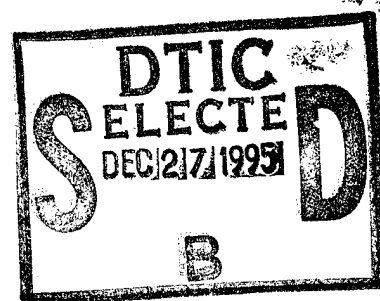


**NAVAL POSTGRADUATE
SCHOOL
Monterey, California**



THESIS

**POTENTIAL APPLICATIONS OF THE
ORBCOMM GLOBAL MESSAGING SYSTEM
TO US MILITARY OPERATIONS**

by

David R. Coverdale

June 1995

Principal Advisor:

Paul H. Moose

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19951226 117

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE (Leave Blank)		2. REPORT DATE June 1995		3. REPORT TYPE AND DATES COVERED Master's Thesis
4. TITLE AND SUBTITLE POTENTIAL APPLICATIONS OF THE ORBCOMM GLOBAL MESSAGING SYSTEM TO US MILITARY OPERATIONS			5. FUNDING NUMBERS	
6. AUTHOR(S) Coverdale, David R.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the United States Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The author presents a detailed description of the components, architecture, links, and operations of the ORBCOMM global messaging and position determination system. ORBCOMM is the first commercial venture to offer worldwide personal communications service (PCS) using non-voice-non-geostationary (NVNG) low earth orbit (LEO) satellite technology. Link budget analyses of the system's satellite up and down links are presented. The author analyzes ORBCOMM's proprietary multiple access scheme for random access channel interference and describes how the system's modified ALOHA protocol achieves a higher throughput than pure or slotted ALOHA based systems. Several commercial and DoD applications of the system are discussed, including beaconing, data exchange, tracking, and two way messaging. Specific DoD applications of ORBCOMM include combat sea-air rescue (CSAR) and deployable communications networks for use in operations other than war (OOTW). With DoD taking an active role as a cooperative partner, ORBCOMM can satisfy the need for a low-cost, commercial space-based system to enhance US military global communications.				
14. SUBJECT TERMS ORBCOMM, Satellite Communication, Personal Communication Services, PCS, Low-Earth Orbit, LEO, DCAAS, ALOHA, OOTW, CSAR, CSEL			15. NUMBER OF PAGES 93	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

NSN 7540-01-280-5500

DTIC QUALITY INSPECTED 3Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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DAVID R. COVERDALE

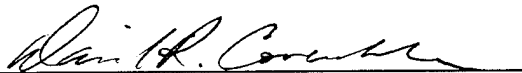
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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN SYSTEMS TECHNOLOGY
(COMMAND, CONTROL, AND COMMUNICATIONS)**
from the

**NAVAL POSTGRADUATE SCHOOL
JUNE 1995**

Author:

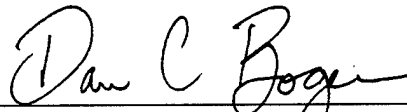


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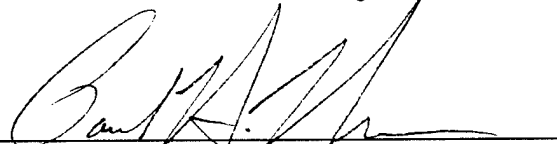
Approved by:



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Command, Control, and Communications
Academic Group

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ABSTRACT

The author presents a detailed description of the components, architecture, links, and operations of the ORBCOMM global messaging and position determination system. ORBCOMM is the first commercial venture to offer worldwide personal communications service (PCS) using non-voice-non-geostationary (NVNG) low earth orbit (LEO) satellite technology. Link budget analyses of the system's satellite up and down links are presented. The author analyzes ORBCOMM's proprietary multiple access scheme for random access channel interference and describes how the system's modified ALOHA protocol achieves a higher throughput than pure or slotted ALOHA based systems. Several commercial and DoD applications of the system are discussed, including beaconing, data exchange, tracking, and two way messaging. Specific DoD applications of ORBCOMM include combat sea-air rescue (CSAR) and deployable communications networks for use in operations other than war (OOTW). With DoD taking an active role as a cooperative partner, ORBCOMM can satisfy the need for a low-cost, commercial space-based system to enhance US military global communications.

TABLE OF CONTENTS

I. INTRODUCTION	1
A. BACKGROUND	1
1. General	1
2. LEO versus GEO	2
3. Little versus Big LEOs	3
B. PURPOSE AND ORGANIZATION	4
II. THE ORBCOMM SYSTEM	7
A. SYSTEM OVERVIEW	7
1. Components	7
2. Architecture	8
3. Links	9
4. Position Determination	10
B. SPACE SEGMENT	11
1. General Description	11
2. Spacecraft Description	12
C. GROUND SEGMENT	17
1. Gateway Earth Stations	20
2. Network Control Centers and Satellite Control Center	22
D. MOBILE SUBSCRIBER TERMINALS	22
E. OPERATIONS	24
1. Frequencies and Channelization	24
2. Links	26
3. Multiple Access	28
F. SUMMARY	31
III. SYSTEM ANALYSIS	33
A. LINK BUDGETS	33
1. GES to Satellite Link Budget	33
2. Satellite to GES Link Budget	34
3. Mobile ST to Satellite Link Budget	34
4. Satellite to Mobile ST Link Budget	35
5. Satellite to Mobile ST UHF Link Budget	35
B. SATELLITE COVERAGE	36
C. CHANNEL INTERFERENCE	38
D. NETWORK CAPACITY	43
1. Pure and Slotted ALOHA	43
2. Reservation ALOHA (R-ALOHA)	45
3. Acquire - Communicate (A-C)	47

E. SUMMARY.....	48
IV. SYSTEM APPLICATIONS.....	51
A. CIVILLIAN SERVICES	51
1. Emergency Service	51
2. Tracking Service	51
3. Data Acquisition Monitoring Service.....	52
4. Messaging Service	52
B. APPLICATIONS.....	52
C. DOD APPLICATIONS OF THE ORBCOMM SYSTEM	53
1. Beacons and Messaging.....	53
2. Operations Other Than War (OOTW).....	56
V. SUMMARY AND CONCLUSIONS	63
A. SUMMARY.....	63
B. CONCLUSIONS	65
APPENDIX A. ORBCOMM INTERNATIONAL STATUS	69
APPENDIX B. ORBCOMM LINK BUDGETS	71
LIST OF REFERENCES	77
INITIAL DISTRIBUTION LIST	79

EXECUTIVE SUMMARY

The availability of commercial worldwide communications capability in the form of Personal Communications Services (PCS) will have a great impact on DoD in the next decade. Recognizing the potential for these satellite-based systems to be cost effective means to satisfy growing communications requirements, DoD is pursuing an initiative to determine how to integrate PCS into its global architecture. Since it will be the first of the PCSs to reach operational status, and therefore may be the first such commercial satellite communications system to be integrated into DoD communication planning, the focus of this thesis is on the ORBCOMM 'little' LEO system. The author's purpose is to present a description and analysis of the system, its technology and architecture, and then to provide the reader with a discussion of its commercial as well as potential military applications.

The ORBCOMM data communication and position determining system is designed to provide users two-way, on-the-move location and data messaging services anywhere on the globe. The system will achieve worldwide coverage by using small mobile terminals and a constellation of non-voice, non-geostationary low-earth orbiting satellites instead of fixed-site terrestrial relays. The satellites will be linked with existing telecommunications networks via gateway earth stations and a network control center. ORBCOMM employs VHF burst transmissions and digital packet switching, store-and-forward data network technology to provide users low speed data exchange and alphanumeric messaging capability.

The author presents an analysis of the operational capabilities and expected performance of the ORBCOMM system. Given ORBCOMM's defined edge-of-coverage for satellite links, the system is designed with adequate link

margins to assure required signal-to-noise ratios. ORBCOMM's primary constellation of 32 satellites, combined with the four satellite supplemental polar planes, incorporates redundancy design and provides the coverage and re-visit rates for adequate global messaging and position determination services for users. ORBCOMM's dynamic channel activity assignment system (DCAAS) has the capability of efficiently managing the frequency spectrum used for ORBCOMM subscriber / satellite transmissions. Finally, a comparison of standard ALOHA multiple access schemes and the ORBCOMM Acquire-Communicate protocol shows how the system achieves a network capacity of approximately 60,000 messages per hour.

ORBCOMM will offer consumers choice of four levels of communication services. These include basic emergency alert, tracking, data acquisition monitoring, and full two-way on-the-move data transfer and messaging. Some of the first commercial applications will be in the shipping industry for cargo and container tracking, and in the energy industry for well head and pipeline monitoring.

ORBCOMM represents the first opportunity for DoD to enhance US military global communications with commercial PCS. Requirements to exchange secure data can be easily accomplished in the ORBCOMM system using current DoD encryption techniques (i.e., use of the KL-43 series Digital Encryption Device, Digital Encryption Chips, or an encryption method like that used in STU-III secure telephones). ORBCOMM's low power, short burst transmissions give it low probability of detection / intercept characteristics required for some potential DoD applications. Using miniaturized transmission devices, DoD could immediately apply commercially available ORBCOMM services to meet beaconing and tracking requirements. Development of a "fly in" mobile ground station / network control center would open a host of potential applications, including filling

the requirement for a rapidly deployable regional communications infrastructure suited for needs encountered in operations other than war.

With DoD taking an active role as a cooperative partner, ORBCOMM can satisfy some of DoD's need to find low-cost commercial space-based systems to enhance US military global communications. The Government will benefit in the short term by being able to meet urgent requirements; DoD would have access to a dual-use communications network, designed, developed, and operated by an American company that will provide affordable connectivity anywhere in the world. Development of a deployable "mini" NCC / GES suitable for use on board a ship, plane, helicopter, or mounted on a vehicle such as a HUMVEE, could provide enormous flexibility in addressing communications requirements in many situations including defense, natural disaster, or humanitarian efforts.

DoD participation in a dual-use partnership with ORBCOMM would be beneficial. Such an arrangement would mean lower costs for the Government, since ORBCOMM has been a totally privately developed and financed project. Operations and maintenance costs would be largely shared by the commercial users, thus reducing annual outlays such as are incurred with systems owned and operated solely by DoD. Commercially produced equipment (such as mobile subscriber terminals) could be used in many DoD applications, taking advantage of the cost reductions from economies of scale of the large number of terminals manufactured.

The commercial sector would also benefit from such a team effort. Industry would gain from DoD economic "pump priming" by spinning on to a new commercial technology. Demand for miniaturized beacons / hand-held terminals is well documented in DoD; demand for low cost beacons in the commercial sector is probably an order of magnitude larger than DoD's. The miniaturization of ORBCOMM transmitter beacons, and development of

transportable ground stations / network control centers, has the potential for huge expansion of the uses of the system, and therefore, to generate a number of new commercial ventures.

Destined to be the first system to offer PCS to users on a global scale, ORBCOMM is a pioneer in satellite communications. It is the first commercial attempt at worldwide coverage using LEO satellite technology, and is one of the first commercial ventures to take advantage of the relatively lower costs of the Pegasus launch system to insert satellites into operating orbits. The first two ORBCOMM satellites were launched on 13 April, 1995. Both the communications industry and DoD are waiting to see how these first satellites, and the system overall, perform under actual operational conditions.

I. INTRODUCTION

A. BACKGROUND

1. General

The availability of commercial personal communications systems offering global connectivity will be a reality by the end of this decade. Several international consortiums, made up of such leading high technology companies as Motorola, Hughes, TRW, Raytheon, Marconi, Loral, Aerospatiale, and Orbital Sciences Corporation (OSC), are currently developing systems which will compete to offer consumers various levels of worldwide personal communications services (PCS).

PCS is a generic term which encompasses a variety of mobile communications services such as voice, data, and facsimile. It is a service, not a particular technology, which draws on expanding the technologies of digital modulation, cellular and cordless telephone, and sophisticated network protocols.

The Federal Communications Commission defines PCS as "a family of mobile or portable radio communications services which could provide service to individuals and businesses and be integrated with a variety of competing networks. . . the primary focus of PCS will be to meet communications requirements for people on the move" [Ref. 1]. PCS will enable us to communicate from person to person regardless of physical location. While the services cover a wide range, from simple paging to voice and more advanced functions, the major benefit will be the capability to communicate from virtually anywhere to virtually anywhere on a planet-wide basis.

Most of the PCS systems envision a similar concept: subscribers with portable, lightweight hand-set type instruments providing them with access to a ubiquitous network. Although they differ on how they will actually

perform their functions, the current systems under development all use low earth orbit (LEO) communication satellites to provide network connectivity.

2. LEO versus GEO

Today's commercial and military communication satellites are generally in a geostationary (GEO) orbit some 22,000 miles directly above the equator. Each satellite moves in the same direction and at a velocity that matches the earth's rotation, making it appear to be stationary directly above a point on the equator. GEO satellites offer several distinct advantages for communications:

- Each satellite can view 42% of the earth's surface.
- Earth station tracking antennas don't require complex and costly tracking mechanisms because they remain stationary (pointed at the satellite).
- GEO satellite design has been refined over the past twenty years; many standard designs are already in use.

However, GEO satellites have several disadvantages:

- Satellites and earth stations require high power transmitters to ensure signal propagation across the 22,000 mile distance.
- GEO Satellites are costly to build, launch and insure.
- Satellites cannot view latitudes greater than about 77 degrees.
- Active orientation and stabilization systems are needed to keep the satellite pointing correctly.

In contrast to a GEO satellite, a satellite in low-earth orbit will always move relative to an earth station. Therefore, LEO earth station antennas must either have tracking mechanisms or be omni-directional. LEO satellites, with their orbit altitudes of between 100 - 1000 miles, have a much smaller portion of the earth (or 'footprint') visible at any given instant in time. Complete and continuous global coverage can only be achieved using constellations of many LEO satellites in orbital planes inclined about the equator.

The great advantage of LEO, with the relatively low satellite altitudes, over geostationary orbits is that the satellite is much closer to the user's terminal. This shorter signal path reduces transmission delays from 230 ms to around 40 ms, and reduces the free-space signal loss by about 21 dB [Ref. 2]. This allows for the hand-held terminal with an omni-directional antenna to communicate with a satellite by transmitting at low enough power levels so as to not be dangerous to the user. LEO satellites also require lower power transmitters and generally do not need active stabilization and orientation, allowing them to be smaller and cheaper to build, launch, and insure. On the other hand, LEO systems are more complicated to manage because they have a smaller footprint and are moving so fast (approximately 7,500 m/s) [Ref 2]. Additionally, to guarantee uninterrupted communication LEO systems must include enough satellites to ensure that when one sets over the user's horizon there is always another rising to take over the call. This satellite-to-satellite hand-off is not a simple problem to solve.

3. Little versus Big LEOs

There are two distinguishable types of LEO systems in the current field of global PCS systems under development. The less sophisticated of the two, and closest to being commercially available, are known as 'little' LEOs. These systems will provide inexpensive data exchange and short messaging services only, primarily to niche markets in commerce, service, and industry. Because they are packet switched and employ burst communications, their network design does not need to incorporate inter-satellite link or satellite-to-satellite hand-off technology. There are currently two 'little' LEOs under development: ORBCOMM and STARSYS.

In contrast, the 'big' LEOs, consisting of IRIDIUM, GLOBALSTAR, ODYSSEY, ARIES, ELLIPSO, and PROJECT 21, will use advanced state-of-

the-art satellite communication, network, and processing technology to achieve continuous global coverage. These systems will offer data and voice services for a charge of a few dollars per minute to a much broader target market of millions of subscribers. While the first of the 'little' LEO satellites are now being inserted into orbit and will soon be operational, the first 'big' LEO systems are not expected to offer service until 1998 at the earliest.

