



Communications
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SHIPBOARD SATCOM TECHNOLOGY INVESTIGATION

Final Report for Period 1 Sept. 97 through 31 Mar. 98
CRAD Work Unit WU 1bb17 "Satcom Technology"

by

E. Barry Felstead and J. Claude Bélisle

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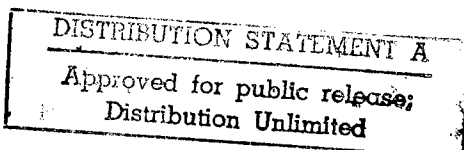
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October 1998
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ABSTRACT

Satellite communications (satcom) is becoming the essential Navy link. There are many topside satcom problems including physical size, weight, blockage, cost, and electromagnetic interference (EMI) between the many shipboard electronic systems. There is a need for innovative antenna technology to reduce these problems. A previous study provided a brief overview of Allied use of milsatcom and trends in shipboard terminals. In the present study, the work is carried further. First, parameters and features needed by the Navy are outlined. Then, the features of a variety of military and commercial satcom systems that could satisfy these needs are provided. A brief overview of shipboard terminals is provided. Finally, a road map for future research and development for shipboard antennas is given, and consisted of two directions.

The shorter-term first direction involves the use of available demonstrator antennas and electro-magnetic interference (EMI) simulation software. In the longer-term second direction, it is proposed that advanced-antenna approaches be pursued. Again, two directions are proposed. One direction is already currently underway at DREO. This effort could be called the "building-block" approach to phased arrays, wherein certain components of array elements are developed. In a second advanced-antennas direction, it is proposed that innovative antenna approaches be investigated. Four such approaches are suggested and more should arise as work progresses.

RÉSUMÉ

L'utilisation de satellites comme moyen de communications devient de plus en plus essentielle pour la Marine. Il y a cependant plusieurs problèmes reliés à ce medium, tels la dimension physique des antennes, le blocage du lien par les structures du navire, le coût, et les interférences électromagnétiques entre les différents systèmes électroniques à bord des navires. Il y a donc un besoin pour développer de nouvelles technologies d'antennes pour réduire ces problèmes. Dans une étude précédente, un bref aperçu de l'utilisation des satellites comme moyen de communications par nos Alliés ainsi que des nouvelles tendances dans le développement de terminaux pour la Marine ont été donnés. Dans le présent rapport, cette étude est poursuivie. Premièrement, les paramètres et caractéristiques requis par la Marine sont énumérés. Les caractéristiques de divers systèmes de communications par satellites, militaires et civils, pouvant satisfaire ces besoins sont décrits. Un bref aperçu de terminaux pour applications maritimes est donné. Finalement, un plan de recherche et développement pour de nouvelles antennes maritimes est décrit. Ce plan est constitué de deux volets.

Dans une première étape, à court terme, il est proposé d'analyser, par méthodes numériques, les problèmes d'interférences électro-magnétiques et de tester à bord de navires, une antenne peu complexe. Dans le deuxième volet, à plus long terme, il est proposé d'étudier certaines approches innovatrices dans le design d'antennes. Une première approche, présentement à l'étude au CRDO, consisterait à développer certaines composantes d'une antenne à ouverture de phase. Une deuxième approche, plus globale, consisterait à développer des techniques innovatrices de conception d'antennes. Quatre approches sont proposées et plusieurs autres pourraient être proposées au cours du projet.

EXECUTIVE SUMMARY

Future Navy satellite communications (satcom) needs are creating considerable demand upon cost and topside resources. There are numerous problems in implementing shipboard satcom including physical size, weight, blockage, cost, and electromagnetic interference (EMI) between the many shipboard electronic systems. There is good opportunity for innovative antenna technology to overcome these problems. Furthermore, a major refitting of the Canadian Patrol Frigates (CPF) is planned for the period around the year 2010. It would therefore be an excellent opportunity to plan for the introduction of new satcom equipment. Since the Canadian Navy cannot wait until 2010 to equip its ships with these new services, interim solutions will need to be found. Therefore, it is imperative that the suitable equipment be researched and developed for both the interim and the 2010 periods.

The work for this Report continues the background study started in a previous report for the Director Maritime Ship Support (DMSS). That study provided an overview of allied use of milsatcom and trends in shipboard terminals. Various antenna technologies were briefly described such as multi-band-multi-beam reflectors and phased arrays. In the present study, the work is carried further in four topics as follows.

In the first topic, parameters and features needed by the Navy are examined in general outline. The approach used here is to list the parameters and features desired by the Navy but tempered by a number of practical constraints. This list is therefore a "wish list" rather than strict requirements. Included in this list were items from both the Canadian Military Satellite Communications (CMSC) office and from USN planning sources. The list included:

1. Services, Types, and Connectivity Categories
2. Throughput and Its Impact on Robustness
3. Interoperability
4. Coverage
5. Data Security
6. Electronic Protective Measures (EPM) (both anti-jam and low-probability of exploitation (LPE) techniques)
7. Antenna Limited Small-Deck Ships
8. Adaptability, Flexibility, and Automation

In the second topic, a variety of current and future satcom systems, especially ones that would be useful to satisfy the identified needs, were compared in tables as to how they correspond to the features listed above. Examples of satcom systems of potential use to the Navy were given under the categories of:

1. Existing Commercial Geostationary Systems
2. Existing Non-US Military Satcom Systems
3. Existing US Military Satcom Systems
4. Emerging US Military Satcom Systems
5. Commercial Low or Medium Earth Orbit Low Data-Rate Satcom Systems
6. Commercial High Data-Rate Satcom Systems

In the third topic a very brief overview of shipboard terminals is provided. The existing DND inventory is outlined. The vast number of military terminal types is indicated and it is noted that such a proliferation of types is a problem.

In the final topic, a road map for future research and development for shipboard antennas is given. There are two directions recommended. The shorter-term first direction involves the use of available demonstrator antennas and electro-magnetic interference (EMI) simulation software. Such work would be useful for determining or predicting shipboard EMI conditions and as an educational tool. In the longer-term second direction, it is proposed that advanced-antenna approaches be pursued. Again, two directions are proposed. One direction is already currently underway at DREO. This effort could be called the "building-block" approach to phased arrays, wherein certain components of array elements are developed. In a second advanced-antennas direction, it is proposed that innovative antenna approaches be investigated. Four such approaches are suggested and more should arise as work progresses. These four are 1) Integrated antennas wherein multiple antennas are combined in one "stack", 2) continuous transverse stub arrays, 3) photonics for distribution and control of RF signals, and 4) use of hybrids of mechanical and electronic steering along with distributed apertures. Such advanced approaches have potential for greatly reducing costs and many of the topside antenna problems.

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1. INTRODUCTION

The communications requirements for Canadian Navy ships are ever increasing. Present communications systems are already being used at capacity and will therefore not be able to support the increased demand. However, with the advent of many new satellite communications (satcom) services, both military and commercial, there are unprecedented possibilities for providing future ship-communications needs. Satcom is now viewed as "the essential link" within the US Navy (USN) [1]. Similarly, it is stated in [2] that the next generation of satcom is critical to the goal of efficient employment of smaller USN force structures. It goes on to discuss nine USN functions that could be significantly enhanced by satcom connectivity.

A major refitting of the Canadian Patrol Frigates (CPF) is planned for the period around the year 2010. It would therefore be an excellent opportunity to plan for the introduction of new satcom equipment. Of course, the Canadian Navy cannot wait until 2010 to equip its ships with these new services, and interim solutions will need to be found. Therefore, it is imperative that the proper equipment be researched and developed for both the interim and the 2010 periods.

There are numerous problems in implementing shipboard satcom including physical size, weight, blockage, cost, and electromagnetic interference (EMI) between the many shipboard electronic systems. There is good opportunity for innovative antenna technology to overcome these problems.

As a first step toward innovative antenna technology, a study [3] was commissioned by Director Maritime Ship Support (DMSS) in the area of future naval satellite communications (satcom) for the Canadian Navy. It was performed at the Defence Research Establishment Ottawa (DREO). It provided a brief overview of Allied use of military satellite communications (milsatcom), and trends in shipboard terminals. Various antenna technologies were briefly described such as multi-band-multi-beam reflectors and phased arrays. The present study attempts to correlate these technologies with the characteristics of present and proposed satellite services in light of future Navy communications needs.

In this report, parameters and features needed by the Navy are examined in general outline in Chapter 2. Then, in Chapter 3, the features of a variety of current and future satcom systems, especially ones that would be useful to satisfy the

identified needs, are provided. An overview of potential shipboard terminals is provided in Chapter 4. Finally, a road map for future research and development for shipboard antennas is given in Chapter 5.

2. TASK 1— IDENTIFICATION OF COMMUNICATIONS PARAMETERS AND FEATURES

2.1 INTRODUCTION

In this Chapter, an attempt is made to identify future needs of the Navy in satellite communications. Identification of those needs, however, is a difficult task since the requirements process is always ongoing and evolving. The approach used here, is to list the parameters and features desired by the Navy but tempered by a number of practical constraints. This list is therefore a "wish list" rather than strict requirements. Included in this list were items from both the Canadian Military Satellite Communications (CMSC) office and from USN planning sources.

