PERSISTENT MILITARY SATELLITE COMMUNICATIONS COVERAGE USING A CUBESAT CONSTELLATION IN LOW EARTH ORBIT

by

JACQUELINE M. NELSON

A thesis submitted in partial fulfillment of the requirements
for the Honors in the Major Program in Electrical Engineering
in the College of Engineering and Computer Science
and in the Burnett Honors College
at the University of Central Florida
Orlando, Florida

Spring Term 2010

Thesis Chair: Dr. Linwood Jones

ABSTRACT

This thesis describes the approach to designing a Low Earth Orbit CubeSat constellation capable of nearly constant coverage. The software package Satellite Tool Kit is used to create simulated multi-satellite systems that maintain a communication link between Tenby, Pembrokeshire, Wales and tactically chosen locations in the United States of America. The research will attempt to find the constellation capable of maintaining a set of design parameters (such as signal to noise ratio and altitude), with the minimum possible number of CubeSats. The downlink location, antenna design and the orbital planes are the negotiable parameters in the system, with little to no set constraints, and thus will be altered until the most favorable system is successfully designed.

DEDICATIONS

I dedicate this thesis and all the work that went into it to my parents and Ryan, who have given me tremendous love and support in all of my endeavors.

I dedicate this thesis to my brother, Paul, whose many successes and accomplishments have continuously inspired me to create new, greater goals for myself – I would not be where I am today without his influence.

ACKNOWLEDGEMENTS

With the utmost respect and admiration, I would like to express my gratitude and appreciation for the professors on my committee:

Special thanks to my thesis chair, Dr. Linwood Jones, of the Department of Electrical Engineering and Computer Science.

To Dr. Parveen Wahid, of the Department of Electrical Engineering and Computer Science, and

And to Dr. Kurt Lin, of the Department of Mechanical, Materials and Aerospace Engineering.

These three individuals have time and again demonstrated their wealth in knowledge, and have given me the guidance to further my own understanding of the world of satellite system design and communications.

It is also necessary to acknowledge the individuals at the U.S. Army Space and Missile Defense Command that developed the research topic of this thesis, Mr. Pete Kirkland and Mr. Kevin Nash. Their willingness and enthusiasm to support my aspiration to complete a thesis in collaboration with a Department of Defense facility has both honored and humbled me.

I wish to acknowledge that the use of the Satellite Tool Kit software was provided without charge under the University Partnership Program with The University of Central Florida. As this software was crucial to the completion of the research, I am appreciative of STK’s participation in the partnership program, since it is the unmatched first choice in designing satellite constellation scenarios.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

AGI: Analytical Graphics, Inc.

COTS: Commercial-Off-The-Shelf

DFS: Doppler Frequency Shift

GEO: Geosynchronous Orbit

GPS: Global Positioning System

HEO: High Earth Orbit

IFOV: Instantaneous Field of View

InSAR: Interferometric Synthetic Aperture Radar

LEO: Low Earth Orbit

MEO: Medium Earth Orbit

NAF: No Access Found

P-POD: Poly-Picosatellite Orbital Deployer

RAAN: Right Ascension of the Ascending Node

SAR: Synthetic Aperture Radar

SNR: Signal to Noise Ratio

SPP: Satellites Per Plane

STK: Satellite Tool Kit

T/R: Transmitter/Receiver

CHAPTER 1 – INTRODUCTION

Over the course of the past few decades, artificial satellites have become a critical element of beyond line-of-sight communications. Satellites are now so commonplace that they have made their way into the everyday lives of most people in developed countries. Modern convenience items such as satellite television services and Global Positioning Systems are easy examples of this reality. It is also interesting to note that virtually all satellite applications began as military research endeavors – GPS was developed primarily by the Space and Naval Warfare Systems Command before it became the revolutionary industry it is today.

There are unlimited applications for satellite technology in industry, in academia, and of course, in the military. The goal of this research is to create a realistic Low Earth Orbit (LEO) CubeSat constellation for applications in novel military endeavors. This thesis is in collaboration with the U.S. Army Space and Missile Defense Command, a Department of Defense facility located in Huntsville, Alabama.

The first privately launched LEO constellation was put into orbit by Motorola in 1998. The original design called for 77 active satellites, which earned it the name IRIDIUM (after the element with the atomic number 77). The final design was optimized to 66 active satellites to lower the cost of the system. Each satellite in the constellation maintains an altitude of 780 kilometers and weighs about 680 kilograms. The purpose of the system was to provide wireless global communication links for personal communication devices such as cell phones, while avoiding the delay caused by the extreme altitude of geostationary orbit satellites. [1]

As was mentioned before, the ultimate objective of this thesis is to design an LEO CubeSat constellation capable of persistent coverage of any ten kilometer by ten kilometer area of interest, with a minimized number of sensors for a robust system. In the real-world application of this research, the area of interest will be an area of conflict (whether it be natural or manmade), in which near constant monitoring is highly desirable.

