STARS

University of Central Florida

STARS

Electronic Theses and Dissertations, 2004-2019

2008

Data Communication With A Nano-satellite Using Satellite Personal Communication Networks (s-pcns)

Khudeja Khan
University of Central Florida

Part of the Electrical and Electronics Commons

Find similar works at: https://stars.library.ucf.edu/etd

University of Central Florida Libraries http://library.ucf.edu

Showcase of Text, Archives, Research & Scholarship

DATA COMMUNICATION WITH A NANO-SATELLITE USING SATELLITE PERSONAL COMMUNICATION NETWORKS (S-PCNs)

by

KHUDEJA SHAHBAZ KHAN
B.E. National University of Sciences and Technology, Pakistan, 2007

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the School of Electrical Engineering and Computer Science
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2008

ABSTRACT

Satellites typically communicate with locations on the ground to receive commands and send data back. Establishing reliable communications generally requires dedicated ground stations, which in turn require hardware and expertise. Developers of nano-satellites, however, may not have the expertise or resources necessary for establishing a dedicated ground station. Therefore, the use of an existing communication system, such as the Satellite Personal Communication Networks (S-PCNs), is attractive. Another shortcoming of the fixed ground stations, already available, is that they are normally only able to communicate with Low Earth Orbit (LEO) nano-satellites four times per day (two10-minute windows separated by 90 minutes, followed 12 hours later by two more such 10-minute windows). This drawback is also overcome by the use of S-PCNs which provide increased access times, smaller gaps in contact between the satellites and ground stations, and easier tracking of satellite health. In this thesis, the capabilities of S-PCNs for communications with a nano-satellite are explored. Software simulation and analysis have been performed to assess system performance. Ground testing of the hardware is done to understand the use of such systems for small satellites.

Dedicated to my parents…

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF FIGURES

x

LIST OF TABLES

CHAPTER 1: INTRODUCTION

A 'nano-satellite' is an artificial satellite having a mass of 1-10 kg. Nano-satellites are popular because of their small size, light weight and low cost. Due to these factors, a dedicated launch is not required for these satellites, as they can instead be piggy-backed on other launches. Some of the applications of nano-satellites include Earth remote sensing, earthquake prediction, ecological monitoring and studies of ionosphere [1]. Nano-satellites, like almost all other satellites, need to communicate with the locations on the ground in order to send the data collected and to receive commands.

1.1 Objective of this Thesis

This thesis presents a method for communicating with nano-satellites, which utilizes the already developed communication system: Satellite Personal Communication System (S-PCNs). A Personal Communication System (PCS) includes all forms of radio-telephone communication that are interconnected to the Public Switched Telephone Network (PSTN) [2]. These wireless communications include cellular-based systems, cordless systems, satellite-based systems, etc [3]. A PCS based on satellites is called Satellite Personal Communication Network (S-PCN). The S-PCNs have a number of ground stations placed on the Earth for communicating with the users all around the world through their satellite constellation.

The method presented here would use an S-PCN modem, placed in a nano-satellite, to downlink and uplink data using the satellite constellation and gateways of the S-PCN.

1.2 Background

Nano-satellites presently communicate with ground stations *directly,* as opposed to talking through a constellation, as suggested here. This method has its drawbacks. Firstly, the organizations interested in using nano-satellites may not have the expertise and resources to install and maintain the ground stations. Secondly, the ground stations which are already deployed are very few in number and communication can take place only in specific time slots. Typically, a nano-satellite can communicate with a ground stations four times per day: two 10-minute windows separated by approximately 90 minutes, followed 12 hours later by two more such 10-minute windows. As there is a long gap in between the contact times, the satellite must have sufficient memory to store the data collected until it can communicate with the ground station again. If something goes wrong with the satellite during the gap period, the ground stations cannot take any measures and correct errors. This adds risk in the life of the satellite and makes it more vulnerable to errors. These errors, if not corrected in a timely manner, may harm the satellite and corrupt the data.

A method which other small Low Earth Orbit satellites use to communicate is Tracking and Data Relay Satellite System (TDRSS). This system is owned by National Aeronautics and Space Administration (NASA). It consists of seven satellites in Geo-synchronous Earth Obit (GEO) which relay the information from a Low Earth Orbit (LEO) satellite to NASA/customer control facilities and vice versa. However, the same method is not feasible for nano-satellites because the cost budget and power budget for a nano-satellite are low. Therefore, a nano-satellite

cannot account for powerful and expensive transceivers required to communicate with the TDRSS.

Using S-PCNs instead is expected to be an inexpensive way to communicate with nano-satellites. Moreover, it provides better coverage, which in turn allows more opportunities for nano-satellites to transmit housekeeping data and report errors.

1.3 Related Work

The potential for using S-PCNs for nano-satellites has been discussed in [4]. In that paper simulations were performed in Satellite Tool Kit (STK) software to analyze the coverage for two S-PCNS (Globalstar and Orbcomm) for a nano-satellite. A number of factors, that were required to be considered for using this approach, were also presented. However, the simulation presented was for a 24-hrs period, too short for a complete understanding of the system. Also, no specific S-PCN was examined in this document.

More recently, in a project by the Russian Institute for Space Device Engineering [5], verification of using the Globalstar satellite equipment for communication between a nano-satellite and the Globalstar ground stations was presented. However, the information released does not provide any detailed simulation and analysis of the experiment conducted. It also did not specify which Globalstar modem was used.

In this thesis, analysis of the coverage available for 2 representative altitudes of nano-satellites in 3 different potential inclination angles is presented. The parameters which may get affected when the system (S-PCNs), designed for ground based users, is used for a nano-satellite, are explained. The modem suggested by the Globalstar service providers for this application is

explained as well. Ground testing of this hardware is done to understand the use of such systems for small satellites.

1.4 Thesis Organization

This thesis is organized in seven chapters. Chapter 2 describes the available Satellite Personal Communication Networks (S-PCNs). On the basis of coverage, altitude, data rate, availability of service and hardware; the Globalstar System is selected. A detailed description of the Globalstar Satellite system is given in Chapter 3. Chapter 4 describes the data modem, a commercial off the shelf item designed for use with the Globalstar system, which can be used to achieve the objective. Chapter 5 discusses the factors which should be considered when using Globalstar service in space. The results of coverage analysis, simulated in Satellite Tool Kit (STK) software, are explained in Chapter 6. Chapter 7 presents the conclusion and recommendations for future work.

CHAPTER 2: AVAILABLE SATELLITE PERSONAL COMMUNICATION NETWORKS (S-PCNs)

A number of Satellite Personal Communication Networks are available throughout the world. A satellite, in an S-PCN, plays the same role as a base station in cellular technology. The instantaneous area which a satellite can serve depends on the altitude of the satellite. No one satellite can cover the entire surface of the Earth. Therefore, a constellation of satellites is required to cover all, or most, of the Earth's surface. Based on the altitudes of the satellites, a satellite constellation can be classified into three categories: Geostationary Orbit (GEO), Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite systems. GEO satellites have orbits at an altitude of about 35,786 km above the surface of Earth. Satellites in GEO orbits have a 24 hour period and appear to be stationary from Earth. LEO satellites can be at any orbit up to 1500 km in altitude. The MEO or Intermediate Circular Orbit (ICO) satellites have orbits with altitudes between 1500 km and 35,000 km. [6]. Constellations using GEO satellites include Inmarsat, Thuraya and Asia Cellular Satellite (AceS) [7]. LEO based S-PCNs include Iridium, Globalstar and Orbcomm. The MEO based systems include Ellipso. In this research, a feasibility study is carried out to see which of the S-PCNs will be suitable for use in a nano-satellite. Out of these seven systems, two GEO (Inmarsat and Thuraya) and two LEO (Iridium and Globalstar) systems are studied in the following discussion.

2.1 Feasibility Study Parameters

Before examining the selected satellite systems, the parameters that will be used to ascertain which system is the most suitable, need to be specified. The parameters that will be considered are: coverage offered, availability of hardware and service in the U.S. for ground testing, and the appropriate specifications of hardware.

2.2 Candidate S-PCNs Considered for Feasibility Study

Details of the four S-PCNs considered are given in this section. The available modems for each of these systems are also described. Each S-PCN has three main components, namely: satellite segment, ground segment and user terminal that are considered.

2.2.1 Inmarsat Satellite Network

International Maritime Satellite (Inmarsat) was established in 1979, basically for providing communications to ships at sea. It now also provides land based communications. There are 10 Inmarsat satellites in geostationary orbits [8]. The main controlling headquarters for Inmarsat is in London. The Inmarsat system uses Time Division Multiplexed (TDM) channels, where each channel is transmitted on a unique frequency.

Services offered by Inmarsat include Regional Global Area Network (BGAN, GAN); High quality voice and data service (INMARSAT-M); two-way data-only service (INMARSAT-C) and two-way short messaging (INMARSAT- D+) [9].

The Inmarsat device that may be considered for the use in our application is the 'Thrane M4' data modem. This modem is specifically designed for Supervisory Control and Data

Acquisition (SCADA) system. It provides both packet data and circuit switched data services.

Some of the specifications are given in Table 1 [9]:

Table 1 Specifications of Thrane M4 Data Modem by Inmarsat

Power Supply	9.5 V - 20 VDC
Channel Spacing	1.25 kHz.
Dimension	43.5 mm x 154 mm x 201 mm
Mass	1.25 kg
Rx Freq. Band	1525.0 - 1559.0 MHz
Tx Freq. Band	1626.5 - 1660.5 MHz
Operating Temperature	-25° C to +55° C
Storage Temperature	-40° C to +80° C

2.2.2 Thuraya Satellite Network

Thuraya Satellite Network is based in the United Arab Emirates (UAE). In this system, there are two satellites positioned in GEO orbits inclined at 6.3°. The system provides coverage to one third of the globe. The entire network for Thuraya is handled by a primary gateway in Sharjah, UAE. The frequencies used by Thuraya, for satellite communication, are 1526.5 - 1659 MHz, for Global Positioning System (GPS): 1575.42 MHz and for Global System for Mobile communications (GSM): 890 - 960 MHz. The system uses the Frequency Division Multiple Access (FDMA) scheme with a carrier channel bandwidth of 27.7 kHz. Services offered by Thuraya include voice, fax, data (9.6 kbps), short messaging and location determination [10].

The data modem by Thuraya called 'ThurayaModule' provides only circuit switched voice/data service, short messaging service (SMS), and GPS. The specifications include a data rate of 9.6 kbps, dimensions of 72 mm x 52 mm x 9.5 mm and a mass of 60 gm [10].

2.2.3 Iridium Satellite Network

The Iridium Satellite Network has 66 satellites at an altitude of approximately 780 km. These satellites are evenly spaced in 6 orbital planes. The orbital planes are near-polar with an inclination of 86.4° [11]. Unlike the Globalstar system, the Iridium system provides coverage to the Polar Regions. The distinguishing feature of the Iridium system is that it has Inter-Satellite links, which means that the satellites not only work as bent pipes, but they also communicate with each other. Each satellite is cross linked with two satellites in the same plane and two in the adjacent plane [12]. These cross links relay the signal between satellites until the signal reaches the satellite that is overhead the user being called. The signal is then relayed back to earth. The inter-satellite links and onboard processing feature increase the flexibility in message routing.

As the satellites are at a lower altitude than a GEO satellite, less power is required by the satellite and the mobile handset. This also decreases the satellite antenna size, and the time delay. Moreover, it increases the angle of elevation. Iridium has a minimum elevation angle of 8.2° [13].

An Iridium satellite travels at a rate of 7.52 km per second and the orbital period is 100 minutes. A given satellite is in view, and can handle a call, for only ten minutes before the call is handed over to the next satellite. At least one satellite provides coverage to a given place 24 hours a day.

Iridium uses three phased array antennas, each producing 16 beams, resulting in a total of 48 beams per satellite. It uses a combination of FDMA and TDMA. The available spectrum is divided into 31.5 KHz sub-bands. In each sub-band 89.96ms of TDMA frames are transmitted using Quadrature Phase Shift Keying (QPSK). It uses the same frequencies, i.e., L band (1616-1626.5 MHz), for the uplink and downlink. This is possible without interference due to the TDMA scheme employed. For Inter-Satellite Links (ISLs), Ka- band (23.18-23.38 GHz) is used. This system also has telemetry, tracking and control links, which use the Ka-band, i.e., 19.4-19.6 GHz for downlink and 29.1-29.3 GHz for uplink [11].

The data modem by Iridium is called '9522 L band Transceiver'. The services provided by this modem include Circuit Switched Data Services and Short-Burst Data (SBD) Service. The specifications are given in Table 2 [12].

Table 2 Specifications of Iridium 9522 L band Transceiver

Power Supply	+4.0 VDC to +4.8 VDC
Dimension	216.1 mm x 82.6 mm x 39 mm
Mass	659 g
Freq. Band	1616 MHz to 1626.5 MHz
Operating Temperature	–20° C to +60° C
Storage Temperature	–40° C to +85° C

2.2.4 Globalstar Satellite Network

The Globalstar Satellite System has a satellite constellation at an altitude of 1414 km and 52° inclination. The orbital period is 114 minutes. There are 48 satellites in a Walker constellation (8 satellite planes with 6 satellites per plane). A Walker constellation is defined as a

group of satellites in circular orbits having same period and inclination [14]. Globalstar provides

coverage in the area between 70° South latitude and 70° North latitude [15]. User Terminals can

be served by a satellite 10 to 15 minutes out of each orbit. Globalstar satellite serves as a bent

pipe for communication and there are no cross links among the satellites. All data processing is

completed by the terrestrial gateways. The Globalstar system uses Code Division Multiple

Access (CDMA) for communication waveforms.

The satellite receives user signals at L-band (11610 -1626.5 MHz). It amplifies the signal,

converts it to C-band, and relays it to a gateway. This link, i.e., from the user terminal to the

satellite and then to the gateway, is called the reverse link. The signal from the gateway, also in

L-band, is received by the satellite, amplified, converted to S-band (2483.5- 2500 MHz), and

transmitted to the user. This is called the forward link. The allocated bandwidth is divided into

thirteen 1.25 MHz channels.

The modem by Globalstar is called 'GSP-1720 – Duplex Modem'. It provides data and

voice communications. Some of the specifications are given in Table 3.

Table 3 Specifications of GSP-1720 by Globalstar [16]

Power supply		+4.7 VDC to 5.1 VDC
Dimension		119 mm x 65 mm x 14 mm
Mass		< 60 g
Freq. Band		1610 MHz to 1626.5 MHz
Maximum Transmit Power		31 dBm
Power Consumed Typically :	Transmit Mode	3.65 W
	Standby Mode	0.5 W
	Shutdown Mode	3.5 mW
Operating temperature		–30° C to +60° C
Storage Temperature		–40° C to +85° C

A comparison of the systems explained above is summarized in Table 4.

Table 4 Comparison of the candidate S-PCNs

	INMARSAT	THURAYA	IRIDIUM	GLOBALSTAR
Orbit Type	GEO	GEO	LEO	LEO
No. of Satellites	10	2	66	48
Orbital Plane	-	-	6	8
Orbit Inclination	-	6.3°	86.4°	52°
Altitude	35,786 km	35,786 km	780 km	1414 km
Satellite Beams	250-300 [6]	-	48	16
Access Schemes	TDMA	FDMA	FDMA &TDMA	CDMA
Operating Freq.	2/ 2.2 GHz	1526.5 - 1659 MHz MHz 1526.5 - 1659	L band (1616-1626.5 MHz), 29.1-29.3 GHz for uplink L band (1616-1626.5 MHz), Ka-band (19.4- 19.6 GHz) downlink	11610 -1626.5 MHz uplink S-band (2483.5-2500 MHz) C- Band downlink
ISL Frequency	-	-	Ka- band (23.18-23.38 GHz)	-
Data Rate for Modem	2.4 kbps	9.6 kbps	2.4 kbps	9.6 kbps
Primary Operator	London	UAE	US	US

2.3. Selection of the Best System

The nano-satellite considered here can be at altitudes between 300 km and 600 km. A lower limit of 300 km is chosen, as significantly lower altitudes are infrequently used due to their limited life-time. The upper limit is set at 600 km since higher altitudes than that may not comply with international agreements on orbital debris. The higher the distance between the nano-satellite and the S-PCN's constellation, larger will be the coverage provided by the constellation. This means that the GEO satellites will provide better coverage than the LEO ones. However, the problem with using GEO systems (Inmarsat and Thuraya) is that due to the large distance

between the GEO satellites and nano-satellites, the power required to send the signals is more than that required for the LEO satellites. For a nano-satellite there are strict power constraints, and a GEO system is therefore not preferred. Among the LEO systems, the Iridium satellites, at altitudes of 780 km, are closer to the nano-satellite than the satellites in the Globalstar system. Therefore, it is expected that the coverage provided by the Globalstar system will be greater than the coverage provided by the Iridium system. Another advantage of using the Globalstar system is that it is simpler to understand than the Iridium system, which employs complex inter-satellite links.

For transmitting information from a nano-satellite, a secure connection is required. As the Globalstar system uses CDMA, it provides a secure connection. The modem by Globalstar also weighs less than the other modems. In addition, the Globalstar operators are based in the U.S. and the information about their modem is readily available. Hence, the Globalstar system is chosen for the simulation and analysis in this thesis.

CHAPTER 3: GLOBALSTAR SATELLITE NETWORK

This chapter explains the Globalstar system in detail. The Globalstar system was designed to provide communication anywhere in the world other than the poles. It works like a cellular network where the satellites are the base stations relaying data from one point on Earth to another. The Globalstar system provides both voice communication and data communication. The constellation has the capacity to serve up to 30 million subscribers (not simultaneously) [17].

In the first section, the main components of the Globalstar system are described. In the second section, the access scheme used by Globalstar is explained in detail, and some of the special features associated with Globalstar (Diversity Combining, Rake Receiver and Channel Characteristics) are described. The last section explains the complete flow of a call using the Globalstar system.

3.1 Components of the Globalstar System

3.1.1 Space Segment

The Globalstar Space Segment consists of 48 satellites distributed equally in 8 planes. These satellites are at an altitude of 1414 km, inclined in non-polar circular orbits at 52°. The system provides coverage to the region between 70° North latitude to 70° South latitude. The inclined and non-polar orbit ensures that the coverage is concentrated in the mid-latitudes and more populated areas. It also increases the overlapping satellite coverage resulting in increased system capacity and robustness [17]. When the user terminal communicates with the satellites at

an elevation angle greater than 10°, coverage is provided by at least two satellites for the temperate regions. However, at the equator and at latitudes above 60°, multiple satellite coverage is not available. During each orbit a satellite can typically serve a user for 10 – 15 minutes at higher elevation angles (>10°). After that the communication is handed over seamlessly to the following satellite.

Figure 1 shows a Globalstar satellite [18]. Each satellite is three-axis stabilized with the earth facing panel always parallel to the orbit tangent. The mass of each satellite is approximately 450 Kg. The components of the satellite displayed in the figure are explained as follows (the font is italicized to distinguish).
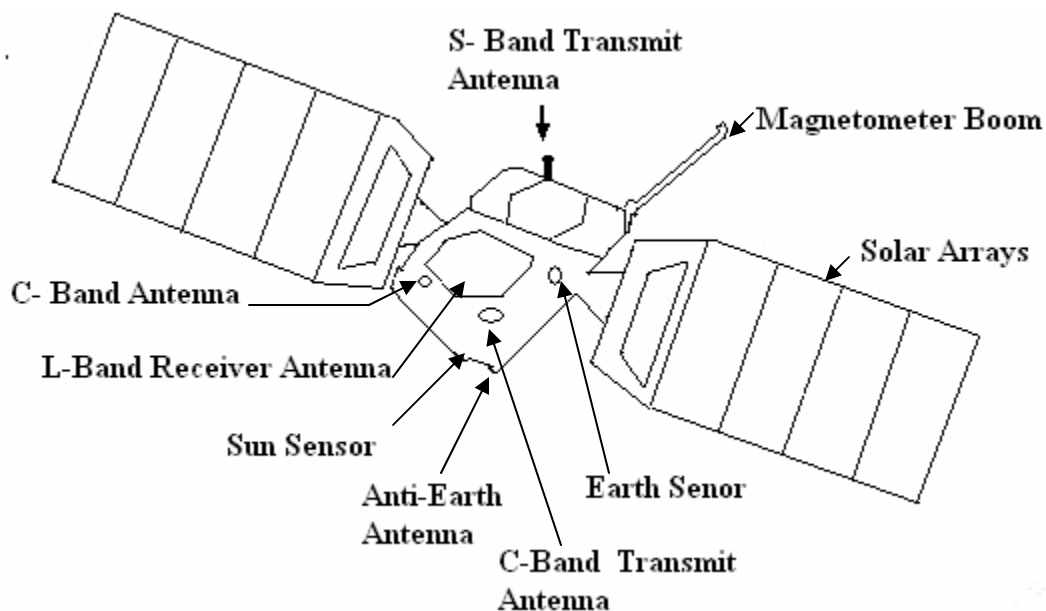
Figure 1 A Globalstar Satellite [18]

Solar Arrays and a large nickel-hydrogen battery provide power to the satellite. Yaw steering is employed to keep the solar panels oriented towards the sun to gain maximum energy.