The parameter and features topics were divided into eight categories and form the basis of the following eight sub sections. These categories are:

1. Services, Types, and Connectivity Categories
2. Throughput and Its Impact on Robustness
3. Interoperability
4. Coverage
5. Data Security
6. Electronic Protective Measures (EPM) (both anti-jam and low-probability of exploitation (LPE) techniques)
7. Antenna Limited Small-Deck Ships
8. Adaptability, Flexibility, and Automation

2.2 SERVICES, TYPES, AND CONNECTIVITY CATEGORIES

Communications services, types and connectivity for Navy ships are many and varied [4]. As an indication of the complexity that can arise, the perceived US Navy service requirements as seen in 1997 are illustrated in Fig. 1 [1]. For simplicity, the categories of interest to the Canadian Navy have been reduced in [5]. Therein, the communications services are simply categorized as voice, record message traffic, data links, imagery, and video. The types are categorized as secure, plain, store and forward, and series messages. Connectivities include ship to shore to ship, inter ship, terrestrial, air to ground to air, and air to ship to air.

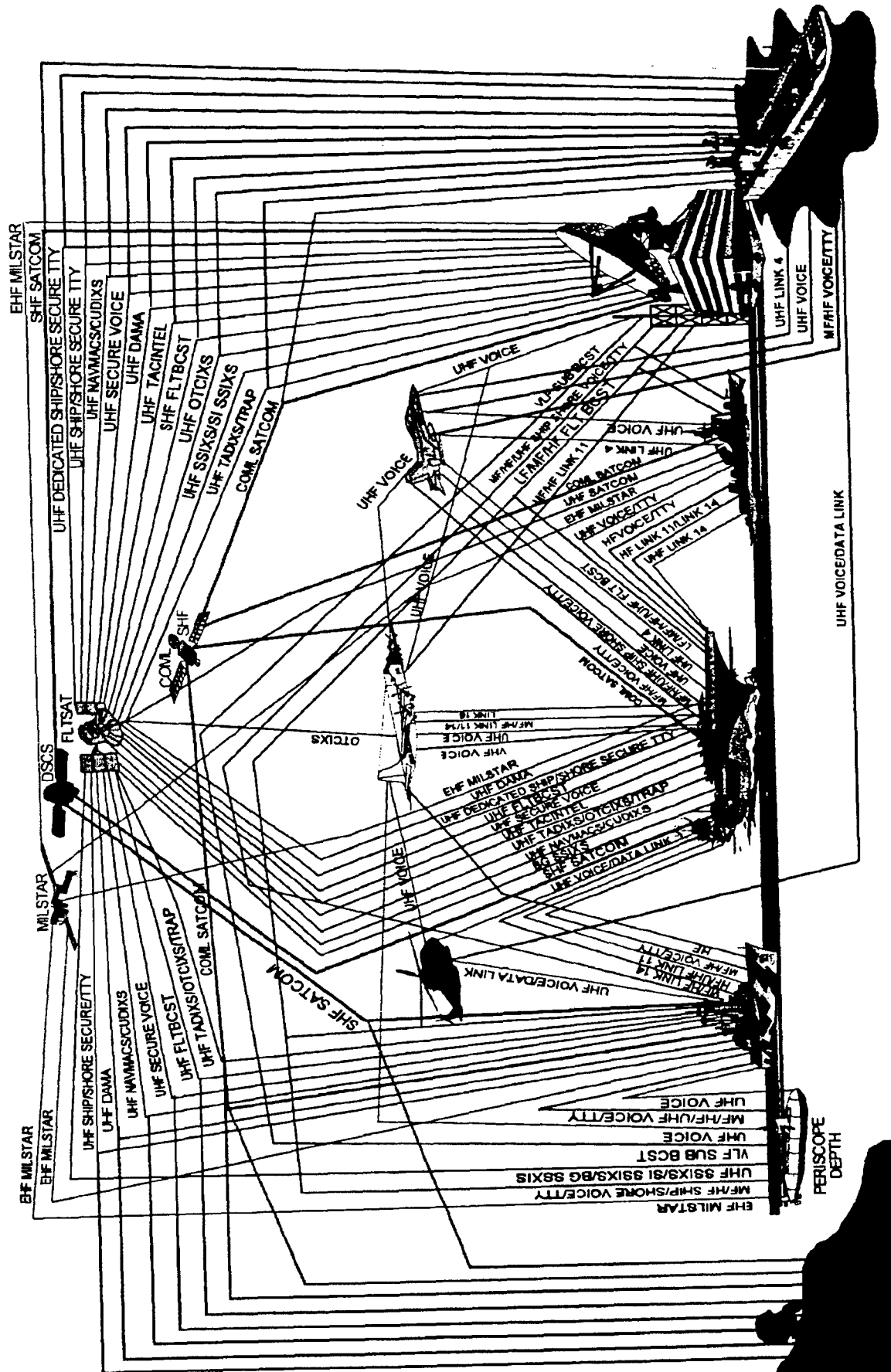


Fig. 1. US Navy service requirements diagram as seen about 1997 [1].

To simplify the large and complex set of needs, systems, and applications, the US DoD has divided missions into two broad categories: core war-fighting missions, and general purpose missions. Diagrams of such categories have been a feature of DoD presentations since about 1993. One such diagram [6] is illustrated notionally in Fig. 2 but with applications and satcom systems modified to better fit the CF needs. Also in this diagram is an indication of where some applications fit in, and systems that meet the missions. Also in Fig. 2 are some representative satcom systems. Later, the trade off of robustness for throughput will be discussed.

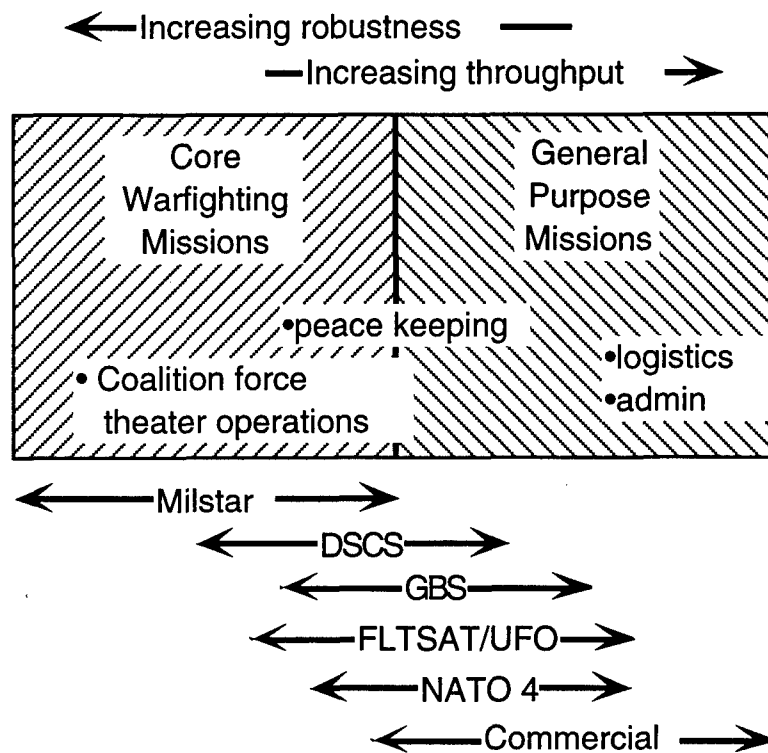


Fig. 2. A notional diagram of CF mission categories as modified from the two US communications mission categories. Considerable liberties were taken. It is assumed that milsatcom space segment will be provided by the US through an MOU.

2.3 THROUGHPUT AND ITS IMPACT ON ROBUSTNESS

In [5], it is stated that "For the foreseeable future, it is assumed that the capacity of any communications medium will never be larger than the operators requirements. The medium's capacity will always be the limiting factor; therefore, in general terms communications capacity requirements are for as much capacity as can be provided." In [6], it was pointed out that up to the end of the Cold War, the viewpoint of DoD was that satcom robustness and other military considerations

were of more concern than throughput capacity. The Gulf war changed that concept. Since then, it is considered that capacity is the dominating factor, echoing the above quote from [5].

As suggested in Fig. 2, there tends to be a tradeoff between throughput and robustness with increasing robustness to the left of the diagram, and increasing throughput to the right. However, such a tradeoff arises from technical and cost considerations rather than requirement considerations.

In view of the above, it is realized that a detailed listing on needs in Mbit/s for various ship types, and applications would always be out of date. Nonetheless, as a starting point, the gross throughput requirements were estimated in 1996 by the CMSC Project Office [7] as:

- Total CF throughput: 55 Mb/s
 - 27 Mb/s commercial
 - 28 Mb/s military, normal operations
 - 3 Mb/s military in stressed conditions

The Navy requirements were :

- Each warship throughput: 300 kb/s.
- Aggregate throughput: 3 Mb/s.

The ratio of commercial, military, and stressed was not specified.

Whether these future requirements will actually be satisfied cannot be predicted here. For purposes of this Report, two concepts will be used. For robust military communications (see Fig. 2), the throughput capacity will be provided by the CMSC Project based upon stated Navy requirements. For the commercial based communications, the throughput will be open ended, and will be limited by cost, real estate, weight, and networking factors.

In some applications, the traffic flow is asymmetrical with rates in one direction being much larger than in the other. The primary example is the Global Broadcast System (GBS) which is one-way communications to the ship.