The CubeSat standard will be a critical component of the research. A CubeSat is defined as a ten centimeter by ten centimeter satellite bus, having a total weight no more than 1 kilogram. [2] The small size and weight limits the amount of sensors and components available for use onboard. Redundancy must be avoided in order for a real-time communication link to be both plausible and efficient, and inter-satellite communication links will be necessary to relay information.

The purpose of designing such a system of satellites is providing a foundation for LEO CubeSat constellations capable of Synthetic Aperture Radar (SAR) missions, which would provide continuous high-definition imaging data about the area of interest being monitored. Persistent and reliable coverage is only a small portion of the SAR dilemma, so this thesis will serve as an essential starting point to future research concerning the advancement of SAR methods.

CHAPTER 2 – BACKGROUND

Man-made satellites and space exploration have been a musings of theorists and science fiction authors long before the first artificial satellite became reality. Beginning in the early 1940's, authors such as Isaac Asimov and Arthur C. Clarke postulated many futuristic space and technological accomplishments. Some of these ideas continue to capture the imaginations of readers today, while others have proved to be prophecy.

In a contribution to a 1945 publication of *Wireless World,* Clarke accurately theorized a communication system independent of the physical limitations of a wired system through the use of geostationary satellites. He concluded that a satellite with an orbit radius of 42,000 km, and a "plane coincided with that of the earth's equator, would revolve with the earth and would thus be stationary above the same part of the planet." [3] He went a step further to suggest an arrangement of three such stations separated by 120 degrees would "ensure complete coverage of the globe." In reality, his altitude figure was miscalculated by approximately 164 km, and his arrangement excludes coverage at the poles, but the concept behind the system is remarkably accurate. This was over a decade before humans were able to put anything into orbit.

Since 1957, the human race went from having no manmade objects in Earth orbit to "more than 8,500 catalogued objects" in orbit. As of 1999, approximately 600 of those objects were classified as active spacecraft. [4] Scientists and engineers around the world are continuously discovering new and exciting applications for satellite technology, and this thesis is an example of an attempt to advance the possibilities that extra-terrestrial systems offer.

2.1 The Beginning of Artificial Satellites

On October 4th, 1957, the Soviet space program inspired awe and fear in people around the world with the first successful launch of an artificial satellite, dubbed Sputnik-I. In the more than half a century since that day, the human presence in the extraterrestrial realm has become commonplace, with an exponentially increasing population of spacecraft in orbit around the Earth.

In the infancy of space technology, satellites were small out of necessity. The rocketry required to launch heavy satellites into space was not yet available in most countries, including the United States, so spacecraft needed to be lightweight in order to make the flight into orbit. As rocket science progressed, satellites with heavier payloads made it into space, but at much greater construction and launch costs. The current trend in satellite development is again a preference for smaller satellites for many reasons. With cheaper costs, a wider array of small organizations, academic institutions, and industries will be able to utilize satellites to a fuller, more advantageous potential. [2]

2.1.1 Satellite Classification

Satellites can be classified in many different manners. They can be classified by their mission, like weather satellites, communications satellites, or GPS satellites, just to name a few. They can also be classified by their purpose, as in military, commercial, or research oriented. Another option is classification by physical properties, such as mass or diameter. For the purpose of this thesis, the mass criterion is the most relevant factor. Table 1, adapted from [2] with added examples, demonstrates satellite classification based on mass.

Table 1: Satellite classification by mass criterion

Satellite Class	Examples	Mass
Large Satellite	Tropical Rainfall Measuring Mission (TRMM), Hubble Space Telescope	>1000 kg
Minisatellite	IRIDIUM Satellites , GIOVE-A	100 – 1000 kg
Microsatellite	Sputnik -1, Cerise	10 – 100 kg
Nanosatellite	Vanguard -1, SNAP-1	1 – 10 kg
Picosatellite	Canadian Advanced Nanosatellite eXperiment – 2 (CanX-2), CubeSat	0.1 – 1 kg
Femtosatellite	Satellite-on-a-chip	1 – 100 g

2.1.2 The CubeSat Standard

The idea of the CubeSat standard began as a project at the Space Systems Development Laboratory of Stanford University in1999. The premise was to develop a relatively inexpensive, standardized design for picosatellites, as well as the launching platform. [2]

The standard stipulates that CubeSats must have a mass under 1 kg, and be a cube with each side measuring 10 cm. They must have sufficient materials and construction to withstand the extreme forces incurred during launch. In collaboration between Stanford University and the California Polytechnic State

University, the launching platform was developed. CubeSats are placed into orbit using Poly-Picosatellite Orbital Deployers (P-PODs). Three CubeSats are held in the P-POD until the desired altitude is reached. [5] Once the CubeSat reaches orbit, it either remains contained or unfolds so that the onboard sensors can be utilized. Due to the low mass of each P-POD, they can easily be attached to vehicles already making the journey into space, with only a minimal addition to that vehicle's payload.