Battery recharging takes place over the oceans, where there are fewer signals to handle due to

less traffic. A *Magnetometer, Earth Sensor* and *Sun Sensor* are used for attitude control [19].

An *S-Band Transmit Antenna* is used for the communication between Satellite to User

(downlink). It is a 91 element active phased array antenna. The frequencies used are 2483.5 to

2500 MHz. The antenna has a multi beam pattern having16 beams, and each beam has a separate

satellite transponder. A separate power divider network is used for each of the beams to shape

and position them on the earth's surface. The isoflux pattern is obtained by shaping the beam so

that the gain at the edge of coverage is higher than at the beam center. Both Right Hand Circular

Polarization (RHCP) and Left Hand Circular Polarization (LHCP) are used. The purpose of using

such beam patterns are explained in detail in Section 3.2 The beam pattern is shown in Figure 2.

Channel Assignments
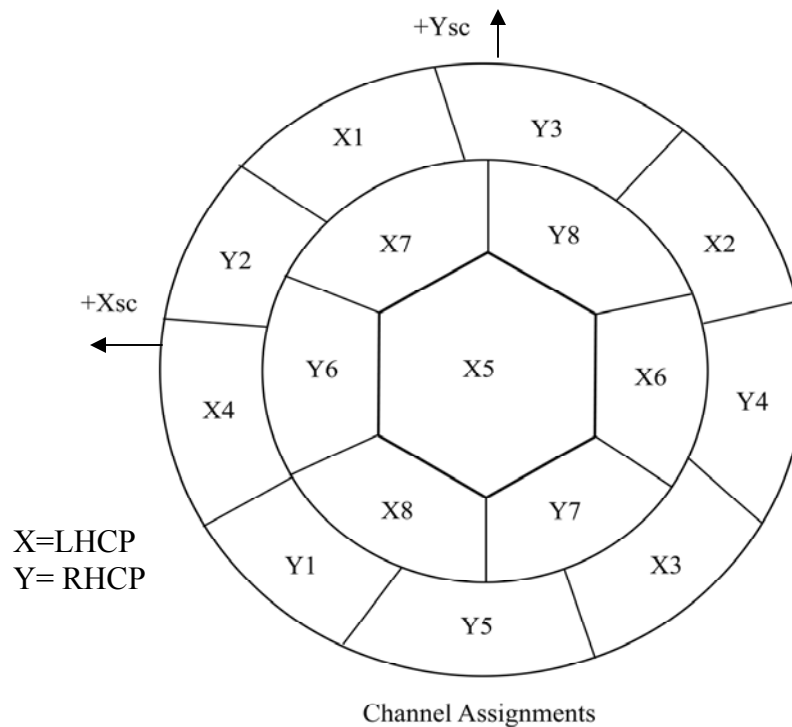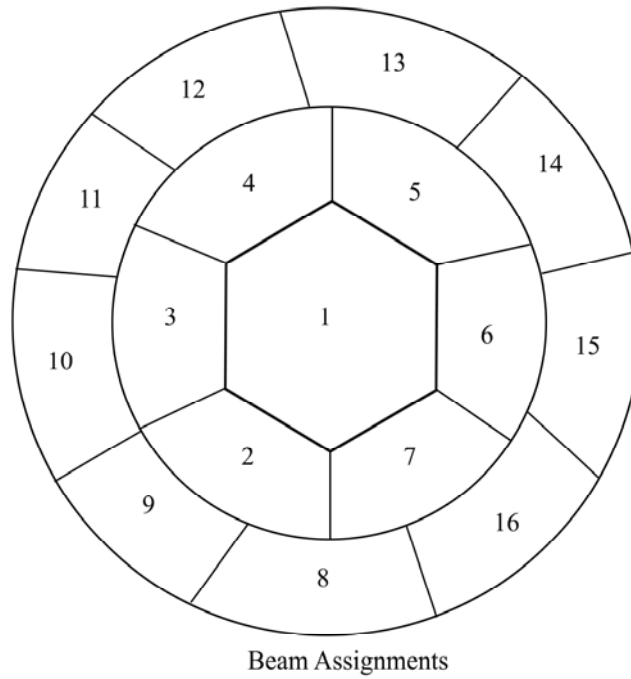
Figure 2 S-Band Beam Pattern (View from Satellite looking at Earth Nadir) [19]

An *L-Band Receiver Antenna* is used for the communication between User and Satellite (uplink). It is a 61 element active phased array antenna. The frequencies used are 1610 to 1626.5 MHz. The L -Band pattern also consists of 16 beams as shown in Figure 3.
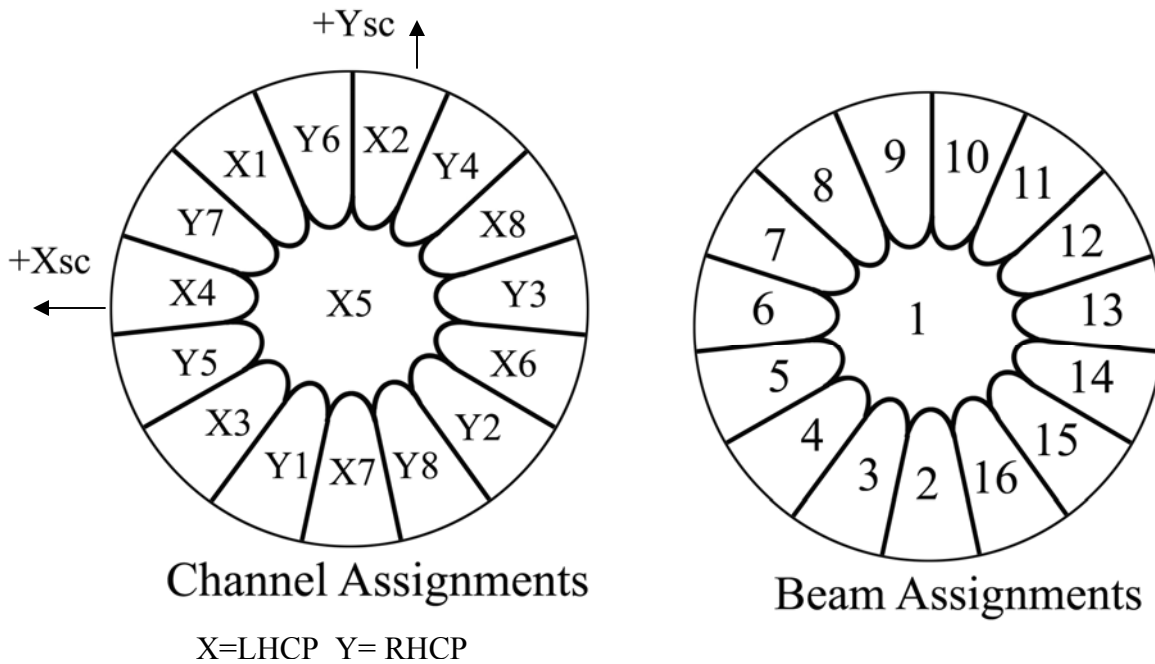
Figure 3 L-Band Beam Pattern (View from Satellite looking at Earth Nadir) [19]

A *C-Band Transmitter and Receiver Antenna* is used for the transmission and reception between the Globalstar satellites and the Gateways. The gateway uses a parabolic antenna to receive and transmit C-band signals to the satellite. The transmit frequencies and received frequencies used are 6875 to 7053 MHz and 5091 to 5250 MHz respectively. During normal on-orbit operation, the same C-band Receive antenna is used for both communication traffic and Telemetry and Control (T&C).

An *Anti Earth Antenna* is used for Telemetry and Control when the satellite is not oriented correctly and there are problems in communicating with the satellite. The anti Earth antenna does not have a low noise amplifier, so it needs to receive a higher power signal from the ground station. It is possible for the ground station to provide this higher power signal for

17

commanding, because there will be no other communication taking place due to the disorientation of the satellite.

In case of Return Link (transmission of signals from User terminal to the Gateways through the satellites), the Satellite receives the L-Band signal from the User Terminal. The signal then enters the L-Band Low Noise Amplifier (LNA) and is amplified and converted to a C-band signal. The signal is amplified again and transmitted to gateways. The gateway then performs its functions as explained in Section 3.3. For Forward Link (transmission from the Gateways to the User terminal through the Satellites), the satellite receives a C-band signal from the gateways. This signal is then down converted to the S-band signal and radiated to the User terminal by the satellite.

3.1.2 User Segment

'User Segment' is also referred to as User Terminal (UT). Globalstar provides a variety of user terminals both for voice and data communications, such as handheld phones, car kit, fixed phones and data modems. There are two kinds of *Handheld Phones*. The first is a 'Bi-mode' phone, which works with the GSM system, as well as the Globalstar system. The second kind is a 'Tri-mode' phone which works with both Globalstar technology and GSM technology, as well as with AMPS (Advanced Mobile Phone Systems) technology. These phones have a separate antenna, relatively large in size, to communicate with the satellites when working with the Globalstar system. This antenna is required to be positioned upwards to have a clear view of the sky. For the cellular mode (GSM and AMPS), a smaller antenna, as in regular cell phones, is used. The *Car Kit* includes a handheld unit inserted in an adapter in the vehicle. It includes a

handsfree speaker and microphone, outdoor unit with antenna and a connection with the vehicle battery. The user can select the preferred mode for both the handheld phones and car kits. However, the Fixed Phones and Data Modems only work under Globalstar mode. Globalstar offers both Simplex and Duplex data modems. The modems may require a higher antenna gain and more transmitter power than the mobile phones. The antennas and power source are external to the modem.

The function of the user terminal is made clear in the last section of this chapter where the flow of a call is explained.

3.1.3 Ground Segment

3.1.3.1 Globalstar gateways

Globalstar's ground stations on Earth are called gateways. These are the interconnection points between the Globalstar satellite constellation and existing terrestrial-based telecommunications networks. A gateway usually comprises of three or four dish antennas, a switching station and routing controllers. A single Gateway provides service in an area as large as Western Europe.

In the Return Link, the gateway receives the signal from satellites, down converts to an intermediate frequency and gives it to Telemetry and Control Unit (TCU) for processing. The communication part of the signal is given to CDMA subsystem for demodulation. For the Forward Link, the gateway sends the CDMA signal combined with the commands to the satellites in C-band. These steps are performed with the help of the components shown in Figure 4 [19].

The *Gateway RF Subsection* (GRS), shown in Figure 5, provides the basic interface between the gateways and users through the satellites. It has 4 antennas which are approximately 5.5 meters in diameter. These antennas are used to track the Globalstar satellites passing overhead and for transmitting and receiving signals from them. There are four antennas because most areas are covered by 2 to3 satellites, with each being tracked by a separate antenna. The antenna structure contains drive mechanisms for positioning the antenna, low noise receivers and high power transmitters. The TCU provides the link between the satellite constellation and the Satellite Operation Control Center (SOCC) through the router in the Gateway Management System (GMS). All Gateways equipped with T&C Units have the ability to command the satellite. The GMS provides interface of the gateway with the Satellite Provider's Control Center (SPCC). The *CDMA Sub System* has a Globalstar Transceiver Subsystem (GTS), which accounts for the implementation of the Air interface. The *Gateway Switching Subsystem* GSS handles switching and links to the Public Switched Telephone Network (PSTN).
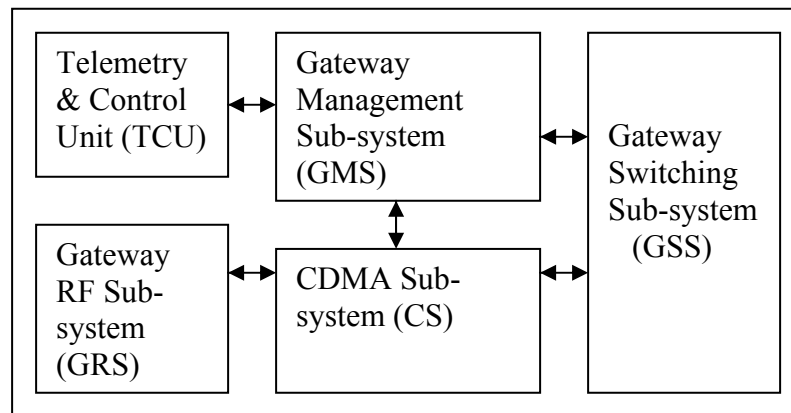
Figure 4 Components of the Globalstar Gateway [19]

3.1.3.2 Globalstar control centers

The Globalstar Control Center is responsible for the management and operation of the complete Globalstar system. There are two operation control centers so that if one fails, due to any reason, such as power failure, the other can take over operations. The Operation Control Center includes a Satellite Operations Control Center (SOCC), a Ground Operations Control Center (GOCC) and a Globalstar Business Office.

The SOCC manages the satellites. It checks for the satellite health and battery state by communicating with the TCU in the gateways. It informs the Ground Operation Control Center (GOCC) about satellite availability capacity, and ephemeris. The encryption of commands to be sent to the satellites is also done in this center. GOCC plans and manages the resources for the satellite constellation and gateways [20]. This center monitors the system performance and generates traffic plans. It reports the usage of satellites to SOCC. Both the GOCC and SOCC are manned facilities, and can be located in the same physical location connected via Local Area Network (LAN). If not collocated, the GOCC and SOCC are linked via the Globalstar Data Network (GDN).

The Globalstar Business Office has Globalstar Accounting & Billing System (GABS) which deals with the account handling and financial matters of Globalstar.

3.2 Access Scheme Used by Globalstar

The access scheme used by Globalstar is Code Division Multiple Access (CDMA), a scheme originally developed for terrestrial communication. Interim Standard (IS-95) is a standard for CDMA. CDMA is used because of its attractive properties. With CDMA, it is

possible to re-use the same frequency in the adjacent cells. That is why it is often said that for CDMA the frequency reuse pattern is one [11]. Thus, CDMA provides a higher capacity compared to non-spread access schemes. It has an inherent security feature as each user is assigned a different code.

The frequencies used for uplink (user to satellite) are 1610 to 1626.5 MHz and for downlink (satellite to user) are 2483.5 to 2500 MHz. This 16.5 MHz band for each is divided into 13 FDM channels each having bandwidth equal to1.23 MHz. Each 1.23 MHz band can be used for multiple data and voice calls simultaneously by using PseudoNoise (PN) codes. The channels defined by IS-95 are pilot channel, paging channel, synchronization channel and traffic channels. For CDMA in Globalstar, Walsh Codes [9] along with PN codes [9] are used. This helps in taking advantage of cross-correlation properties of Walsh Codes and auto-correlation properties of PN Codes.

For a forward link in the Globalstar system, 128 channels are available with 119 traffic channels, 1 pilot channel, 7 paging channels and 1 orthogonal channel. The pilot channel is used for the determination of signal strength which in turn is used for power handling schemes and handoff implementations (the power control and handoff system are explained in Chapter 5). This signal is continuously sent by gateways for user terminals. A paging channel is used by gateways for sending commands to the user terminal. A synchronized channel is used to determine the initial timing to acquire synchronization. For forward link, two PN sequences are generated each having length 2^{17}-1 [9]. A fixed offset is added in PN code to create a unique signal for each user [19]. In forward link, the Walsh code is determined by the gateway.

For return link, traffic channels and access channel are used. An access channel is a slotted random access channel. It is used for tasks like initiating the call, getting registered with the gateway, etc. It also uses two PN sequences, one having length 2^{17}-1 and the other 2^{42}-1. The latter is used for the identification of the user at the gateway [9]. For the return link, the Walsh code is determined by the information being sent.

The IS-95 standard also introduced the implementation of a Rake Receiver for CDMA. Globalstar gateways and user terminals all have Rake Receivers. The main function of a Rake Receiver is to individually process several multi-path signals and combine them to give out the signal with the best Signal-to-Noise Ratio (SNR). This helps in combating multi-path problems. Generally, a Rake Receiver has several correlators (called *fingers*) to process the incoming signals from different sources, individually.

Globalstar utilizes Rake Receivers to provide path diversity and handoff control in addition to mitigating multi-path problems. The coverage provided by Globalstar at any point on the Earth is usually provided by more than one satellite. This means that at any time, a user terminal may receive more than one signal coming from different satellites. By the use of Rake Receivers, the signal with best SNR can be chosen. This is called 'Path Diversity' or 'Diversity Combining'. With this feature, availability increases and the breaks in coverage are decreased. The handoff handling capability in the Globalstar system is explained in Chapter 5.

The fading in the Globalstar system is modeled by a Rician distribution [9]. A Rician distributed channel is the result of the antenna receiving a large number of reflected waves along with the direct signal component.

3.3 Call Flow in Globalstar System

When a user makes a call, a 'call request' is sent to the gateway which serves the area in which the user is located. The gateway checks for an available CDMA channel and informs the user. It also establishes the connection with the dialed number. If the dialed number is being serviced by the same gateway, the call is completed within the gateway. If the dialed number is not a Globalstar number, the call is routed through the PSTN. The call setup time depends on the Globalstar system setup time and the other system setup time.

This chapter explained how the Globalstar system works. The next chapter describes the use of a Globalstar modem for our application.