B. PURPOSE AND ORGANIZATION

The availability of a commercial worldwide mobile communications capability afforded by these PCSs can have as great an impact on DoD as it will in the civilian sector. During the Gulf War the required size, complexity, and robustness of the command and control network identified that DoD has a clear need for more satellite communication assets. The capacities of the US military communication satellites were stretched to their maximum limits to support both in-theater (tactical) and long-haul communication nets. In the area of data communications, user demand climbed to such a point that circuits became so jammed with the backlog of messages that systems virtually ground to a standstill [Ref. 3]. According to Rear Admiral Charles Saffel, Deputy Director for Unified Command C4 Support, Joint Staff/J-6, this growth in military satellite communication requirements is expected to continue throughout the decade. As can be seen in Figure 1, it will require a combination of military and commercial satellite communication systems to meet these future requirements [Ref. 4].

In recognition of the need to determine how commercial satellite communications systems can be cost effectively used by DoD to satisfy the requirements for both fixed and mobile services, Congress directed the Secretary of Defense in 1992 to commence a Commercial Satellite Communications Initiative (CSCI) study [Ref. 5]. As a result, DoD is today pursuing the study of the opportunities of using commercial PCS in

conjunction with military systems to satisfy the communications need for future warfighters.

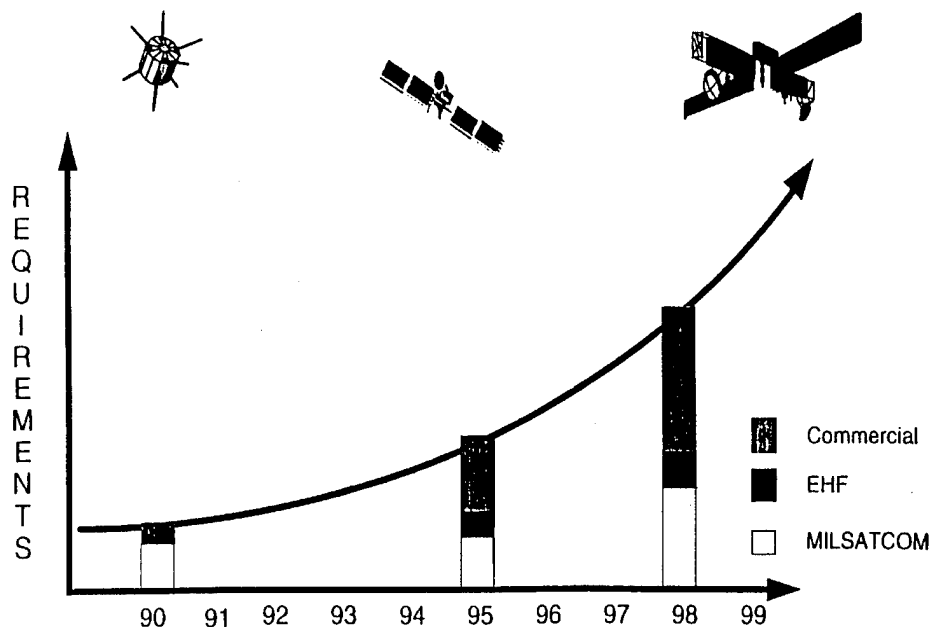


Figure 1. Role of commercial systems in meeting growing DoD requirements. After Ref. [4].

Since it will be the first of the PCSs to reach operational status, and therefore may be the first such commercial satellite communications system to be integrated into DoD communication planning, the focus of this thesis is on the ORBCOMM 'little' LEO system. The author's purpose is to present a description and analysis of the system, its technology and architecture, and then to provide the reader with a discussion of its commercial as well as potential military applications. Finally, a review will be offered summarizing

the system's capabilities, followed by some concluding comments on the potential economic benefits of Government participation in the ORBCOMM venture.

II. THE ORBCOMM SYSTEM

A. SYSTEM OVERVIEW

The ORBCOMM data communication and position determining system is designed to provide users two-way, on-the-move location and data messaging services anywhere on the globe. The system will achieve world-wide coverage by using small mobile terminals and a constellation of non-voice, non-geostationary (NVNG) low earth orbiting (LEO) satellites instead of fixed-site terrestrial relays. The satellites will be linked with existing telecommunications networks via gateway earth stations and a network control center. Commercial users will be able to select among different ORBCOMM services ranging from basic alert and location service to fully mobile digital messaging.

Users of ORBCOMM mobile terminals will be provided location data via a Doppler shift technique. In addition, Global Positioning System (GPS) time signals, with an accuracy of one millisecond, will be provided free of charge to all users as part of the basic package. [Ref. 5]

The ORBCOMM system employs digital packet switching, store-and-forward data network technology to provide users low speed data exchange and alphanumeric messaging capability. The ORBCOMM data network uses CCITT X.400 (e-mail) and X.25 (packet switch) communication protocols. ORBCOMM will be accessible through Internet, public and private data networks (i.e., SPRINT), dial-up circuits (fax and voice), or public e-mail services.

1. Components

The ORBCOMM network consists of three main components - a space segment, a ground segment, and mobile terminals. These components will be discussed in detail later. The key links in the system are the satellites and

gateway earth stations (GES), which provide the connectivity between mobile subscriber terminals (ST) and the network control centers (NCC). The NCCs are the pathways between ORBCOMM and external public network circuits, in addition to being the internal routing and forwarding centers for the network. A total of 23 countries are currently licensed to build ground facilities and offer ORBCOMM services to their local markets. Appendix A contains a list of countries which already have an ORBCOMM license in place and a listing of those countries currently seeking license agreement. There will be only one NCC in each country, but larger nations may require several GESs.

2. Architecture

When a message is transmitted from a mobile ST, it is received by an ORBCOMM satellite, then downlinked to the first available GES. The GES relays the message via dedicated terrestrial line or very small aperture satellite (VSAT) link to the NCC, where the message recipient's location is determined. If the recipient is outside the ORBCOMM network, the NCC routes the message to an external gateway. If the recipient is another ORBCOMM mobile ST, the NCC routes it to the appropriate GES, which uplinks the message to a satellite for transmittal down to the addressee of the message.¹

Both the NCCs and satellites have the ability to store messages. The NCC may deliver messages via active circuits or store them in memory for retrieval at the customer's convenience [Ref. 5]. When communications between a satellite and any NCC is not possible, the satellite will

¹ The NCC may or may not have to relay the message to another regional NCC for transmission to the GES.

acknowledge mobile ST transmissions, but store the messages in memory until they can be downlinked to a GES for transmission to an NCC.

Messages addressed to mobile STs originating from outside the ORBCOMM network arrive at the NCC through a gateway and are transmitted to the recipient in a similar fashion described above. The end-to-end time for transmitting and receipt of a message is approximately three seconds, assuming the satellite can communicate with an NCC or the NCC does not store the message [Ref. 5]. Figure 2 shows the components of the ORBCOMM system and the network architecture.

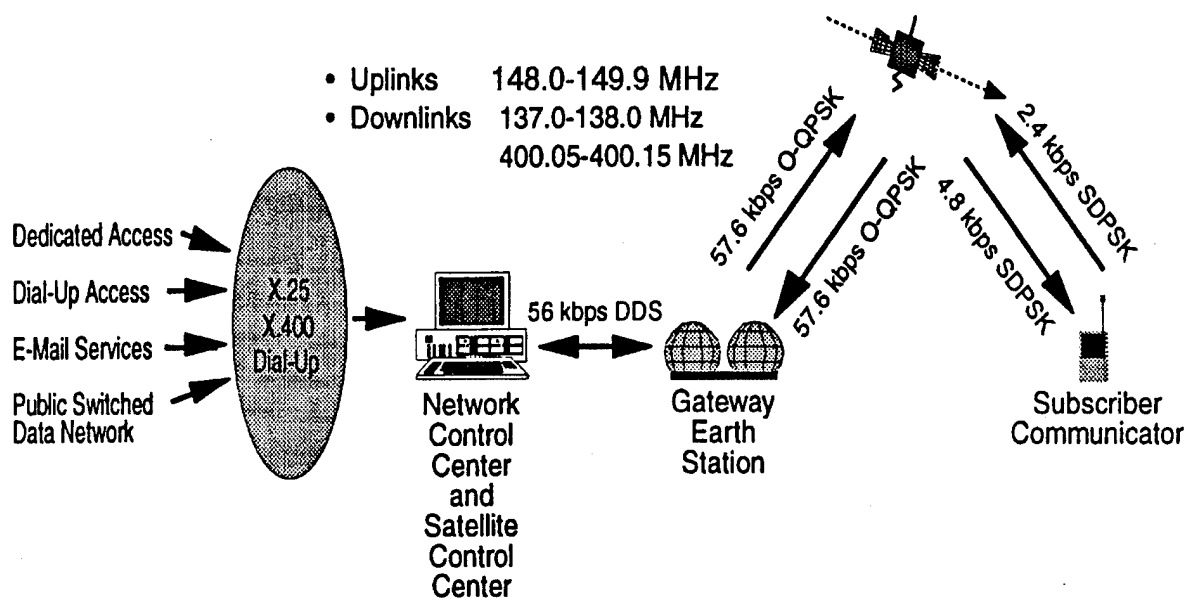


Figure 2. ORBCOMM system architecture. After Ref. [6].

3. Links

ORBCOMM has been licensed by the FCC to utilize the VHF spectrum for its operational links. The GPS time broadcast, however, will be in the UHF spectrum (400 MHz). All downlink transmissions will be in the 137 -

138 MHz band, while all system uplink transmissions will be between 148 and 149.9 MHz. Mobile ST data rates will be 2400 bits per second on the uplink and 4800 bits per second on the downlink. Transmissions between satellites and mobile STs will employ Symmetric Differential Phase Shift Keying (SDPSK) modulation format. Transmissions between satellites and GESs will employ Offset Quadrature Phase Shift Keying (OQPSK) modulation, achieving a data rate of 56,700 bits per second on both the up and downlinks. [Ref. 6]

4. Position Determination

As mentioned earlier, ORBCOMM terminals will use a Doppler position determination technique to provide mobile users with location data. There will be three levels of position resolution available to users who require this capability. Capability and complexity of the mobile ST will determine how accurate calculation of terminal position will be. Note that the system uses the satellite VHF and UHF downlinks to determine position, thus minimizing subscriber transmissions and use of scarce spectrum. [Ref. 5]

Mobile STs will measure Doppler shift on satellite downlink signals. Each satellite will use GPS to determine its own position. The combination of satellite location via GPS data and Doppler measurement enables STs to determine their own position with a general accuracy of between 100 and 1000 meters; level of accuracy will depend on which frequencies the terminal uses to derive location. [Ref. 5]

Using time and position data from the satellite, the mobile STs will use one of three frequency plans to calculate its position: single frequencies of 137 MHz or 400 MHz, and a dual frequency plan using 137 and 400 MHz together [Ref. 5]. The STs internally analyze the satellite downlink frequencies and determine the shape of the curve of variance from the known carrier frequency to produce a most likely user position. On a single satellite

pass basis, least accurate of the three types of mobile STs will be units that derive position from a single downlink frequency. Using a single downlink frequency for high resolution position determination will require a number of discrete measurements to be made over several satellite passes.

Using a single frequency, the time for an initial position fix will be on the order of seven minutes. Mobile STs using the 137 MHz downlink frequency will have a single satellite pass resolution of 3600 feet (about 0.7 miles) for stationary or slow moving users. STs using the 400 MHz downlink are projected to have a single pass resolution of 1200 feet (about 0.2 miles) for stationary users. Position resolution for both types of mobile STs will improve by 30% on the second satellite pass, which will nominally occur within 24 minutes. [Ref. 5]

The top-of-the-line mobile STs will measure Doppler shift from a signal derived from the combination of the satellite's 137 MHz and 400 MHz carriers [Ref. 5]. Use of the two carriers significantly improves position resolution by enabling the ST to remove the propagation path errors caused by ionospheric refraction of the radio waves [Ref. 6]. These STs have a single pass projected resolution of 120 feet, with second and third pass resolution improving to 85 and 70 feet, respectively [Ref. 5].

B. SPACE SEGMENT

1. General Description

The ORBCOMM system will be the first to make use of a constellation of LEO satellites to provide global communications coverage. The system's space segment will consist of 36 satellites launched into six orbital planes. The satellites will be inserted into 775 km altitude circular orbits. All satellites will have an orbital period of 105 minutes. The main constellation will be made up of four planes of eight satellites each; each of these four

planes will be inclined 45 degrees with respect to the equator. The eight satellites in each plane of the main constellation will be spaced 45 degrees apart. ORBCOMM will offer enhanced polar coverage with two supplemental, 70 degree inclined orbital planes. Each of the supplemental polar planes will contain two satellites which will be spaced 180 degrees apart. The configuration of the constellations is designed to allow continuous two-way data and message transfer capabilities, in addition to mobile ST position determination, over all of the United States and most of the world. [Ref. 7]

2. Spacecraft Description

The design of all 36 of the ORBCOMM satellites is identical. The satellites are engineered to use the maximum capacity of Orbital Science Corporation's Pegasus XL low cost launch vehicle [Ref. 6]. Before deployment, the satellites are disk shaped - 41 inches in diameter and just 6.5 inches thick. One full plane (eight satellites) can be simultaneously launched to 775 km at 45 degrees inclination on a Pegasus XL [Ref. 6]. After insertion into orbit, the solar panels and antenna deploy. Figure 3 shows the satellite in its deployed configuration.

The satellites contain four main subsystems: communication subsystem, antenna subsystem, attitude control and station keeping subsystem, and the electrical power subsystem.

a. Communications Subsystem

The principal payload of the satellites is the communication subsystem, which is composed of four sections: subscriber communications section, gateway communications section, satellite network computer, and UHF transmitter section. [Ref. 6]

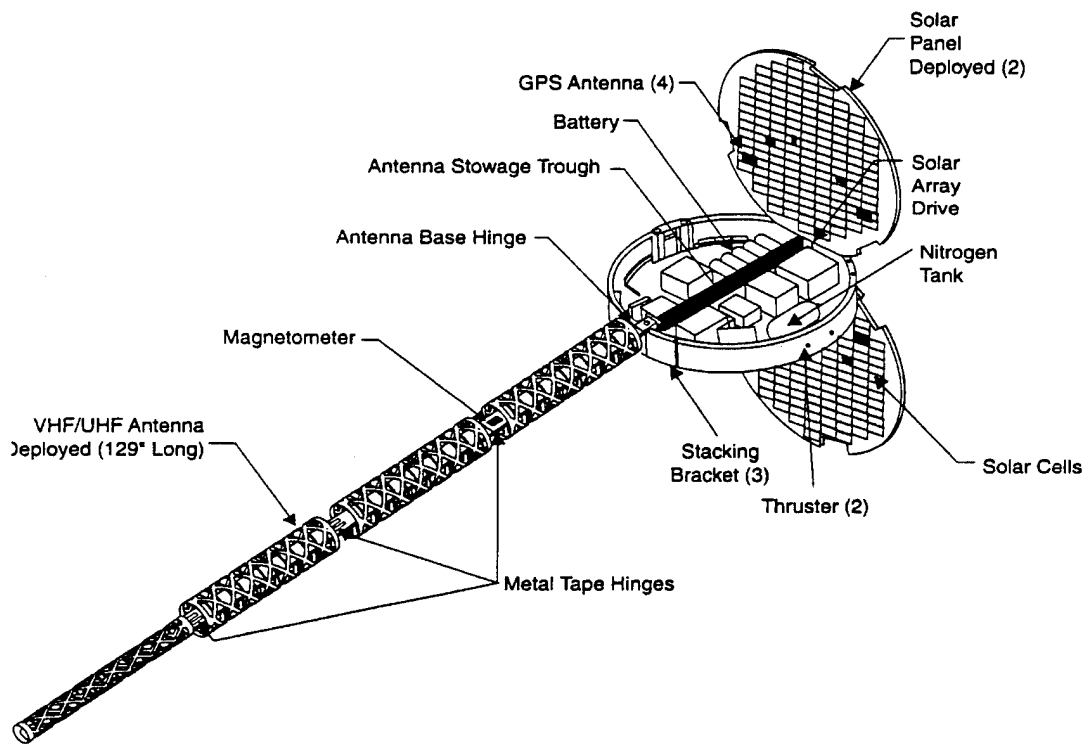


Figure 3. Deployed ORBCOMM satellite. From Ref. [6].