Figure 1, an image that appears in [6], is an example of a satellite that follows the CubeSat standard, dubbed the Aerocube-2. This picosatellite was launched in April, 2007, and placed into a 700 km polar orbit. It was developed by The Aerospace Corporation, for scientific research purposes.

Figure 1: The Aerocube-2 CubeSat

Since CubeSats follow an established standard, commercial off-the-shelf (COTS) parts can be used with greater frequency. Designing every individual aspect of a satellite for a specialized purpose is a lengthy, cumbersome and expensive process – the amount of hours spent engineering each facet of a non-standard system is not an efficient use of resources. [2] COTS parts allow for increased ease in design and replication, significantly lowering construction costs. [7]

Due to the size and weight restrictions implied in the CubeSat standard, it becomes obvious that there are limitations to the types of sensors and equipment a CubeSat can carry. As a result of the limitations in each individual CubeSat, most learning endeavors only pursue simple communications missions. However, CubeSats should not be dismissed in real-world applications.

A lot of work is being done to develop efficient algorithms to manage formations and communications between multiple satellites in what are referred to as systems, networks, or “constellations.” [1], [8], [9], [10], [11] CubeSats, because of their relatively low cost in construction and deployment, become an obvious choice to form these constellations. The sensors and processing can be distributed across a constellation of CubeSats to accomplish more complex missions than one CubeSat can accomplish alone.

The CubeSat standard is an extraordinary idea that developed into a worldwide practice because of its economical and accessible concept of design and implementation. There is no doubt that more applications for the miniaturized satellite standard will emerge.

2.2 Orbits

The orbit of one object around another is the result of the unyielding attractive force of gravity. Newton's law of universal gravitation, first published in 1687 in his work *Mathematical Principles of Natural Philosophy*, defines the gravitational force experienced by objects in orbit. [12] For two objects of masses m_1 and m_2 (in kilograms), separated by a distance of r meters, the gravitational force is defined as:

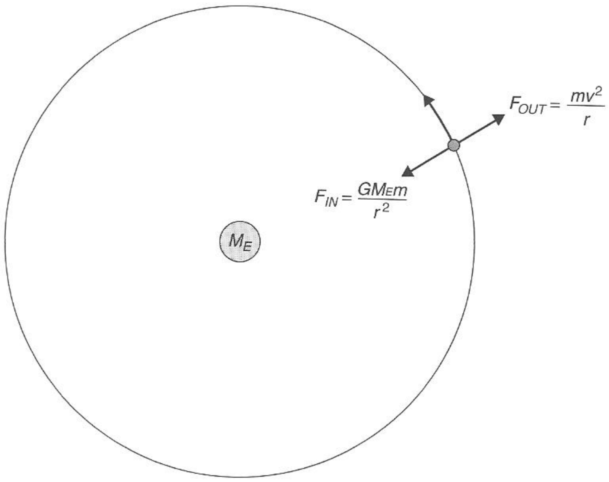
$$F_g = G\frac{m_1 m_2}{r^2}, \quad (N)$$

where G is the universal gravitational constant:

$$G = 6.673 \times 10^{-11}, \; (N \cdot \frac{m^2}{kg^2})$$

In
Figure 2 below, taken from [13], the forces experienced by a satellite of mass *m* in an orbit a distance of *r* away from the center of the earth, are illustrated.