CHAPTER 4: GLOBALSTAR MODEM- GSP 1720

The GSP 1720 modem by Globalstar provides full duplex voice and data communication [16]. Asynchronous communications or packet data communications are the two options available for data communication. For both the types, the modem talks to the system serially. The data rate provided is 9.6 kbps, but due to overhead the throughput is 7.6 kbps. While the modem can be configured (e.g., baud rate and port configurations) using Globalstar's User Terminal Program Support Tool (UTPST), the modem used for testing was configured by the company. The modem is shown in Figure 5.
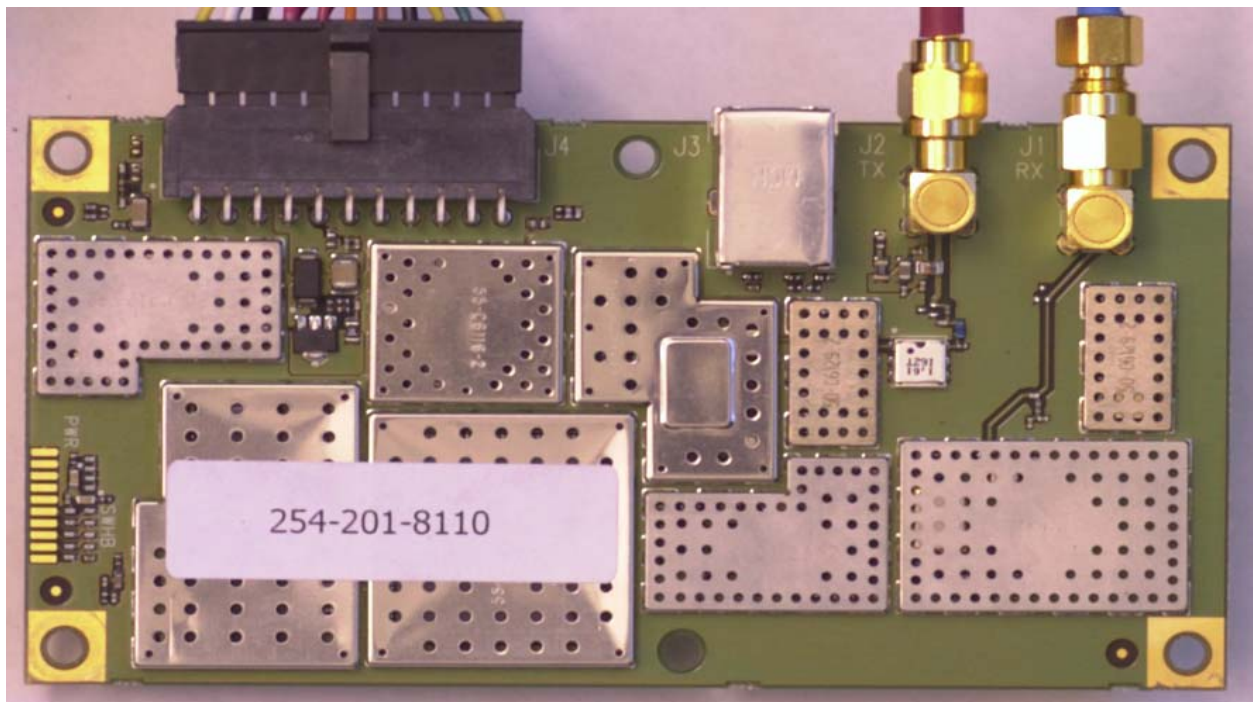
Figure 5 GSP-1720 Globalstar Modem

This first section of this chapter describes the components required by the modem to work in the desired way. The next section explains the port configurations used. The third section explains the reset process for the modem. The last section describes the procedure for making a data call. The information about the modem was obtained from the Globalstar integrators manual for the modem [21].

4.1 Components Used for Testing

In addition to the basic modem the following components were used along during testing: passive patch antenna, power supply, developers' cable and an enclosure to protect the modem. A Personal Computer (PC) with serial ports (or Serial to USB port cable) is used for communicating with the modem. The platform for the PC used is Windows XP. However, when using the modem on a nano-satellite, any device capable of serial communication can be used. The components used are described as follows:

4.1.1 Passive Patch Antenna

A passive patch antenna with two cables: transmit (Tx) and receive (Rx), is used. The maximum loss for an antenna cable of any length is 1.0 dB at 1.6 GHz for transmission frequencies and 3 dB at 2.5 GHz for reception. Each RF cable is 17". The antenna is mounted on the enclosure for the modem, and needs a clear view of the sky to the satellite in order to communicate.

For actual use on a nano-satellite, two patch antennas, one on the top and the other on the bottom of the satellite could be used. A splitter will be used to divide the signal power equally

between the two. Mounting two antennas will help in communication with the satellite whenever the satellite is disoriented due to some problem (rare case).

4.1.2 Power Supply

The power required to run the modem with a passive antenna is 4.7-5.1 V DC, 1 Amp (maximum). With an active antenna, the requirement is 7 volts. To protect the modem, a fuse with a minimum melting rating of 0.02 A^2 is used. The Globalstar developers' cable comes with its own power supply. It needs an external source of 12 volts, and has a switch to either give 5 volts or 7 volts to the modem. An AC adapter (12V, 1.5 A), by Radioshack, was used as the 12V external source.

4.1.3 Developers' Cable

A special developers' cable by Globalstar was used for testing. On one end of the cable there is a connector that attaches to the modem. The other end of the cable has the following: connections: Data Port, Control Port, Power Supply leads, Ground leads, Audio In/Out, VEXT_ON_N lead.

The *Data port* is a DB-9 connector which goes to the COM port of the PC or the SCADA device being used. A USB Port can also be used for the data port, but this requires that either the user purchases the UTPST software to configure the modem, or that the manufacturer configures the modem accordingly. This port can be used for dedicated data transfers only or can be used alternately for both control commands and data transmission. This is decided on the basis of the configuration used. The types of configuration are defined in the next section. The baud rate for

the data port is configured to be 19200 bps by the manufacturer. This can be re-configured (300-38400 bps) using the UTPST, if required.

The *Control port* is a DB-9 connector serial port which goes to either another COM port on the same PC where the data port is connected, or to a different PC, according to the requirement. The control port is used for sending AT commands to the modem without disturbing the data flow through the data port. The baud rate is fixed and is configured to 9600 bps.

The *power supply leads* in the developers' cable go into the power supply that comes with the developers' cable. These leads provide either 5V or 7V to the modem, depending on what the voltage switch on the power supply is set to. In our case, as the passive antenna is used, the 5V setting is selected.

There are three *ground leads* provided: one for the power ground, one for audio ground, one for the antenna ground. Although different leads are provided, these all are common along with the four corners of the mounting hole ground pads on the modem.

The *Audio In/Out* cables are used for voice communication, which is not needed for our application.

The *VEXT_ON_N lead*, when grounded, is used for powering up the module. This lead is also used for resetting the module.

4.1.4 Enclosure

For protecting the modem the module was enclosed in a protective plastic enclosure. A fiberglass enclosure may also be used. The antenna was mounted to the top of the enclosure, and the power supply for the modem was attached outside the enclosure for convenience.

4.2 Configuration Used for the Modem

There are three options available for the port configurations: Only Control Port, Only Data Port, Both Control Port and Data Port. In the first mode, only AT *commands* can be sent to the modem, and data cannot be transferred. For Only Data Port mode, both *commands* and *data* are sent through the same port. For successful transmission, the arbitration behavior must be clearly understood by the user first. For the third mode, the commands and data can be sent simultaneously using different ports. AT commands are sent to the control port and data can be sent without interruption on the data port.

For testing purposes, Only Data Port mode is chosen since it is simpler. In this case, the 'Control Port' in the developers' cable is not connected to anything. In the text when ever we refer to the 'modem being connected to PC', it implies that only the data port of the modem is connected to the PC. The basic configuration settings used are shown in Table 5.

Table 5 Port Configurations of the modem used

Parameters	Value
Port Used	Data Port Only
Control Port Baud Rate	9600 kbps
Data Port Baud Rate	19200 kbps

4.3 Resetting the Modem

There are two ways to reset the modem. It can be done either by raising the voltage of the VEXT_ON_N lead for 2 seconds and then grounding it, or in software by sending the command 'ATF' to reset the modem to default factory settings. Another command 'ATZx' can also be used, where 'x' is 0, 1 or 2. If it is '0', it implies resetting the module to default factory settings (equivalent to ATF). If '1' or '2' is sent, it resets the module to the profile 1 or profile 2 settings, respectively. The profile 1 or 2 settings can be defined in the modem for a specific configuration.

4.4 Testing a Data Call

There are two ways to make a data call with the modem: Asynchronous data call and Packet data call. The modem was tested for both types of calls. Before these calls were made it was necessary to see if the modem was able to talk to the PC alone. This was checked by first connecting all the connectors of the developers' cable. Then, using the PC, a HyperTerminal connection was established to the port on which the modem's data port was connected. The settings for the HyperTerminal connection used are shown in Table 6.

Table 6 Data-Port Settings in HyperTerminal

Parameter	Value
Baud rate (bits/sec)	19200 kbps
Number of data bits	8
Parity	None
Stop bit	1
Flow control	Hardware

To check if the modem was able to talk with the PC, the 'AT' command was sent. A return of 'OK' indicated that the connection is established.

Once it was established that the modem was able to talk to the PC, it was necessary to check if the Globalstar service was available so that the call could be placed. This was checked by using the 'AT$QCSTATUS' command. The response of the modem to this command indicated if the satellites were available and what the signal strength was (ranging from 0-4). Other than using the 'AT$QCSTATUS' command, the schedule given on the Globalstar website was used to have an idea when there would be an available satellite pass. Moreover [22] was used to track the satellites live. When the service was available these calls were made:

4.4.1 Asynchronous Data Call

An Asynchronous data call connects the modem through a Globalstar Gateway and the PSTN. In this mode the satellite modem can be called directly using its phone number. To test this type of call, on one end the modem was setup as explained above. On the other end another computer was connected to a regular PSTN line. This represented the host system or the ground system which will be calling the modem in a nano-satellite. For this PC, HyperTerminal was connected to the built-in modem connecting the PC to the phone line. For illustration purposes, the satellite modem end is referred to as terminal A and the PSTN line connected to the PC is referred to as terminal B. A call was then made from terminal B to terminal A by entering the modem phone number. When the number was dialed, "RING" appeared on the HyperTerminal of terminal A, and the call was answered by typing "ATA". Once the call was answered a test file was sent using the "send file" command in HyperTerminal on terminal A. On terminal B the

31

file was received by clicking "receive file" or by setting the option of receiving files automatically. The user can specify where to store the received files in HyperTerminal's settings. This asynchronous call is called 'mobile-terminated asynchronous call' since the modem was being called. For 'mobile originated asynchronous call' the same process was repeated but this time the call was made by terminal A, i.e., the satellite modem. The test file used was a Microsoft Word file of size 32 KB. The file selected was smaller in size since the Globalstar network is having problems with its data service so a longer continuous pass is rare. The data rate achieved was 8 kbps (kilo bits per second).

For our application, 'mobile-terminated asynchronous call' would mean calling the modem on the satellite from the locations on ground while 'mobile originated asynchronous call' simulates the nano-satellite calling the ground station.

This type of call was tested in order to understand the steps that will be required to work with the modem and the data rate that can be achieved. Once the modem is placed in a nano-satellite, these steps will remain the same; however it will be required to automate the process. This was not possible in this study due to time and resource constraints. Automating will be a matter of programming these steps in a controller interfaced with the device.

4.4.2 Packet Data Call

For packet data calls, the satellite modem makes a connection to the internet using a dial-up connection. For dial-up configurations the driver for a standard 19200 bps modem in Windows was used. The dial-up connection was set up to talk to the port to which the modem was attached. The number '#777 'was then dialed to connect to the internet. '#777' is a special

number which indicates the data connection. After connecting to the internet, for user satellite simulation, initially a Client/Server approach was used. A free FTP client called 'FileZilla Client' was installed on the PC. It was then connected to a server at UCF where it could upload and download data. The test file used for this call was a Microsoft Word text file of 31.5 KB size. The data rate achieved was 5 kbps (kilo bits per second). Although the asynchronous data has lesser data rate than that of packet data (due to overheads in the former because of the frame size) but the test results were different. This can be because of the traffic variations on the Globalstar network on different days.

A free FTP server called 'FileZilla Server' was also installed on the same PC to see if the computer attached to the modem could act as a server. The advantage of this method would be that the host computer on the ground can connect to the satellite modem by connecting to its Internet Protocol (IP) address. But this could not be achieved during testing, as the Globalstar modem did not have a public IP address, but a private IP address (10.xxx.xxx.xxx address). The solution to this problem is setting up a Virtual Private Network on the modem side which can then be addressed by a real IP address. Globalstar gave their consent to setting up a VPN for ground testing but due to time and resource constraints this could not be explored further.

4.5 Conclusion

Both types of data calls can be used for our application. A combination of both can also be used since each has its own advantages. The advantage of asynchronous data calls is that the modem can be accessed directly using its phone number. This provides a more secure one-to-one connection with the modem. The disadvantage is that when the user nano-satellite moves away

33

from the home region, long distance charges will apply. On the other hand, as Packet data

connects the computer to the internet, no long distance charges will apply. Another advantage is

that the data rate for packet data is more than that for the asynchronous data due to more

overhead (larger frame size) in the latter. But being able to address the modem is still an issue for

packet data calls, unless a VPN is implemented. In addition, some sort of security measures will

be required to avoid any intrusion from the internet.

Hence, a tradeoff needs to be made. For instance, for saving cost, up-linking of data can

be done using only asynchronous calls and for down-linking data, packet data calls can be used.

The issues that need to be dealt with when using the modem in space are explained in the

next chapter.

CHAPTER 5: FACTORS TO CONSIDER WHEN USING THE GLOBAL STAR DATA MODEM IN SPACE

Globalstar Satellite Service is designed for communications by ground based users. When using the service and hardware on a nano-satellite, the effects on some key features need to be considered. These features are the percentage coverage in space, Doppler shift, power management, operating temperature conditions, frequency requirements, handoffs and path diversity, electromagnetic disturbance/ interference, data rate, and service costs.

The terms 'user satellite' and 'nano-satellite' are used interchangeably in this document.

5.1 Percentage Coverage in Space

Globalstar provides coverage to all the regions on the surface of Earth except the polar regions. Figure 6 shows the Globalstar satellites' footprint (coverage) on the Earth's surface. This coverage map was generated using STK. The Two line elements used are given in Appendix A. to a user satellite the footprints of the satellites in the Globalstar constellation will appear smaller than shown in Figure 6 due to the decrease in the distance between the satellite constellation and the user. The coverage will decrease as the user satellite gets closer to the Globalstar constellation. Chapter 6 describes the simulations done to analyze the coverage for a user satellite.
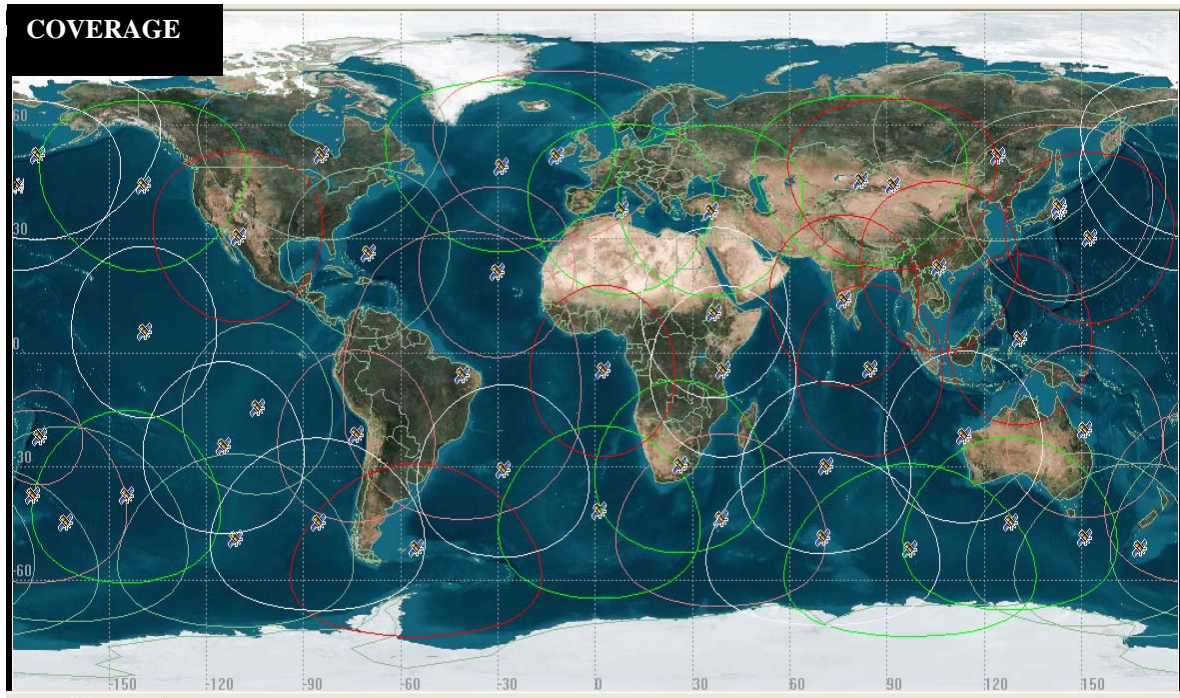
Figure 6 Globalstar Coverage

5.2 Doppler Shift

The Globalstar User Terminals (UT) can either be stationary or moving. In both cases, there exists a varying relative velocity between the UT and Satellites. Similarly, there exists a relative velocity between the Satellites and Gateways. Due to these relative velocities the frequencies which the components of Globalstar (Gateway, Satellite, and UT) receive are different from the assigned frequencies in rest frame. This shift in frequency is called the Doppler shift. Due to this effect, it appears to the receiver that there is a change in the frequency of the carrier wave to which the receiver needs to be tuned. It is therefore necessary, to make corresponding correction for this frequency shift.

The Doppler Shift is given by:

$$\Delta f = (fv)/c \qquad\qquad 5.1$$

where Δf is the change in frequency (Doppler shift), f is the frequency of the wave, c is the speed of light/wave in vacuum and v is the relative velocity between the transmitter and receiver.

In the LEO satellite systems, the satellites move with a higher speed relative to the Earth. This introduces high values of Doppler frequency shift. In this section we investigate the Doppler frequency shift when the modem is placed inside the user satellite. If Globalstar modems or phones are used anywhere on Earth the values for the Doppler shift are given in Table 7.

Table 7 Worst Case Doppler Shift in Globalstar system for Earth based users

PATH NAME	FROM	TO	Frequency(f)	Doppler (Δf)
Forward Downlink	Satellite	UT	2500 MHz	46.5 kHz
Return Uplink	UT	Satellite	1626.5 MHz	30.2 kHz

For ground based users, as the user terminal is considered to be stationary relative to the Earth, the frequency shift is quite significant as shown in Table 7.

However, for spaced based users where the user satellite is at a certain altitude (300km - 600km), the Doppler shift is expected to decrease for pro-grade orbits (as in our case) due to a decrease in the relative velocity. To calculate this Doppler shift we need to find the orbital velocities of the two satellites and the angle of arrival for the beam.

The velocity of a satellite is given by

$$V_o = \sqrt{mu/r} \qquad\qquad 5.2$$

where 'u' is the gravitational constant $(6.67259 \times 10^{-11}\ \text{Nm}^2/\text{kg}^2)$, 'm' is the mass of earth $(5.98 \times 10^{24}\ \text{kg})$, 'r' is the distance of satellite from the centre of the Earth (i.e., the sum of the altitude of satellite and radius of earth 7792 km).

For a Globalstar satellite at an altitude of 1414 km, the velocity is:

$$V_{GS} = 25758.47290\ \text{km/hr} = 7.16\ \text{km /sec}$$

Whereas the orbital velocity for a user satellite at 600km, is:

$$V_{US} = 27219.02732\ \text{km/hr} = 7.56\ \text{km/sec}$$

Generally the Doppler shift is given by

$$\Delta f = \frac{fv}{c}\cos\theta \qquad\qquad 5.3$$

where fv/c is the maximum Doppler shift (fm), which occurs when the transmitter is moving directly towards or away from the receiver or vice versa ($\theta = 0,\ \pi$). When a large number of waves arrive at the receiver, the spectrum of received signal will consist of a set of spectral lines, each occurring at a random frequency in the range $f \pm fm$.

In our case,

$$\Delta f = [f\,(V_{US} - V_{GS})\cos\theta\,.\,\cos(\varphi 1 - \varphi 2)\,]/c \qquad\qquad 5.4$$

The value of θ is found to be; 90 –52° (cone angle) = 38°. The difference in the inclination of the orbits is given by ($\varphi 1 - \varphi 2$). When the user satellite and the Globalstar satellites are at the same orbit inclination, the Doppler shift is greater than when they are at different orbit inclination angles. The Doppler shift for the same orbital inclination is given in Table 8.

Table 8 Doppler shift when the user satellite is at 52° inclination and 600 km

PATH NAME	FROM	TO	Frequency(f)	Doppler (Δf)
Forward Downlink	Satellite	UT	2500 MHz	2.67 kHz
Return Uplink	UT	Satellite	1626.5 MHz	1.73 kHz

The values calculated above are not large compared to the shifts for ground based users. One of the factors that might affect the values given in Table 8 is the interaction of signals with free electrons in the ionosphere. These effects are not considered in this thesis.