The largest section of the satellite communication subsystem is the subscriber communications section. It consists of seven identical receivers, two transmitters, and associated receive / transmit filters and hybrid couplers. In normal operations, six of the receivers will be subscriber receivers used to process inbound traffic, and the seventh will be the Dynamic Channel Activity Assignment System (DCAAS) receiver. Each of the receivers are direct conversion Digital Signal Processor (DSP) driven receivers. When selected by ground command to function as the DCAAS receiver, each receiver is capable of scanning the 148 - 149.9 MHz band with 2.5 kHz resolution in five seconds. (DCAAS will be covered in greater detail in a later section.) The subscriber receivers use a single uplink antenna and Low Noise Amplifier (LNA) which has been designed to operate linearly in the presence of high levels of interference. Analog and digital filters are incorporated after the LNA to reduce the impact of VHF transmissions from terrestrial mobile communications systems on the subscriber receivers. Following SDPSK demodulation, the digital signals are routed to the satellite on-board network computer for processing. [Ref. 6]

The subscriber communication section also includes two subscriber transmitters which are capable of transmitting at a nominal output power of 11 Watts. The output transmitters receive packets for downlink from the satellite on-board network computer, modulate and amplify the signals, then feed the signals into the antenna subsystem. To protect frequency bands outside 137 - 138 MHz from out of band transmissions, output filters and diplexers are used. [Ref. 6]

The gateway communications section consists of a transmitter and receiver in a single package, with separate antennas used for transmit and receive functions. The antennas have opposing circular polarization, while the nominal power of the transmitter is 5 Watts. Data packets

destined for a GES are routed from the satellite network computer to the gateway transmitter. [Ref. 6]

The 56.7 kbps satellite downlink to the GES is transmitted using OQPSK modulation and Time Division Multiple Access (TDMA) format. The gateway receiver demodulates OQPSK 56.7 kbps TDMA signal uplinks from the GESs and forwards data packets to the satellite network computer. [Ref. 7]

As already described, the satellite network computer processes uplinked packets from the subscriber and gateway receivers for distribution to the proper downlink transmitters. The satellite network computer functions are actually performed by a distributed computer system consisting of several microprocessors [Ref. 6]. The computer system is also responsible for identifying clear uplink channels using the DCAAS receiver, and for interfacing with the satellite GPS receiver to distribute information required by the communication subsystem.

The UHF transmitter section consists of a specially constructed 1 Watt transmitter which emits a 400 MHz signal coupled to a 2 dB peak gain antenna [Ref. 6]. As mentioned earlier, the use of this UHF beacon, combined with the normal VHF subscriber downlink, significantly improves performance of the position determination function of the mobile STs.

b. Antenna Subsystem

The ORBCOMM satellite antenna subsystem consists of a deployable, four segment antenna boom and the necessary RF splitters, phase shifters, and impedance matching transformers required to feed the various antenna elements. The boom contains seven separate circularly polarized quadifiler antenna elements which are combined into the following five separate antennas [Ref. 6]:

- Combined Subscriber Receive/Transmit Antenna #1

- Subscriber Transmit Antenna #2
- UHF Transmit Antenna
- Gateway Receive Antenna
- Gateway Transmit Antenna

Prior to satellite deployment, the antenna is folded into a trough measuring approximately 6x6x38 inches. The antenna deploys to its full 141 inch length after the satellite solar panels are released. The antenna boom also serves as the mounting point for a 3-axis magnetometer and a gravity gradient weight used by the attitude control subsystem. [Ref. 6]

c. Attitude Control and Station Keeping Subsystem

The function of the satellite attitude control subsystem (ACS) is to keep the antenna pointed toward the earth, as well as solar pointing to maximize the efficiency of the solar cells. As mentioned earlier, the ACS includes a three axis magnetic control system which operates with a combination of sensors. The gravity gradient weight at the nadir-end of the antenna boom enhances stabilization. The ACS, in conjunction with the antenna subsystem, maintains an average pointing loss of approximately 0.2 dB for the satellites in the 45 degree inclined planes and within a few tenths of a dB for the 70 degree inclined plane polar coverage satellites. [Ref. 6]

The satellites in the two ORBCOMM constellations will maintain their relative positions to within plus/minus five degrees, i.e., 45 ± 5 degrees separation for the main constellation and 180 ± 5 degrees for the two supplementary polar planes [Ref. 6]. Separation velocity from the Pegasus launch vehicle will be accomplished via springs, then braking will be performed using a nitrogen gas (GN₂) blowdown system to accomplish the required initial spacing within each plane. ORBCOMM will utilize a proprietary station-keeping technique to maintain correct intra-plane spacing. ORBCOMM technical publications indicate this proprietary

technique is "cost free" because it does not require use of satellite fuel [Ref. 5].

d. Electrical Power Subsystem

The electrical power system for ORBCOMM satellites will produce approximately 70 Watts of power on an orbit average basis at the end of a satellite's four year life. This is enough power to operate the full payload through the end of satellite life, even under worst-case eclipse conditions. Each satellite has enough solar cells to support operation in eclipse orbit after four years; the solar array is designed with excess capability and generating margin to account for degradation over the satellite's lifetime. The batteries are sized for 20,000 discharge cycles, approximately equating to an eclipse every 100 minutes for four years. Tables 1, 2, and 3 show the satellite power budget, solar array requirements, and battery sizing data. [Ref. 6]

C. GROUND SEGMENT

ORBCOMM's system design employs relatively simple, inexpensive satellites. Therefore, most of the "intelligence" in the ORBCOMM system is in its ground network. The ground segment is comprised of gateway earth stations (GESs), network control centers (NCCs), and a single satellite control center. Each country licensed to provide ORBCOMM service will have one NCC and at least one GES. The geographic size of the country will determine how many GESs are required to provide the satellite coverage needed by the network. For instance, there will be four GESs located near the corners of the continental US (New York, Georgia, Washington, and Arizona) [Ref. 7].

<u>Subsystem</u>	Peak Power with contingency (W)	Orbit Average (WHr)
<u>Bus</u>		
Computer	2.2	3.7
ACS Subsystem	5.7	5.4
Power Subsystem	9.2	11.6
Harness	0.2	0.4
GPS Receiver	3.7	6.3
<u>Payload</u>		
DCAAS Receiver	0.9	1.6
ST Receivers (6)	5.6	9.4
GES Receiver	3.3	5.6
ST Transmitters	33.5	56.2
GES Transmitter	9.1	15.3
UHF Transmitter	4.2	2.3
Peak Power Requirements	77.8	W
Total Energy per Orbit	117.8	WHr
Orbit Average Power Requirements	70.2	W

Table 1. Satellite Power Budget. From Ref. [7].

Required Energy	141	WHr (worst case)
Average Power	129	W
Collection Efficiency	90	% (Pointing and Shadowing)
Required Solar Array Power (end-of-life)	143	W
Degradation over Lifetime (4 yrs)	67	% (Radiation, UV, Thermal)
Required Solar Array Power (beginning of life)	213	W
Array Power	236	W
Margin	11	%

Table 2. Satellite Solar Array Requirements. From Ref. [7].

Maximum Depth of Discharge (DOD)	35	% (20,000 discharge cycles)
Maximum Storage Required	46	WHr
Battery Sizing	132	AHr
Bus Voltage	14.0	V (5 NiH at 2.8 Volts each)
Required Cell Sizing	9.4	AHr
Actual Cells	10.0	AHr
Actual Maximum DOD	33	%
DOD Design Margin	2	%

Table 3. Satellite Battery Sizing. From Ref. [7].

1. Gateway Earth Stations

The GESs are highly automated, regional gateways linking ORBCOMM spacecraft with the NCCs and the satellite control center. It is this combination of satellites and GESs that provide the mobile user transparent access to the network. GESs are connected to the network control center via leased terrestrial or VSAT links. They are designed to be unattended, highly redundant, and provide the following functions:

- Acquire and track satellites (using orbital data received from the NCCs).
- Transmit to and receive from satellites.
- Transmit to and receive from NCCs.
- Monitor and report status of GES hardware and software to NCCs.
- Monitor and relay system level performance data of satellites "connected" to the GES. [Ref. 8]

To track and communicate with the satellites as they cross the horizon, each GES uses two steerable, 18 foot aperture high gain VHF antennas. The antennas are conical horn with a disc-o-cone feed structure that have extremely low side lobes. At ORBCOMM frequencies (VHF), the beamwidth of these antennas is approximately 22 degrees. This relatively large beamwidth means two or more satellites will be in, or near, the main beam of the same GES antenna a large percentage of the time. By using a time division multiple access protocol (TDMA), the GESs can communicate with multiple satellites simultaneously and seamlessly "hand-off" satellites from one GES to another. ORBCOMM mobile subscriber multiple access protocols will be discussed in more detail later. Schematic representation of a typical GES is shown in Figure 4. [Ref. 6]

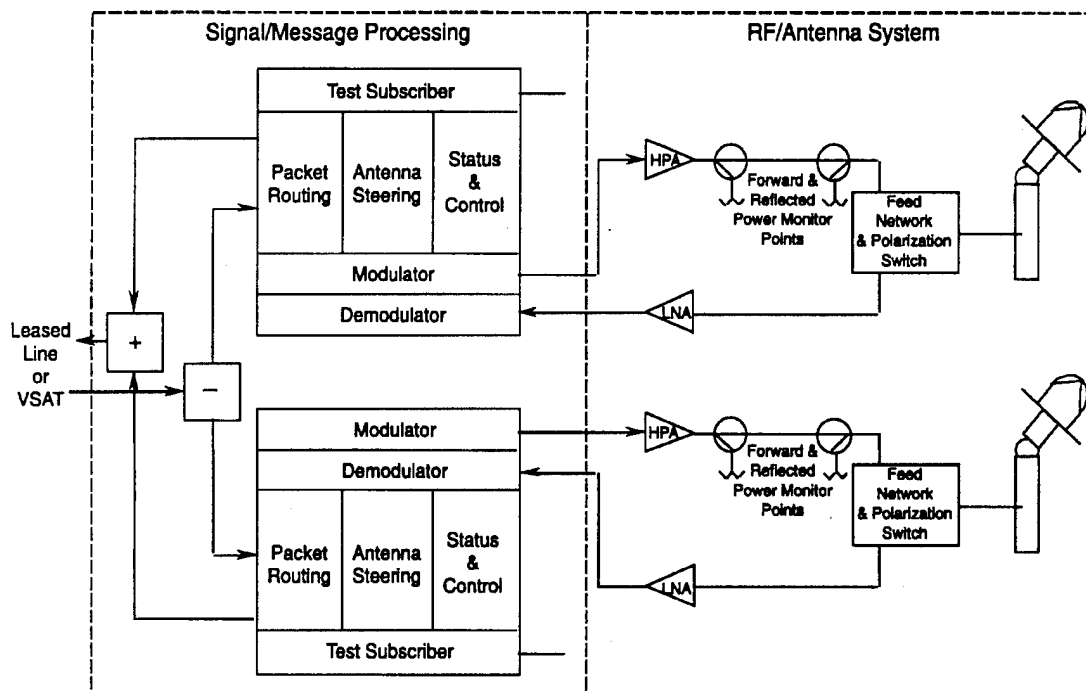


Figure 4. Typical GES configuration. From Ref. [8].

2. Network Control Centers and Satellite Control Center

ORBCOMM NCCs provide message routing, satellite control, and customer services in each country. The NCC in the US will be operated by ORBCOMM; NCCs abroad will be operated under license. The NCC is comprised of highly available dual processor computers running ORBCOMM's UNIX based proprietary software, automatic switch overs, and mirrored disks [Ref. 8]. Figure 5 shows general NCC configuration.

Customer connectivity to the NCCs from external networks will be over leased lines and the public data networks. The NCC will provide the following functions [Ref. 8]:

- Message handling - management of the delivery of data messages within and in/out of the ORBCOMM system
- Network management - statistics, diagnostics, configuration control
- Message transfer/gateway - delivery of data messages, conversion to/from other message delivery receipt formats
- Customer service - live operators providing a customer service interface

The ORBCOMM system has one satellite control center (SCC) which will be co-located with the NCC in Dulles, Virginia. The SCC will provide satellite control (via any of the GESs) and constellation optimization, in addition to satellite management services such as telemetry monitoring, analysis, and fault identification [Ref. 7].

D. MOBILE SUBSCRIBER TERMINALS

The ORBCOMM system will utilize several different types of mobile STs - ranging from fully integrated personal communicators about the size of a flip-top cellular telephone to ruggedized "black box" industrial communications engines designed for autonomous remote tracking and data reporting [Ref. 8]. Several companies, including Panasonic, Texas

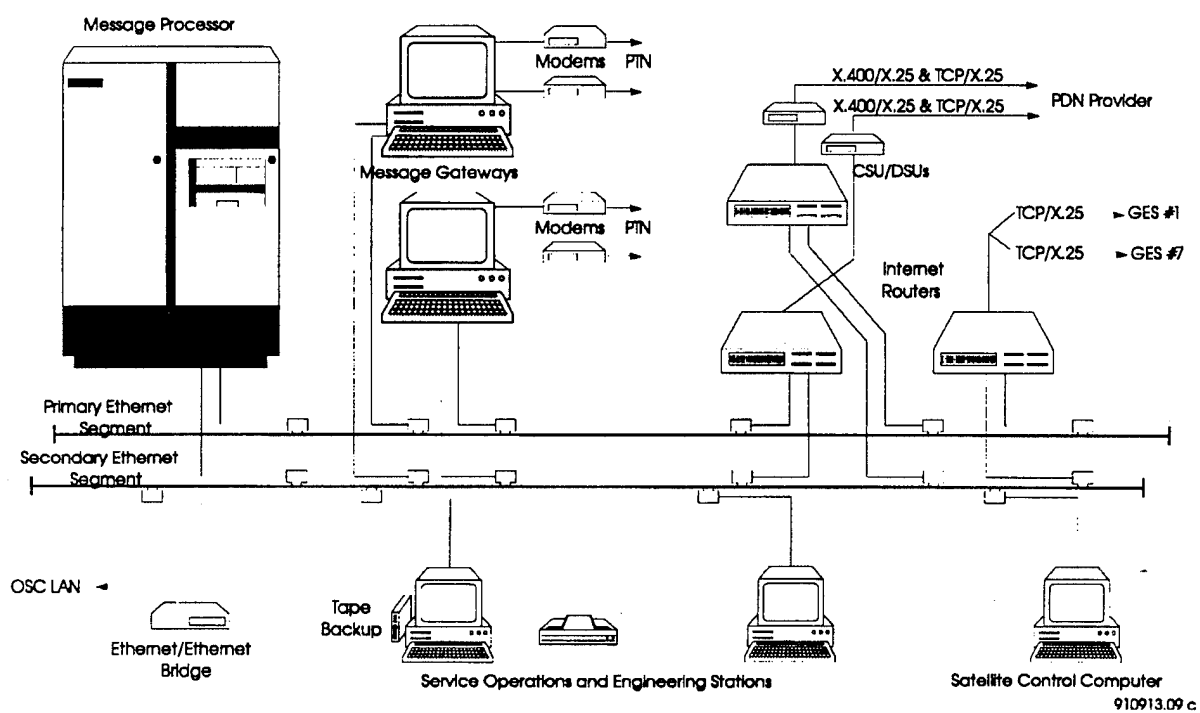


Figure 5. ORBCOMM NCC configuration. From Ref. [8].