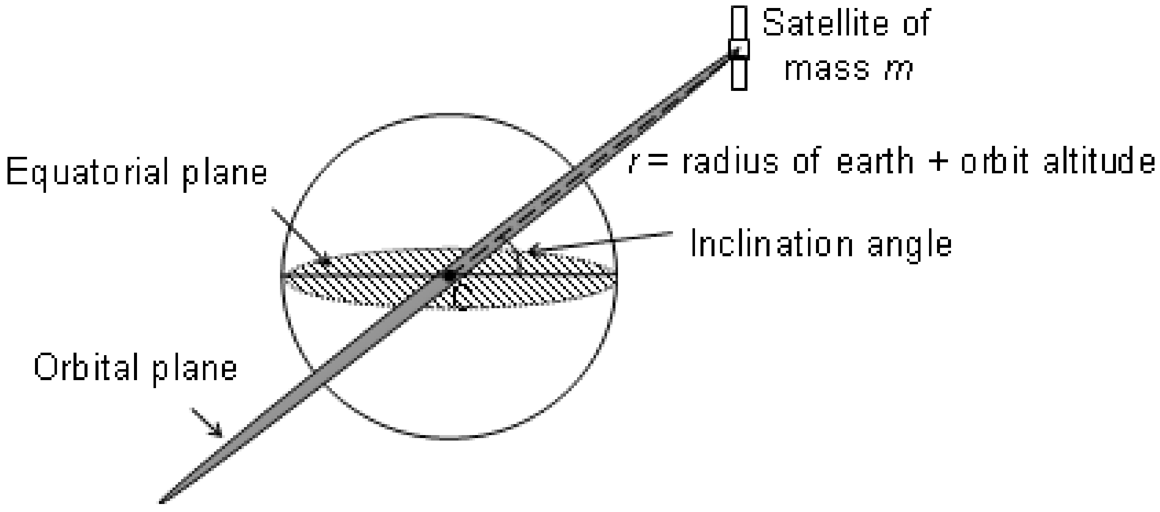
Figure 2: General forces experienced by a satellite in orbit about the earth



A satellite's orbit around the earth is defined by several key factors. The altitude of the satellite is an essential component, as the equation above indicates. The mass of the satellite, in conjunction with the altitude, affect the speed of the orbit. From the above equation, it is easy to tell that the farther away the satellite is from the earth, the slower the velocity that satellite will have, providing all masses are constant.

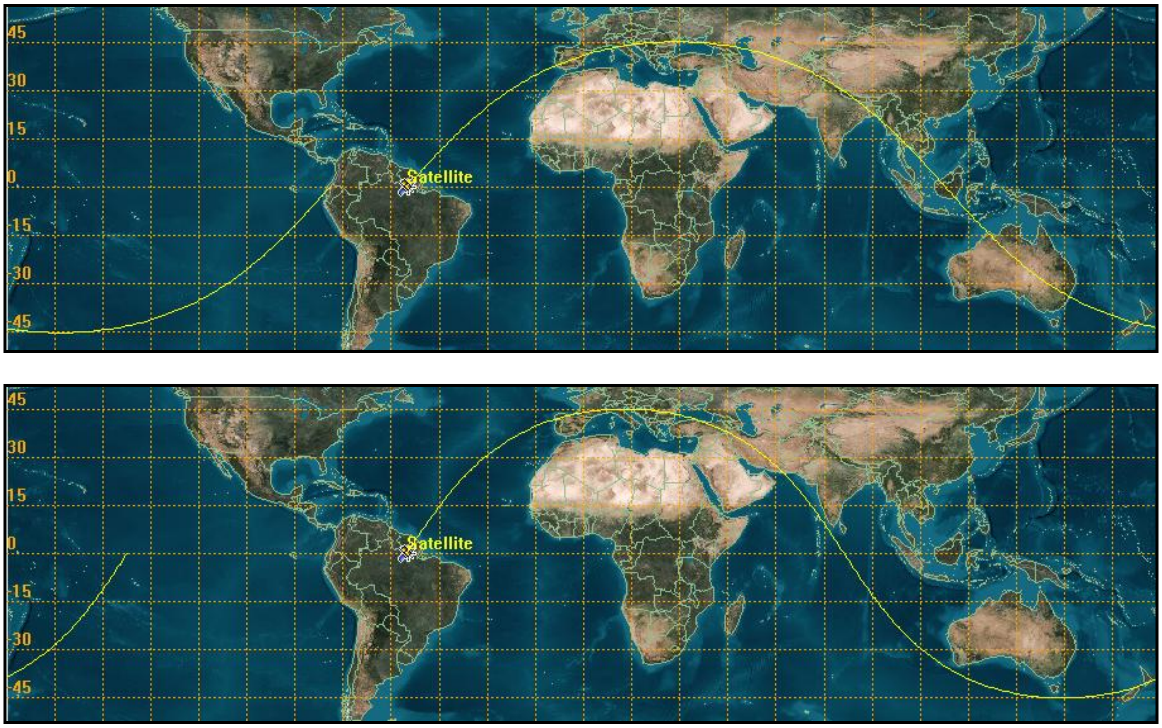
Another important attribute of a satellite's orbit is the inclination angle. Simply put, the inclination angle defines the orbital plane in relation to the equatorial plane. In Figure 3, the factors that define a satellite's orbit are illustrated.

