significant cost benefits to the training of staff in the use and operation of TACSAT systems and consideration should be given to the type of facility best suited to this simulation.

The need for rapid build-up of an operational capability when a theatre crisis is identified, has been interpreted as a need for Users and Operators to be pre-trained and familiar with real TACSAT systems. It is therefore recommended that both Users (of the information provided by the system) and Operators (of the hardware assets of the system) should complete their training with exercises conducted on real TACSAT systems.

In addition, work will need to be undertaken to establish an appropriate balance between the cost/complexity of simulator facilities used to support the training function and cost/value of access to real, on-orbit TACSAT systems for training activities.

A consequence of this recommendation of the use of real TACSAT systems to support training is that TACSAT system concepts which use long-life satellites–possibly stored in orbit (and therefore potentially available for training)–may provide a lower cost approach to regular training than the repeated launching of short-life TACSATs. The recommendation may therefore be a significant driver towards longer life TACSATs.

7.5 Need For Expeditious Design and Study Efforts

In the six mission areas addressed by this report, spacecraft replacements will be needed in the 2002 to 2005 timeframe. If TACSATs for NATO are to be considered as major options for these replacements, the NATO operations and design studies must be completed and reviewed for action by 1995.

The Working Group recommends NATO pursue these studies immediately with the goal of deciding on whether to pursue TACSATs as a part of the NATO force structure, in the summer of 1995.

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14. Abstract

Tactical Satellites (TacSats) are studied to determine their utility in meeting the needs of theatre commanders. Six mission areas are studied: battlefield surveillance, communications, tactical missile warning and assessment, regional maritime surveillance, navigation and weather. The synergistic role between strategic and tactical satellites is also considered. TacSat system concepts are provided in most mission areas as are means of implementing TacSat systems, including the launch and ground system segments. Issues raised in these areas are discussed. Finally, TacSat costs are discussed and the Working Group's conclusions and recommendations are provided.

This Advisory Report has been prepared at the request of the Avionics Panel of AGARD.

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