Instruments, Torrey Science & Technology, Elisra, and ETA Technologies Corporation, are licensed to produce ORBCOMM mobile STs [Ref. 9]. A number of different versions of each type are currently under design or in pre-production status.

The personal communicator versions of the mobile STs are full function, lightweight devices powered by long life batteries. In addition to ORBCOMM transmit and receive electronics, the communicators will consist of small alpha-numeric keypads for composing messages and an LCD screen to read incoming messages, as shown in Figure 6. The "black box" industrial units have ORBCOMM transmit and receive components but no keyboards or displays. Designed to integrate with and pass data and/or position reports from autonomous equipment anytime, anywhere, these units will interface with other systems via RS-232C ports. A third general variation of the mobile ST designed for direct (serial port) interface with personal computers will also be available; this type of unit will be similar in function to an internal/external modem and operate in the same manner as the industrial "black box" type units. [Ref. 6]

All versions of the mobile STs will be able to transmit on any of the DCAAS assigned channels between 148 and 149.9 MHz, and receive any of the satellite downlink channels between 137 and 138 MHz. Using SDPSK modulation, the mobile STs will transmit at 2400 bps and receive at 4800 bps. As discussed earlier, single satellite pass position accuracy will depend on the number of frequencies the mobile ST uses for Doppler shift processing.

E. OPERATIONS

1. Frequencies and Channelization

The ORBCOMM system operates principally in the VHF frequency bands. Downlinks from the satellites to both the GESs and mobile STs

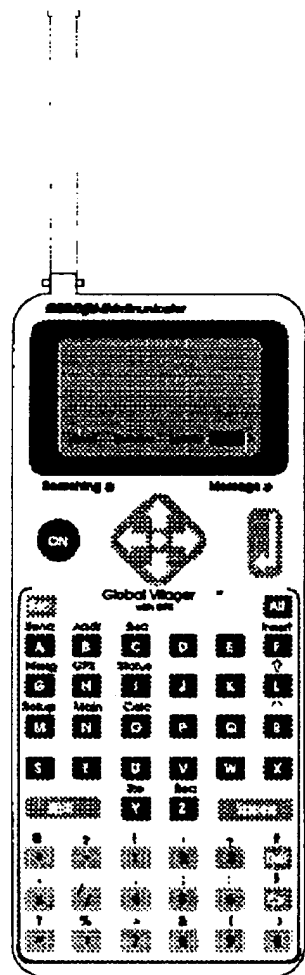


Figure 6. ORBCOMM mobile ST. From Ref. [8].

occur in the 137 - 138 MHz band. All transmissions to the satellites (mobile ST and GES) use the 148 - 149.9 MHz band. The satellites also transmit a UHF beacon at 400.1 MHz. Table 4 shows the system frequency and channelization plan.

Link Description	Frequency Band (MHz)	Channels (satellite)	Channels (system)	Data Rate (kbps)	Channel Bandwidth (kHz)
Mobile ST to satellite uplink	148-149.9	6	DCASS ²	2.4	10.0
GES to satellite uplink	148-149.9	1	1	57.6	50.0
Satellite to Mobile ST downlink	137-138	2	18	4.8	15.0
Satellite to GES downlink	137-138	1	1	57.6	50.0
Satellite to Mobile ST beacon	400.05-400.15	1	1	NA	18.0

Table 4. ORBCOMM Frequency Band and Channelization. From Ref. [6].

2. Links

The following paragraphs discuss ORBCOMM communication links.

a. Satellite to Mobile ST

The system uses a total of 18 channels with 15 kHz bandwidth for the satellite to mobile ST downlinks. Each satellite will be assigned two of the 18 channels for downlinks. This number is a function of the number of satellites which will simultaneously be visible to the subscriber population and the number of satellites simultaneously visible to each other.

² DCAAS can access up to 760 channels [Ref. 6]. See description of DCAAS in sub-section d.

ORBCOMM predicts that for 20 percent of the time three satellites, each in different orbital planes, will be simultaneously visible to the user population. Therefore, to avoid intra-system interference, the three satellites will have to use different downlink frequencies. These three satellites will also have to avoid frequencies being used by the other two co-planar satellites whose footprints overlap with their coverage areas. Thus, the total number of satellites that ORBCOMM must consider for intra-system coordination is nine - the three satellites simultaneously in view of the population and their six co-planar satellite neighbors. With two downlink frequencies per satellite, a total of 18 downlink channels are required. [Ref. 6]

b. GES / Satellite

ORBCOMM utilizes TDMA for its GES / satellite links to simultaneously use single 50 kHz channels for uplink and downlink. TDMA has several advantages, including sharing of the single channel by multiple satellites / GESs and "seamless" hand-over of satellites from GES to GES. According to ORBCOMM, this assignment is sufficient to service the entire constellation of satellites. [Ref. 6]

c. Mobile ST to Satellite

The mobile ST to satellite links are designed to operate in the high interference environment which exists in the 148 - 149.9 MHz band. The mobile ST uplinks are designed to be frequency agile. The uplinks will be able to access 10 kHz channels on a burst-to-burst basis using ORBCOMM's proprietary DCAAS multiple access protocol for channel assignment. [Ref. 6]

d. DCAAS

DCAAS is the "heart" of the system's interference avoidance design. DCAAS uses a scanning receiver to sample small bandwidths and measure interference power across the spectrum every five seconds or less. The interference information is processed by the satellite's onboard computer to yield a list of the "best" uplink channels. This list is prioritized based on an algorithm which predicts the interference power expected on the next scan. DCAAS selects channels to use from the stored set of possible uplink channels based on this prioritized list. The satellites distribute the channel assignment information to the mobile STs via an order wire during the satellite / subscriber handshake procedure which is required before a mobile ST is allowed to transmit. [Ref. 6]

3. Multiple Access

Multiple access for mobile subscribers in the ORBCOMM system is achieved via a satellite / subscriber handshake procedure and use of a proprietary multiple access network protocol.

a. Order Wire

Before a mobile subscriber terminal can transmit, it must receive the satellite downlink order wire transmission. The order wire contains packets of information the mobile ST needs to successfully transmit and receive message packets with the satellite. Updated every few seconds, the order wire distributes the following information [Ref. 6]:

- Information on the satellite / GES connection being used.
- Partitioning of the multiple access / messaging uplink and downlink channels.
- The current frequencies selected by DCAAS.
- Other pertinent system information (i.e., time and synchronization data).

b. Acquire-Communicate

The ORBCOMM system uses a proprietary modified ALOHA scheme called Acquire-Communicate (A-C) as its multiple access protocol [Ref. 5]. A-C is similar to slotted ALOHA multiple access protocol in that a common communication channel is used by many subscribers to transmit packets, and packet transmissions are made in short bursts since the entire channel bandwidth is used [Ref. 10]. Additionally, the channel is slotted in time and users are required to synchronize their packet transmissions into assigned fixed-length channel time slots [Ref. 5].

A-C is a two-phase process; the uplink channel is organized into two distinct windows. In the acquisition phase, the satellites provide the users with uplink information (i.e., frequency and time correction data) and the mobile STs identify communications needs to the satellites. In addition, the mobile STs receive the slot assignments for follow-on transmission of information packets during this phase. The information packets are then transmitted during the communication phase. Figure 7 depicts the sequence of events in the A-C process. The length of the communications window nominally allows up to 14 short packet transmissions from the mobile ST. However, this window can be shortened or lengthened as directed from the network control center (NCC). [Ref. 5]

When a mobile ST has packets to send, it commences an A-C sequence. The sequence begins with the terminal software initiating a "random access" process by selecting:

- A channel from the current list of in-use A-C channels (given to the mobile ST by the satellite on the order wire).
- A number between 1 -127. (This is the burst ID number. It identifies a ready user to the satellite, and is used by the satellite to assign slots).
- A start time within its acquisition window.

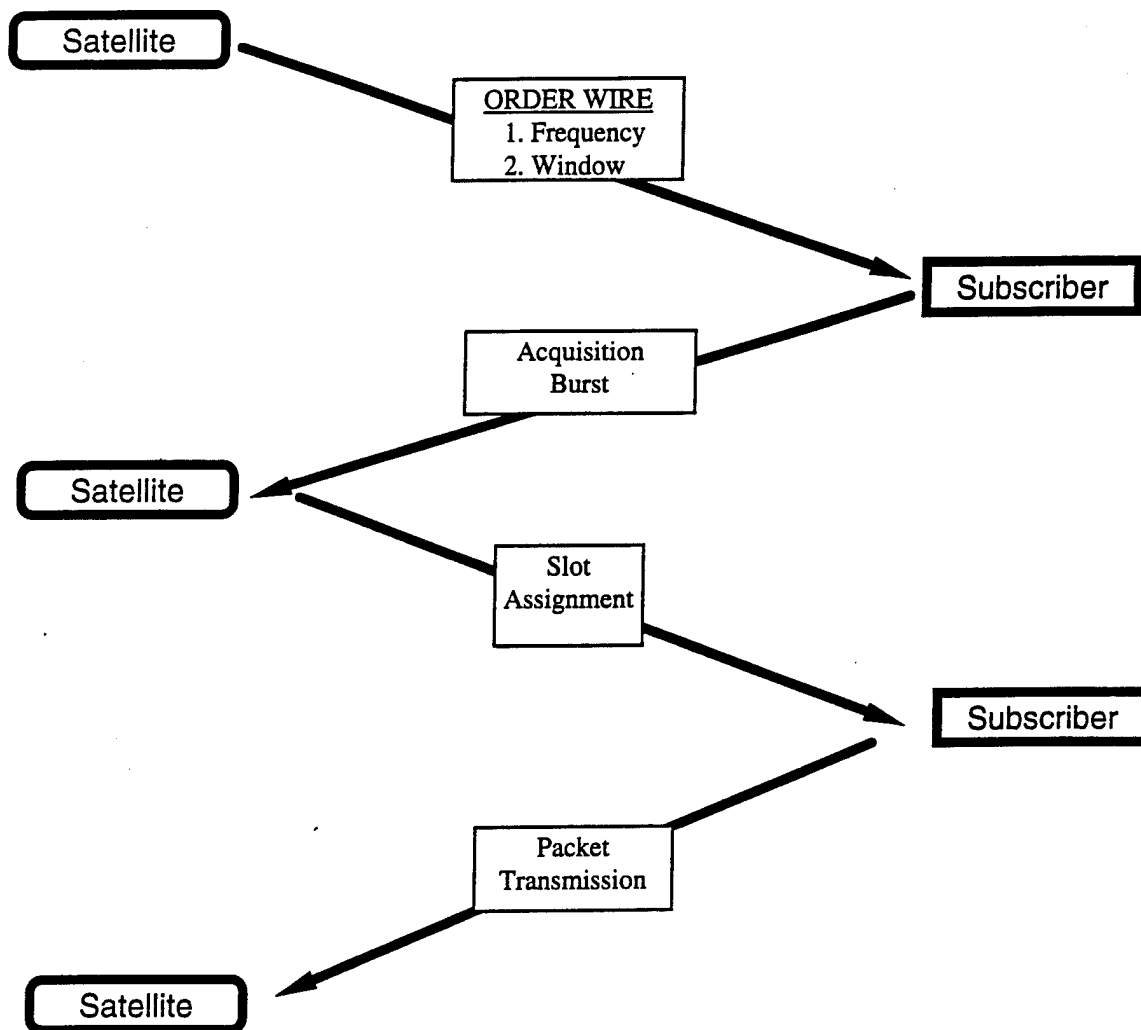


Figure 7. Sequence of events in ORBCOMM's A-C protocol.

The mobile ST transmits an eight-bit burst at the randomly selected start time within its acquisition window. Then it goes back to receive mode to wait for slot assignment packets to arrive on the downlink channel. The satellite assigns slots by burst ID. If the mobile ST does not receive a slot assignment for its burst ID, the A-C process is restarted up to n times. The value of n is contained in the uplink information provided on the order wire. [Ref. 5]

Under the A-C scheme, the satellites use the downlink channels to transmit control information and/or message traffic to users. The satellites transmit messages to subscribers in a stream of bits that is organized into one-second frames. The downlink frames are further decomposed into 25 byte segments or time slots. ORBCOMM STs will reserve all, or a portion of one, of these time slots for their data traffic. Thus, subscribers will only receive messages addressed to them; transmissions during the other time slots will not be received by the mobile STs. [Ref. 7]

F. SUMMARY

ORBCOMM is a digital data communications and navigation system that provides mobile two-way information exchange and position location anywhere in the world. ORBCOMM is the world's first commercial LEO satellite system, and is designed to use relatively simple, inexpensive satellites and mobile communicators in combination with "intelligent" terrestrial stations. ORBCOMM employs VHF burst transmission and packet switching, store-and-forward communications network technology. The system does not utilize simple "bent-pipe" type satellite communication relays. The satellites demodulate and use on-board computers to process messages, re-modulating them into message packets for transmission on the downlink.

III. SYSTEM ANALYSIS

This chapter presents an analysis of the operational capabilities and efficiencies expected from the ORBCOMM system. The analysis focuses on system link budgets, orbits and coverage predictions, random access channel interference, and network throughput.

A. LINK BUDGETS

System link budgets were calculated for edge-of-coverage as defined by ORBCOMM. The budgets are based on a geometry with the satellites at five degrees elevation angle from the mobile user or GES. Corresponding angle at the 775 km altitude satellite is 62.5 degrees off-nadir [Ref. 6]. Appendix B contains the details and calculations associated with each of the link budgets. Note that ORBCOMM satellites do not use turn-around transponders; all packets are demodulated and re-modulated prior to re-transmission. A number of worst case conditions are assumed in the link calculations. Actual instantaneous link margins on the various paths will depend on a number of dynamic conditions (i.e., current geometry, local blockage, multipath losses) [Ref. 11].

The system bit-error-rate (BER) requirements are based on modulation type and bit rates. BER for the GES / satellite links is $1:10^6$, while BER required for satellite / subscriber links is $1:10^5$.

1. GES to Satellite Link Budget

The GES to satellite link calculation indicates a 2.48 dB excess margin for the communication uplink. Contributing to this calculation is the earth station's 40 dBW EIRP derived from a 17 dB gain VHF transmit antenna and a 330 Watt high power linear amplifier (HPA). Losses between the HPA and transmit antenna are predicted at 2.2 dB. The GES receiver on the satellite has a noise figure on the order of 7 dB and antenna gain of 1 dB when the

source of the inbound GES signal is 62.5 degrees off nadir. The satellite LNA to antenna loss is predicted at 1.4 dB. The satellite's calculated G/T is reduced approximately 0.9 dB to account for an expected antenna temperature above 290 degrees Kelvin caused by sky noise at the operating frequencies. [Ref. 6]

An interference margin of 20 dB is included to account for interference from terrestrial mobile communications systems which operate in the VHF band. The GES to satellite uplink channel is 50 kHz wide, while terrestrial mobile systems are channelized on 25 kHz center frequencies. The interference margin accounts for the satellite receiver having to operate in the presence of unwanted signals from at least two terrestrial mobile channels. [Ref. 6]

2. Satellite to GES Link Budget

The 3.6 dB excess margin on the satellite-to-GES communication downlink is based on a satellite EIRP of 6.5 dBW for transmissions at 62.5 degrees off nadir. This EIRP is derived from a 0.8 dB antenna gain, amplifier-to-antenna loss of 1.3 dB, and transmit power of 7 dBW (from a 5 Watt amplifier) [Ref 6]. At the GES end, G/T is derived from a 17 dB gain antenna, antenna-to-LNA loss of 0.9 dB, and effective LNA noise figure of 2.2 dB [Ref 6]. At VHF and UHF operating frequencies sky temperatures can range from a low of 100 degrees Kelvin to over 1000 degrees Kelvin in the presence of solar and galactic noise [Ref. 12]. The author uses 400 degrees as a mid-range, in addition to allowing a degradation of 2 dB to account for expected sky temperature above 400 degrees Kelvin.