Figure 3: Illustration of the inclination angle establishing orbital plane



It is also interesting to note the relationship between the inclination angle and the satellite's ground track. The path of the satellite projected onto the earth's surface will reach its maximums and minimums at the latitude line equal to the inclination angle in degrees. For example, a satellite with an inclination angle of 45° will have a ground track that culminates at 45°N and 45°S, regardless of altitude, as illustrated in Figure 4.

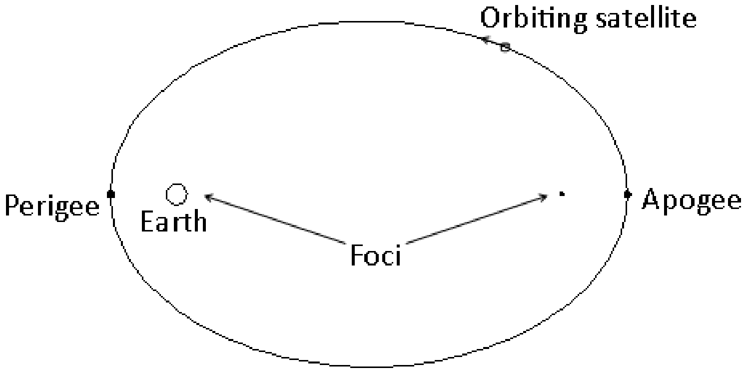
Figure 4: Inclination angle affecting ground track maxima and minima
Top) Satellite in 500 km orbit; Bottom) Satellite in 10,000 km orbit



2.2.1 Orbital and Satellite Geometry

Just as Kepler's First Law of Planetary Motion states, "the orbit of any smaller body about a larger body is always an ellipse, with the center of mass of the larger body as one of the two foci."[13]. The altitudes of apogee and perigee are what indicate whether the shape is elliptical with two distinct foci, or generally circular, with overlapping foci (although, perfectly circular orbit is difficult to achieve in a realistic situation). Perigee is the point at which the satellite is closest to the center of the earth; apogee is the point at which the satellite is farthest. An orbit that is regarded as circular has the attitude of apogee equal to or nearly equal to the altitude of perigee. An orbit is considered elliptical (Figure 5) if the apogee and perigee differ significantly.

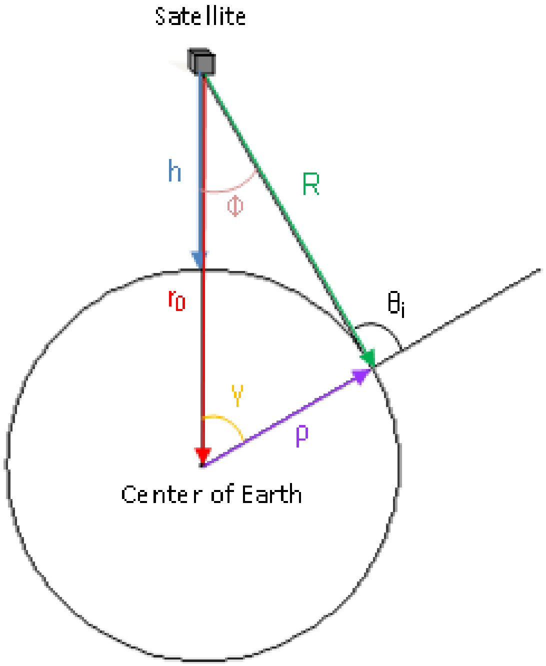
Figure 5: Demonstration of the apogee point and the perigee point of a satellite in elliptical orbit (not to scale)



To understand a satellite's position relative to the earth, it is geometrically defined by several angles, vectors and magnitudes in the incidence plane. The nadir direction is the vector that originates at the center of mass of the satellite, and terminates at the center of the earth. The slant range, R, is the distance from the satellite to the ground facility or object with which it is observing or communicating. The angle in between these two vectors is referred to as the cone or nadir angle, Φ. The point on the earth's surface with the nadir vector crosses is the sub-satellite point. The distance from the sub-satellite point to the satellite itself is the altitude, h, of the satellite.

Another angle is created by ρ, the radial vector from the center of the earth to the point on the earth where the antenna is pointing, and the nadir vector. This is the earth angle, γ. If that same radial vector were continued out and away from the earth, it would create the incidence angle, θ_i , with the line-of-sight of the satellite, along the slant range. These angles and vectors are illustrated in Figure 6.