2.4 INTEROPERABILITY

There are a number of interoperability issues of concern. In [5], interoperability with the USN was of major concern. Also, the Communications System and Network Interoperability (CSNI) project was highlighted as a solution to a number

of military system and network problems. Other interoperability areas noted in [5] were with NATO, and cryptographic.

2.5 COVERAGE

Satcom coverage relates to the locations in the world where satcom can be achieved. Quoting from [5]:

"The nature of maritime operations is such that the forces of Maritime Command could be deployed anywhere in the world in response to a tasking from the government. ... Canada does not have the resources to establish a national military satellite communications network with world-wide coverage; therefore, achieving this requirement will require a flexible, multi-thrust approach."

The military satcom coverage viewpoint from the CMSC office is stated in a different way that the Navy requirements were for coverage from Hawaii to the Mediterranean and as far north as possible [7]. However, it is intended that outside this region some limited capacity would be needed on rare occasions, and military satcom service would necessarily have to come from allies on a secondary basis.

Coverage will ultimately depend upon what systems are actually used. It will likely vary considerably from satcom system to satcom system, whence the need for the "multi-thrust" approach mentioned in the above quote.

2.6 DATA SECURITY

Navy data security needs are summarized in [5]:

"It is vital, for multi-level security reasons, that embedded crypto be integrated into information transfer systems, ... Cryptography must be available at user terminals, thus eliminating the need for large red/black areas and allowing information compartmentation to take place down to the user level. Further levels of security can be added through Transmission Security (TRANSEC) or Communications Security (COMSEC) systems."

Both TRANSEC and COMSEC are obviously part of any milsatcom system in which Canada would be involved. Conversely, in commercial satcom, it would be necessary to add COMSEC to the system if possible. Such added capability seems to be moderately common and seen from a number of examples. INMARSAT supports full STU-III capability. A second example is that ANIK-E has an encrypted TT&C channel which was paid for by DND so as to provide extra security for North Warning satcom links. A third example is that a number of upcoming personal

communications satcom are touting STU-III compatibility. These companies are clearly after military business. Finally, a STU-III interface has been developed at CRC and exploited commercially for MSAT use.

2.7 ELECTRONIC PROTECTIVE MEASURES (EPM)

Electronic Protective Measures (EPM) are techniques used to combat hostile electronic actions against the communications. These techniques include low probability of exploitation (LPE) and anti-jam (AJ).

LPE describes the capability of being resistant to exploitation of intercepted signals. The exploitation includes simple detection of signals, direction finding, geolocation, and demodulation of received signals. Low probability of interception (LPI), and low probability of detection (LPD) are subsets of LPE. There are a variety of techniques used to provide some level of LPE. The main methods of obtaining LPD and LPI for terminals are waveform techniques through the use of spread spectrum, and antenna techniques through the use of narrow beams and spread spectrum.

Because ships have no possibility of terrain shielding, they are especially prone to such exploitation, so that LPE is very important to the Navy. The USN views LPE as very important. An indication of the importance is found in the JMCOMS Master Plan [8] where a major R&D effort is proposed on the topic of "low-observable and multi-function antennas". The desire is to develop multi-function antennas with low radar cross section (RCS) for shipboard use.

There are a variety of techniques used to combat jamming. These techniques include spread spectrum and antenna spatial techniques. The spatial techniques include use of antennas with narrow beams and low side lobes, up to nulling antennas. In milsatcom, uplink jamming of satellites is more of a concern than downlink jamming of terminals. As a result, antenna spatial techniques are often done at the satellite but rarely at the terminal. The robust milsatcom systems all use various levels of spread spectrum.

Because of the crowded shipboard electro-magnetic (EM) environment, there is considerable potential for self interference on satcom receivers and vice versa. The classical example, perhaps apocryphal, is the H.M.S. Sheffield turning its radar off during a satcom session and thereby missing detection of the incoming Exocet. Fortunately, for milsatcom, robustness against jammers provides similar protection against "friendly" interference.

Fortuitously, spread spectrum, narrow beams, and low sidelobes all provide various degrees of *both* LPE and AJ capability.

2.8 ANTENNA LIMITED SMALL-DECK SHIPS

The problem with ship board antennas was summarized in [5] as:

"Naval implementation of shipboard SATCOM technology has, and will continue to have, integration problems in the area of antenna installation onboard HMC Ships. Physical size and weight considerations of current and future SATCOM antennae are an ongoing engineering problem."

Similarly, with the USN, the problem is stated in [9] as:

"... 'small-deck' ships — anything that isn't an aircraft carrier. The mission effectiveness of U.S. Navy surface combatants is currently 'antenna limited.' We are not limited by how many more computers we might put below decks, we are limited by how many more antennas we can put topside. While each one performs useful functions, each one also contributes to one or more undesirable ship characteristics:

- Topside weight and moment*
- Radar cross-section*
- Electromagnetic interference (EMI)*
- Physical obstruction of other antennas*
- Electromagnetic distortion of other antenna patterns"*

An indication of the importance is again found in the JMCMS Master Plan [8] on the topic of "low-observable and multi-function antennas". The USN is looking at a variety of methods to mitigate these problems through innovative technology. The concern is the current proliferation of single function, large aperture topside antennas.

An example of the topside-antenna considerations needed when trying to develop a new satcom system is found in [9] and [10]. A Ka band terminal was installed on the USS Princeton (CG 59) to operate up to 1.5 Mb/s full duplex using the ACTS satellite. On the Princeton, there were 26 systems that could involve EMI problems. Extensive measurements were made on the effects of these 26 systems on the Ka demonstrator system, and vice versa. Obviously, an enormous amount of effort was needed for these measurements. Five locations were considered for the antenna as shown in Fig. 3. Position number 5 was the best position from a blockage viewpoint. It is seen in the blockage pattern of Fig. 4 that antenna has a 360° unobstructed view of the sky for elevation angle above 45°, except for a slight intrusion by an HF whip antenna. Such blockage measurements are an important step in installing new systems. It is also clear that by introducing multi-function multi-band antennas, the blockage problems are reduced. Similarly, flat phased-array antennas would also be useful.

2.9 ADAPTABILITY, FLEXIBILITY, AND AUTOMATION

As discussed in [5], it is important that future Naval communications have the features of adaptability, and flexibility, as well as a considerable degree of automation. From [5]:

“Multi-media communications refers to the concept of transmitting information through an assortment of communication links and services [available on a ship] which are transparent to the user. Today's fixed, dedicated communications architecture with single users assigned exclusive modems and radio equipment, is both inefficient and wasteful of personnel resources and communications bandwidth. Future communications systems must be priority based, shared access, multi-media systems that provide flexible access to all communications links” By multi-media is meant the transmission of information through an assortment of communication links and services that are transparent to the user.

In order to combine such features with the various communications systems, it is necessary to have suitable signal distribution, protocols, networks, automatic controllers, etc. In the JMCMS architecture [8], a major effort, called the “Automated Digital Network System (ADNS)”, is devoted to incorporating these features. The ADNS links the many shipboard user applications with the many shipboard communications systems. A corresponding effort in Canada, along with

other NATO countries is the Communications System and Network Interoperability (CSNI) project. A variety of tests and demonstrations have taken place.

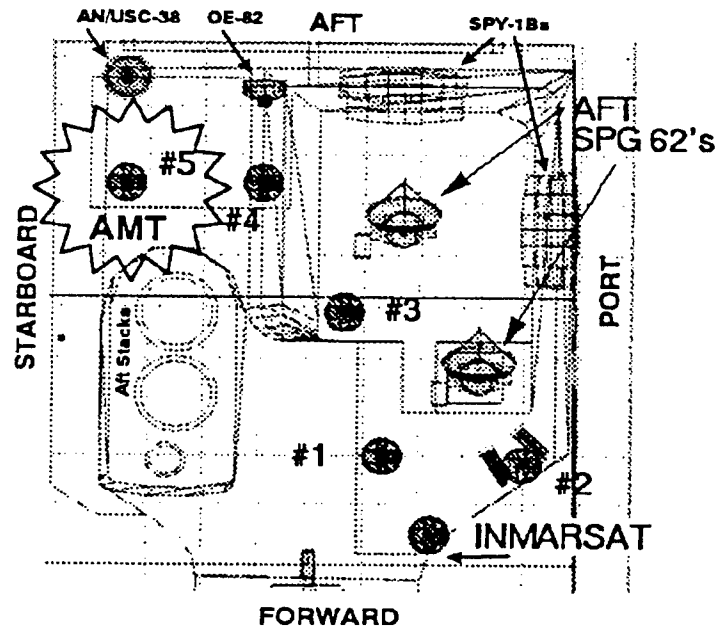


Fig. 3. The five topside locations considered for the Ka-band demonstrator antenna.