3. Mobile ST to Satellite Link Budget

The mobile subscriber-to-satellite communication uplink calculations show a 4.92 dB excess margin. This is based on a mobile communicator EIRP

of 7.5 dBW derived from a 5 Watt transmitter and 0.5 dB gain omni-directional whip antenna. The satellite receive antenna gain when mobile STs are 62.5 degrees off nadir is 3.6 dB. Satellite antenna-to-LNA loss is 2.3 dB, and receiver noise figure is 2 dB. Again, a G/T degradation of 0.8 dB accounts for higher than 290 degrees Kelvin antenna noise temperature. [Ref. 6]

4. Satellite to Mobile ST Link Budget

The satellite-to-subscriber communication link calculations indicate a 1.1 dB surplus margin. This is based on a satellite EIRP of 12.5 dBW, for transmissions at 62.5 degrees off nadir. The satellite HPA output is 11 Watts, with a nominal loss to the antenna of approximately 1 dB, and an antenna gain of 3.2 dB. On the receive side, the mobile ST uses a 0 dB gain omni-directional whip antenna with a 2 dB receiver noise figure. Losses between the antenna and the LNA are on the order of 0.7 dB. A degradation allowance of 0.5 dB is included to account for expected sky temperatures above 400 degrees Kelvin. [Ref. 6]

5. Satellite to Mobile ST UHF Link Budget

The UHF transmissions from the satellite are used for Doppler position determination only. Since there is no data being exchanged over this channel, received signal-to-noise ratio is the criteria for analysis.

The UHF downlink budget indicates received signal-to-noise will be on the order of 17 dB. The budget is based on a satellite transmit EIRP of 2.5 dBW derived from a 0 dBW transmitter, HPA to antenna loss of 0.7 dB, and an antenna gain of 3.2 dB. The subscriber G/T of -29.8 dB is based on a 0 dB gain omni-directional antenna, antenna to receiver loss of 1.0 dB, and a receiver noise figure of 3.0 dB. Degradation allowance of 0.5 dB has been included to account for sky temperatures greater than 400 degrees Kelvin.

B. SATELLITE COVERAGE

ORBCOMM's primary constellation of 32 satellites is designed to permit efficient two-way data and message transfer service and subscriber position determination over all coverage areas where satellite access to a GES is available. When a GES is not in view or not available for access the satellites function in a store-and-forward mode, storing subscriber messages until the first GES is available for downlink. The satellites are configured with approximately 512 kilo bytes of memory for storing messages.

The system will provide near-continuous, high quality coverage to all areas of the world between 10 and 55 degrees latitude, with reduced coverage at the equator and latitudes up to about 60 degrees. The ORBCOMM satellite footprint is 2500 nautical miles in diameter, based on a satellite half beamwidth of approximately 60 degrees [Ref. 5]. Figure 8 shows predicted daily satellite coverage for different latitudes. Note that the average number of satellites simultaneously visible at locations between 10 degrees and 55 degrees latitude is greater than 1.5, and for significant periods of time between two and three satellites will be simultaneously visible. ORBCOMM predicts the maximum outage time for locations in the 25 to 50 degree latitude range will be on the order of five minutes or less, with 90% of the outages less than two minutes in duration [Ref. 7]. The four supplemental ORBCOMM satellites in polar orbits will provide polar area coverage every one-half hour for 14 minutes [Ref. 5].

ORBCOMM is designed with redundancy at the system level. With 36 satellites in the system, the loss of one, or even several, satellites should not seriously impact overall service offered by the system. A lost satellite will impact the subscriber in the form of a reduction in coverage. The impact due to satellite loss is therefore a function of the total number of satellites in the system. If a single satellite is lost, the overall system coverage will be

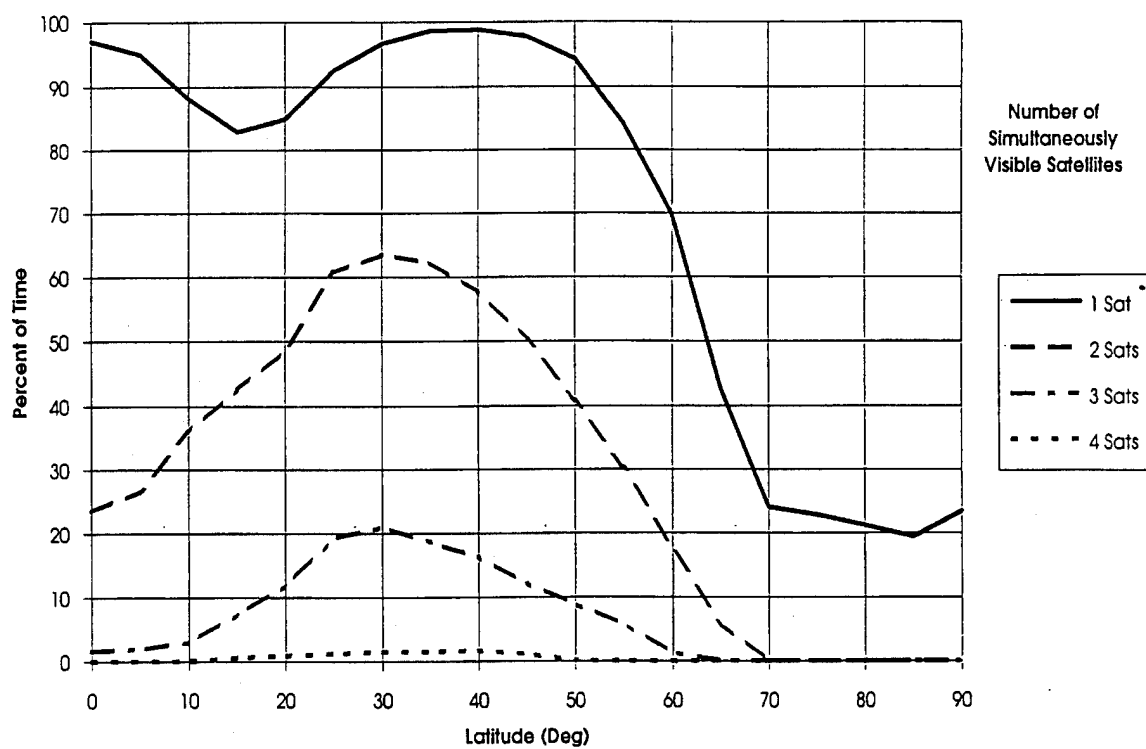


Figure 8. ORBCOMM satellite coverage statistics. From Ref. [7].

reduced by less than 3 percent, and the loss of two satellites will reduce coverage by about 5 percent. ORBCOMM has conducted failure analysis, based on the actual design of the satellite components and sub-assemblies, which indicates the probability of a single satellite failing, due to random part failure, within the four year constellation lifetime is about 30 percent. The probability of two satellites failing is approximately 8 percent, and the probability of more satellites failing is exceedingly small. [Ref. 6]

C. CHANNEL INTERFERENCE

ORBCOMM mobile subscriber message transmissions are based on a multiple access scheme that uses burst packet communications over frequencies assigned by DCAAS. Each uplink transmission is initiated by a short packet burst over one of the assigned random access channels.³ This can be simply a "request for service", an acknowledgement, or a short message such as terminal geolocation. If the terminal needs to transmit a longer message requiring additional packets to be sent, the "request for service" burst would be followed by additional coordinated message bursts.⁴ Each message transmission includes a period of carrier, a brief data preamble, and typically 30 - 50 characters and occurs on uplink frequencies at specified slot times directed by the satellite; the satellites can vary mobile ST frequency from burst-to-burst.

Data from ORBCOMM's Capability Demonstration Satellite (CDS) shows DCAAS has a 95% success rate in predicting free channels on the next scan. Results from the CDS indicate DCAAS is expected to change the frequencies of the random access channels on average every 5 - 15 seconds,

³ During the acquisition window on the DCAAS assigned channels; see Chapter II, page 29.

⁴ The message bursts will also use a short transmission format expected to average about 250 milliseconds in duration [Ref. 7].

which will ensure avoidance of extended interference to terrestrial mobile systems and improve service to subscribers [Ref. 6].

If the transmission of each random access "request for service" packet burst is treated as an "event" that is either successful or unsuccessful (depending on whether it arrives successfully at the satellite), a statistical analysis can be developed which examines the efficiency of DCAAS and the random access scheme by analyzing the probability of a successful "request for service" transmission over available random access channels.

First, assume the satellite uses the order wire channel to broadcast a list of r random access channels from which subscribers may choose to initiate a communication sequence.⁵

Let q be the number of subscribers that have packets to send and attempt to contact the satellite by choosing one of the r channels at random. These q subscribers, perhaps a subset of all subscribers with packets to transmit, attempt to contact the satellite simultaneously. In such a situation, if all q subscribers don't choose different channels, then at least two will choose the same channel and will interfere with each other.

The probability of no interference, i.e., that all q subscribers choose different channels from the r available channels, is

$$P_q = \frac{r(r-1)(r-2)\dots(r-q+1)}{r^q} = \frac{r!}{(r-q)!r^q}, \quad q = 0, 1, \dots, r. \quad (3-1)$$

If $q > r$, that is there are more subscribers than channels, then at least two subscribers will interfere. Therefore

$$P_q = 0, \quad q > r. \quad (3-2)$$

⁵ Since the satellite has a total of six subscriber receivers and uses a separate receiver for DCAAS, $r = 6$. See Chapter II, page 14.

In addition to choosing different channels, the packets sent by each of the q subscribers must arrive and be decoded correctly by the satellite. Let P_{cs} be the probability of a successful packet transmission through each of the q chosen channels. Thus the probability of successful transmission through all q channels is

$$P_{total} = P_{cs}^q. \quad (3-3)$$

Then P_{tq} , the probability of the q subscribers all making successful contact with the satellite, is:

$$P_{tq} = \frac{r!}{r^q (r-q)!} P_{cs}^q, \quad q = 0, 1, \dots, r \quad (3-4)$$

and

$$P_{tq} = 0, \quad q > r. \quad (3-5)$$

Now let Q , the number of users attempting to contact the satellite during some time interval t be a random variable. If λ is the average arrival rate of users, Q may be modeled as a Poisson process. Thus, the probability of having q new users attempting to establish contact during time t is

$$\Pr(Q = q) = \frac{(\lambda t)^q e^{-\lambda t}}{q!} \quad q \geq 0. \quad (3-6)$$

Thus, the probability of no interference in the system is

$$P_{NI} = \sum_{q=0}^{\infty} P_{iq} * \Pr(Q = q) , \quad (3-7)$$

which upon combining (3-4), (3-5), and (3-6) becomes

$$P_{NI} = \left[\sum_{q=0}^r \frac{r!}{(r-q)!q!} \left(\frac{P_{cs}}{r} \lambda t \right)^q \right] e^{-\lambda t} . \quad (3-8)$$

As expected, this analysis indicates P_{NI} will be a function of traffic intensity. Figure 9 shows the relationship between P_{NI} and increasing user arrival rates, λ . Assuming $t = 1$ time slot and $P_{cs} = 0.98$ ⁶, we see P_{NI} is approximately 0.9 at $\lambda = 1$ and reaches an approximate level of 0.2 at about $\lambda = 5$. Note that the satellite only has $r = 6$ channels which users can simultaneously access.

Our model assumes each subscriber "request for service" packet burst requires one full acquisition window time slot at the satellite. In fact the ORBCOMM acquisition window may accommodate several of the short "request for service" packets which users transmit at random times within the window. In addition, the ORBCOMM NCCs can change the length of the acquisition window as traffic level increases. Both of these factors will effectively increase P_{NI} for high user arrival rates. However, ORBCOMM was not able to provide information predicting actual length of the "request for service" packets to the author.

⁶ This is ORBCOMM's prediction of P_{cs} which is based on simulation results. [Ref. 6]

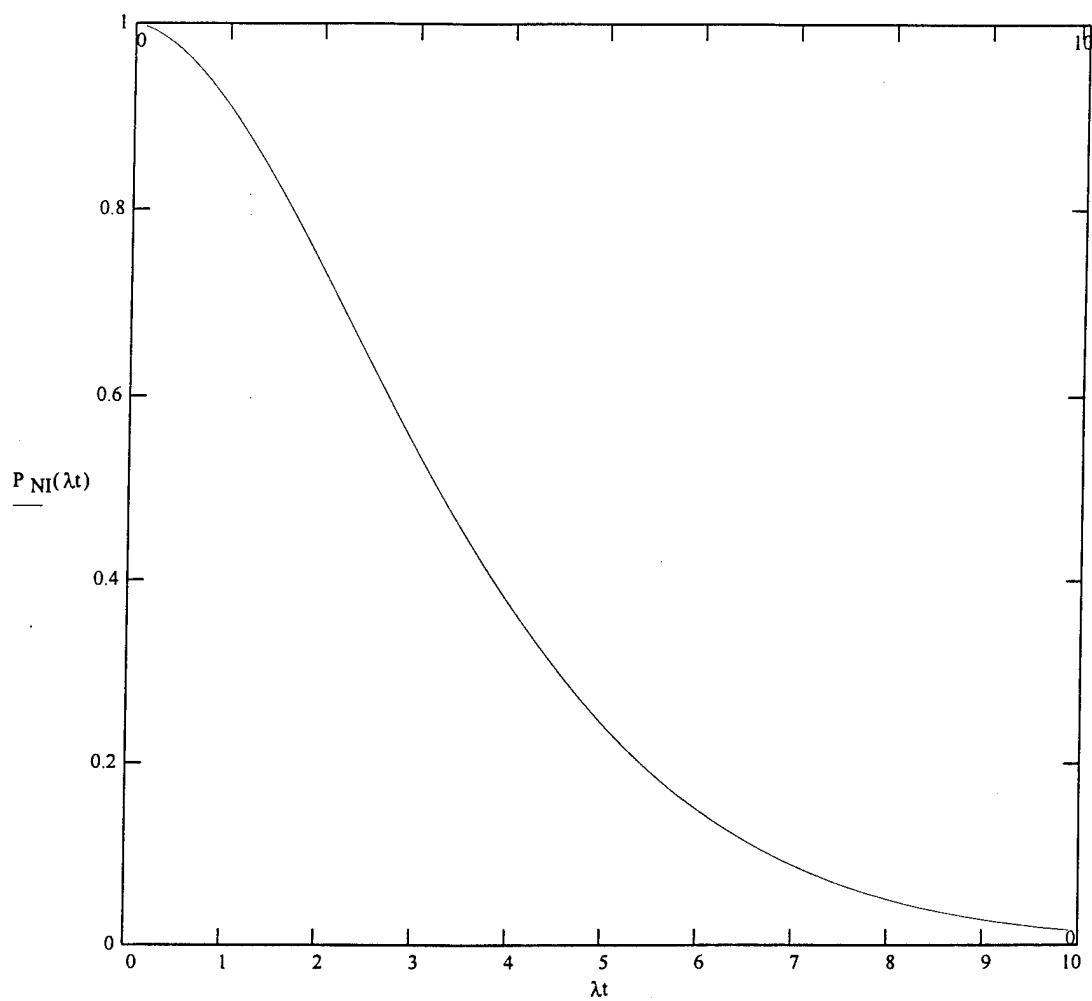


Figure 9. Effect of traffic intensity on random access channel interference.