Figure 6: Satellite geometry in the incidence plane



2.2.2 Low Earth Orbit Constellations

An object is defined as in Low Earth Orbit if it has an orbit altitude below 2000 kilometers. [14] Logically, a LEO constellation is a network of satellites which are all below 2000 km. Conversely, orbits above 2000 km are considered to be in either Medium Earth Orbit (MEO) or High Earth Orbit (HEO). A special case of HEO is Geostationary Earth Orbit (GEO), where the satellite orbits at the same speed as the earth rotates, so it maintains a constant sub-satellite point somewhere on the equator. This occurs at an altitude of 42,164.17 km above the earth's surface. [13]

There are some trade-offs between having satellites in LEO versus HEO. The main advantage of the LEO system is the increased signal strength due to closer proximity to the earth's surface. This refers to all types of signals; stronger communications signals can be sent and received, higher resolution images can be captured, and sensors with lower ranges can be utilized.

However, the coverage area of a satellite in LEO at any point in time is much less than a satellite in HEO.[13] This is the result of the simple geometry seen in similar triangles. If two satellites, one at an altitude of 500 km and the other with an altitude of 1,000 km, have the same antenna beamwidths, then the satellite with the 1,000 km altitude will have a larger instantaneous field of view (IFOV).

Another disadvantage of LEO satellites are their speed. LEO satellites are rapidly changing their positions as they move along their orbit tracks. Combined with a small IFOV, this leaves a very small window of opportunity for communications between the satellite and the ground to occur, before the satellites are lost on the horizon. HEO systems can monitor a single area for a much longer duration, and with fewer satellites than LEO networks.

As with any system design, these trade-offs must be evaluated with respect to the mission objectives. Although an LEO system may require more satellites, the benefits of the close proximity are critical for some missions. Even though there may be more satellites, the cost of designing and launching these satellites can be much less. This is especially true when using picosatellites such as CubeSats, and this thesis makes an attempt to design such a system.