5.3 Power Management

Globalstar incorporates power management schemes in both the forward links and the return links. The initial step in controlling the power transmitted is to determine a target value for the SNR. Once that is established, the next step is to maintain this desired value, which is done by comparing the frame energy against the target value and asking for an increase or decrease in transmit power accordingly. Acquisition time increases if the target value is not established correctly. To carry out this process, Globalstar uses a combination of open loop control (referred to as the outer loop) and closed loop control (referred to as the inner loop). The open loop sets the target value by observing the frame error rate in the recent past. The closed loop controls to this target value, on the basis of 1 control bit every 20ms frame (50Hz) on both reverse and forward links. The rate is kept slow compared to cellular systems because the propagation delay is much larger (9.4ms to 23.4 ms). So implementing frequent closed loop control will be ineffective. On the other hand, the open-loop power control strategy, which does not need power

control command feed back, will be effective here because signal variations due to shadowing and distance losses are slow.

The distance between the user terminal (present on the surface of Earth) and the constellation, is 1414 km. When the user terminal is placed in a nano-satellite (at 600 km) the distance between the constellation and the user terminal reduces to 814 km. As the distance is now 0.576 times the original distance (0.576 *1414 =814), the received power from the nano-satellite will increase 3 times, i.e., the modem will receive 3 times more power than that received on ground. Globalstar has confirmed that this will not damage the modem. However, in order to avoid any harmful effects on the modem, one idea is to put two antennas on the user satellite. Also, if the satellite loses its orientation the modem will still be able to communicate with the help of any one of the two antennas pointing upwards (towards the Globalstar Satellites).

5.4 Operating Temperature Conditions

It is necessary to figure out if the modem will be able to survive and operate in the extremely fluctuating temperature in space. For the module we are using, the temperature range for operation is given as -30°C to 60° C and the temperature for storage ranges from -40° C to 85° C. Similarly, for the Antenna being used the operating temperature is from -55°C to 85° C. These temperature conditions are close to the typical operating temperature range for electronics on spacecraft. This means that the modem temperature conditions are within the temperature control capabilities required by satellites.

5.5 Handoffs, Roaming and Use of Path Diversity

In the Globalstar System, handoffs between different satellites and different beams within a gateway are allowed. However, handoffs between different gateways (known as roaming) are not allowed for data communication. This means that if a user roams out of one gateway, the connection needs to be re-established after the user gets registered to the next gateway. The process for this handoff is explained below for the forward link and the reverse link.

For the forward link, the User Terminal continually checks the signal strength of the pilot signal and reports it to the gateway. The gateway then decides whether to consider the proposed pilot signal in diversity combining or not. If the pilot signal strength is greater than a certain threshold, the gateway tells the User Terminal to add it in the diversity combining process. The User terminal can combine up to two different links simultaneously in the diversity combiner.

For Reverse Link the gateway has 6 fingers for diversity combining. If the signal to noise ratio is less than the threshold it automatically exits the diversity combiner. This diversity combiner capability is present only on traffic channels during a call and not for the access channel which is used for initiating a call.

For Earth based users, the diversity combiner plays an important role in seam-less handovers. It ensures 'soft-hand over', i.e., before the connection is broken due to low signal strength a new one is made (use of Rake receiver). However, in space this feature may not be exploited as effectively as on Earth. The reason is that at higher altitudes there is only one satellite covering the same area most of the time (percentage given in chapter 6), as opposed to on Earth where there are usually two or three satellites covering the same area. This implies that

in space, hard hand-over will take place most of the time, i.e., the connection will be broken

before it is handed over. Moreover, as nano-satellites move with a very high speed compared to

Earth based users, the handovers will be very frequent. Besides these handovers, for both 'packet

data call' and 'asynchronous data call', the connection will need to be re-established when the

satellite moves from one gateway to the other, i.e., when it is roaming. For our application the

satellite is in a roaming state most of the time.

5.6 Frequency Usage

The frequency bands allocated for the UTs, present on *ground,* are 1610-1626.6 MHz for

uplink and 2500-2520MHz for downlink. However for inter-satellite links the Federal

Communication Commission (FCC) has allocated bands which do not include these Globalstar's

frequency bands. Hence a special waiver from FCC rules might be requested by the nano-

satellite developers for using the Globalstar service in a nano-satellite.

5.7 Data Rate

The data rate provided by the modem is 9.6 kbps theoretically. However, the effective

throughput is 7.4 kbps due to overheads for packet data. For asynchronous data it is a little less

than that because of the PSTN module training time. When the modem is being used in space

these data rates should not be affected.

5.8 Service Cost

Globalstar Network provides two types of data services, Packet data calls and

Asynchronous data calls, as described in Chapter 4. For packet data, i.e., when connected to the

internet, no long distance charges apply. On the other hand if an asynchronous data call is made, long distance charges or roaming charges will apply. The basic service charges, other than the roaming charges are given in Table 9 [16]. Only four plans are presented here. The other plans available are essentially the same but having additional minutes.

Table 9 Globalstar Data Service Plans

PLAN NAME	Freedom 50	Liberty 600	Freedom 150	Liberty 1800
Monthly fee	$ 50	-	$65	-
Annual fee	-	$ 600	-	$ 780
Bundled data minutes	50/ month	600/ year	150/ month	1800/ year
Additional minutes	$ 0.99	$0.99	$ 0.99	$0.99
Activation fee	$ 50	$ 50	$ 50	$ 50
Number of bundled 15- second burst data sessions (internet)	200/month	2400/ year	600/month	7200 / month
Additional 15- second burst data session	$0.25	$0.25	$0.25	$0.25

Bundled data pricing is not available for roaming. The roaming charges are different for different countries. For instance when calling from Australia to the U.S, the call rate is $1.28 per minute; when in Switzerland this rate is $1.39 per minute.

CHAPTER 6: SIMULATION AND RESULTS OF COVERAGE IN STK

The objective of this chapter is to describe the *coverage* offered by the Globalstar constellation to a user satellite. The coverage describes the percentage of time that the user satellite can communicate through the Globalstar constellation to the ground. Calculations are presented for two altitudes (300 km and 600 km) and three inclination angles (0°, 52° and 90°), which are representative of those most likely to be used for a nano-satellite. Due to their complexity, calculations are done using Satellite Tool Kit software (STK 8.0.2) as described in the next section.

6.1 Building a Scenario in STK

A scenario is first created in STK using the current Globalstar satellite constellation. The Two Line Elements (TLE) set used for the constellation is given in the Appendix. A 'TLE' is a specific format set by NASA which defines the complete parameters (name, eccentricity, inclination angle etc.) of a satellite.

To indicate the coverage available for these satellites, conical sensors pointing towards the Earth are attached to each satellite. The sensors represent the antenna beam. Similarly, on the user satellite, a sensor (antenna beam) pointing upward towards the Globalstar constellation is created. This beam points upwards since the objective is to find the Globalstar coverage on the User. The coverage is calculated in terms of time-duration, for which the user satellite can send signals through the Constellation. As the distance between the user satellite and the constellation decreases, the coverage (contact time) between the two will also decrease. Once the user satellite

communicates with a satellite in the Globalstar constellation, the Globalstar satellite relays the signals to the ground station. Hence, a number of Globalstar gateways have been created in the scenario. The following sections describe each step in detail.

6.1.1 Generation of Globalstar Satellite Constellation

For the satellites to be created and placed in their correct positions, ephemeris information is required. The ephemeris information for Globalstar is taken from the STK satellite database. Another requirement for the generation of satellites is to decide which perturbations should be considered. Perturbations are the external forces influencing the orbit of satellites. STK provides four choices of orbit propagators having different levels of perturbations.

Simplified General Perturbation (SGP4) is chosen so that TLE files can be loaded into a scenario. Globalstar satellite TLE is loaded from the STK database using this propagator.

SGP4 orbit propagator considers variations due to Earth oblateness, solar and lunar gravitational effects, gravitational resource effects, and orbital decay calculated using a simple drag model. This propagator is the standard of AFSCOM (Air Force State Command).

Once the Globalstar constellation is created, it is used to analyze how much of the Earth surface is being covered. The instantaneous coverage of each satellite is defined by a conical Field-of-View (FOV) that intersects the Earth surface and forms a circular foot print. For simulating this satellite FOV, conical sensors pointing down towards the Earth are attached to each satellite.

Conical sensors are used to simulate the coverage instead of antennas because it simplifies the calculations. If antennas are used, several parameters, such as power and frequency,

are required. This isn't necessary for our simulations, as Globalstar has already covered the

power budgets for antennas. Therefore, all that is required here is to simulate the *coverage area*

provided by the antenna. For this purpose, a conical sensor with a FOV equivalent to that of the

antenna is used. From here on the terms 'antenna' or 'antenna beam' will be used to refer to

these sensors.

The cone angle 'α', i.e., the satellite FOV angle, for the antenna beam can be found using

the formulae given in Equations 6.1 and 6.2. ε in equation 6.1 is the minimum value of the

ground elevation angle. The ground elevation angle is the angle formed by the horizon and the

satellite beam. ε = 0 for horizon. For Globalstar satellites ε = 10°. This means a Globalstar User

terminal, when inside the satellite footprint, can communicate through the satellites when the

elevation angle is ≥ 10° (i.e., ≥ 10° above the horizon). This elevation accounts for atmospheric

losses and obscuring objects. The altitude of the satellite is given by 'h', which is 1414 km for

the Globalstar satellites. The equatorial radius of earth is 'r_e', which is 6378.1 km. Putting these

values in equation 6.1 yields a cone angle of 53.7º. This cone angle had to be calculated since the

Globalstar documents did not provide it. They did provide information about the radius of the

coverage area, however, and therefore one can double check the value for the cone angle using

equation 6.2. The radius of the area covered by each of the Globalstar satellites on the ground is

2880 km (d= 2880 in Figure 7). The Earth central angle of coverage is given by 'θ'. Using this

information, the cone angle using Equation 6.2 is found to be 54°, which verifies the previous

calculation. However, for simulation purposes, the cone angle is considered to be 52° to be on

the safe side. This gives an elevation angle of 15.7°.

$$\sin \alpha = \frac{\cos \varepsilon}{1 + \dfrac{h}{r_e}}$$

6.1[1]

$$\text{or } \sin \alpha = \cos(\varepsilon + \theta), \quad \text{where} \quad \theta = \frac{360d}{2\pi\, r_e}$$

6.2

[1] Source: From [23]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.
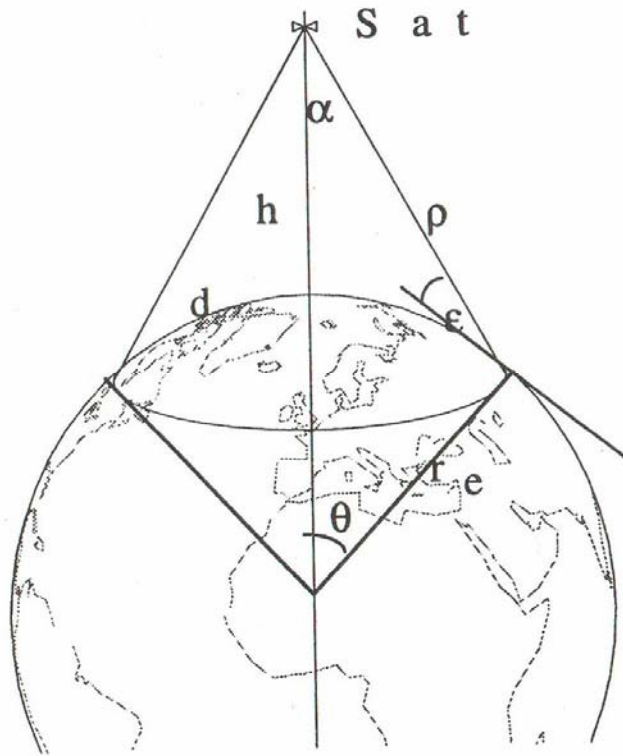
Figure 7 Defining Cone Angle α **(© From [23]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)**

6.1.2 Generation of Globalstar Gateways

As mentioned earlier, for Earth based users to communicate through the Globalstar system, a number of gateways have been spread across Earth. Table 10 shows the Globalstar satellite gateways considered for the simulation. These gateways are created in STK using the 'facility' feature which requires the latitude and longitude of the gateway.

Table 10 Globalstar gateways data used for simulation

No.	Globalstar Gateways Location
1.	Dubbo, Australia
2.	Mount Isa, Australia
3.	Meekatharra, Australia
4.	Novosibirisk, Russia
5.	Moscow, Russia
6.	Khanarovsk, Russia
7.	Karkkilla ,Finland
8.	Aussaguel, France
9.	Yeoju, South Korea
10.	Bosque, Argentina
11.	Riyadh, Saudi Arabia
12.	Beijing, China
13.	San Martin, Mexico
14.	Managua, Nicaragua
15.	Petrolina, Brazil
16.	Manaus, Brazil
17.	Presidente Prudente, Brazil
18.	Lurin, Peru
19.	Clifton, Tx
20.	Sebring, Fl, USA
21.	Avezzanno, Italy
22.	CaboRojo, Puerto Rico
23.	Las Palmas, Puerto Rico
24.	Ogulby, Turkey
25.	High river, Canada
26.	Smiths Fall, Ontario, Canada
27.	Los Velasquez, Venezuela
28.	Wasilla, Alaska

6.1.3 Generation of a User Satellite at a Particular Inclination and Altitude

The last component of the system is the user satellite, from which we wish to transmit data using a Globalstar modem. Two cases for altitudes are selected, 300 km and 600 km. The orbit inclination for each case is chosen to be 52°, in order to see the effect of the user moving along the Globalstar satellite constellation's inclination. For comparison purposes, the same calculation is done for 0° and 90° orbit inclination.

49

To simulate the FOV of the patch antenna of the modem on the user satellite, the same properties are used as for the Globalstar satellite, but with the antenna beam pointing upwards towards the Globalstar satellite constellation.

6.1.4 Determination of Simulation Time Period

The simulation can be run for any period of time. In order to understand the pattern of contact times, i.e., how will they repeat, one complete orbit regression period is simulated. This means starting from the original position and continuing the calculation until the orbit comes back to the same position (ascending node is at the same longitude). The orbit shifts due to the Earth's equatorial bulge, a phenomenon called Nodal Regression. The Nodal Regression Rate is given by:

$$\Omega = -2.064 \times 10^{14} \times a^{-3.5} \times \cos i \left(\frac{1}{1-e^2} \right)^{-2} \quad \text{deg /day [24]} \tag{6.3}$$

where 'e' is the eccentricity of the orbit, which is the measure of deviation of the orbit from being circular. The semi major axis of the orbit is given by 'a', which is defined as the longest radius of the ellipse. The angle at which the orbit is inclined is represented by 'i'.

For the Globalstar satellites, $e \approx 0$, $i=52°$, and $a= 7792$ km ($r_e + h$, where $r_e = 6378.1$ km). Using these values in equation 6.3, the regression rate is found to be -3.04 deg/day. The minus sign indicates westward movement. For the user satellite with $e \approx 0$, $a= 6978.1$ km ($r_e+ 600$ km) and $i =52°$, the regression rate is -4.48 deg/day. Hence, nodal regression periods for the

50

Globalstar satellites and the user satellite are 118.3 and 80.42 days respectively. For the user

satellite at i= 0° the regression rate is -7.27 deg/day and for i= 90° it is 0 deg/day.

For the second case with the user satellite at 300 km, a = 6678.1 km, and i= 52°, the

regression rate is -5.22 deg/day. For i= 0° it is -8.48 deg/day and for i= 90° it is 0 deg/day. The

time frame considered for the simulation for each of these cases is summarized in Table 11.

Table 11 Regression Rate and Simulation Time Period for the cases considered

Satellite Altitude: 600km			
Inclination angle (deg)	**Regression Rate (deg/day)**	**One Regression Period (days)**	**Simulation Period**
52	-4.48	80.4	1 Jul 2008 12:00:00 - 18 Sep 2008 21:36:00
0	-7.27	49.5	1 Jul 2008 12:00:00- 20 Aug 2008 00:00:00
90	0		1 Jul 2008 12:00:00- 2 Jul 2008 12:00:00
Satellite Altitude: 300km			
Inclination angle (deg)	**Regression Rate (deg/day)**	**One Regression Period (days)**	**Simulation Period**
52	-5.22	68.9	1 Jul 2008 12:00:00-8 Sep 2008 09:36:00
0	-8.48	42.5	1 Jul 2008 12:00:00-13 Aug 2008 00:00:00
90	0		1 Jul 2008 12:00:00-2 Jul 2008 12:00:00

6.2 Parameters Considered and their Computation in STK

Two parameters are considered to analyze the coverage: Access Times (the contact times

between the user satellite and ground stations through the Globalstar constellation) and Gap

times (when the user satellite cannot communicate to ground stations). The access times

calculated are presented in the form of graphs that demonstrate the frequency (number of occurrences) of different access durations available throughout the simulation period. For comparison purposes, contact times for the following four cases are considered:

1. User satellite communicating directly to a station on ground (traditional method).

2. User satellite communicating through the Globalstar constellation to a single ground station (gateway).

3. User satellite with all of the ground stations in the Americas communicating through the Globalstar satellites.

4. User satellite with all of the Globalstar gateways listed in Table 10 communicating through the Globalstar satellites. Gap times for this case are also calculated.

Case 1 helps in analyzing the difference between the traditional method and the scheme presented in this paper. Case 2 gives the times when data can be relayed by the Globalstar constellation to a single ground station. This helps in analyzing the distribution of communication time among the stations. The gap times determine the memory required by the user. Case 3 helps in determining the cost issues with respect to roaming outside the US. Case 4 gives the total contact time available with all the ground stations listed in Table 10.

This section describes the method followed in STK to compute the above four cases. The STK Commands/ options used are given in inverted commas (''). The term Access Time in the above cases means the time when at least one of the Globalstar satellites is in view of the user (cross link) and at least one of the Ground Stations is in view of that satellite. For simulating this complete link the 'Chains' and 'Constellations' features, in STK, are used. Globalstar satellites

are grouped in one constellation and the gateways are grouped in another constellation. The number of gateways is different for each of the cases. A 'chain' is then created having the three components in the following order: 1) User satellite sensor, 2) Globalstar satellites constellation and 3) Gate way constellation. The order defines the path in which the communication takes place. The order can be reversed to represent uplink. Once the chain is constructed, access is computed by using the 'Compute' command. A report for 'Complete Chain Access' is then created. This report shows times during which access among all objects in the chain is possible through one or more paths (termed 'strands' in STK). Conditions can be set to select the number of strands required. The requirement here is to generate a report, which has the access times for all the possible strands with overlap time considered only once, avoiding multiple counting. There is an option to set 'constraints' in the 'Constellation' created. Therefore, one can specify whether all of the objects, any one object, or none of the objects in the constellation are to be considered for computing access. For both the Gateways Constellation and the Globalstar satellite constellation, this constraint is set to be 'Anyof'. This means that the requirement is to calculate the access of the user satellite with *any* satellite (within the user satellite footprint) with *any* gateway (within that satellite foot print).Since the complete chain access is found, it will consider only those gateways, which can complete the full link. These were the conditions set for calculating Access Times.

In order to find the gaps, the constraints set are different. This time, the Constellation constraint needs to be set to 'Noneof' for the gateways constellation. This would give the times

when the user satellite cannot communicate to the ground either because no satellites are

available, or because *none* of the ground stations are present.

The reports obtained are used to display the results in the form of graphs and tables,

explained in the next section.

6.3 Results for User Satellite at 600 km

From the reports, graphs are generated using MATLAB. This section shows the graphs

for three scenarios: when the satellite at 600 km is at the inclination angle of 52°, 0° or 90°.

6.3.1 For Inclination Angle of 52°

For each instance of inclination angle, the following four calculations have been done.

The simulation period considered is given in Table 11.