D. NETWORK CAPACITY

In addition to channel allocation, another problem with a multiple-user satellite-based messaging system is to resolve the conflict among users desiring to transmit on the assigned channels. As mentioned earlier, ORBCOMM uses conventional TDMA to manage the single channel access between the satellites and GESs, but uses its proprietary A-C protocol to preclude potential collisions at the satellite when two or more mobile users wish to simultaneously transmit messages on an assigned channel. This section will focus on expected per-channel network capacity of the mobile subscriber / satellite links. First an understanding of the limitations of ALOHA multiple access protocols will be developed, then a comparison of the expected channel capacity of A-C, ORBCOMM's proprietary modified ALOHA protocol, will be presented.

1. Pure and Slotted ALOHA

The ALOHA system was developed in 1971 by the University of Hawaii. The system used a random access protocol, communication satellite, and radio channels to interconnect several of the university's computers on different islands.

In an ALOHA system a large number of users communicate with a central station over a common channel in an uncoordinated manner. Generation of information by the users is a random process, which results in bursty traffic statistics [Ref. 5]. The common channel is instantaneously available to any user that has a packet of information to send, and transmissions are made in relatively short bursts since the entire channel bandwidth is used [Ref. 10].

Using a model and mathematical analysis developed by Sklar [Ref. 13], we can evaluate the performance of ALOHA protocols. Sklar's model shows

that channel throughput in an ALOHA system will be a function of traffic intensity; as traffic levels increase more packets will collide on the network. In a pure ALOHA system,

$$\rho = Ge^{-2G} \quad (3-9)$$

where ρ = normalized throughput and G = normalized total traffic. Total traffic includes new traffic plus retransmissions of packets that have collided. In Figure 10 we see that ρ increases as G increases until a point is reached

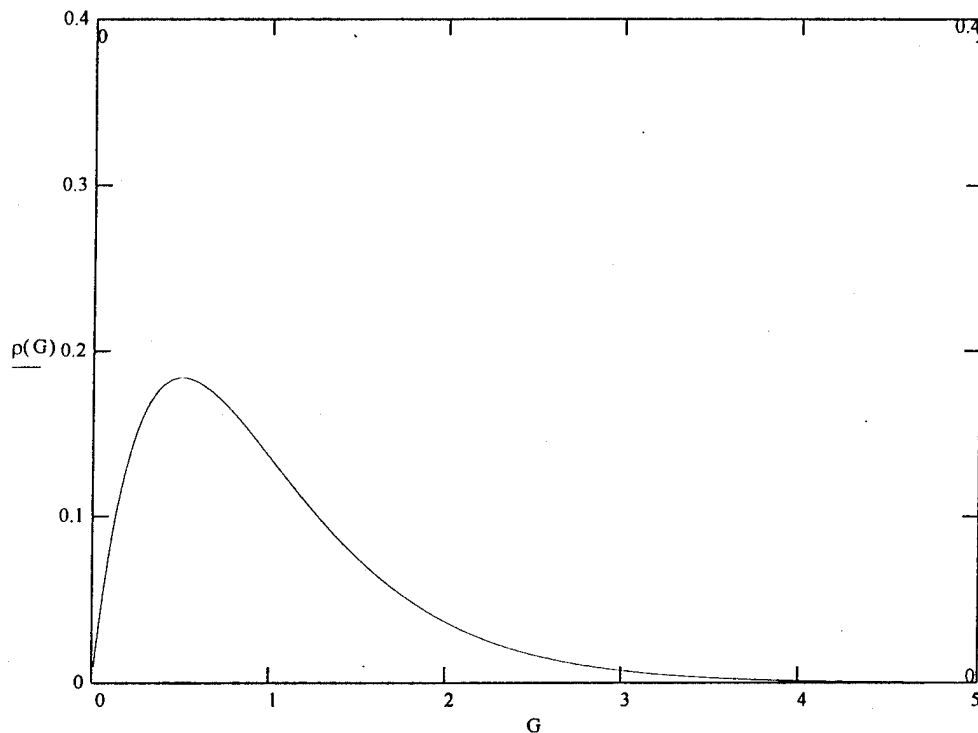


Figure 10. Throughput in pure ALOHA channels.

where the additional loading on the system starts causing more packet collisions and recollisions, and a reduction in throughput occurs. The

maximum throughput occurs at $G = 0.5$, where the value of $\rho = 1/2e = 0.18$. So, for a pure ALOHA system, the best we can hope for is a maximum of 18% of the channel resource being utilized when the total offered load is 50 percent. Such a system trades off channel capacity for the simplicity of uncoordinated access. [Ref. 13]

Slotted ALOHA improves on pure ALOHA by establishing a small amount of order in the system. Slotted ALOHA systems require synchronization and coordination among users on the network. In a slotted ALOHA system, the channels are slotted in time. Users are required to synchronize their packet transmissions into fixed length channel time slots. Messages can be transmitted only at the beginning of a time slot. This simple change has the end result of reducing the rate of collisions by half, since the only packets which may interfere with one another are those transmitted in the same slot. Sklar uses the same reasoning developed for pure ALOHA to show this reduction in the "collision window" changes the relationship between normalized throughput and normalized total traffic to

$$\rho = Ge^{-G} . \quad (3-10)$$

We see in Figure 11 that for slotted ALOHA the maximum value of ρ is $1/e = 0.37$, which is double the maximum throughput available in a pure ALOHA system. [Ref. 13]

2. Reservation ALOHA (R-ALOHA)

As we have seen, the best ALOHA-based protocol will never achieve channel efficiency above $1/e$. However, to make good use of a single shared channel at high channel loads, time-division multiplexing (TDM) can be used [Ref. 14]. A significant improvement to the ALOHA protocol was made with

the introduction of R-ALOHA, which acts like normal slotted ALOHA at low channel utilization and moves over to some kind of TDM as the channel load grows.

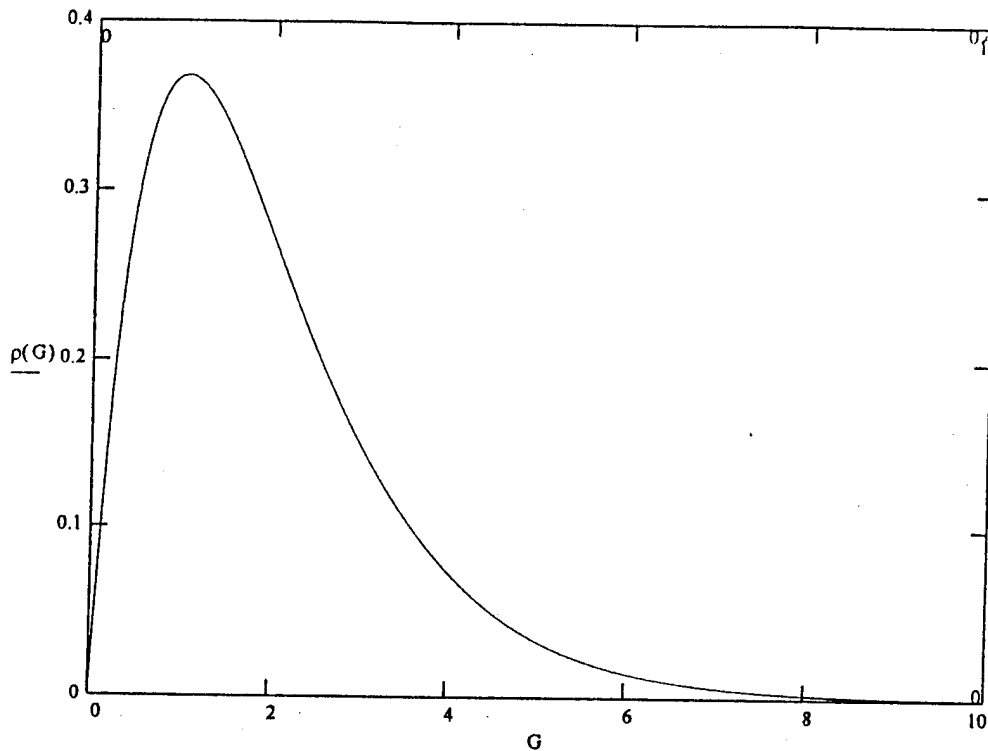


Figure 11. Throughput in slotted ALOHA channels.

An R-ALOHA system has two basic modes, which Sklar calls the "unreserved mode (or quiescent state)" and "reserved mode" [Ref. 13]. In the unreserved mode a frame is established and divided into small subslots. Subscribers use these small subslots to transmit requests for reserved message slots. After the reservation is requested, the subscriber listens for an acknowledgment and slot assignment to transmit message packets.

In the reserved mode, the time frame is divided into $N + 1$ slots. This occurs whenever a reservation is made. The first N slots are used to transmit

message packets; the last slot is utilized to transmit reservation requests. In the R-ALOHA system, users can only send message packets during their assigned portion of the N message slots.

Control is distributed throughout the system; all users receive the downlink transmission disseminating synchronization and information on the reservations and timing format. When there are no reservations for message slots, the system reverts back to its unreserved format of subslots only. [Ref. 13]

Sklar evaluates the performance of R-ALOHA by comparing its average delay versus throughput curve to that of slotted ALOHA. For throughput values of less than approximately 0.20, slotted ALOHA shows less average delay than R-ALOHA. The collisions and retransmissions inherent in slotted ALOHA increase rapidly for $\rho > 0.20$ causing the system to reach an unbounded delay at $1/e = 0.37$. For throughput values greater than 0.20, the more coordinated structure of R-ALOHA causes the degradation to grow in a more orderly fashion, with unbounded delay reached at a much higher throughputs. Slotted ALOHA performs somewhat better at lower traffic intensity; this is because slotted ALOHA does not require the overhead of reservation slots as does R-ALOHA. Therefore, at low throughput levels, R-ALOHA pays the price of greater delay due to higher overhead. [Ref. 13]

3. Acquire - Communicate (A-C)

ORBCOMM's A-C protocol for coordinating multiple user access to its satellite channels appears to function very much like an R-ALOHA scheme. Distributed control is provided by the satellites to mobile users via the order wire. The apparent net effect of the coordinated partitioning of the messaging uplink and downlink channels (TDM), combined with

continuously updated frequency and time synchronization, is to greatly increase the unbounded limit of the ORBCOMM network. Note that due to the proprietary nature of A-C, detailed information about the protocol was not available to the author.

ORBCOMM simulation results indicates their modifications to the standard slotted ALOHA scheme will enable the system to achieve throughput values of $p = 0.57$ for the uplink channels [Ref 6]. This is significantly higher throughput than fixed-length packet, purely random or slotted ALOHA systems. However, as was shown in the previous section, the additional overhead associated with A-C will cause a somewhat higher delay at lower traffic intensity levels than would be encountered using a pure or slotted ALOHA protocol.

Based on an average message length of 50 bytes, ORBCOMM predicts its satellites will have an inbound and outbound capacity of more than 60,000 messages per hour [Ref 6]. Tables 5 and 6 show simplified capacity calculations for the ORBCOMM system. Both tables use queuing overhead values obtained from extensive simulations of the data flow through the system. Network overhead values are based on mixtures of expected system packets. In both tables packet error rates are conservatively based on average expected packet lengths and average expected available link margins. In Table 5, five of the six uplink channels are accounted for; the sixth channel is used for the signaling channel. The "system overhead" term in Table 6 includes order-wire information, as well as satellite ephemeris data and uplink channel availability information [Ref. 6].

E. SUMMARY

The author has presented an analysis of the operational capabilities and expected performance of the ORBCOMM system. Given ORBCOMM's

Data Rate per Channel	2400	bps
Queuing Overhead at Maximum System Loading	80	%
Physical Capacity	1920	bps
Packet Errors (95% success rate)	95	%
Link Capacity	1824	bps
System Overhead (25% Overhead)	75	%
Network Capacity per Channel	1368	bps
Number of Channels	5	
Network Capacity	6840	bps
Average Message Length (50 Bytes)	400	bits
Average Messages per Second	17.1	Messages
Number of Seconds per Hour	3600	Seconds
Average Messages per Hour	61560	Messages

Table 5. Subscriber to satellite channel capacity. After Ref. [6].

Data Rate per Channel	4800	bps
Queuing Overhead at Maximum System Loading	85	%
Physical Capacity	4080	bps
Packet Errors (98% Success Rate)	98	%
Link Capacity	3998	bps
System Overhead (15% Overhead)	85	%
Network Capacity per Channel	3399	bps
Number of Channels	2	
Network Capacity	6797	bps
Average Message Length (50 Bytes)	400	bits
Average Messages per Second	16.9925	Messages
Number of Seconds per Hour	3600	Seconds
Average Messages per Hour	61173	Messages

Table 6. Satellite to subscriber channel capacity. After [Ref. 6].

defined "edge-of-coverage" for satellite links, we have seen the system is designed with adequate link margins to assure required signal-to-noise ratios. ORBCOMM's primary constellation of 32 satellites, combined with the four satellite supplemental polar planes, incorporates redundancy design and provides the coverage and re-visit rates for adequate global messaging and position determination services for users. It was shown that DCAAS has the capability of efficiently managing the frequency spectrum used for ORBCOMM subscriber / satellite transmissions. Finally, ALOHA multiple access schemes and the A-C protocol were compared to show how ORBCOMM satellites could achieve a network capacity of approximately 60,000 messages per hour.

IV. SYSTEM APPLICATIONS

A. CIVILIAN SERVICES

The ORBCOMM system will provide four basic categories of service for civilian use: emergency services, tracking, data acquisition monitoring, and two-way messaging.

1. Emergency Service

The most basic service offered by ORBCOMM will be its "SecureNet" emergency service. Requiring the least sophisticated type of ORBCOMM transceiver, SecureNet will process emergency calls for help, determine the user's position, transmit the location to appropriate response agencies, and confirm back to the user reception of the emergency signal. The SecureNet transceiver will be triggered either by the user, or automatically using sensor input, and will continue transmitting a distress signal until acknowledgment. In addition to hand-held units, SecureNet transceivers will be available for integrated home installation and into a variety of vehicles to send alarm messages automatically if trouble is sensed. [Ref. 15]

2. Tracking Service

The system's tracking service will be known as "MapNet". MapNet will be strictly for transmitting position information and is designed for applications where there is a need to know where property, vehicles, or personnel are located. MapNet position reports will either be obtained through polling of the user terminal or transmitted by a pre-set terminal timer. The level of sophistication, cost, and accuracy of the MapNet

terminals will be determined by the number of satellite frequencies they receive to resolve their location.⁷

3. Data Acquisition Monitoring Service

"DataNet" will be the data acquisition monitoring service provided by ORBCOMM. The primary DataNet application will be to communicate digital data to and/or from remote, unattended sensors and equipment. The DataNet transceivers will be configured with memory to store data to be read at time of transmission or to be available for sampling on request. For example, a DataNet user could remotely activate machinery or reconfigure settings on a remote control device.

4. Messaging Service

Two-way personal messaging will be provided by ORBCOMM's most extensive service level, "VitalNet". Designed to meet the requirements of people who need communication and location reporting from anywhere in the world, VitalNet user's will require ORBCOMM's most sophisticated terminal units. VitalNet terminals will include the hand-held, fully functional mobile STs, as well as units which will connect to other equipment (i.e., laptop and personal computers) via an RS-232 data port.

B. APPLICATIONS

The author expects that as these general services become readily available they will eventually be applied in many different roles, especially within the business, commerce, agriculture, and research sectors. The demand is expected to be generated by a variety of commercial applications, including the following examples [Ref. 16]:

⁷ See Chapter II, page 10.

- Cargo tracking for commercial ships.
- Environmental monitoring and reporting.
- Agricultural uses for irrigation and chemical management.
- Energy industry uses for well head and pipeline operations.
- Electronic mail services to services and transportation industries.
- Use of ORBCOMM in civilian search and rescue applications.

C. DOD APPLICATIONS OF THE ORBCOMM SYSTEM

As mentioned in Chapter I, DoD is faced with the compelling issue of how to cost effectively meet the growing requirements for space-based communications systems needed to support US forces worldwide. ORBCOMM presents the first of possibly several opportunities for DoD to employ commercial LEO systems to enhance US military global communications. The possible DoD applications of ORBCOMM services are many and varied; the following sections will present several of those which have the most immediate potential for implementation.