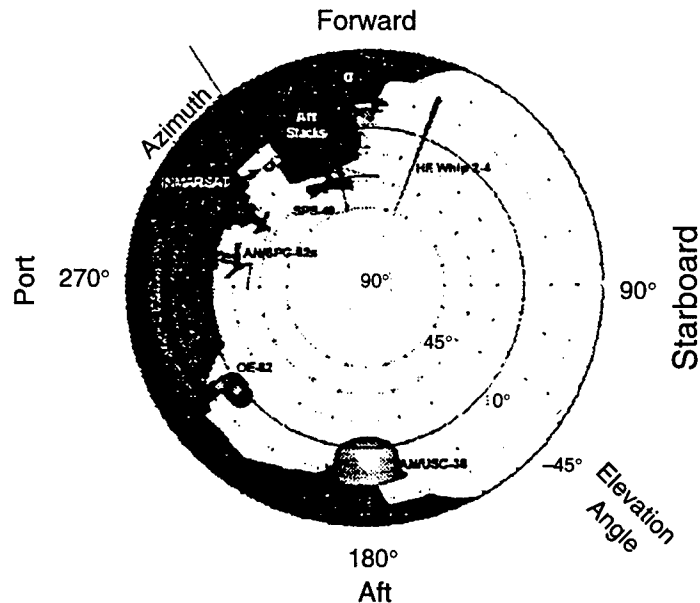


Fig. 4. Blockage plot for the antenna in location #5 shown in Fig. 3.

3. TASK 2— IDENTIFICATION OF SATCOM SERVICES AND CHARACTERISTICS

3.1 GENERAL

In this Chapter, actual and proposed commercial and military satcom systems that could possibly meet the requirements identified in Chapter 2, will be identified. Their relevant characteristics are provided primarily in the form of tables. There are many existing and planned satcom systems. To keep the study within reasonable bounds, the number of systems listed was limited. The commercial systems were chosen on the basis of both the likelihood that the system could potentially be used by the Canadian Navy, and, for future systems, the likelihood of the system actually being deployed. Clearly, not all proposed systems will be successfully deployed and put in use. The military systems were chosen based upon the likelihood of access by the Canadian Navy. Use of the US DoD systems will be provided by an MOU through the CMSC Office.

The information for the tables came from a variety of sources including references [4], [11], [6], and [12]. The names at the head of the columns usually describe specific satcom system with a constellation of satellites. However, in DBS and GBS, it is more a generic type being described. The Tables have been divided into six categories:

- Existing commercial GEO lower-rate satcom systems
- Existing non-US military satcom systems
- Current US military satcom systems
- New and emerging US military satcom systems
- Commercial LEO/MEO low-rate satcom systems
- Commercial high-rate satcom systems

Here, GEO, LEO, and MEO refer to geostationary, low-earth, and medium-earth orbits, respectively.

3.2 TABLES OF SATCOM SYSTEMS AND THEIR CHARACTERISTICS RELATED TO SHIPBOARD USE

3.2.1 Existing Commercial GEO Systems

In the category of commercial GEO satcom systems, three are listed in Table 3.1. Inmarsat is already used by the Navy. ANIK E is used by DND for North Warning satcom links but is not likely of potential use to Navy ships. MSAT is listed because

because it is a Canadian system which could be used from ships but limited to near the two coasts and the Caribbean. Typical Inmarsat connectivity is illustrated in Fig. 5. Inmarsat is an umbrella system that makes use of three satellite systems, MARISAT, INTELSAT V, and MARECS. The ocean coverage is illustrated in Fig. 6 which shows a small gap off the Pacific coast of South America.

TABLE 3.1. Characteristics of existing commercial GEO lower-rate satcom systems.

System Parameter	Inmarsat A & B	ANIK E	MSAT/AMSC
Service provided	voice, facsimile, slow-scan TV, telex, & low rate data. Inmarsat B ≤ 64 kb/s, sufficient for video teleconferencing	E1 primarily for business services. E2 broadcast comms mainly for TV	Mobile and fixed voice up to 4800 b/s, STU-III interface available
User band(s)	L (see Fig. 5)	C and Ku	L
Coverage	Leases satellites from MARISAT, INTELSAT, and MARECS. See Fig. 6 for ocean coverage.	Canada and northern US coverage, relatively little coverage over the east and west coasts	GEO satellite coverage of Canada, US, Mexico and Caribbean
Connectivity	Ship \leftrightarrow shore 0.85m to 1.2m reflector ship antennas. See Fig. 5.	Would need special antenna mounts for shipboard use.	Mobile and fixed, primarily land based but ship terminals available
Time frame	Operational	Operational	Operational
EPM	Low (not intended for EPM). See [11].	Low (not intended for EPM).	Low (not intended for EPM). See [11].
LPE	Poor (not intended to have LPE) See [11].	Poor (not intended to have LPE).	Poor (not intended to have LPE). See [11].
Cost considerations	Expensive: Inmarsat-B terminals for CF fleet \$1.6M plus large usage charge. Mini-M terminals start at \$3000US plus >\$3US/min.	No information obtained.	About \$5000/terminal (not confirmed) plus US\$0.85 to US\$1.99/min charges
Comments	There is a need for methods to multiplex the 64kb/s channel to make more cost effective.	Probably not practical for shipboard use.	Limited ocean coverage makes it of limited use to Navy shipboard use

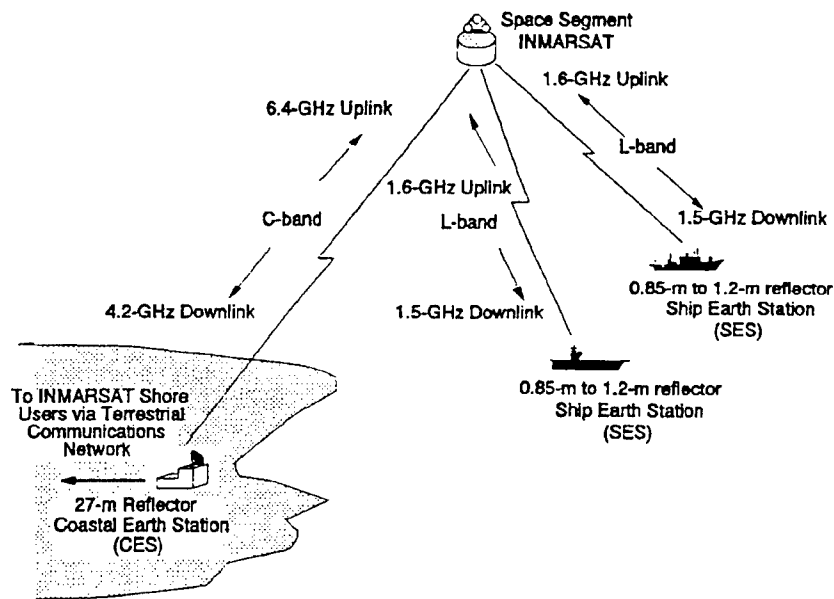


Fig. 5. Typical Inmarsat connectivity (from [4, p. 290]).

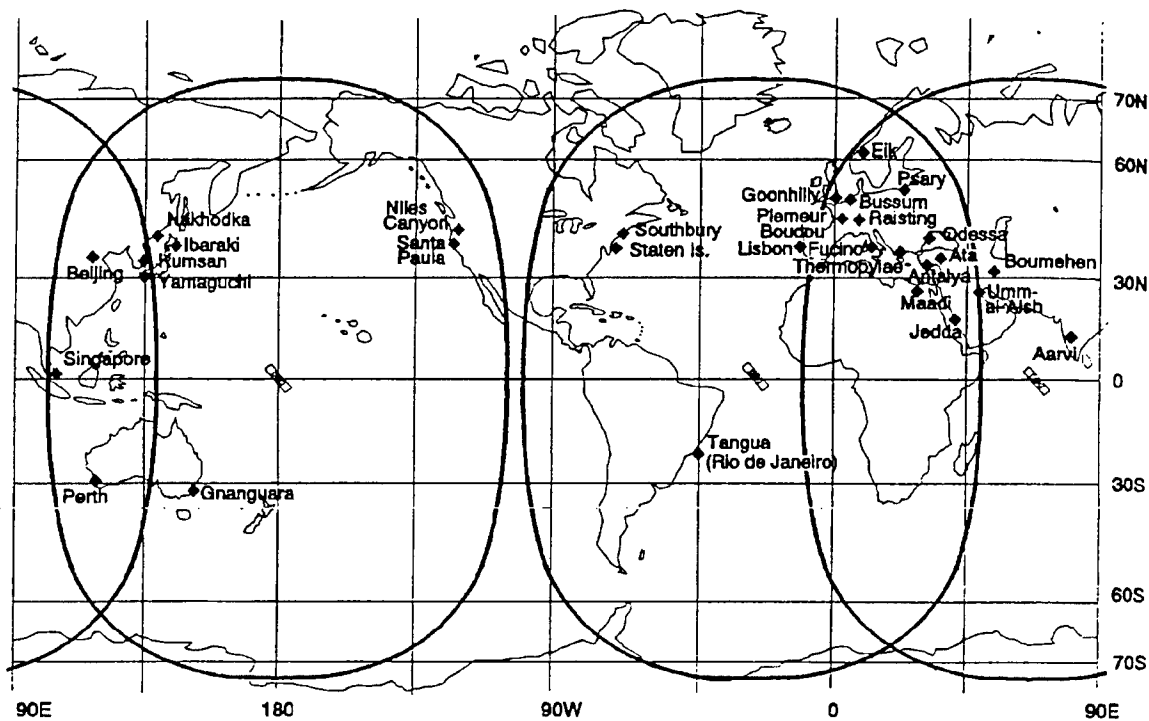


Fig. 6. Inmarsat coverage in the three ocean regions (from [4, p. 292]).