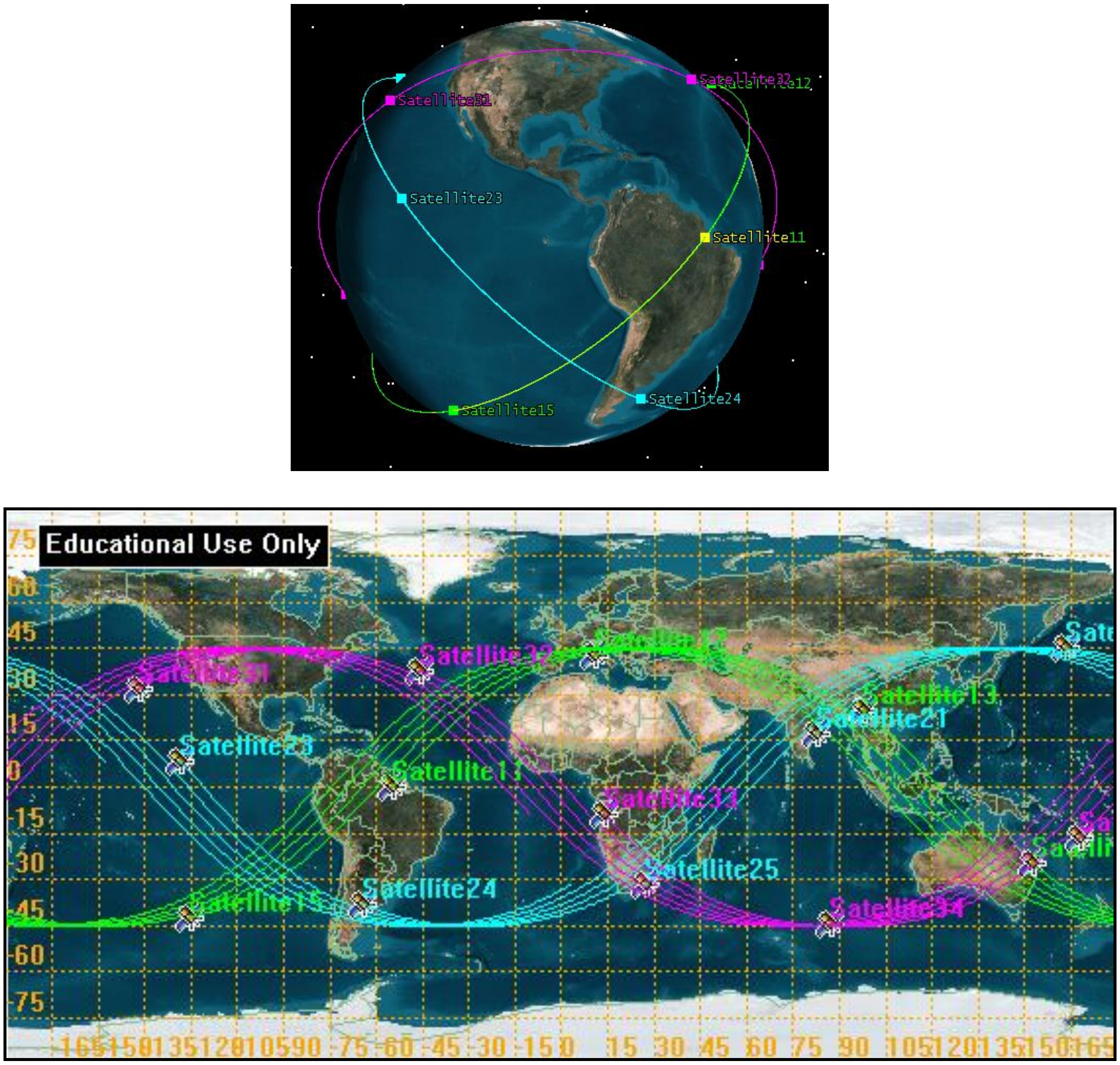
2.2.3 The Walker Delta Configuration

The Walker delta configuration for satellite constellations was developed by J.G. Walker in the early 1980s. Walker was able to develop a function dependent on the number of desired orbital planes, the number of desired satellites in each plane, and a phase parameter that defines the inter-plane spacing. This function produces the optimal configuration of orbital planes to provide even coverage of the globe by discerning the appropriate Right Ascension of the Ascending Node (RAAN) for each plane. The RAAN is essentially the insertion point, relative to the lines of longitude and measured in degrees, of the satellite in its orbit plane.

The simulation software used in this thesis, Satellite Tool Kit, is well equipped to generate Walker configurations. A “seed” satellite is created with the desired angle of inclination, altitude, mass, and RAAN. From the seed satellite, a Walker constellation can be created by allotting the number of planes and the number of satellites per plane. Figure 7 illustrates an example of a Walker constellation, where the seed satellite had an inclination of 45° and an altitude of

500km. Each orbit plane is represented by a different color, with each satellite denoted by either a tick mark (in the 3-D view) or a satellite icon (2-D view). The 2-D view shows the ground tracks of the satellites, while the 3-D view shows the aerial trajectories of the satellites.

Figure 7: Walker Delta Constellation: 3 Planes, 5 Satellites per Plane
Top) 3-D view; Bottom) 2-D view



2.3 Satellite Link Budget

There are many factors that contribute to the overall signal quality transmitted and received in remote sensing and remote communications. A satellite link budget table is a common and effective method of parameter design. It is a “tabular method for evaluating the received power and the noise power in a radio link.” [13] The overall signal to noise ratio (SNR) is usually one of the most useful outputs of a link budget table.

Many equations and link specifications are required to construct an accurate link budget table. The antenna gain, transponder power and bandwidth, uplink/downlink frequencies, signal bandwidth, and various losses are all factors that contribute to the effectiveness of a transmission. The conditions surrounding the link also play their part, since a transmission through clear air is obviously stronger than a transmission through rain. All of these elements must be considered in the design process of a realistic system.

2.3.1 Calculation of the Signal to Noise Ratio

A common calculation in a link budget table is the system noise power:

$$N = kT_{sys}B_n, \qquad \text{(W)}$$

where k is Boltzman’s constant, T_{sys} is the system noise temperature, and B_n is the noise bandwidth. As one would expect, this system noise power is used in the calculation of the SNR.

The other necessary calculation to determine the SNR is the link equation itself, which is fundamentally the received power:

$$P_r = \frac{P_t G_t G_r}{(4\pi R/\lambda)^2}, \qquad (\mathrm{W})$$

where the term P_t is the transmitted power, and the term G_t is the gain of the transmitting antenna. The product of these two terms is referred to as the effective isotropically radiated power (EIRP). The denominator of the link equation is the path loss, which is dependent on the range of the transmission and the wavelength of the signal. The remaining term, G_r, is the gain of the receiving antenna. The receiving antenna gain is dependent on the effective aperture area of the antenna, and, like the path loss, the signal wavelength. [13]

Link calculations are usually converted to dB for increased ease in perception and understanding when evaluating the legitimacy of a result by inspection, and in combining terms. After converting the received power and the system noise power to dBW, the SNR is easily calculated by simple subtraction:

$$\frac{C}{N} = P_r - N, \qquad (dB)$$

Typically, the magnitude of the dBW value of the noise power is greater than the magnitude of the dBW value of the received power. Since these calculations are both characteristically negative, however, the subtraction in the dB scale attains a positive SNR.