1. Beaconing and Messaging

ORBCOMM could meet the requirements addressed in the critical Mission Needs Statements which were the genesis of Project RADIANT SNOW. RADIANT SNOW is a US Navy Tactical Exploitation of National Capabilities (TENCAP) research and development project to build and field test GPS-based UHF beacons used to covertly and overtly target and track high interest targets. The project addresses several critical areas, including: Combat Survivor Evader Locator, Logistics Moving and Tracking System, Combat Identification, and Joint Law Enforcement Operations. [Ref. 16] The RADIANT SNOW development project provides the tactical commander with the capability to:

- Place a beacon on cooperative and non-cooperative targets.
- Data relay from ground, surface, and airborne assets.
- Use ground terminals and airborne receivers to display asset position.
- Use a dissemination and display architecture to transmit beacon targeting data worldwide.

The beacons developed for the project are composed of GPS receivers and low-power UHF transmitters about the size of a VHS cassette. Time, position, and altitude reports are transmitted by the beacon to low-earth orbit UHF satellites, line-of-sight aircraft, or ground stations, and then relayed to RADIANT SNOW terminals. [Ref. 16]

By July 1993, after completion of Phase 9 of its test program, two major material deficiencies were encountered with the project. The first problem was limited satellite availability; the RADIANT SNOW satellites provided coverage for only approximately 5% of the time. The second issue was the high cost (approximately \$12,000) of each beacon. [Ref. 16]

The ORBCOMM system can readily resolve these two material deficiencies. ORBCOMM offers near continuous worldwide satellite coverage, and commercial beacons which integrate GPS with an ORBCOMM transceiver are projected to be available for a cost of less than \$1000 per unit [Ref. 9].

The system will also easily accept integration of a DoD approved communications security system. ORBCOMM data and message transmissions can be encrypted via incorporation of a Digital Encryption Standard (DES) computer chip or using the same methodology utilized by STU-IIIs to encrypt classified voice and data transmissions over the public telephone network. In addition, DoD's KL-43 series Digital Encryption Device could be used to encrypt data prior to transmission within the ORBCOMM system. [Ref. 8]

In addition, according to Naval Air Warfare Center Indianapolis (NAWC) engineers, miniaturization and ruggedization of the cellular phone size commercial version of the ORBCOMM ST to something the size of a pager would not be difficult. While a lengthy micro-miniaturization effort is probably not feasible or desirable, the unit could be significantly reduced in size through efforts in parts count reduction and circuit board redesigns using the following technology:

- Pin Grid Array packaging (PGA).
- Fine Pitch Surface Mount (FPSM).
- Wire-bonded Multichip Modules (MCM).
- Tape Automated Bonding (TAB).
- Chip On Board (COB) and Flip Chip.

Reducing the size of the transceiver device would enable it to be used in special non-cooperative classified operations, by Special Operations Forces, and integrated into the survival vests and flight suits of aircrew safety equipment. [Ref. 16]

The smaller ORBCOMM units could have many parallel applications in the military and civilian world. They could lead to the spawning of an entirely new commercial industry, much as did miniaturized GPS. The potential military applications include, but are not limited to:

- Single vehicle, aircraft, and maritime craft tracking. Tactical commanders could receive via satellite near real time location data on all assets in an operation area under their control.
- Target tracking and intercept. Beacons could automatically transmit location of high interest targets at specified intervals or when polled, enabling commanders more leeway and control in executing intercept operations.
- Logistics tracking. Miniaturized beacons could be employed as shipping container "tags" enabling commanders to globally track flow of parts, supplies, shipments.

- Data relay from environmental buoys. Drift buoys could autonomously disseminate multi-sensor data on ocean environment, weather, or pollution conditions.
- Global VIP / Flag Officer tracking and messaging. Worldwide availability of cooperative tracking and secure communication with VIP's while on airlines, in staff cars, or engaged in off duty activities.
- Combat Identification (Ground). Cooperative identification of US Army units engaged in land-based operations via installation of beacons on vehicles and connectivity to command and control (C2) dissemination and display architecture.
- Combat Sea-Air Rescue (CSAR) and Combat Survivor Evader Locator (CSEL). Adding small, ruggedized ORBCOMM beacons to aircrew survival gear to enable search and rescue units to easily target, track, and locate downed aviators for extraction in hostile environments. ORBCOMM supports the DoD requirement for low probability of detection / intercept (LPD / LPI) CSAR / CSEL. ORBCOMM emergency signal / position reports use low power (5 Watt) burst transmissions of about 15 milliseconds duration. ORBCOMM's DCAAS is also a form of burst-to-burst frequency agility. Each satellite's footprint is approximately 3,000 miles across, with potentially thousands of uplinks broadcast. Thus, intercept and triangulation of all transmissions by hostile Electronic Support Measures (ESM) is very difficult.

2. Operations Other Than War (OOTW)

The unprecedented deployments of US forces in OOTW has created a new range of problems for the essential communication support services that are critical to mission success. As was the case in Somalia, such operations may require a US Joint Task Force (JTF) to establish robust and reliable communications facilities in regions resembling a war zone, where there is no existing telephone service or basic communications infrastructure of any kind. In addition, the very nature of the Somalia and Rwanda relief operations has shown a critical requirement for close US coordination with the UN, representatives of local government, and a need for communications

connectivity to non-traditional on-scene teams like the Red Cross and other private relief organizations.

Using ORBCOMM to augment DoD's inventory of rapidly deployable satellite communications systems is a feasible and potentially cost effective solution to the following communications requirements identified in lessons learned from OOTW operations in Somalia and Rwanda.

a. Deployability

The intense competition for limited airlift resources during the early stages of a JTF deployment is a major constraining factor. Therefore, communications planning for this phase must incorporate small, lightweight, reliable systems that require minimal airlift and, to the degree practical, can be moved on the same aircraft as the initial deployment of the JTF headquarters. As an example, USPACOM's advanced JTF Component C2 rapid deployment support package includes [Ref. 17]:

- UHF/SHF/EHF Satcom.
- UHF/SHF Satcom (DAMA).
- Small Switchboard.
- Portable Commercial Band Satellite Terminal.
- Secure VOX.
- Land Mobile Radio.
- HF/SSB Radio.
- UHF/VHF Air/Ground Radio.
- Secure Facsimile.
- Cellular Telephone.
- Information Management System.

Incorporating ORBCOMM mobile user terminals, in conjunction with a deployable, scaled-down version of an integrated ORBCOMM NCC/GES, into the rapid deployment package would provide additional

satellite communications support to the JTF while enroute and upon initial arrival at the projected beddown location in the operation area.

Some initial work on the deployable, "mini" NCC/GES concept has already been completed. NAWC Indianapolis is conducting preliminary feasibility study of the optimal way to use the Navy's AN/SMQ-11 local user terminal to demodulate ORBCOMM satellite signals.

The AN/SMQ-11 is a deployable meteorological satellite receiving and processing system which was used on the RADIANT SNOW project. The VHF capability of the AN/SMQ-11 is optimized for 137 MHz, and as of 1993 there were 63 units in the Navy inventory. Currently, the system is undergoing planned product improvement. Old, proprietary hardware is being replaced with new programmable processing hardware based on the TAC-4 computer. The Unix operating system and open system architecture of the TAC-4 will enable porting of applications written in such languages as C++. Porting vendor-supplied applications to the AN/SMQ-11 will give it the capability to readily process RF signals from various and emerging satellite families such as ORBCOMM. [Ref. 16]

According to NAWC and ORBCOMM engineers, a deployable, fully functional, HUMVEE-mounted hybrid AN/SMQ-11 - NCC/GES would be relatively easy to design and build from currently available commercial off-the-shelf (COTS) technology [Ref. 16].

b. Area coverage

During the sustained operations phase in Somalia, extreme distance between the various echelons of the JTF demonstrated the need for more long-range communications. Infantry units commonly operated more than 50 miles from their headquarters, while transportation and engineer units were often hundreds of miles from their bases. Maintaining long-range communications while on the move was especially difficult. Long-haul

convoy operations quickly exceeded organic FM radio and Mobile Subscriber Equipment (MSE) multi-channel transmission capabilities. Either HF or Tactical Satellite (TACSAT) were potential answers, but both equipment and available net resources were limited. [Ref. 18]

After supporting the initial deployment phase, the ORBCOMM system could be effectively used to augment the JTF's extended regional communications capabilities. As discussed in Chapter II, mid-latitude countries will receive an approximate 95% satellite availability rate. With the deployment, insertion, and establishment of a "regional" NCC/GES by the JTF in-country, any units throughout the operating area equipped with ORBCOMM terminals would have virtually continuous, near-real-time, over-the-horizon messaging and data exchange service. According to ORBCOMM, one "fly-in" NCC/GES deployed in theater rear can service a 3,000 square mile area. To put this in perspective, for Operation Desert Storm, deploying NCC/GESs to Turkey and Riyadh, Saudi Arabia could have provided service for the entire Middle East [Ref. 8].

In addition, the NCC/GES would also provide a point of connectivity between ORBCOMM and other JTF data networks, creating a "JTF internet" based on standard X.25 packet switch and X.400 e-mail protocols. Introduction of a Defense Data Network (DDN) e-mail host to the JTF network would thus enable messaging and data transfer connectivity to CONUS from ORBCOMM-equipped units operating anywhere in the region. This could have a potential two-fold benefit: Defense Switched Network (DSN) voice lines to CONUS would be freed of data traffic, and field deployed personnel would have easy access to a relatively inexpensive alternative method to INMARSAT for making morale "calls" back to families in the US.

c. Interoperability

JTF communications planning for OOTW must be prepared to support interoperability for various types of forces and organizations. The possibilities include [Ref. 19]:

- A combined command made up of forces from contributing nations.
- A formal UN command with a Special Representative and JTF Commander working together.
- An ad-hoc coalition.

In addition to the forces and organizations described above, JTF OOTW communications planning should incorporate the flexibility to encompass connectivity for other organizations which may be in the operations area supporting the mission. These include but are not limited to [Ref. 19]:

- Other agencies of the US government.
- UN relief organizations.
- Non-governmental organizations (NGO).
- Private voluntary organizations (PVO).
- Host governments.
- Media.

The aforementioned JTF deployable ORBCOMM messaging and data exchange network could be expanded to provide an interoperable, flexible, and effective communications infrastructure to support these various entities. Instead of HF radios, as was the case in Somalia, low cost ORBCOMM mobile terminals could be distributed to coalition units and representatives from other organizations who are in-country participating in the operation. Such a network would enable long-range communications interoperability across the spectrum of organizations involved in a peacekeeping or humanitarian effort and provide connectivity to even the most remote sites. Again, with the "regional" NCC/GES established at JTF HQ, US forces would control and manage the network. Message processing

and routing would be maintained and centralized at the "mini" NCC/GES, providing additional network control to the JTF.

V. SUMMARY AND CONCLUSIONS

A. SUMMARY

Destined to be the first system to offer PCS to users on a global scale, ORBCOMM is a pioneer in satellite communications. It is the first commercial attempt at worldwide coverage using NVNG LEO satellite technology. ORBCOMM is one of the first commercial ventures to take advantage of the lower costs of the Pegasus launch system to insert its satellites into operating orbits. This, in the author's opinion, is where ORBCOMM presents its highest risk; in pursuit of lower costs, ORBCOMM is relying on new, relatively unproven technology for its delivery system. In addition ORBCOMM's low cost satellites, designed to be mass produced, are operationally unproven. The first two full function ORBCOMM satellites were launched on 13 April 1995, and many interested parties in both the communications industry and DoD are waiting to see how these first satellites, and the system overall, perform under actual operational conditions.

This thesis has presented a description and analysis of the ORBCOMM system components and functional architecture. ORBCOMM is designed to provide its users with world-wide geolocation as well as on-the-move data exchange and messaging services. Several types of mobile user terminals, which will vary in sophistication and performance depending on level of functionality, will be offered to consumers by ORBCOMM licensed manufacturers. ORBCOMM's 36 digital packet switching, store-and-forward capable LEO satellites function as the data and message relay points for users within the system. GESs and national NCCs form the ground component of the network architecture, and are the switching and routing "brains" of the system.

One view of the system is as a global data network, with connectivity to other networks performed at the NCC gateways. ORBCOMM employs X.400 and X.25 network protocols; ORBCOMM users will be able to seamlessly exchange data and e-mail with users on public data networks and the Internet. Human operators at ORBCOMM NCCs will be able to transcribe and forward voice messages arriving on the PSTNs to user's mobile terminals.

System connectivity is achieved via a combination of terrestrial and satellite links. Leased, high data rate terrestrial (and possibly VSAT) links connect the ground components. Four VHF satellite links connect mobile users and ground components; the satellites also transmit a UHF beacon which is used to increase the geolocating accuracy of the mobile terminals. Link budget analysis of the five satellite links indicates the system incorporates enough margin to perform at the level needed to meet required signal-to-noise ratios.

DCAAS, ORBCOMM's proprietary frequency sampling and assignment scheme, manages subscriber uplink channel allocation in a manner similar to demand access multiple assignment (DAMA). DCAAS will ensure mobile users are assigned the best available channel for each transmission burst, and that the system avoids interference with terrestrial / other satellites using the VHF spectrum.

ORBCOMM's proprietary multiple access technique uses a combination of subscriber / satellite handshake procedure and R-ALOHA multiple access protocol. This technique introduces order into the purely random access system, which enables ORBCOMM to achieve high deterministic throughput levels.

ORBCOMM will offer consumers choice of four levels of communication services. These include basic emergency alert, tracking, data acquisition

monitoring, and full two-way on-the-move data transfer and messaging. Demand for ORBCOMM access will be generated from the many applications of these services in business, industry, commerce, and research. Some of the first commercial applications will be in the shipping industry for cargo and container tracking and in the energy industry for wellhead and pipeline monitoring.

ORBCOMM represents the first opportunity for DoD to enhance US military global communications with commercial PCS. Requirements to exchange secure data can be easily accomplished in the ORBCOMM system using current DoD encryption techniques (i.e., use of the KL-43 series Digital Encryption Device, Digital Encryption Chips, or an encryption method like that used in STU-III secure telephones). ORBCOMM's low power, short burst transmissions give it the LPD / LPI characteristics required for some potential DoD applications. DoD could immediately apply commercially available ORBCOMM services to meet beaconing and tracking requirements. Development of a "fly in" mobile GES / NCC would open a host of potential applications, including filling the need for a rapid deployment regional communications infrastructure suited for needs encountered in OOTW.

B. CONCLUSIONS

ORBCOMM's capabilities and global coverage offers both commercial opportunity as well as potential enhancements to current DoD space-based communications. The commercial applications identified in this thesis indicates only a few of the various uses of ORBCOMM by the service and industrial sectors. It is expected that once the system becomes operationally available and reliable, many more diverse commercial uses of its geolocating, beaconing, data transfer, and message exchange capabilities will be applied.

ORBCOMM can also respond to two critical issues facing DoD: cost and availability of space-based communications systems. With DoD taking

an active role as a cooperative partner, ORBCOMM can satisfy some of DoD's need to find low-cost commercial space-based systems to enhance US military global communications. The Government will benefit in the short term by being able to meet urgent requirements; DoD would have access to a dual-use communications network, designed, developed, and operated by an American company that will provide affordable connectivity anywhere in the world. Development of a deployable "mini" NCC / GES suitable for use on board a ship, plane, helicopter, or mounted on a vehicle such as a HUMVEE could provide enormous flexibility in addressing communications requirements in many situations including defense, natural disaster, or humanitarian efforts.