3.2.2 Existing Non-US Military Satcom Systems

In Table 3.2 are listed two existing non-US military satcom systems. These two were listed because they appear to be the only current ones that DND uses.

TABLE 3.2. Characteristics of existing non-US military satcom systems.

System Parameter	NATO 4	Skynet 4
Service provided	2 25- kHz channels at UHF 135, 85, 60, and 60 MHz channels at SHF	2 25- kHz channels at UHF 135, 85, 60, and 60 MHz channels at SHF
User band(s)	UHF and SHF (7/8 GHz)	UHF and SHF (7/8 GHz)
Coverage	One GEO at 18°W. Other at 6° E.	GEO's at 4A 34° W, 4B ? 4C 1° W, 4D 54° E
Connectivity	Presumably, similar to Skynet 4 but with different mix.	UHF: small army terminals SHF: many land and ship (40) terminals in use. SCOT antennas on ships
Time frame	Operational	Operational
EPM	Similar to Skynet 4	Onboard processing at UHF provides low level of protection. Use of spread spectrum (DS or FH with Universal Modem provides some AJ.
LPE	Similar to Skynet 4.	Modest level at SHF through SS and narrower beams.
Cost considerations	Usage through MOU. Requests assigned in proportion to Canada's NATO contribution or on <i>quid pro quo</i> basis. Standard UHF terminals. Avg of all US SHF terminals US\$850 k [6]. Shipboard SHF terminal costs available at CMSC Project Office.	UK system. DND use based on past <i>quid pro quo</i> MOU. Latest rewrite of MOU will expand beyond single terminal use. Standard UHF terminals. Avg of all US SHF terminals US\$850 k [6]. Shipboard SHF terminal costs available at CMSC Project Office.
Comments	Already used by CF. Navy is obtaining SHF terminals for use on NATO 4.	Standard Canadian access based on army 2.4kb/s secure voice. Existing CF Navy terminal should function with Skynet 4.

3.2.3 Existing US Military Satcom Systems

In the category of existing US military satcom systems, two are listed in Table 3.3. These two were chosen, again, on the basis of some chance of DND usage. The coverage of the overall USN UHF satellite constellation is shown in Fig. 7. The system consists of Gapfiller, FLTSAT, LEASAT, and UFO satellites.

TABLE 3.3. Characteristics of some existing US military satcom systems.

System Parameter	US SHF DSCS	US UHF (FLTSAT, LEASAT, UFO)
Service provided	Total usable BW \approx 400 MHz Channel 2: 75 MHz for tactical users including USN	5 & 25 kb/s channels • Fleet broadcast • Information exchange systems (IXSs) for low rate data, • secure voice Some 500 kb/s "wideband"
User band(s)	SHF (7/8 GHz)	UHF (243 to 319 MHz), EHF on some UFOs, Fleet Broadcast is SHF up and UHF down
Coverage	GEO world wide except for poles	Primarily GEO world wide except for poles. See Fig. 7. US has a few classified polar coverage UHF satellites
Connectivity	USN ship-shore C2 & exchange of acoustic data. WSC-6 ship terminals (4 ft ant, EIRP 70 dBW)	Ship/shore, ship/ship plus Fleet broadcast. Many ship terminal types including the WSC-3
Time frame	Operational	Operational
EPM	Moderate robust performance through use of nulling antennas, each channel with a limiter, spread spectrum capable	Transponded UHF results in very limited AJ
LPE	Modest level at SHF through SS and narrower beams.	UHF means very limited LPE
Cost considerations	Avg of all SHF terminals US\$850 k [6]	Least expensive of military satcom terminals. Avg. UHF terminal cost US\$133 k [6].
Comments	Some potential future use by CF Navy.	Some current use by CDN Navy in joint operations with WSC-3 terminals. About 17000 terminals in DoD.

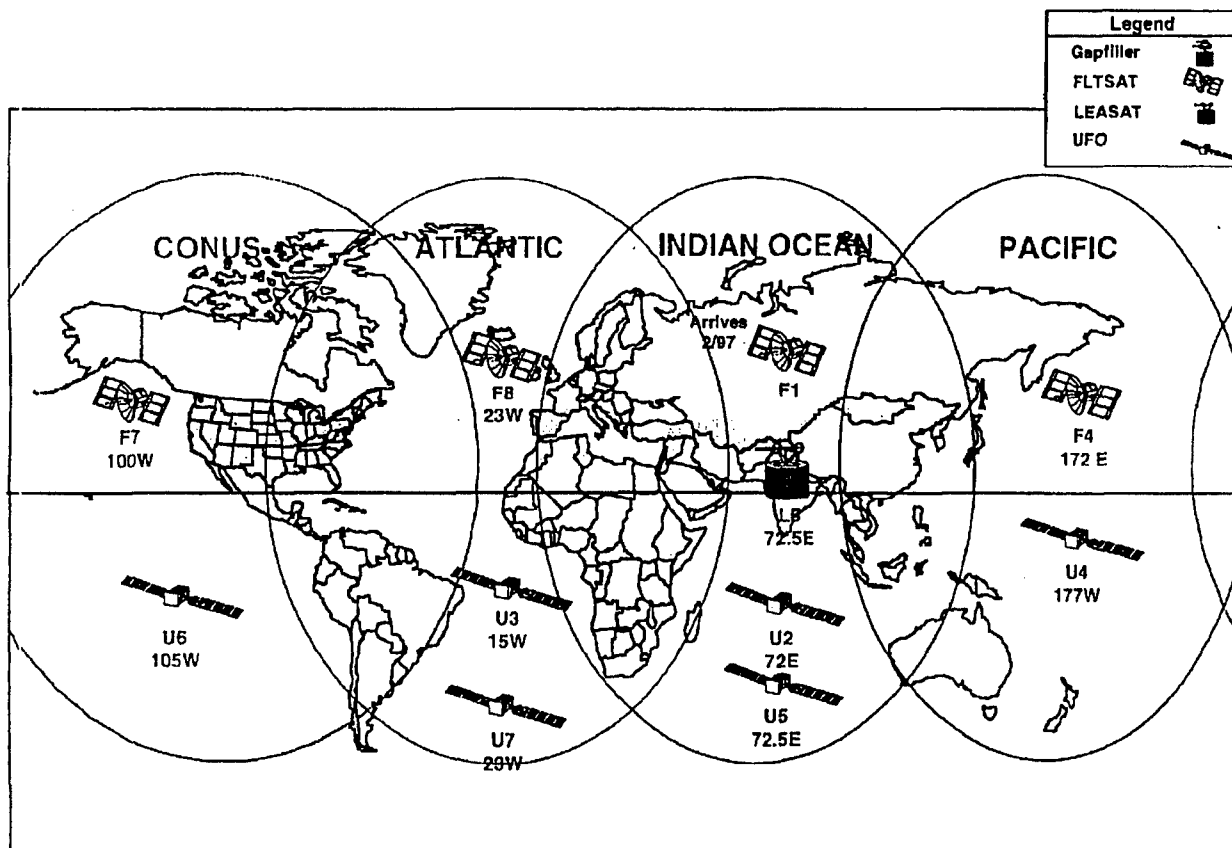


Fig. 7. The US UHF satellite constellation (from [6]).

3.2.4 Emerging US Military Satcom Systems

In the category of new and emerging US military satcom systems, two are listed in Table 3.4. These two were chosen, again, on the basis of some chance of DND usage. Milstar and other EHF military satellites are the most robust of all satcom systems. DND is considering EHF for its highly protected requirements.

Direct Broadcast Systems (DBS) are commercial systems that provide one-way wideband services to the home. The US, UK and Australia are very interested in developing military equivalents. The US has commenced work on what they call the "Global Broadcast Service" (GBS). Both DBS and military broadcast provide only one-way communications. Requests from ships for information will have to be made through a reach-back channel. On this issue, we quote from [13]:

"...include the well known "Warrior Pull" where the warrior browses and selects the necessary information, and "Smart Push" in which information meeting the warriors a priori requirements is pushed to the user. However, our investigation of the information needs of the war fighter indicate clearly that there is yet a third

TABLE 3.4. Characteristics of new and emerging US military satcom systems.

System Parameter	Milstar and other EHF (current)	GBS
Service provided	Simplex, half full duplex LDR: Data: 75 to 2400 b/s Voice: 2400 b/s MDR: Data: 4.8 to 1544 Mb/s	Simplex; Data to 23 Mb/s in Phase 1 Ku band; T1 to 23 Mb/s receive in Phase 2 UFO hosted. Therefore will support imagery, video, Internet, etc.
User band(s)	Milstar primary is EHF (44/20 GHz) with secondary UHF UFO has secondary EHF	Ku and Ka are contenders. Commercial proof of concept mostly at Ku. Ka recommended for Phase II interim operational [14].
Coverage	2 Block 1 LDR GEOs, Flight 1 at 120° W (Pacific coast); Flight 2 at 4° E (Atlantic & Mediterranean) Due for 4 more launches.	Phase 2 (UFO hosted) has 3 GEO satellites with a gap off west coast of South America. Has 3 spot beams or 2 spots + 1 wide area beam.
Connectivity	Point-to-point, point-to- multipoint, and conference	Primarily shore to ship
Time frame	LDR operational. MDR coming on Block 2 Flights	Commercial Ku band currently being used for proof of concept. Phase II (1998-2001) interim operational system on UFO.
EPM	Very robust against jamming	Since primary service is DL to ships, jamming is less likely. Also, Ka-band operation implies narrow beams. Low threat of UL jamming from sanctuary shore stations
LPE	EHF permits best LPE performance of all satcom systems	Since primary ship use is receive, automatically has LPD. Against radar, work is proceeding on making low observable antennas.
Cost consid- erations	The most expensive satcom sys- tem of all time. Avg of all EHF terminals US\$660 k [6]. Navy terminals likely to be larger than this avg. Connection costs will probably be in the form of lump sum contributions to US.	Objective is to use COTS components to drive down terminal costs to levels very low compared to traditional military terminals. However, initial receive terminals are ≈100k to 150k\$US of which 40-60% is crypto costs.
Comments	Usage will be part of an MOU.	The limited number of beams means that only a few theater areas can be supported at one time in early phases. Usage part of MOU discussions

mode which must be accommodated: "Warrior Push". In this mode, the warrior is the source of the information, and the user is generally a supporting organization, or..."