6.3.1.1 Traditional contact time for user satellite communicating directly to a station on ground

As mentioned in Section 1.2, traditionally a nano-satellite communicates with a ground

station only a couple of times during one regression period. This scenario simulates this access

time. For the calculation, the Globalstar gateway in Manaus, Brazil, is assumed to be the

dedicated ground station already deployed for direct communication with the nano-satellite.
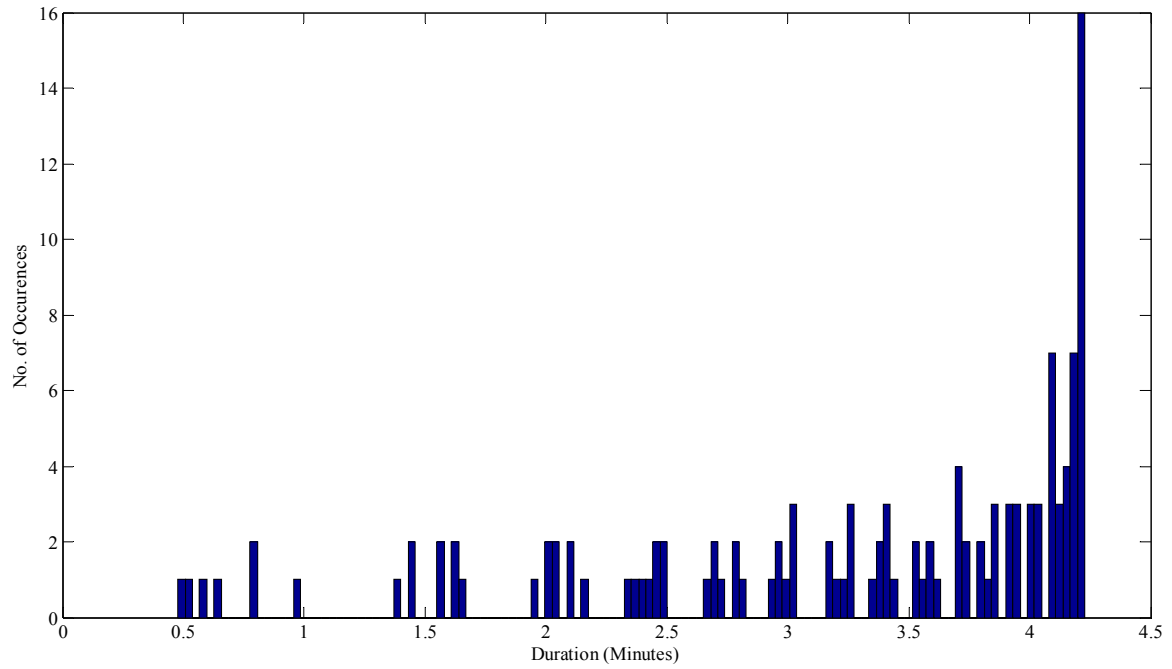
Figure 8 Access Time for a user satellite (600 km, 52°) communicating directly to a ground station

Figure 8 shows the frequency of the time periods available for access. It shows that during the simulation period, the nano-satellite will have sixteen 4.2 minutes passes. Table 12 summarizes the information given in the graph. It is observed that the satellite can communicate with one ground station for 0.35 % of the total time (simulation period).

Table 12 Access data for a user satellite (600 km, 52°) communicating directly to a ground station

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	408.2 min (6.8 hrs)
Minimum Access Time	29 sec
Maximum Access Time	254 sec
Total Percentage for Access	0.35 %

6.3.1.2. Contact time for user satellite with one station communicating through Globalstar

In contrast to the above scenario, now the satellite is made to communicate with the gateway through the Globalstar constellation. Contact time was calculated with one station (in Manaus, Brazil) to calculate how much one station contributes in Globalstar communication with the nano-satellite. It is found that the total contact time by one ground station is 29580.142 seconds which is 0.42 % of the total simulation time period.
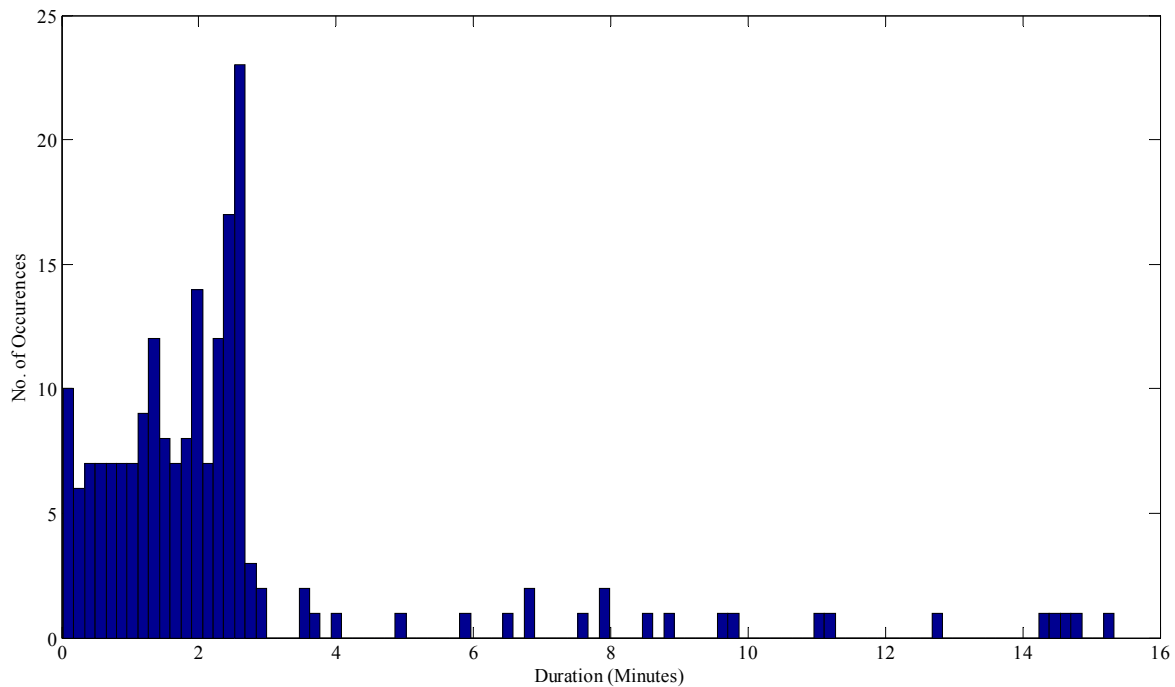
Figure 9 Access Time for a user satellite (600 km, 52°) communicating with one station through Globalstar

Figure 9 shows that the number of passes has increased for this case. The reason is that in this case the user satellite gets more opportunities to talk to the ground station because of the number of satellites present in the Globalstar constellation. The minimum and maximum access

times for this case are shown in Table 13.

Table 13 Access data for a user satellite (600 km, 52°) communicating to a ground station through Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	493 min (8.2 hrs)
Minimum Access Time	1.3 sec
Maximum Access Time	925 sec (15.4 min)
Total Percentage for Access	0.42 %

6.3.1.3. Contact time for user satellite with all stations in the Americas communicating through Globalstar

The access time between the user satellite and the gateways in the Americas

communicating through Globalstar satellites is also calculated. This helps in determining the

time available for contact when we do not want to communicate outside of the Americas due to

long distance and roaming charges. The gateways considered for this part of calculation are

listed in Table 14.

Table 14 Globalstar gateways in the Americas

No.	Globalstar Gateways Location
1.	Bosque, Argentina
2.	San Martin, Mexico
3.	Managua, Nicaragua
4.	Petrolina, Brazil
5.	Manaus, Brazil
6.	Presidente Prudente, Brazil
7.	Lurin, Peru
8.	Clifton, Tx, USA
9.	Sebring, Fl, USA
10.	CaboRojo, Peurto Rico
11.	Los Velasquez, Venezuela

Figure 10 shows the duration of access periods available and their number of occurrences. In this case, the user satellite can communicate with the gateways in the Americas for 3.7% of the total regression period (80.4 days). This means that for 3.7 % of the regression period, a nano-satellite can talk to the ground stations without paying roaming charges. Table 15 shows the summary of results for this case.
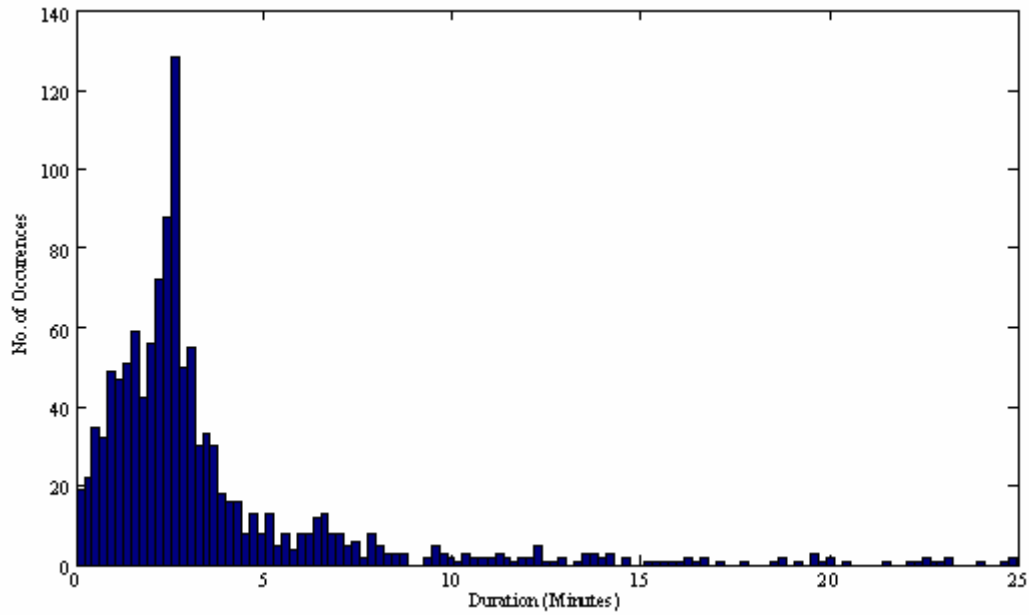
Figure 10 Access Time for communication between user satellite (600 km, 52°) and gateways in the Americas through Globalstar

Table 15 Access data for the communication between user satellite (600 km, 52°) and gateways in the Americas

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	4347 min (72.4 hrs)
Minimum Access Time	0.3 sec
Maximum Access Time	1497 sec (25min)
Total Percentage for Access	3.7 %

6.3.1.4. Contact time for user satellite with all Globalstar gateways communicating through Globalstar satellites

The graph in Figure 11 shows the access time available for the user satellite to communicate with all of the Globalstar gateways (listed in Table 10) through the Globalstar constellation. The total access time during the 80.4 day regression period is 15907 minutes (265 hrs). Hence the total percentage of time that the data can be up-linked or down-linked to or from the user satellite during this period is *13.7%.*
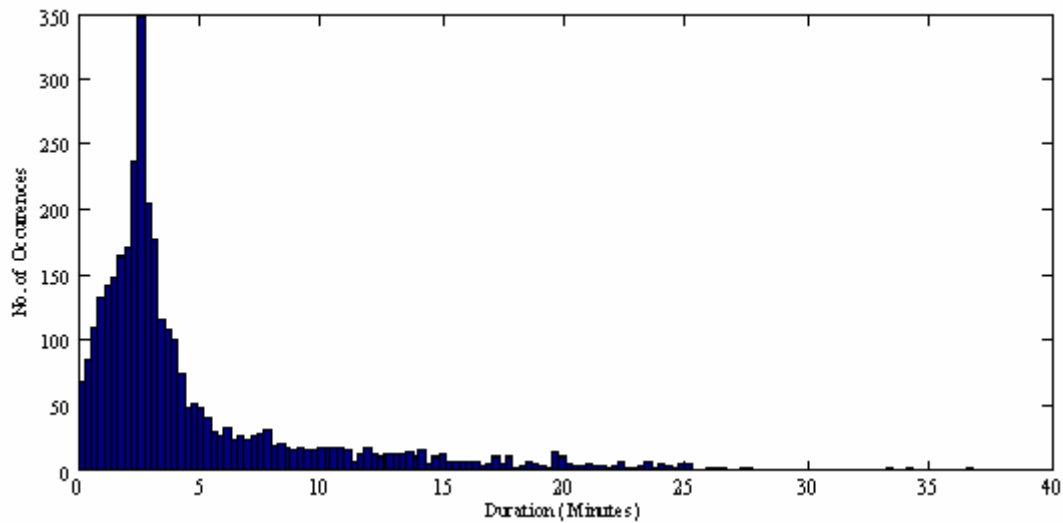
Figure 11   Access Time for communication between user satellite (600 km, 52°) and all the gateways considered using Globalstar

From the graph it can be seen that the access periods between 2 and 4 minutes are most frequent. Table 16 summarizes the results for this case.

Table 16 Access data for communication between user satellite (600 km, 52°) and all the gateways considered using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	15907 min (265 hrs)
Minimum Access Time	0.3 sec
Maximum Access Time	2217 sec (37 min)
Total Percentage for Access	13.7%

The total gap time in the transmission in 80.4 days is 99869 min (1664.5 hrs). Hence, the total percentage of time that the data can neither be up-linked nor down-linked is 86.3%. Figure 12 shows the access times available.
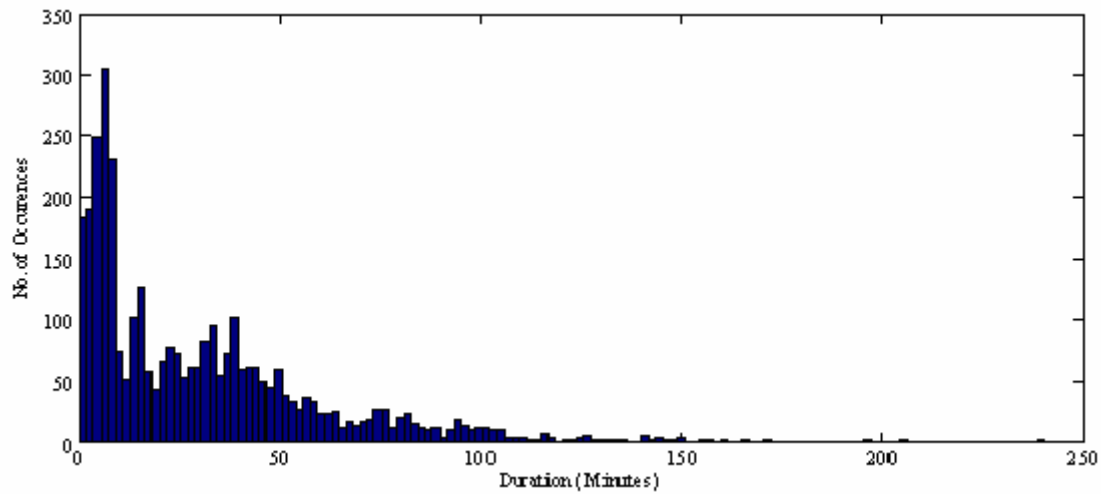
Figure 12 Gap Time for communication between user satellite (600 km, 52°) and all the gateways considered using Globalstar

60

The maximum gap time is calculated to find the memory requirement when all the gateways present are being utilized. Table 17 indicates that the user satellite should have enough memory to store data during the 4 hours of gap time when it cannot view any Globalstar satellite or any gateway via Globalstar satellites. When the same calculation is done for the gateways in Americas the maximum gap time is 7.9 hrs.

Table 17 Gap Time for communication between user satellite (600 km, 52°) and all the gateways considered using Globalstar

DATA FOR GAPS IN TRANSMISSION FOR ONE REGRESSION PERIOD	
Total Gap Time	99869 min (1664.5 hrs)
Minimum Gap Time	0.3 sec
Maximum Gap Time	241 min (4 hrs)
Total Percentage for Gap	86.3 %

The result for this case is important as it analyzes the overall communication access time available with all of the gateways considered in the simulation.

6.3.2 For Inclination Angle of 0°

The above case, in which user satellite is in the same inclination angle as the Globalstar constellation (52°), is most likely to be the best case, in terms of the access time available, since the user moves in line with the Globalstar satellites. Therefore, to see the impact of other inclination angles, similar calculations are done for the user satellite at 0° at 600 km.

61

6.3.2.1 Traditional contact time for user satellite communicating directly to a station on ground

In this case the access time available is 3.84 % of the total time. In general, the higher the inclination angle, the greater the coverage is on the Earth. However, in Section 6.3.1.1 the percentage was 0.35 % for a larger inclination angle (52º), which is less than this case. This is because of the location of the ground station chosen (Manaus, Brazil). It is possible that the area on earth being covered by the 52º nano-satellite is actually greater, but the particular area where the Manaus gateway is located is not being covered that frequently, even with the higher inclination angle. Figure 13 and Table 18 show the results for this case.
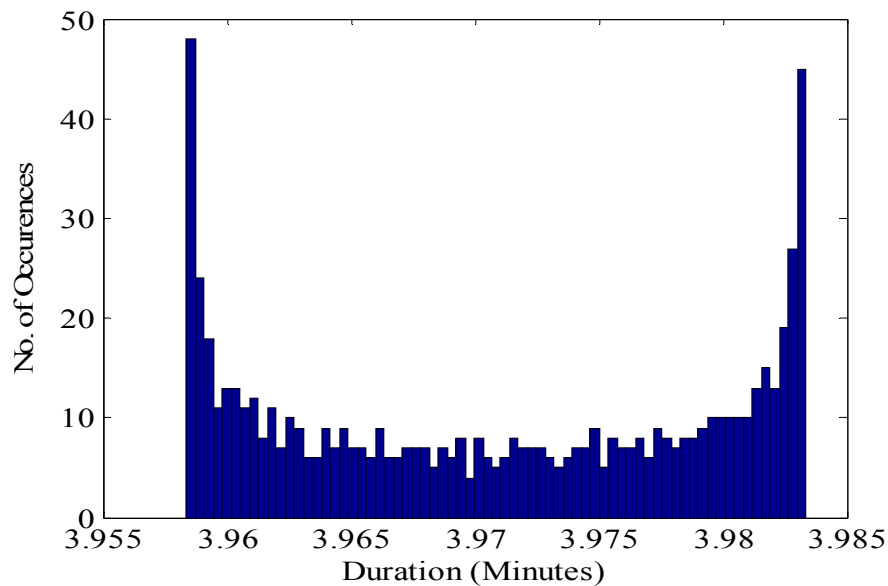
Figure 13 Access Time for a user satellite (600 km, 0°) communicating directly to a ground station

Table 18 Access Data for a user satellite (600 km, 0°) communicating directly to a ground station

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	2740 min (45.6 hrs)
Minimum Access Time	3.95 min
Maximum Access Time	3.98 min
Total Percentage for Access	3.84 %

6.3.2.2. Contact time for user satellite with one station communicating through Globalstar

For the nano-satellite at 0° inclination angle the access time available for this case is

1.8% as compared to 0.42 % for the inclination angle of 52°. This is shown in Figure 14 and

Table 19.