DoD participation in a dual-use partnership would mean lower costs for the Government. ORBCOMM has been commercially developed and financed, with no Government assistance. Operations and maintenance costs would be largely shared by the commercial users, thus reducing annual outlays such as would be incurred if the system were owned and operated solely by DoD. Commercially produced equipment (such as mobile subscriber terminals) could be used in many DoD applications, taking advantage of the cost reductions from economies of scale of the large number of terminals manufactured.

The commercial sector and industry would also benefit from such a team effort, primarily as a result of economic "pump priming" by DoD. Demand for miniaturized beacons / hand-held terminals is well documented in DoD; demand in the commercial sector is probably an order of magnitude larger but only at a lower cost. The miniaturization of ORBCOMM transmitter beacons, along with the development of deployable "mini" GES / NCCs, has the potential for greatly expanding the uses of the system. Such additional capability would certainly generate a number of new commercial

ventures. Using the GPS experience as a parallel, it is easy to see how the private sector would "spin on" to new ORBCOMM commercial applications derived from DoD related technology .

In the long-term, a cooperative Government partnership with ORBCOMM, and other American companies fielding LEO-based PCS systems, will stimulate and maintain US leadership in space-based digital information and communications systems design and architecture. These systems have the potential to have the same type of parallel positive impact in the next decade and beyond as did the development of the telephone in the first half of this century. Just as the US has dominated the telephone industry, the opportunity now exists to lead and dominate the space-based wireless industry. With the Government participating as an interested partner, American companies would easily become the world leaders in development and implementation of the new PCS technologies.

APPENDIX A: ORBCOMM INTERNATIONAL STATUS

COUNTRIES WITH LICENSE AGREEMENT IN PLACE:

- | | | |
|--------------|---------------|------------------|
| 1. Argentina | 10. Honduras | 19. Peru |
| 2. Bolivia | 11. Hungary | 20. Russia |
| 3. Brazil | 12. Indonesia | 21. South Africa |
| 4. Canada | 13. Israel | 22. Uruguay |
| 5. Chile | 14. Japan | 23. Venezuela |
| 6. China | 15. Korea | |
| 7. Columbia | 16. Mexico | |
| 8. Ecuador | 17. Nigeria | |
| 9. Guatemala | 18. Panama | |

COUNTRIES SEEKING LICENSE AGREEMENT:

- | | | |
|--------------|------------------|--------------|
| 1. Australia | 7. Mozambique | 13. Zimbabwe |
| 2. Egypt | 8. New Zealand | |
| 3. India | 9. Philippines | |
| 4. Malaysia | 10. Saudi Arabia | |
| 5. Mongolia | 11. Thailand | |
| 6. Morocco | 12. West Europe | |

APPENDIX B: ORBCOMM LINK BUDGETS

GES to Satellite uplink

Transmit EIRP	40.0	dBW
Free Space Loss	-144.7	dB
Atmospheric Loss	-2.0	dB
Polarization Loss	-0.1	dB
Satellite Pointing Loss	-0.2	dB
Multipath Fade Loss	-5.0	dB
Power @ Satellite Antenna (IRL)	-112.0	dBW
Satellite G/T	-32.02	dB
G/T Degredation (ant. temp. >290K)	-0.9	dB
Sum	-144.92	dBW
Boltzman's Constant	<u>-(-228.6)</u>	dBW
C/No	83.68	dB
10log(Bit Rate)	<u>-47.6</u>	dB
Eb/No	36.08	dB
Required Eb/No (QPSK)	-10.6	dB
Modulation Implementation Loss	-3.0	dB
Interference margin	<u>-20.0</u>	dB
Remaining Margin	2.48	dB

General Information:

Satellite altitude	785 km
Elevation angle	5 degrees
Gateway angle from nadir	62.5 degrees
Slant range to satellite	2749 km (edge of coverage, minimum elevation)
User data rate	57,600 bps
Required BER	1 in 1,000,000 (10^{-6})
Uplink frequency	149.40 MHz

Calculations:

$$FSL = 32.44 + 20\log(2749) + 20\log(149.40) = 144.7 \text{ dB}$$

$$G(\text{ant}) = 1.0 \text{ dB} \quad L_a = 1.4 \text{ dB} \quad l_a = 10^{(L_a/10)} = 1.38 \quad NF(\text{rcvr}) = 7.0 \text{ dB} \quad T(\text{sky}) = 290\text{K}$$

$$G/T(\text{satellite}) = G(\text{net}) - 10\log[T(\text{sys})]$$

$$G(\text{net}) = 1.0 \text{ dB} - 1.4 \text{ dB} = -0.4 \text{ dB}$$

$$T(\text{sys}) = T(\text{ant}) + T(\text{rcvr})$$

$$T(\text{sys}) = 290\text{K} + 1163\text{K} = 1453\text{K}$$

$$G/T(\text{satellite}) = -0.4 - 10\log(1453)$$

$$G/T(\text{satellite}) = \sim -32.02 \text{ dB}$$

$$T(\text{rcvr}) = (NF - 1)T_o$$

$$NF = 10^{[NF(\text{dB})/10]} = 10^{(7.0/10)} = 5.0$$

$$T(\text{rcvr}) = (5.0 - 1)290 = 1163\text{K}$$

$$T(\text{ant}) = [(l_a - 1)290\text{K} + T(\text{sky})]/l_a$$

$$T(\text{ant}) = [(1.38 - 1)290 + 290]/1.38 = 290\text{K}$$

Satellite to GES downlink

Satellite Transmit EIRP	6.5	dBW
Free Space Loss	-143.97	dB
Atmospheric Loss	-2.0	dB
Polarization Loss	-0.1	dB
Satellite Pointing Loss	-0.2	dB
Multipath Fade Loss	-5.0	dB
Power @ Gateway Antenna (IRL)	-144.7	dBW
Gateway G/T	-11.1	dB
G/T Degredation (ant. temp. >400K)	-2.0	dB
Sum	-157.8	dBW
Boltzman's Constant	<u>-(-228.6)</u>	dBW
C/No	70.8	dB
10log(Bit Rate)	<u>-47.6</u>	dB
Eb/No	23.2	dB
Required Eb/No (QPSK)	-10.6	dB
Modulation Implementation Loss	<u>-3.0</u>	dB
Margin	9.6	dB
Required Margin (interference/req'd margin)	<u>-6.0</u>	dB
Excess Margin	3.6	dB

General Information:

Satellite altitude	785 km
Elevation angle	5 degrees
Gateway angle from nadir	62.5 degrees
Slant range to satellite	2749 km (edge of coverage, minimum elevation)
User data rate	57,600 bps
Required BER	1 in 1,000,000 (10^{-6})
Uplink frequency	137.20 MHz

Calculations:

$$FSL = 32.44 + 20\log(2749) + 20\log(137.20) = 143.97 \text{ dB}$$

$$G(\text{ant}) = 17.0 \text{ dB} \quad L_a = 0.9 \text{ dB} \quad l_a = 10^{(L_a/10)} = 1.23 \quad NF(\text{rcvr}) = 2.0 \text{ dB} \quad T(\text{sky}) = 4000\text{K}$$

$$G/T(\text{gateway}) = G(\text{net}) - 10\log[T(\text{sys})]$$

$$G(\text{net}) = 17.0 \text{ dB} - 0.9 \text{ dB} = 16.1 \text{ dB}$$

$$T(\text{sys}) = T(\text{ant}) + T(\text{rcvr})$$

$$T(\text{sys}) = 355\text{K} + 170\text{K} = 525\text{K}$$

$$G/T(\text{gateway}) = 16.1 - 10\log(525)$$

$$G/T(\text{gateway}) = -11.1 \text{ dB}$$

$$T(\text{rcvr}) = (NF - 1)T_o$$

$$NF = 10^{(NF(\text{dB})/10)} = 10^{(2.0/10)} = 1.585$$

$$T(\text{rcvr}) = (1.585 - 1)290 = 170\text{K}$$

$$T(\text{ant}) = [(l_a - 1)290\text{K} + T(\text{sky})]/l_a$$

$$T(\text{ant}) = [(1.70 - 1)290 + 400]/1.70 = 355\text{K}$$

Mobile ST to Satellite uplink

Transmit EIRP	7.5	dBW
Free Space Loss	-144.68	dB
Atmospheric Loss	-2.0	dB
Polarization Loss	-4.1	dB
Satellite Pointing Loss	-0.2	dB
Multipath Fade Loss	-5.0	dB
Power @ Satellite Antenna (IRL)	-148.48	dBW
Satellite G/T	-25.3	dB
G/T Degredation (ant. temp. >290K)	-0.8	dB
Sum	-174.58	dBW
Boltzman's Constant	<u>-(-228.6)</u>	dBW
C/No	54.02	dB
10log(Bit Rate)	<u>-33.8</u>	dB
Eb/No	20.22	dB
Required Eb/No (DBSK)	-10.3	dB
Modulation Implementation Loss	<u>-2.0</u>	dB
Margin	7.92	dB
Required Margin	<u>-3.0</u>	dB
Excess Margin	4.92	dB

General Information:

Satellite altitude	785 km
User elevation angle	5 degrees
Subscriber angle from nadir	62.5 degrees
Slant range to satellite	2749 km (edge of coverage, minimum elevation)
User data rate	2400 bps
Required BER	1 in 100,000 (10^{-5})
Uplink frequency	148.95 MHz

Calculations:

$$FSL = 32.44 + 20\log(2749) + 20\log(148.95) = 144.68 \text{ dB}$$

$$G(\text{ant}) = 3.6 \text{ dB} \quad L_a = 2.3 \text{ dB} \quad l_a = 10^{(L_a/10)} = 1.70 \quad NF(\text{rcvr}) = 2.0 \text{ dB} \quad T(\text{sky}) = 290\text{K}$$

$$G/T(\text{satellite}) = G(\text{net}) - 10\log[T(\text{sys})]$$

$$G(\text{net}) = 3.6 \text{ dB} - 2.3 \text{ dB} = 1.3 \text{ dB}$$

$$T(\text{sys}) = T(\text{ant}) + T(\text{rcvr})$$

$$T(\text{sys}) = 290\text{K} + 170\text{K} = 460\text{K}$$

$$G/T(\text{satellite}) = 1.3 - 10\log(460)$$

$$G/T(\text{satellite}) = -25.3 \text{ dB}$$

$$T(\text{rcvr}) = (NF - 1)T_o$$

$$NF = 10^{[NF(\text{dB})/10]} = 10^{(2.0/10)} = 1.585$$

$$T(\text{rcvr}) = (1.585 - 1)290 = 170\text{K}$$

$$T(\text{ant}) = [(l_a - 1)290\text{K} + T(\text{sky})]/l_a$$

$$T(\text{ant}) = [(1.70 - 1)290 + 290]/1.70 = 290\text{K}$$

Satellite to Mobile ST downlink (VHF)

Satellite Transmit EIRP	12.5	dBW
Free Space Loss	-144.0	dB
Atmospheric Loss	-2.0	dB
Polarization Loss	-4.1	dB
Satellite Pointing Loss	-0.2	dB
Multipath Fade Loss	-5.0	dB
Power @ Subscriber Antenna (IRL)	-142.0	dBW
Subscriber G/T	-28.1	dB
G/T Degredation (ant. temp. >400K)	-0.5 dB	dB
Sum	-171.4	dBW
Boltzman's Constant	-(-228.6)	dBW
C/No	57.2	dB
10log(Bit Rate)	-36.8	dB
Eb/No	20.4	dB
Required Eb/No (DBSK)	-10.3	dB
Modulation Implementation Loss	-3.0	dB
Margin	7.1	dB
Required Margin (blockage/interference)	6.0	dB
Excess Margin	1.1	dB

General Information:

Satellite altitude	785 km
User elevation angle	5 degrees
Subscriber angle from nadir	62.5 degrees
Slant range to satellite	2749 km (edge of coverage, minimum elevation)
User data rate	4800 bps
Required BER	1 in 100,000 (10^{-5})
Downlink frequency	137.50 MHz

Calculations:

$$FSL = 32.44 + 20\log(2749) + 20\log(137.50) = 144.00 \text{ dB}$$

$$G(\text{ant}) = 0.0 \text{ dB} \quad L_a = 0.7 \text{ dB} \quad l_a = 10^{(L_a/10)} = 1.175 \quad NF(\text{rcvr}) = 2.0 \text{ dB} \quad T(\text{sky}) = 400\text{K}$$

$$G/T(\text{subscriber}) = G(\text{net}) - 10\log[T(\text{sys})]$$

$$G(\text{net}) = 0.0 \text{ dB} - 0.7 \text{ dB} = -0.7 \text{ dB}$$

$$T(\text{sys}) = T(\text{ant}) + T(\text{rcvr})$$

$$T(\text{sys}) = 384\text{K} + 170\text{K} = 554\text{K}$$

$$G/T(\text{subscriber}) = -0.7\text{dB} - 10\log(554)$$

$$G/T(\text{subscriber}) = -28.1 \text{ dB}$$

$$T(\text{rcvr}) = (NF - 1)T_o$$

$$NF = 10^{[NF(\text{dB})/10]} = 10^{(2.0/10)} = 1.585$$

$$T(\text{rcvr}) = (1.585 - 1)290 = 170\text{K}$$

$$T(\text{ant}) = [(l_a - 1)290\text{K} + T(\text{sky})]/l_a$$

$$T(\text{ant}) = [(1.175 - 1)290 + 400]/1.175 = 384\text{K}$$

Satellite to Mobile ST downlink (UHF)

Satellite Transmit EIRP	2.5	dBW
Free Space Loss	-153.26	dB
Atmospheric Loss	-2.0	dB
Polarization Loss	-4.1	dB
Satellite Pointing Loss	-0.2	dB
Multipath Fade Loss	-4.0	dB
Power @ Subscriber Antenna (IRL)	-161.06	dBW
Subscriber G/T	-29.8	dB
G/T Degredation (ant. temp. >400K)	-0.5	dB
Receiver Loop Bandwidth	-20.0	dB
Sum	-211.36	dBW
Boltzman's Constant	<u>-(-228.6)</u>	dBW
C/No (Received Signal-to-Noise)	17.24	dB

General Information:

Satellite altitude	785 km
User elevation angle	5 degrees
Subscriber angle from nadir	62.5 degrees
Slant range to satellite	2749 km (edge of coverage, minimum elevation)
User data rate	N/A
Required BER	N/A
Downlink frequency	400.1 MHz

Calculations:

$$FSL = 32.44 + 20\log(2749) + 20\log(400.1) = 153.66 \text{ dB}$$

$$G(\text{ant}) = 0.0 \text{ dB} \quad L_a = 1.0 \text{ dB} \quad l_a = 10^{(L_a/10)} = 1.25 \quad NF(\text{rcvr}) = 3.0 \text{ dB} \quad T(\text{sky}) = 400\text{k}$$

$$G/T(\text{subscriber}) = G(\text{net}) - 10\log[T(\text{sys})]$$

$$G(\text{net}) = 0.0 \text{ dB} - 1.0 \text{ dB} = -1.0 \text{ dB}$$

$$T(\text{sys}) = T(\text{ant}) + T(\text{rcvr})$$

$$T(\text{sys}) = 473\text{K} + 290\text{K} = 763\text{K}$$

$$G/T(\text{subscriber}) = -1.0\text{dB} - 10\log(763)$$

$$G/T(\text{subscriber}) = -29.8 \text{ dB}$$

$$T(\text{rcvr}) = (NF - 1)T_o$$

$$NF = 10^{[NF(\text{dB})/10]} = 10^{(3.0/10)} = 2.0$$

$$T(\text{rcvr}) = (2.0 - 1)290 = 290\text{K}$$

$$T(\text{ant}) = [(l_a - 1)290\text{K} + T(\text{sky})]/l_a$$

$$T(\text{ant}) = [(1.25 - 1)290 + 400]/1.0 = 473\text{K}$$

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