The mission statement for the Global Broadcast Service (GBS) is [6]:

"Provide war fighters with a worldwide, seamless, high throughput broadcast information service to support today's and tomorrow's missions."

The purpose of GBS is [6]:

"Provide efficient, high data rate, broadcast of information products from many sources directly to war fighters worldwide using small, inexpensive terminals."

To these ends, DoD has done a series of proof-of-concept demonstrations using Ku band satellites (Phase I). Phase II will involve packages on 3 UFO satellites and use the Ka band.

3.2.5 Commercial LEO/MEO Low Data-Rate Satcom Systems

Another class of commercial satcom systems of potential use to the Navy are the large LEO/MEO systems directed at worldwide voice, fax and low-rate data. There are four such systems being currently deployed, and are described in Table 3.5. In 1997, a promising system, the Odyssey system, was dropped out of the running and is therefore not described here. Conversely, the Ellipso system had been delayed, but has progressed recently due to a construction approval from the FCC. Unfortunately, earlier doubt about Ellipso's future meant that it had been not studied in any depth in our main reference, [11]. Therefore, information on some aspects, especially EPM and LPE are not complete for Ellipso in Tables 3.5.

An extra row has been added to this Table on COMSEC. In previous Tables, COMSEC was taken for granted on military systems. For details of EPM and LPE on these systems, see Vol. 2 of [11]. Only uplink jamming of the user link will be presented here as this is the most significant vulnerability. Furthermore, the effect of this uplink jamming depends upon whether the jammer is located in the main beam of the satellite. Comments in the Table are for jammers outside the main beam. It turned out that for commercial systems, there was surprising amount of jamming tolerance, albeit much less than for military systems.

TABLE 3.5(a). Characteristics of commercial LEO/MEO low-rate satcom systems.

System Parameter	Iridium	Globalstar
Service provided	2400 b/s: Voice, paging, low-rate data, fax. STU III capability	Variable bit rate, 2400 b/s average, Voice, data, fax. Fixed user: outdoor antenna Mobile user: handset Encrypted links optional.
User band(s)	L band	L band UL, S band (2500 MHz) DL
Coverage	True global coverage including poles through use of 66 LEO satellites	Coverage between 70°S and 70° N through use of 48 LEO satellites.
Connectivity	Point-to-point directly or through ISL and gateways to local PSTN	Between user terminal and gateways to local PSTN. No direct user-to-user connectivity.
Time frame	Expect full service by Nov. 1998	Full operational coverage by 1999
EPM	High power or sophisticated medium power jammer required to jam in satellite sidelobe [11]	Medium power or sophisticated low power jammer required to jam in satellite sidelobe [11].
LPE	Line of sight detection possible at ranges up to several hundreds of km. On-board processing using TDMA complicates message assembly by ground-based eavesdropper	Line of sight detection possible at ranges up to several hundreds of km. Transparent CDMA necessitates use of specialized equipment to capture messages.
COMSEC	Work is well underway to build a security sleeve into the handset for US DoD systems (Aug. 99)	Work is well underway to build a security sleeve into the handset for US DoD systems.
Cost considerations	Projected costs: \$3k US for handset + \$3.00 US/minute	Projected costs: \$750 US for handset + \$0.3-0.6 US/minute
Comments	Handset has dual mode with cellular. DoD will have own gateway in Hawaii.	GSM dual-mode user terminal. Seamless services for global roamers, GSM and AMPS

TABLE 3.5(b). Characteristics of commercial LEO/MEO low-rate satcom systems (continued).

System Parameter	ICO (formerly Inmarsat-P)	Ellipso
Service provided	Voice, data, fax and messaging at 4800 b/s to handsets. Enhanced speeds to 38400 kb/s planned. Wide range of terminal types planned including maritime.	Mobile and fixed voice, data, fax, paging up to 9600 b/s
User band(s)	L band (2000 MHz) uplink, S band (2190 MHz downlink)	L band
Coverage	True global coverage including poles through use of 10 MEO satellites.	Mixed LEO orbits chosen to provide primarily northern hemisphere but also to 55° S.
Connectivity	Calls routed through gateways. Will be integrated with PLMN.	N.A.
Time frame	Reduced service with 6 satellites starting 1999. Fully operational by 2000.	Estimated operational service by 2001
EPM	Medium power or sophisticated low power jammer required to jam in satellite sidelobe [11].	Not analyzed in [11].
LPE	Line of sight detection possible at ranges up to several hundreds of km. TDMA complicates message assembly by ground-based eavesdropper	Not analyzed in [11].
COMSEC	Development work is required to build a government handset with a security sleeve.	Not analyzed in [11].
Cost considerations	Projected costs: \$100's US for handset + \$1 to 2 US/minute	Estimated terminal (handset) cost: \$1000 US. Estimated retail tariff for mobile and fixed telephony: \$0.12 to \$0.50 US/minute.
Comments	Single or dual-mode handset with GSM cellular available. Uses path diversity (2 or more satellites in view) for improved performance against shadowing.	Likely to have the lowest per minute charges.

N.A. = not available

PLMN = Public Land Mobile Network

3.2.6 Commercial High Data-Rate Satcom Systems

In Table 3.6, the characteristics of the Teledesic system are given as an example of commercial high-rate satcom systems. Initially in this study, Celestri was also included but it was merged into a modified Teledesic. The features of Teledesic given here are based upon its second version, and does not reflect any changes brought about by the merger of Teledesic and Celestri.

Only uplink jamming of the user link will be presented here as this is the most significant vulnerability. Furthermore, the effect of this uplink jamming depends upon whether the jammer is located in the main beam of the satellite. The use of Ka band means that raw jammer power is more difficult to generate.

TABLE 3.6. Characteristics of commercial high-rate satcom systems.

System Parameter	Teledesic
Service provided	"Internet-in-the-sky" service: on-demand circuits Standard and business terminals: 16 kb/s to 64 Mb/s full duplex with antennas 16 cm to 1.8 m. Gigalink terminals: 155 Mb/s to 1.244 Gb/s with antennas 0.28 to 1.6 m.
User band(s)	Ka band (28/18 GHz)
Coverage	LEO with almost global coverage via 85° inclination angle.
Connectivity	Fixed point to gateway via ISL links. Dynamic assignment of small active beams to users. Network uses packet switching based on ATM with conversion to and from ATM format done at terminal.
Time frame	Standard operational scheduled for 2002. High rate service in 2003 to 2005.
EPM	Very high power or sophisticated medium power at Ka band req'd to jam in satellite sidelobe [11]. Small satellite beams provide more protection.
LPE	Line of sight detection possible at ranges up to several hundreds of km. High elevation angles with user directional antennas reduce probability of detection. Terrain shielding more effective at Ka band
COMSEC	External data encrypt needed
Cost consid- erations	User costs not stated yet.
Comments	Ships at sea likely benefit from being in low traffic region. Special ship board antennas likely needed.

4. TASK 3— SURVEY OF TERMINALS

A brief summary of satcom terminals in the DND and Navy current and near-term (actively being procured) inventory is given in Table 4.1. It is a short list. A very detailed and in depth look at current and future satcom terminals of potential use to DND was done in [16]. An exhaustive list of DND requirements, circa 1994, for satcom in general, and terminals in particular, is given in [17]. Although dated, it again highlights the vast variety of terminals that need be considered.

TABLE 4.1. A summary of current and near-term DND satcom terminal inventory [7].

- 300 satellite ground terminals DND wide; more than 90% commercial
- Navy has 31 AN/WSC-3 UHF terminals for use with US FLTSATCOM system
- Ships are fitted with AN/SSR-1A UHF receivers for copying broadcasts from US shore stations
- DND has approximately 90 Inmarsat A and B terminals. Majority of use is for outside Canada
- Navy currently replacing analog 'A' Inmarsat terminals with 42 'B' terminals [5].
- Tri-band (C, Ku and X) transportable long range communications terminals (TLRCT) to be deployed in 1998-99.
- SHF terminals are being installed on 2 East coast ships; will be in service by 1 April 99. The Navy would like to expand this to another 4 to 6 more.

Worldwide, the number of different satcom terminals is very large. In [15] are listed military satcom terminals by country. The UK section has at least 30 entries, and the US section has many more. In [6] a list of US military terminals is listed with their "AN" designation. The list is summarized in Table 4.2. The conclusion that is made in [6] is that there are "Too many variations." This notion is echoed among our various DoD colleagues from the US. When commercial terminals are added, the list becomes enormous.