Figure 14 Access Time for a user satellite (600 km, 0°) communicating to a ground station through Globalstar

Table 19 Access Data for a user satellite (600 km, 0°) communicating to a ground station through Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	1249 min (20.8 hrs)
Minimum Access Time	1.3 sec
Maximum Access Time	8.2 min
Total Percentage for Access	1.8 %

6.3.2.3. Contact time for user satellite with all stations in the Americas communicating through Globalstar

For an inclination angle of 52°, the coverage for this case is 3.7 %. Here for 0°, it is 3.5 % of the simulation period. It is more for 52° because the nano-satellite has the same inclination angle as the Globalstar satellites. Hence, it gets more chances to communicate with the satellites and in turn to the ground stations. Figure 15 and Table 20 show the result for these calculations.
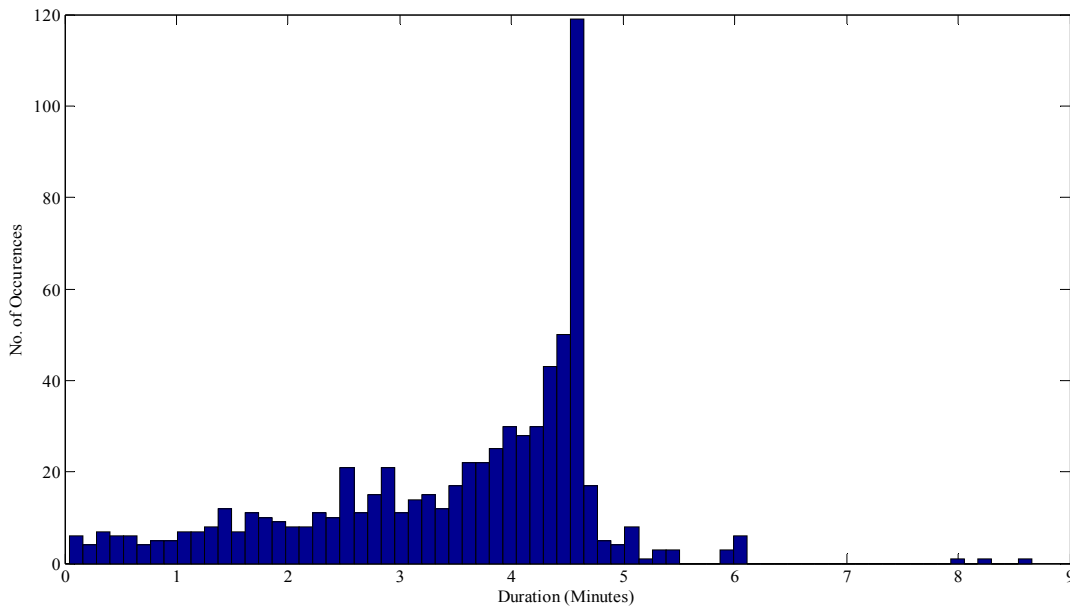
Figure 15 Access Time for a user satellite (600 km, 0°) communicating to the ground stations in the Americas using Globalstar

Table 20 Access Data for a user satellite (600 km, 0°) communicating to the ground stations in the Americas using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	2482.6 min (41.4 hrs)
Minimum Access Time	2.3 sec
Maximum Access Time	8.7 min
Total Percentage for Access	3.5 %

6.3.2.4. Contact time for user satellite with all Globalstar gateways communicating through Globalstar satellites

For this case the percentage of total regression period available to nano-satellite is 4.7 %

as compared to 13.7 % for the case when the nano-satellite is at 52°. This is because of the same

reason given in the previous section, i.e., the nano-satellite has more opportunities to

communicate with the Globalstar satellites when they have the same inclination angle (52°).
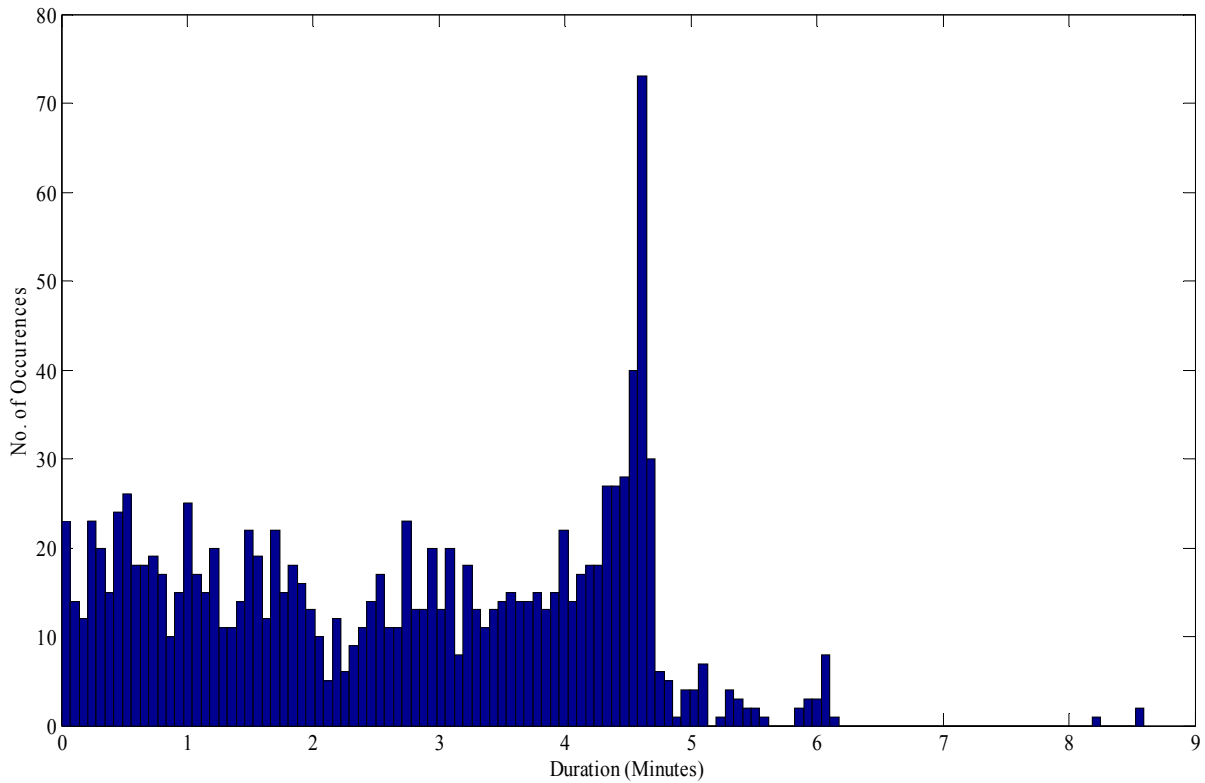
Figure 16 Access Time for a user satellite (600 km, 0°) communicating to the ground stations using Globalstar

Figure 16 shows the frequency of available access durations. Table 21 shows the summary of the results for this case.

Table 21 Access Data for a user satellite (600 km, 0°) communicating to the ground stations using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	3334.6 min (55.5 hrs)
Minimum Access Time	0.1 sec
Maximum Access Time	8.7 min
Total Percentage for Access	4.7 %

The times during which the nano-satellite cannot communicate with any of the gateways are shown in Figure 17 and Table 22. This is a lot more than the access time available. For the 52° inclination, this gap time is 86.3% and here it is 95.3 %. For the former case, the maximum gap time is 4 hrs and here it is 5.2 hrs. This would mean that the satellite at a lower inclination angle (0°) should have sufficient memory to store the data collected during the 5.2 hour continuous gap. When communicating with all the gateways present Americas the maximum gap time is 8.4 hrs.
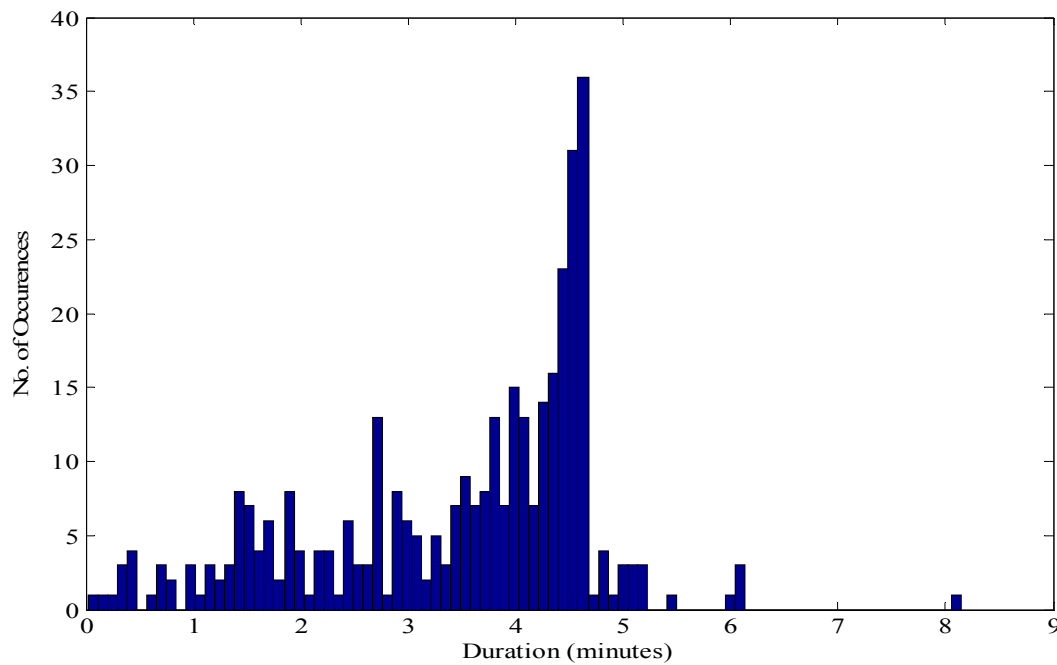
Figure 17 Gap Time for a user satellite (600 km, 0°) communicating to ground stations using Globalstar

Table 22 Gap Time for a user satellite (600 km, 0°) communicating to the ground stations using Globalstar

DATA FOR GAPS IN TRANSMISSION FOR ONE REGRESSION PERIOD	
Total Gap Time	67945.4 min (1132.4 hrs)
Minimum Gap Time	1.4 sec
Maximum Gap Time	313 min (5.2 hrs)
Total Percentage for Gap	95.3 %

6.3.3 For Inclination Angle of 90°

The same calculations have been done for the 90° inclination angle.

6.3.3.1 Traditional contact time for user satellite communicating directly to a station on ground

Figure 18 and Table 23 show the time available for the satellite to communicate directly

with a traditional ground station. The percentage available is 0.36 % as compared to 0.35% for

52° and 3.84 % for 0°.
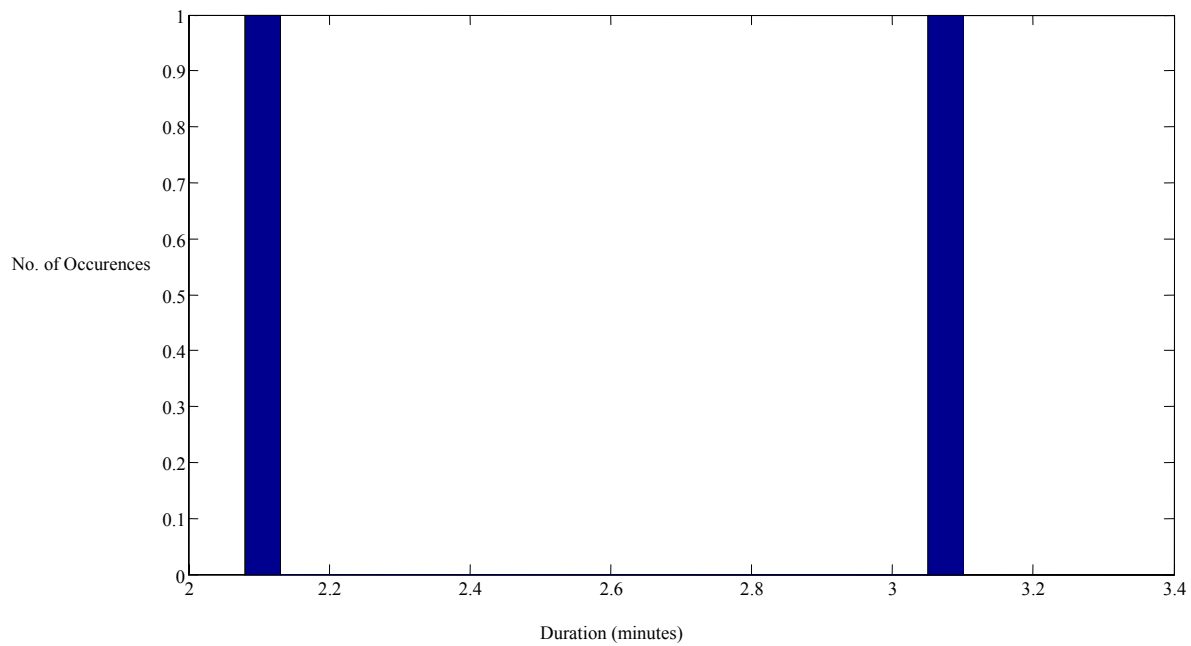
Figure 18 Access Time for a user satellite (600 km, 90°) communicating directly to a ground station

Table 23 Access Data for a user satellite (600 km, 90°) communicating directly to a ground station

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	5.2 min
Minimum Access Time	2.1 min
Maximum Access Time	3.1min
Total Percentage for Access	0.36 %

6.3.3.2. Contact time for user satellite with one station communicating through Globalstar

Figure 19 and Table 24 show the time available for the satellite to communicate to the ground station using the Globalstar constellation. The percentage available is 0.7 % as compared to 0.42% for 52° and 1.8 % for 0°.

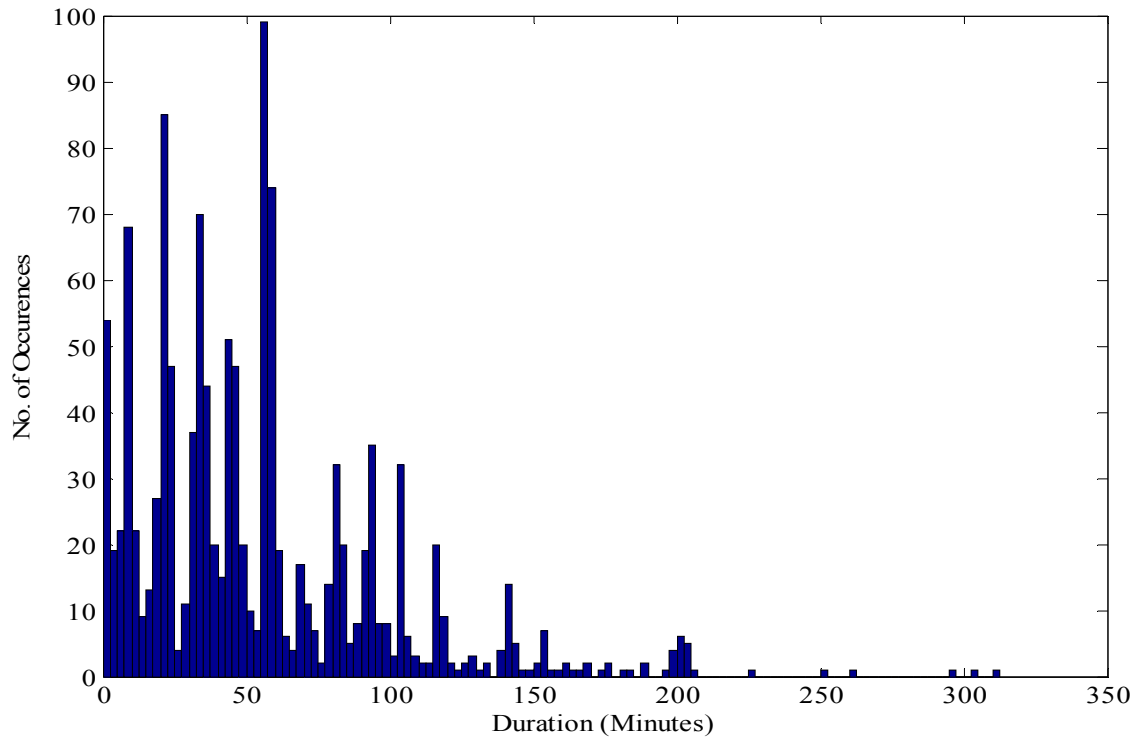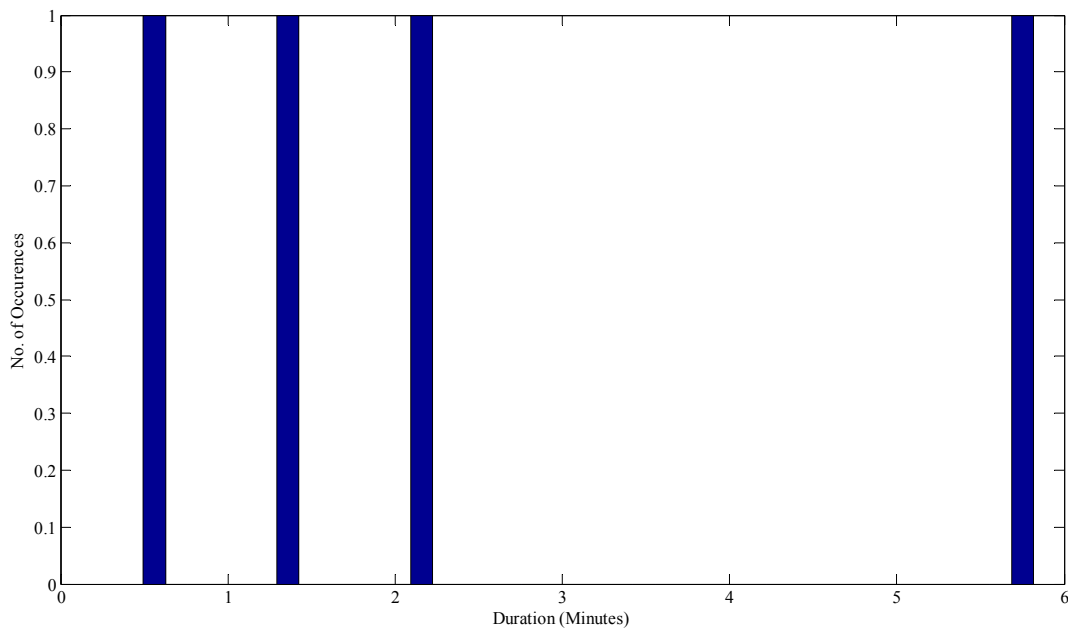**Figure 19 Access Time for a user satellite (600 km, 90°) communicating to a ground station using Globalstar**

Table 24 Access Data for a user satellite (600 km, 90°) communicating to a ground station using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	9.9 min
Minimum Access Time	29.7 sec
Maximum Access Time	5.8 min
Total Percentage for Access	0.7 %

6.3.3.3. Contact time for user satellite with all stations in the Americas communicating through Globalstar

Figure 20 and Table 25 show the time available for the satellite to communicate to the ground station using Globalstar constellation. The percentage available is 2.1 % as compared to 3.7% for 52° and 3.5 % for 0°.
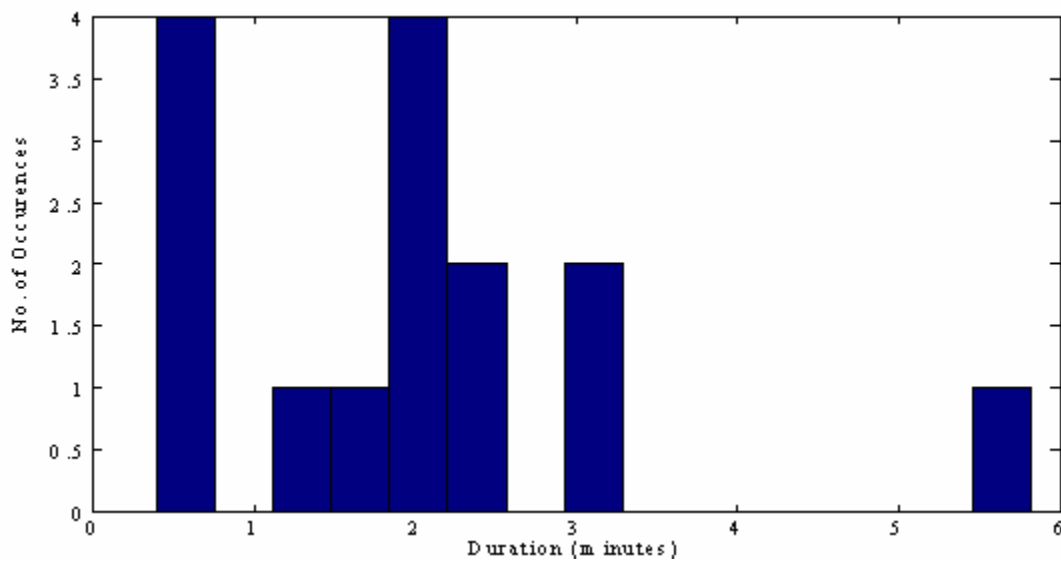
Figure 20 Access Time for a user satellite (600 km, 90°) communicating to ground stations in the Americas using Globalstar

Table 25 Access data for a user satellite (600 km, 90°) communicating to ground stations in the Americas using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	30 min
Minimum Access Time	24 sec
Maximum Access Time	5.8 min
Total Percentage for Access	2.1 %