TABLE 4.2. A summary of the US military satcom terminal types listed in [6].

- 31 SHF types (including multi-band terminals)
- 48 UHF types (including the WSC-3)
- 14 EHF types (including the 3 NESF variations for USN)

5. TASK 4— ROAD MAP TO FUTURE R&D ACTIVITIES

5.1 INTRODUCTION

In the previous Chapters, Navy needs, relevant satcom systems, and terminal concerns are described. In this Chapter, this background is used to describe a number of directions that long-range work could take, and to trace a road map for future activities. It is left to future work to refine the particular work areas, and to scope the effort to fit the financial support.

Although antennas are the main thrust of this work, they should not be studied in isolation from the other parts of satcom terminals. Therefore, this Chapter starts with an overview of overall onboard naval satcom architecture as a background to the subsequent discussion on antennas.

5.2 TERMINAL INTEGRATION

As noted in earlier chapters, there is a big push to reduce the number of terminal types and simultaneously increase their flexibility, and utility. The USN effort in this area is described in [8] and the JMCOMS architecture is depicted in Fig. 8. Three main blocks are identified with the first being the user applications. The second is called the "Automated Digital Network System" (ADNS) (similar to the CSNI discussed earlier) wherein the various user applications are seamlessly tied together so as to provide transparent operation to the users. The third block is the physical layer and consists of low-noise and power amplifiers, up and down converters, signal distribution, antennas, and other electronics.

From an integration point of view, the physical layer is divided into two broad categories with the radios operating below 2 GHz termed "Slice" technology, and those above 2 GHz as the "Integrated Terminal Program" (ITP). It is seen that the antennas will need to operate in various bands and provide a variety of functions. For example, the MERS, which stands for Multifunction Electromagnetic Radiating System, will need to operate in the UHF and VHF and provide direction finding, communications and identification capabilities.

An important research activity could then be to investigate the possibility of integrating a number of frequency bands and functions into one terminal and one antenna structure, thus reducing the overall volume required. There are basically

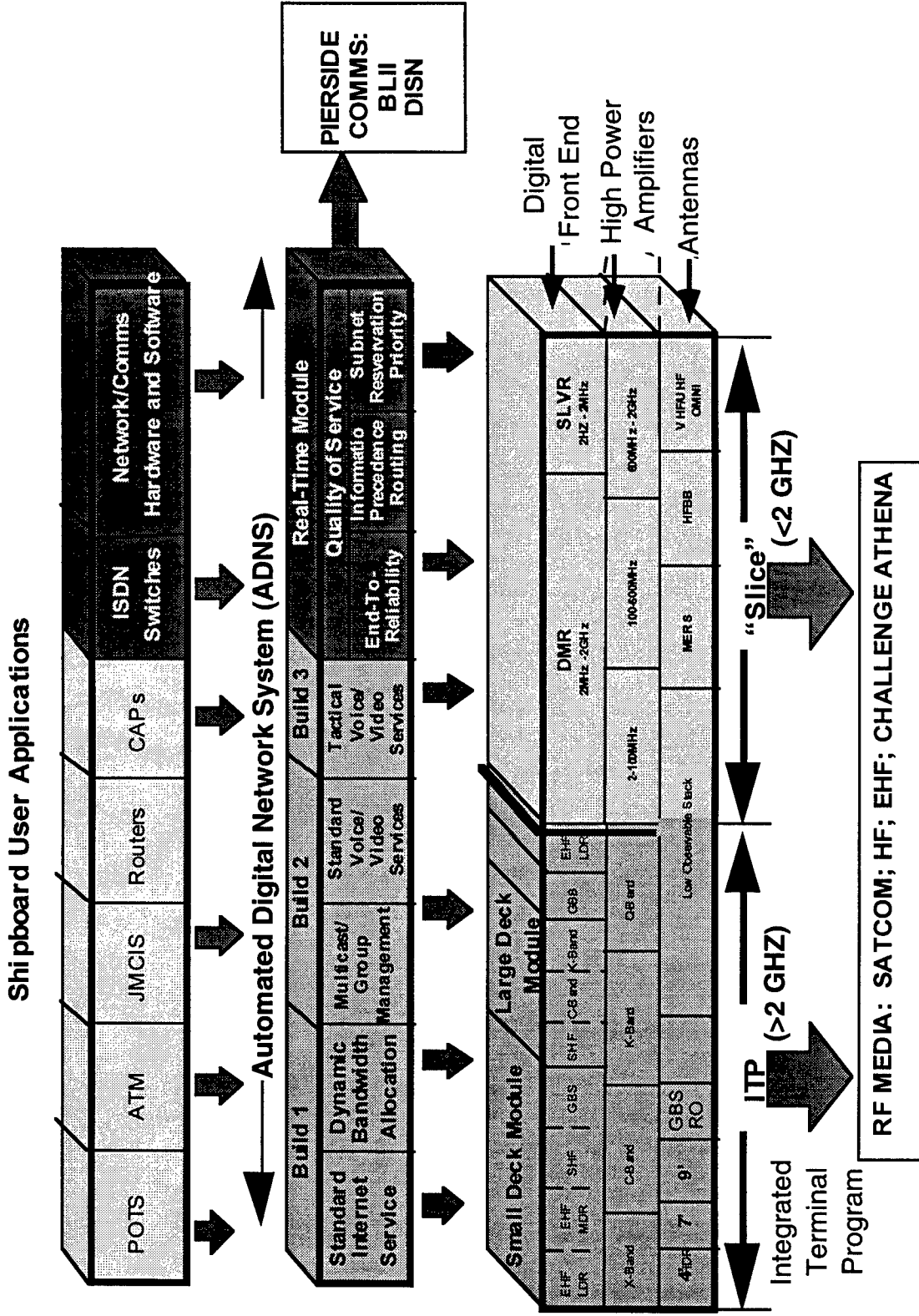


Fig. 8. The USN JMCOMS Architecture [8].

seven frequency bands which could potentially be used by the Navy (UHF, L, C, X, Ku, Ka, and EHF). Communications in each of these bands may be provided by one or more satellite services and each one has its own characteristics in terms of coverage, bandwidth, EMP/LPE protection, and the usage cost varies widely. This terminal and antenna integrating activity could be part of the considerations for the antenna study described in the next section. Initial steps in such work is commencing at DREO with the preliminary name of "Omni-Band Software Radio."

5.3 SHIPBOARD ANTENNA DIRECTIONS

As noted in earlier chapters, there is a big USN effort on an integrated antenna approach with emphasis on reducing combined weight, and space, while having low-observable characteristics and good EMC. Many clever and innovative approaches are being considered. It is clear however, that there are not enough Canadian resources to embark on such an ambitious program. How then do we marshal resources most effectively? It is proposed that long-term work follow a combination of two paths. The first will be called "Non-Complex Demonstrator Antennas and Simulators" which contrast with the second called "Innovative Antenna Approaches."

5.3.1 Non-Complex Demonstrator Antennas and Simulators

The non-complex demonstrator antenna work involves use of available antennas, or otherwise obtaining, selected relatively simple antennas. These would then be used as demonstrators on Navy ships. For each type obtained, it would be necessary to go through the many measurements and tests mentioned earlier. These functions would include EMI measurements, blockage studies, remoting considerations, etc. The work could be complemented or even predominated by simulation work such as with the CRC "Software Tool for EM Environments Modeling" (STEEM) which has already been employed for simulating a particular naval EMI environment.

Such work would be primarily an educational process to learn such things as approximate costs, topside constraints, installation problems, and so on. However, such work would not necessarily lead to solutions to topside problems in the long term. For these solutions, the approach of the following sub section would be needed.

5.3.2 Advanced Antenna Approaches

The long term objective is to enable solution of the satcom antenna needs for the CPF major refitting in the period around the year 2010. "Brute force" approaches implementing full up multi-band and multi-beam phased-array antennas are proving too costly even for the DoD, let alone DND. Therefore, alternative approaches are needed. To this end, two parallel directions are indicated and discussed below. First, and already in place, is what might be called the "building block" approach. Secondly, it is clear that some very clever and innovative approaches are needed to solve the problems in a cost-effective manner. A number of such approaches are proposed in outline below.

5.3.2.1 Building-Block Approach

A "building-block" approach is currently underway in the CRC MMIC and antenna groups. It is sponsored by DREO, through CRAD MITI Work Unit 5ca12. Work is directed at building some of the fundamental building blocks of phased arrays especially those using MMIC's for the antenna elements. Such an approach will lead to a better understanding of phased-array antenna technology in order to advise DND on future procurements, will make a Canadian contribution to the technology knowledge base, and will identify niche technologies for exploitation by Canadian industry.

5.3.2.2 Innovative Antenna Approaches

It is proposed that work be taken on investigating, inventing and developing innovative and novel solutions. This work would be supported under CRAD Work Unit 1bb17. Numerous ideas abound both in the literature and as preliminary concepts at CRC. Some of these are discussed below, and more are likely to arise over time.