6.3.3.4. Contact time for user satellite with all Globalstar gateways communicating through Globalstar satellites

The percentage of time available for this case is 7.3 % as compared to 13.7% for 52° and 4.7 % for 0°. Figure 21 shows the access time periods available for this case. Table 26 shows the statistics.
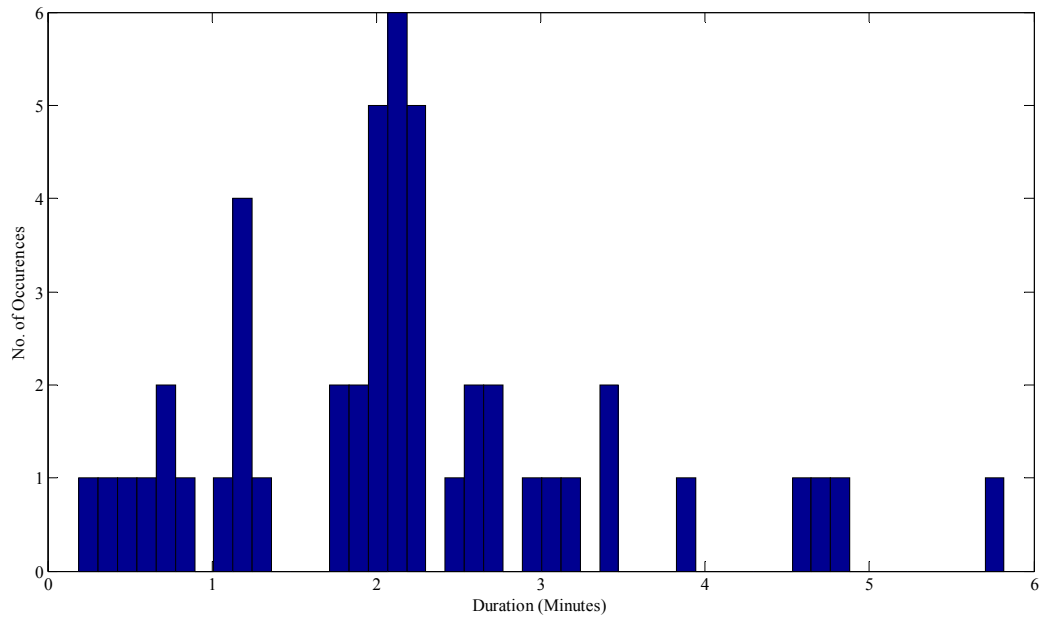
Figure 21 Access Time for a user satellite (600 km, 90°) communicating to ground stations using Globalstar

Table 26 Access Data for a user satellite (600 km, 90°) communicating to ground stations in the Americas using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	105.4 min (1.75 hrs)
Minimum Access Time	11.4 sec
Maximum Access Time	5.8 min
Total Percentage for Access	7.3 %

The maximum gap time, as shown in Figure 22 and Table 27, is 1.8 hours, which is less than both of the previous cases. Hence the memory requirement for this case is less than the previous ones.
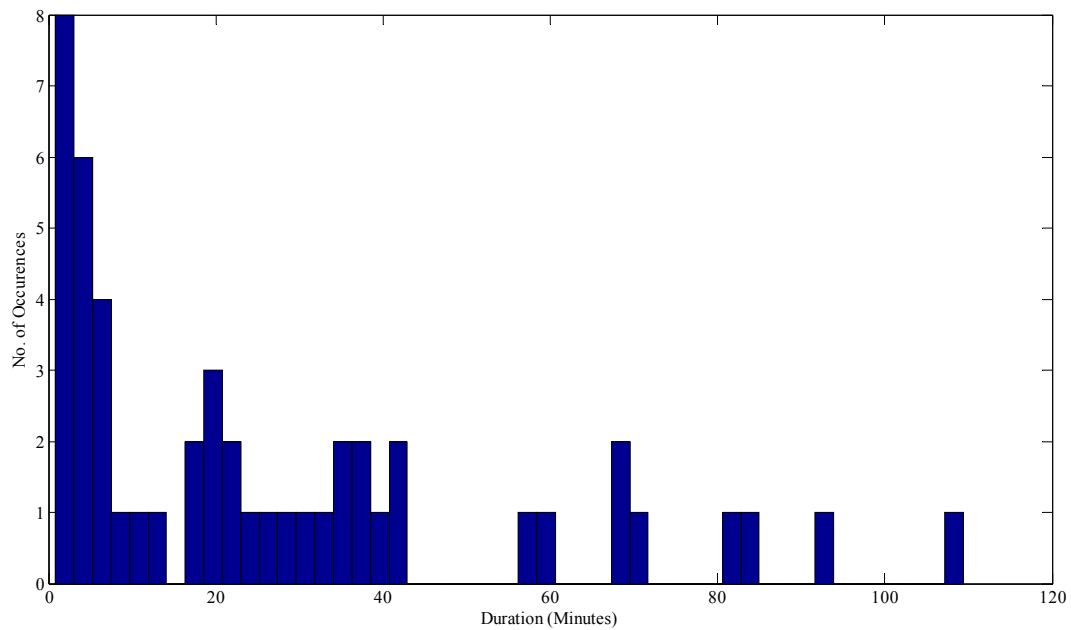
Figure 22 Gap Time for a user satellite (600 km, 90°) communicating to ground stations using Globalstar

Table 27 Data for Gap Time for a user satellite (600 km, 90°) communicating to ground stations using Globalstar

DATA FOR GAPS IN TRANSMISSION FOR ONE REGRESSION PERIOD	
Total Gap Time	1334.5 min (22.2 hrs)
Minimum Gap Time	50.9 sec
Maximum Gap Time	109 min (1.8 hrs)
Total Percentage for Gap	92.7 %

6.4 Results for User Satellite at 300 km

The four cases (mentioned in Section 6.2) for the three inclination angles are simulated for the user satellite at 300 km. In this case the results are likely to improve since the user satellite is now farther from the constellation then it was when it was at 600 km.

6.4.1 For Inclination Angle of 52°

This section presents the results for 52° inclination angle.

6.4.1.1 Traditional contact time for user satellite communicating directly to a station on ground

In this case the access duration for a user satellite (300 km) communicating directly with one ground station is 0.08 % of the total time. This is less than it was for the user satellite at 600 km (0.35%). The reason for this is that as the satellite is now at a lower altitude, its foot print on the Earth's surface will be smaller.
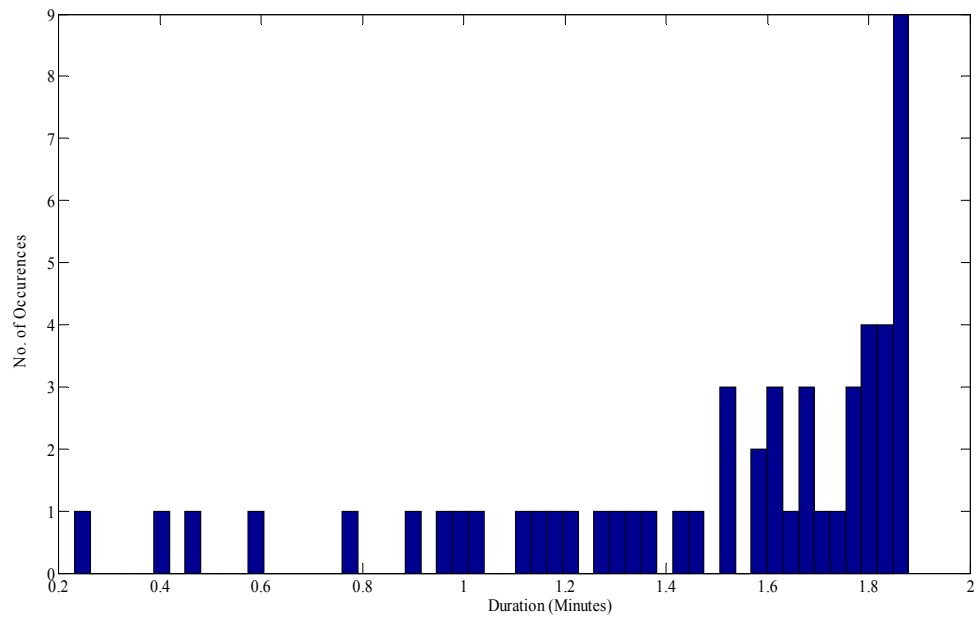
Figure 23 Access Time for a user satellite (300 km, 52°) communicating directly to a ground station

Figure 23 and Table 28 show the results for this case.

Table 28 Access Data for a user satellite (300 km, 52°) communicating to ground stations using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	78.5 minutes (1.3 hrs)
Minimum Access Time	13.9 sec
Maximum Access Time	1.88 min
Total Percentage for Access	0.08%

6.4.1.2. Contact time for user satellite with one station communicating through Globalstar

When the satellite at 300 km communicates via the Globalstar satellites, the access time is increased as compared to the 600 km case. This is because the Globalstar satellites can have larger footprints on the user satellite since the distance between the two has increased.
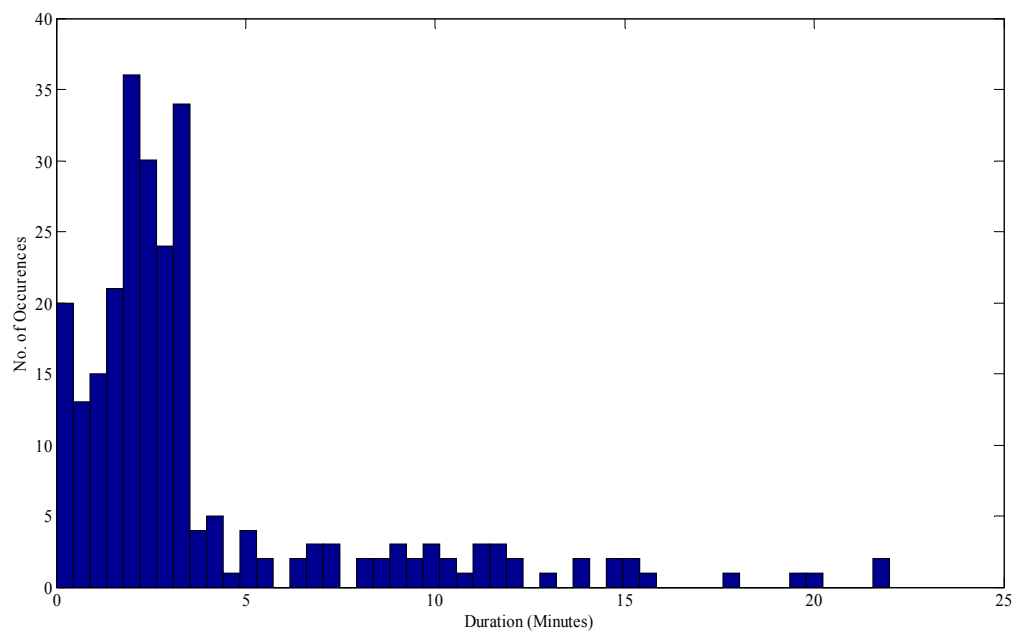
Figure 24 Access Time for a user satellite (300 km, 52°) communicating to a ground station using Globalstar

Table 29 shows that the percentage of time available for the access in this case is 1% as compared to 0.42% for the 600 km (52°) satellite. Figure 24 shows the time available for access.

Table 29 Access Data for a user satellite (300 km, 52°) communicating to a ground station using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	966.6 minutes (16 hrs)
Minimum Access Time	1 sec
Maximum Access Time	22.3 min
Total Percentage for Access	1 %

6.4.1.3. Contact time for user satellite with all stations in the Americas communicating through Globalstar

The contact time between the user satellite and gateways available in the Americas are

displayed in the Figure 25.

Figure 25 Access Time for a user satellite (300 km, 52°) communicating to ground stations in the Americas using Globalstar

Table 30 Access Data for a user satellite (300 km, 52°) communicating to ground stations using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	6473.3 minutes (107.8 hrs)
Minimum Access Time	1.7 sec
Maximum Access Time	26.6 min
Total Percentage for Access	6.52 %

From Table 30 it can be seen that the percentage of time available is 6.52 % as compared to 3.7 % in the 600 km (52°) case.

6.4.1.4. Contact/Gap time for user satellite with all Globalstar gateways communicating through Globalstar satellites

Overall, the contact time in one regression period with all of the gateways considered is 22.3 % for the satellite at 300 km and inclination 52°. For 600 km and inclination 52° this value is 13.7%. The figures for this and the rest of the cases are not shown here. Table 31 shows the access times for this case.

Table 31 Access Data for a user satellite (300 km, 52°) communicating directly to ground stations using Globalstar

ACCESS DATA FOR ONE REGRESSIONPERIOD	
Total Access Time	22141 minutes (369 hrs)
Minimum Access Time	0.1 sec
Maximum Access Time	42.4 min
Total Percentage for Access	22.3 %

The gap time percentage is 77.7% for this case.

77

6.4.2 For Inclination Angle of 0°

6.4.2.1 Traditional contact time for user satellite communicating directly to a station on ground

As shown in Table 32, it is clear that for 1 % of the time direct access is available to the

nano-satellite. This value is 3.84% for the case of 600 km and 0° inclination and for the 300 km

but higher inclination angle (52°) it is 0.08 %.

Table 32 Access Data for a user satellite (300 km, 0°) communicating directly to ground station

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	643 min (10.7 hrs)
Minimum Access Time	58 sec
Maximum Access Time	63.2 sec
Total Percentage for Access	1 %

6.4.2.2. Contact time for user satellite with one station communicating through Globalstar

When communicating through the Globalstar satellites, the access percentage increases

from 0.1 % to 3% as shown in Table 33. For the case of 600 km and 0°, this value is 1.8%.

Table 33 Access data for a user satellite (300 km, 0°) communicating to ground stations using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	1852 min (30.8hrs)
Minimum Access Time	6 sec
Maximum Access Time	12 min
Total Percentage for Access	3 %

6.4.2.3. Contact time for user satellite with all stations in the Americas communicating through Globalstar

In this case the access time is 6% as compared to 3.5 % for 600 km and 0° inclination.
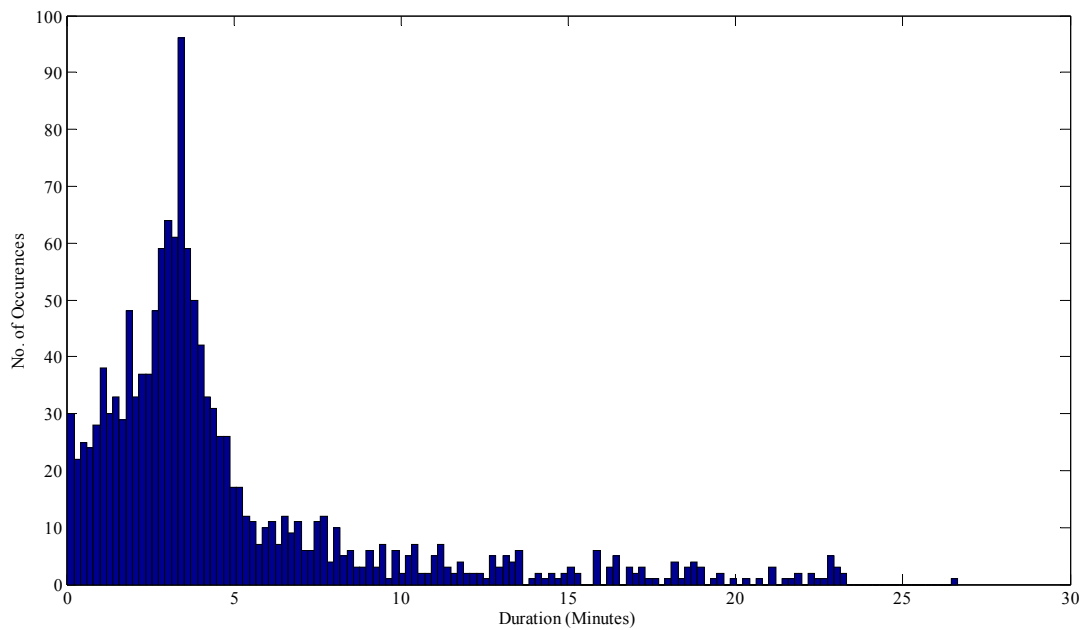
Table 34 shows the results for this case.

Table 34 Access Time for a user satellite (300 km, 0°) communicating ground stations in the Americas using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	3644.6 min (60.7 hrs)
Minimum Access Time	0.5 sec
Maximum Access Time	12 min
Total Percentage for Access	6 %

6.4.2.4. Contact time for user satellite with all Globalstar gateways communicating through Globalstar satellites

In this case the access time is 8.5% as compared to 4.7 % for 600 km and 0° inclination.

Table 35 shows the results for this case.

Table 35 Access Data for a user satellite (300 km, 0°) communicating to ground stations using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	5185 min (86.4 hrs)
Minimum Access Time	0.04 sec
Maximum Access Time	12 min
Total Percentage for Access	8.5 %

6.4.3 For Inclination Angle of 90°

6.4.3.1 Traditional contact time for user satellite communicating directly to a station on ground

The coverage available directly to the satellite at 90° is 0.1% of the time as compared to

0.36 % of the time for 600 km and 90° case. This is because the lower the satellite is, the smaller

is its foot print on the ground. Table 36 shows the access time for this case.

Table 36 Access Data for a user satellite (300 km, 90°) communicating to a ground station directly

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	84.843 sec
Access Time	84.843 sec
Total Percentage for Access	0.1 %

6.4.3.2. Contact time for user satellite with one station communicating through Globalstar

When the user satellite communicates through the Globalstar satellites to one ground

station (Manaus, Brazil), the percentage of access time available increases from 0.1% to 0.8 %.

The result for the case of 600 km and 90° satellite, as mentioned above, gives 0.7% of coverage

time. This is less than the current case because the distance between the nano-satellite and the

constellation is smaller, resulting in less coverage. Table 37 summarizes the access time

available.

Table 37 Access Data for a user satellite (300 km, 90°) communicating to a ground station using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	11.5 min
Minimum Access Time	66.8 sec
Maximum Access Time	170 sec
Total Percentage for Access	0.8 %

6.4.3.3. Contact time for user satellite with all stations in the Americas communicating through Globalstar

As shown in Table 38 the access time available is 3.5 % of the time as compared to 2.1 %

in the case of the 600 km satellite.

Table 38 Access Data for a user satellite (300 km, 90°) communicating to ground stations in Americas using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	50.3 min
Minimum Access Time	1.8 sec
Maximum Access Time	7 min
Total Percentage for Access	3.5 %

6.4.3.4. Contact time for user satellite with Globalstar gateways communicating through Globalstar satellites

As shown in Table 39 the contact time available is 11.5 % of the time as compared to 7.3

% in the 600 km satellite case.

Table 39 Access Data for a user satellite (300 km, 90°) communicating to ground stations using Globalstar

ACCESS DATA FOR ONE REGRESSION PERIOD	
Total Access Time	166 min (2.8 hrs)
Minimum Access Time	1.8 sec
Maximum Access Time	7 min
Total Percentage for Access	11.5 %

6.5 Summary of Results

Comparison of above results shows that the inclination angle and altitude of the satellite have a significant effect on the coverage. It is clear from Table 40 and Table 41 (case 1 and 4) that using S-PCN provides more access time than communicating directly to the ground.

Table 40 Comparison of percentage of Access at 600 km

CASE	Access (%) 52 deg	Access (%) 0 deg	Access (%) 90 deg
1. Between user sat. to one gateway directly	0.4	3.8	0.4
2. Between user sat. to one gateway via Globalstar sat.	0.4	1.8	0.7
3. Between user sat. to 11 gateways in the Americas via Globalstar constellation	3.7	3.5	2.1
4. Between user sat. to 28 gateways via Globalstar sat	13.7	4.7	7.3

Table 41 Comparison of percentage of Access at 300 km

CASE	Access (%) 52 deg	Access (%) 0 deg	Access (%) 90 deg
1. Between user sat. to one gateway directly	0.08	1	0.1
2. Between user sat. to one gateway via Globalstar sat.	1	3	0.8
3. Between user sat. to 11 gateways in the Americas via Globalstar constellation	6.5	6	3.5
4. Between user sat. to 28 gateways via Globalstar sat	22.3	8.5	11.5

The same calculations were also done with the TLE of satellites for a different date. The values (corresponding to the cases in Table 40 and 41) came out to be approximately the same with a mean difference of ± 0.4 between the values.