1. Integrated antennas:—

As part of the USN Integrated Topside Design effort, a number of technology demonstrations have been initiated. One example is the Multifunction Electromagnetic Radiating System (MERS) [18], which can be seen to be part of the JMCOMS Architecture in the lower right of Fig. 8. The objective of MERS was to "demonstrate the feasibility of combining at least four shipboard functions: Direction finding, JTIDS (Joint Tactical Information Data System) transmit and receive, UHF line-of-sight transmit and receive, and IFF (Identification Friend or

Foe) transmit and receive into a single, low observable, light-weight antenna system." A representation of the MERS "stack" is shown in Fig. 9. This stack obviously reduces the space and weight needed quite considerably. It also greatly simplifies the EMI/EMC problems, at least for the functions in the stack, because the stack was designed specifically for internal EMC. Furthermore, the layout of the stack and certain design features gives this stack a low observable characteristic. Extension of this approach to higher frequencies and satcom are clearly possible. An important aspect of this approach is that the volume of each antenna remains the same as with separate antennas, the stacking results in a considerable saving of mast space since they are now not blocking each other.

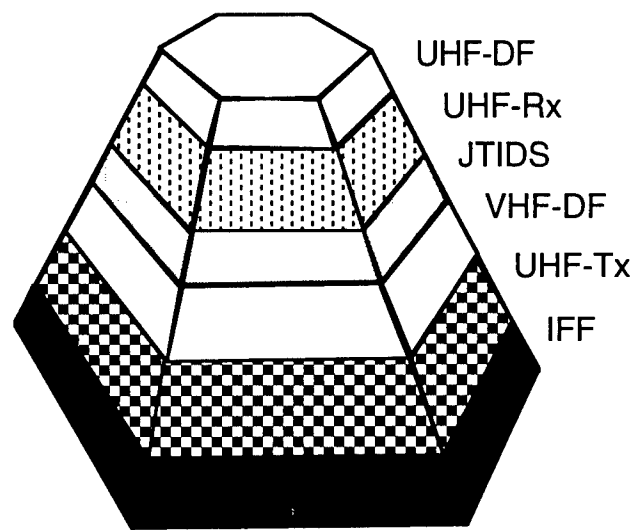


Fig. 9. The MERS stack [18] for mounting on mast.

2. Continuous Transverse Stub (CTS) Array:—

At Hughes, a novel antenna structure has been invented [19] that appears to be the most exciting development in antennas for many years. It has considerable promise for satcom. It can be made in a flat or a conformal format, has good scanning ability, high efficiency, and very wideband capability for multiband operation. All these features come with the potential for very low cost compared to traditional antennas for the same features. Numerous antennas have already been built and tested, or under development. For example, in one antenna under development, GBS receive full-duplex operation in the extended band (17.5-21.5 GHz) is combined with EHF Milstar transmit (43.5-45.5 GHz) operation. It is being developed for the USAF for airborne use.

3. Photonics:—

Photonics has a variety of potential applications for shipboard antennas. One application is for the distribution of the many forms of RF signals between below deck and the topside. Such usage is part of the USN Integrated Topside Design effort [18]. There, photonics is used not only for distribution between below deck and topside, but within the MERS integrated antenna. A second application is to phased-array antennas wherein photonics augments or replaces some of the functions of phase shifting, distribution, etc. One example is seen in [20] where a 1 to 18 GHz relatively flat antenna is reconfigurable between bands via photonics.

A photonics capability applied to array antennas has been developed within CRC and involves a number of complementary groups. It is supported by internal CRC funding and the Canadian Space Agency (CSA). Among other things, a 3-element demonstrator signal distribution and phasing system for a phased array operating at 5-GHz has been built for radar applications.

4. Antennas Using Combined Mechanical and Electronic Steering, and Distributed-Apertures:—

A number of ideas for innovative approaches have been generated at CRC. In one concept, various combinations of standard mechanically steered antennas with electronically steered phased arrays are proposed. Such a hybrid of mechanical and electronic steering can result in antennas that maximize the advantages of both while minimizing the disadvantages of both. Some unpublished reports have already been produced on these subjects. Initial considerations show good promise for a beneficial tradeoff between cost, performance, and topside impact.

A second idea is to use what might be called "distributed apertures". Here, antenna panels can be distributed in a cluster together such as in Fig. 9, or distributed over widely separated sections of the ship such as illustrated in Fig. 10. The concept is much the same for both the clustered and widely separated in that the various panels would have to be switched and phased so that they function as a single antenna while accounting for ship motion and direction of satellites. Widely distributed panels such as in Fig. 10 would clearly be a challenge to compute and set the phases in real time. Photonics would be most useful in the distribution of the correct RF signals. Distributed panels have some advantage in increased gain because of combined area. However, large grating lobes can appear for the widely separated distributed apertures, and care must be taken so that these large lobes do

not point at other satellites or at jamming sources. Also, for widely separated panels, the main lobe can be very narrow thereby making steering a challenge. The individual panels can take a variety of forms including other innovative ones such as the CTS and the hybrid mechanical/electronic antennas.

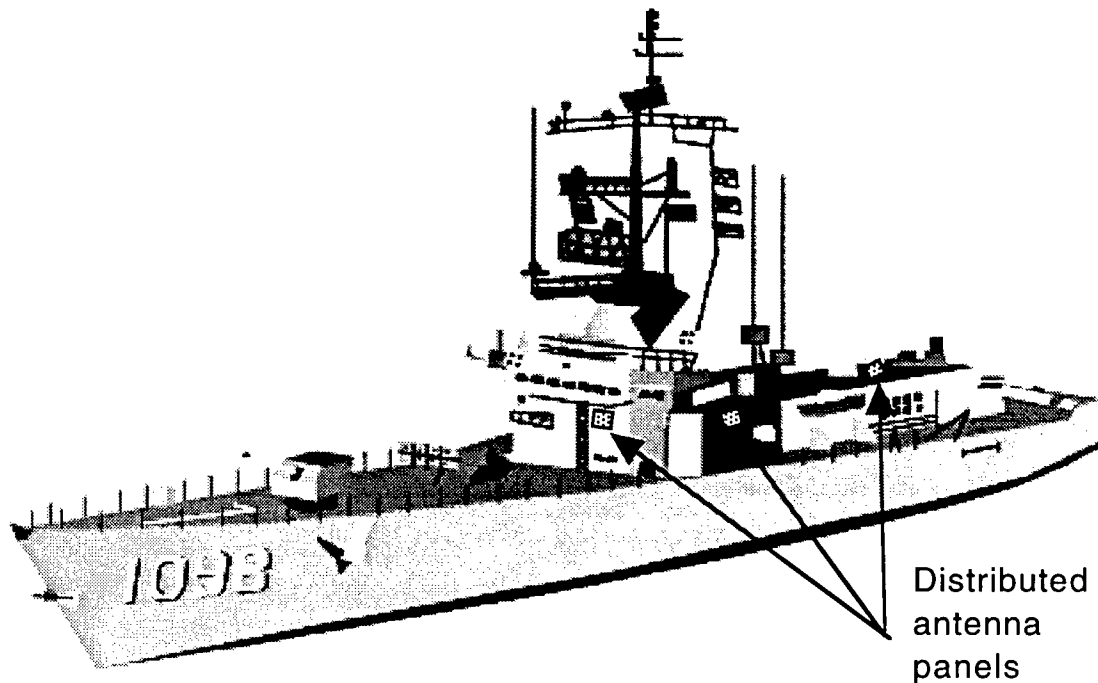


Fig. 10. Conceptual representation of a widely distributed distributed-panel phased-array shipboard antenna using five panels. The fore-pointing, port, and vertical-pointing panels are seen. The aft-pointing and starboard panels are not seen here.

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APPENDIX A: ABBREVIATIONS AND ACRONYMS

CSNI	Communications System Network Interoperability
DL	Down link
EPM	Electronic protective measures
GEO	Geostationary earth orbit
LDR	Low data rate. When applied to EHF, means 75 to 2400 b/s.
LEO	Low earth orbit
LPD	Low probability of detection
LPE	Low probability of exploitation
MDR	Medium data rate. When applied to EHF, means 4.8 to 1544 Mb/s.
MEO	Medium earth orbit
MMIC	Microwave monolithic integrated circuits
PLMN	Public Land Mobile Network
PSTN	Public Switch Telephone Network
SS	Spread spectrum
UL	Up link
USN	US Navy
VTC	Video conferencing

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Satellite communications (satcom) is becoming the essential Navy link. There are many topside satcom problems including physical size, weight, blockage, cost, and electromagnetic interference (EMI) between the many shipboard electronic systems. There is a need for innovative antenna technology to reduce these problems. A previous study provided a brief overview of Allied use of milsatcom and trends in shipboard terminals. In the present study, the work is carried further. First, parameters and features needed by the Navy are outlined. Then, the features of a variety of military and commercial satcom systems that could satisfy these needs are provided. A brief overview of shipboard terminals is provided. Finally, a road map for future research and development for shipboard antennas is given, and consisted of two directions.

The shorter-term first direction involves the use of available demonstrator antennas and electro-magnetic interference (EMI) simulation software. In the longer-term second direction, it is proposed that advanced-antenna approaches be pursued. Again, two directions are proposed. One direction is already currently underway at DREO. This effort could be called the "building-block" approach to phased arrays, wherein certain components of array elements are developed. In a second advanced-antennas direction, it is proposed that innovative antenna approaches be investigated. Four such approaches are suggested and more should arise as work progresses.

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