The access time periods shown in the graphs are offered by multiple satellites. Even one continuous band (without any gap in between) is generally served by multiple satellites. During

such access periods, soft-handoffs are possible between the satellites. This is because of the diversity combining feature of the Globalstar receiver. For the above simulation, the percentage of more than one satellite serving at the same time is 64% of the available access time (for the satellite at 300 km and 52° inclination). Within one access period, diversity combining will play its role and soft-handovers can take place. The only case when the call will drop during these access periods is when the nano-satellite is being switched from one gateway to another gateway (as the satellite is continuously in motion). This will decrease the overall access period by the amount of time required to reconnect. Switching between gateways will significantly increase the number of call drops. The reason for this is that Globalstar does not provide soft-gateway-to-gateway-switch-over.

The number of gateways Globalstar provides is being increased to provide more coverage to Earth based users. According to a press release [25], the number of gateways will eventually increase to 100. This will also increase the access times available for the nano-satellites. Hence the results will be even better than those presented here.

CHAPTER 7: CONCLUSION AND FUTURE WORK

7.1 Conclusion

It can be concluded that using S-PCNs for communication between a nano-satellite and a location on Earth provides better coverage than the traditional method (Case 1 in Tables 39 and 40). However a number of factors, as mentioned in Chapter 5, should be taken into account for this method to be successful

7.2 Future Work

The Federal Communication Commission (FCC) currently does not allow the frequencies used by the Globalstar (L and S bands) to be used for inter-space links. Hence, to use these frequencies nano-satellite developers will have to request a waiver of the FCC rules.

The simulation results present the access time and gap times for the communication between the satellite and the gateways. These access times may further be analyzed to see how many times gateway and satellite switch-overs take place. This will, in turn, determine the number of failed handoffs and call dropping rate, which will help in avoiding connection loss during data transmission.

The modem was tested on the ground manually. However, when placed in the satellite, it should be able to work automatically. Due to time and resource constraints, this could not be tested. A microcontroller may be programmed and interfaced to perform all of the required steps, automatically.

The use of the modem using Virtual Private Network can also be tested in future, for being able to address the modem using packet data connection. This will avoid roaming charges. Furthermore, a complete cost analysis of implementing this system needs to be done.

APPENDIX: GLOBALSTAR TWO LINE ELEMENTS (June 2008)

```
GLOBALSTAR M001
1 25162U 98008A   08157.77862260 -.00000084  00000-0  10000-3 0  9942
2 25162  52.0027  73.8087 0001876  79.2857 280.8208 12.37976246473321
GLOBALSTAR M004
1 25163U 98008B   08157.70299281 -.00000086  00000-0  10000-3 0   249
2 25163  52.0013 306.6762 0004110 172.9369 187.1553 12.63143369475603
GLOBALSTAR M002
1 25164U 98008C   08158.01040409 -.00000071  00000-0  10000-3 0  9187
2 25164  52.0045 354.8099 0000798  64.1094 295.9810 11.61420640461372
GLOBALSTAR M003
1 25165U 98008D   08157.69223862 -.00000086  00000-0  10000-3 0   342
2 25165  51.9957 310.3738 0001398 139.3994 220.6989 12.62267287475501
GLOBALSTAR M014
1 25306U 98023A   08156.39953883 -.00000084  00000-0  10000-3 0  9690

2 25306  51.9934 321.5294 0009814  68.6788 291.5103 12.38371633460716
GLOBALSTAR M006
1 25307U 98023B   08158.02131375 -.00000086  00000-0  10000-3 0  7383
2 25307  52.0002 355.4288 0001354  95.8131 264.2888 12.62266257466714
GLOBALSTAR M015
1 25308U 98023C   08157.05139309 -.00000086  00000-0  10000-3 0  7505
2 25308  51.9985 357.8594 0002710  91.7126 268.4048 12.62260883466594
GLOBALSTAR M008
1 25309U 98023D   08157.50665603 -.00000086  00000-0  10000-3 0  7237
2 25309  51.9969 356.3246 0000656 149.1514 210.9389 12.62262353466663
GLOBALSTAR M023
1 25621U 99004A   08157.58476013 -.00000086  00000-0  10000-3 0  7125
2 25621  52.0121 269.5003 0009398  68.7730 291.4129 12.62202095430198
GLOBALSTAR M040
1 25622U 99004B   08157.69949851 -.00000086  00000-0  10000-3 0  6931
2 25622  51.9929 265.4312 0002519 156.9614 203.1362 12.62266582430224
GLOBALSTAR M036
1 25623U 99004C   08157.26398201 -.00000086  00000-0  10000-3 0  6572
2 25623  52.0016 268.4228 0001926 157.3516 202.7437 12.62267125430187
GLOBALSTAR M038
1 25624U 99004D   08157.62783767 -.00000086  00000-0  10000-3 0  6589
2 25624  52.0016 223.1016 0002370 181.6512 178.4344 12.62260181430979
GLOBALSTAR M022
1 25649U 99012A   08157.77190929 -.00000084  00000-0  10000-3 0  6457
2 25649  52.0092  62.0631 0000594  87.7531 272.3381 12.38619793425470
GLOBALSTAR M041
1 25650U 99012B   08157.72851351 -.00000086  00000-0  10000-3 0  6695
2 25650  52.0095  43.2513 0001860  52.6822 307.4210 12.62265402425805
GLOBALSTAR M046
1 25651U 99012C   08157.77630033 -.00000086  00000-0  10000-3 0  6750
2 25651  52.0055  41.3766 0001237  41.7701 318.3256 12.62265240425793
GLOBALSTAR M037
1 25652U 99012D   08157.73669816 -.00000086  00000-0  10000-3 0  6499
2 25652  52.0046  42.7851 0001177   3.6175 356.4686 12.62265924425754
```

87

```
GLOBALSTAR M045
1 25676U 99019A   08157.67726852 -.00000086  00000-0  10000-3 0  7692
2 25676  51.9972  41.0873 0001307  45.0464 315.0506 12.62266370423349
GLOBALSTAR M019
1 25677U 99019B   08157.76910634 -.00000086  00000-0  10000-3 0  6707
2 25677  51.9935  85.6238 0001735  23.1584 336.9358 12.62258177423302
GLOBALSTAR M044
1 25678U 99019C   08157.71698546 -.00000086  00000-0  10000-3 0  6742
2 25678  52.0035  42.7087 0001539  49.8955 310.2040 12.62265051422694
GLOBALSTAR M042
1 25679U 99019D   08157.40293105 -.00000086  00000-0  10000-3 0  7539
2 25679  52.0004 133.2681 0001068 273.1620  86.9124 12.62259416421827
GLOBALSTAR M025
1 25770U 99031A   08157.74911222 -.00000086  00000-0  10000-3 0  6123
2 25770  51.9952  86.2100 0001356  12.5753 347.5144 12.62259239414625
GLOBALSTAR M049
1 25771U 99031B   08158.12519365 -.00000086  00000-0  10000-3 0  8165
2 25771  51.9947  84.6960 0000999 350.3822   9.7018 12.62258114414671
GLOBALSTAR M047
1 25772U 99031C   08157.78868561 -.00000086  00000-0  10000-3 0  6890
2 25772  51.9948  85.6816 0001187   3.2660 356.8212 12.62260685414632
GLOBALSTAR M052
1 25773U 99031D   08157.85138845 -.00000086  00000-0  10000-3 0  7716
2 25773  51.9912  84.4711 0001484 349.5134  10.5701 12.62264061414647
GLOBALSTAR M035
1 25851U 99037A   08157.73353113 -.00000084  00000-0  00000+0 0  5758
2 25851  52.0012 302.8559 0001960 134.5870 225.5134 11.92952069407792
GLOBALSTAR M032
1 25852U 99037B   08158.21458195 -.00000086  00000-0  10000-3 0  5947
2 25852  51.9985 129.9555 0000944 240.8101 119.2661 12.62258857410928
GLOBALSTAR M051
1 25853U 99037C   08158.07824173 -.00000086  00000-0  10000-3 0  6003
2 25853  51.9973 130.3223 0000841 117.5135 242.5811 12.62266305410909
GLOBALSTAR M030
1 25854U 99037D   08157.22702393 -.00000086  00000-0  10000-3 0  6032
2 25854  51.9982 133.1872 0000431 340.0585  20.0254 12.62263973410793
GLOBALSTAR M048
1 25872U 99041A   08157.53640410 -.00000086  00000-0  10000-3 0  6380
2 25872  52.0039 178.1892 0001720 219.0571 141.0171 12.62259525408956
GLOBALSTAR M026
1 25873U 99041B   08157.57827314 -.00000086  00000-0  10000-3 0  6228
2 25873  52.0046 178.3560 0000906 228.8959 131.1832 12.62267873408951
GLOBALSTAR M043
1 25874U 99041C   08157.51653218 -.00000086  00000-0  10000-3 0  6302
2 25874  52.0027 178.3911 0000535 179.0878 180.9991 12.62259294408941
GLOBALSTAR M028
1 25875U 99041D   08157.49671077 -.00000086  00000-0  10000-3 0  6022
2 25875  52.0023 178.1697 0001048 196.0091 164.0743 12.62266536408948
GLOBALSTAR M024
1 25883U 99043A   08157.66759296 -.00000086  00000-0  10000-3 0  6088
2 25883  52.0071 223.6426 0001995 178.8918 181.1950 12.62259540406083
GLOBALSTAR M027
```

```
1 25884U 99043B   08157.17268055 -.00000086  00000-0  10000-3 0  6027
2 25884  52.0071 225.0406 0000828 155.7365 204.3543 12.62259432406022
GLOBALSTAR M054
1 25885U 99043C   08157.53152029 -.00000084  00000-0  10000-3 0  5860
2 25885  52.0127  13.1523 0002787 102.4994 257.6173 12.38264820403380
GLOBALSTAR M053
1 25886U 99043D   08157.61916691 -.00000086  00000-0  10000-3 0  6125
2 25886  52.0086 223.7165 0000675 172.3920 187.6954 12.62253586406088
GLOBALSTAR M058
1 25907U 99049A   08157.67230484 -.00000086  00000-0  10000-3 0  6074

2 25907  51.9969 221.3387 0001675 186.0835 174.0009 12.62259319402344
GLOBALSTAR M050
1 25908U 99049B   08157.29030424 -.00000084  00000-0  10000-3 0  6107
2 25908  52.0028 281.2405 0004040 132.6841 227.4346 12.39959606401270
GLOBALSTAR M033
1 25909U 99049C   08157.68718780 -.00000086  00000-0  10000-3 0  6022
2 25909  51.9974 221.6559 0001886 188.4490 171.6343 12.62257753402325
GLOBALSTAR M055
1 25910U 99049D   08157.24435200 -.00000086  00000-0  10000-3 0  6221
2 25910  52.0018 267.9214 0001883 144.4597 215.6394 12.62265152401524
GLOBALSTAR M057
1 25943U 99058A   08156.51205076 -.00000086  00000-0  10000-3 0  3049
2 25943  52.0008   0.4396 0000806  33.1739 326.9206 12.62263490398139
GLOBALSTAR M059
1 25944U 99058B   08158.04109657 -.00000086  00000-0  10000-3 0  5893
2 25944  52.0067 355.9424 0002362  74.7056 285.4070 12.62268944398358
GLOBALSTAR M056
1 25945U 99058C   08156.94107847 -.00000086  00000-0  10000-3 0  9209
2 25945  51.9994 313.0945 0000573 212.6438 147.4395 12.62260853398952
GLOBALSTAR M031
1 25946U 99058D   08157.75168520 -.00000086  00000-0  10000-3 0  6077
2 25946  51.9986 311.2973 0004387 122.5558 237.5724 12.62265753399079
GLOBALSTAR M039
1 25961U 99062A   08157.52164353 -.00000086  00000-0  10000-3 0  8896
2 25961  51.9912 131.1499 0000716 246.4158 113.6633 12.62263365394661
GLOBALSTAR M034
1 25962U 99062B   08157.55597777 -.00000104  00000-0  00000+0 0  9099
2 25962  51.9916 177.1856 0002461 204.1059 155.9715 12.62260577393888
GLOBALSTAR M029
1 25963U 99062C   08157.52130385 -.00000086  00000-0  10000-3 0  9033
2 25963  51.9961 266.2763 0002126 146.5542 213.5360 12.62266280404371
GLOBALSTAR M061
1 25964U 99062D   08157.72116971 -.00000074  00000-0  10000-3 0  5573
2 25964  51.9786  80.8807 0005793 145.5019 214.6186 11.76677525389177
GLOBALSTAR M063
1 26081U 00008A   08157.86027049 -.00000086  00000-0  10000-3 0  6572
2 26081  51.9998 310.9203 0002132 132.3369 227.7675 12.62264279392453
GLOBALSTAR M062
1 26082U 00008B   08157.98440884 -.00000086  00000-0  10000-3 0  5661
2 26082  52.0032  86.8535 0000795 356.5384   3.5468 12.62261710384179
GLOBALSTAR M060
```

```
1 26083U 00008C   08157.47949783 -.00000086  00000-0  10000-3 0  6524
2 26083  52.0072 358.7277 0001726 101.7531 258.3528 12.62265931391610
GLOBALSTAR M064
1 26084U 00008D   08157.74154126 -.00000086  00000-0  10000-3 0  8683
2 26084  52.0070 312.5321 0001936 129.1045 230.9984 12.62257251410399
GLOBALSTAR M065
1 31571U 07020A   08157.31113409 -.00000107  00000-0 -16771-4 0  3348
2 31571  51.9912  87.7230 0001606 355.5052   4.5806 12.62259583 48122
GLOBALSTAR M069
1 31573U 07020C   08156.18768051 -.00000086  00000-0  10000-3 0  2031
2 31573  51.9967  46.3676 0001438  86.2528 273.8503 12.62260982 48713
GLOBALSTAR M072
1 31574U 07020D   08158.19682709 -.00000082  00000-0  12137-3 0  3276
2 31574  52.0051 130.6617 0000480 316.6060  43.4754 12.62271336 47475
GLOBALSTAR M071
1 31576U 07020F   08156.22720034 -.00000086  00000-0  10000-3 0  2207
2 31576  52.0095  46.3349 0000546  77.7715 282.3227 12.62260464 48712
GLOBALSTAR M067
1 32263U 07048A   08158.24139545 -.00000104  00000-0  00000+0 0  2808
2 32263  51.9761 265.0693 0002439 151.8913 208.2087 12.62256671 30653
GLOBALSTAR M070
1 32264U 07048B   08158.15227232 -.00000086  00000-0  10000-3 0  2220
2 32264  51.9794 355.3488 0000706 106.5696 253.5248 12.62261831 29132
GLOBALSTAR M066
1 32265U 07048C   08157.63260862 -.00000104  00000-0  00000+0 0  2786
2 32265  51.9677 222.0480 0000458 174.5925 185.4943 12.62271589 31295
GLOBALSTAR M068
1 32266U 07048D   08157.59116866 -.00000148  00000-0  00000+0 0  2829
2 32266  51.9828 188.7645 0017422 153.9534 206.2274 13.90951228 31837
```

Permission to re-print Figure 7, Equation 6.1 and 6.2 from [23]:

AIAA grants permission for you to reprint Figure 15.2 and Equations 15.1 and 15.3 from Orbital Mechanics by Vladimir Chobotov in your Master's Thesis and also for the University of Central Florida to post your paper in their electronic archive. Appropriate credit must be given in the figure caption and as a footnote to the equations (e.g., "From [author and ref. no.]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc."). Note that the original source should be cited in full in the reference list.

Heather Brennan

Senior Editor

American Institute of Aeronautics and Astronautics

1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344

heatherb@aiaa.org

http://www.aiaa.org

REFERENCES

1. Kizilova Anna. "Nano-Satellites – Future of the Future". Internet: http://www.russia-ic.com/education_science/science/science_overview/578/, Sep 20, 2007 [Sep 12, 2008].

2. "Personal Communication System". Internet: http://www.britannica.com/EBchecked/topic/452925/personal-communication-system, [Sep 1, 2008].

3. "Personal Communication Services". Internet: http://www.ntia.doc.gov/opadhome/mtdpweb/povrview.htm, [Sep 1, 2008].

4. Stephen Horan. "The potential for using LEO telecommunications constellations to support nano-satellite formation flying". *The International Journal of Satellite Communications*, vol., pp 1-15, 2002.

5. Yu.M. Urlichich, A.S. Selivanov, A.A. Stepanov. "Two nano-satellites for space experiments".*5th Symposium on Small Satellites for Earth Observation*, April 4-8, Berlin, Germany - IAA-B5-1403

6. "LEO vs. GEO Satellites when used with Mobile Satellite Services". Internet: http://www.globalcomsatphone.com/globalcom/leo_geo.html, [Sep 1, 2008].

7. Janet R. Golio. *Microwave and RF Product Applications*. Boca Raton, Florida: CRC Press, 2003, pp 9-22.

8. "Inmarsat". Internet: http://www.inmarsat.com.html, [Aug 15, 2008].

9. Vanessa Rian Maher. "A Low Power Beacon for Transmitting Location Data via the Globalstar Satellite System." M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2006.

10. "Thuraya Satellite Communications". Internet: http://www.thuraya.com/content/technology.html, [Aug 15, 2008].

11. Abbas Jamalipour. *Low Earth Orbital Satellites for Personal Communication Networks*. Norwood, MA: Atech House, 1998, pp.

12. "Iridium". Internet: http://iridium.com/about/howitworks.php, [Aug 15, 2008].

13. K.E. Crowe, R.A. Raines. "A Model to describe the Distribution of Transmission Path Elevation Angles to the Iridium and Globalstar Satellite Systems." *IEEE Communication Letters,* vol. 3, no. 8, August 1999

14. Victor Alvarez, Amanda Brewer, "Helpful Hints for STK Power User", *Missile Defense Seminar, 2006* p-35

15. Dr. Joel Schindall. "Concept and Implementation of the Globalstar Mobile Satellite System," in Proc. of *4th International Mobile Satellite Conference, Ottawa,* 1995, pp. A-11-16.

16. "Globalstar". Internet: http://www.globalstar.com.html, [Aug 15, 2008].

17. Dan Smith, Rich Hendrickson. "Mission Control for the 48-Satellite Globalstar Constellation". *Military Communications Conference, 1995*, Vol 2, pp:828 - 832

18. "Globalstar Communication Satellite". Internet: http://www.aerospace-technology.com/projects/globalstar/globalstar2.html , [June 15, 2008].

19. Fred J. Dietrich, Paul Metzen, Phil Monte. "The Globalstar Cellular Satellite System." *IEEE Transactions on Antennas and Propagation,* vol. 46, no. 6, June 1998

20. "Gateways to Communication." [On-line]. 38(1), pp. 1-30. Available: www.satellite-evolution.com [June 10, 2008].

21. "Qualcomm GSP-1720 data/ Voice Module Integrator's Reference Manual", *QUALCOMM Incorporated*.

22. "Live Real Time Satellite and Space Shuttle Tracking". Internet: http://www.n2yo.com/?k=17, [September 15, 2008].

23. Vladimir A. Chobotov. *Orbital Mechanics*. Reston, Virginia: AAIA, 1996, pp 402.

24. Matson, Robert. "Nodal Regression". Internet: http://www.satobs.org/seesat/Dec 2003/0065.html, Dec 4, 2003 [May 29, 2008].

25. "Qualcomm awarded $275 million contract as Globalstar gateway manufacturer". Internet: http://www.qualcomm.com/news/releases/1997/press859.html, San Diego - May 07, 1997 [Oct 15, 2008].