2.3.2 Multi-Hop Communications Systems

A multi-hop system is a communications network that utilizes multiple “jumps” or relays, as opposed to a simple “bent-pipe” system, which has a path characterized by a signal traveling from ground station A, to a satellite, then back down to ground station B. Having these relays in a multi-hop system severely complicates link budget calculations, since each separate jump must be calculated separately, for the specific conditions of that hop.

Generally, a simple bent-pipe system only necessitates two link calculations – one for the uplink, and one for the downlink. This is a complicated enough process, considering the satellite is in constant motion around the earth, thus creating a continuously changing slant range between the satellite and ground station (except for the case of a satellite in GEO). Adding the satellite-to-satellite relay of a multi-hop link requires the maintenance and continual updating of another calculation.

One must also consider the effects of the Doppler Frequency Shift (DFS), which is a shift in the frequency of the observed received signal as compared to the sent signal due to the relative difference in the objects' velocities. The most common method of compensation for the DFS is the use of filters.[15] Further investigation should be conducted to determine the proper method of compensation in LEO-LEO inter-satellite links, to ensure any link budget calculations are accurate.

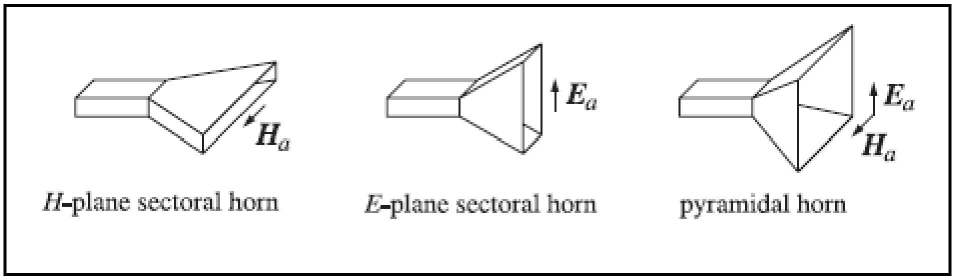
2.4 Basic Antenna Types for Satellite Use

There are four main antenna types commonly found on satellites. They are: 1) wire antennas, 2) horn antennas, 3) reflector antennas, and 4) array antennas.[13] Each antenna type is well equipped for different types of tasks, and is always an important design factor in a satellite design scenario. For example, the appropriate antenna type for the CubeSats in the mission of this thesis would not be the same as the suitable antenna for a GPS satellite.

The wire antenna is the simplest and cheapest antenna type in radio wave transmitters and receivers (T/R). They are found on personal radio systems, automobiles, outside houses for television reception, and of course, on satellites. The biggest problem with wire antennas is the positioning; much attention must be paid to the physical position of the antenna on the satellite (or otherwise) body in order for effective usage. Since the frequency of operation is dependent on the length of the antenna, this type can only operate at a set frequency, for both T/R functions, and are generally inefficient.

Horn antennas are quite different, in both shape and advantages, and are considered waveguide structures. Figure 8, taken from [16], illustrates the three main types of horn antennas, each having different waveguide directions, as influenced by the dimensions of the aperture.

Figure 8: Three types of horn antennas
Left) Flared on long side; Middle) Flared on short side; Right) Flared on both sides



Of the three types shown, the pyramidal horn is the most common, especially when being used as a feed for dish antennas during calibration. The main advantages of horn antennas are the increased directivity (in smaller beamwidths), in conjunction with noteworthy designable gain properties, which are proportional to the size of the antenna aperture and length.

Reflector antennas, such parabolic reflector antennas which are commonly referred to as dish antennas, generally have high gains and narrow main beams.[16] Parabolic reflector antennas have a large aperture surface area (the concave "dish"), that is directed towards a focal point containing the T/R with which it is communicating. When a signal is received, it hits the reflective parabolic surface, which directs the signal to a focal element that takes in the signal. Like the horn antenna, the performance (in terms of gain) of a reflector antenna is directly proportional to the size. In the case of the reflector antenna, the gain is proportional to the diameter of the dish, and they generally provide a larger aperture than horn antennas.

The fourth common type of antenna on standard satellites is the array antenna. This type of antenna is composed of multiple antenna elements positioned into an array. A common type of array antenna is the phased array antenna, which is a group of antennas oriented in such a manner along a surface so that "the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions." [17] When equipped on a satellite, this type of antenna is particularly effective at achieving multiple spot beams or scanning beams on the earth's surface. In fact, phased array antennas are used on the satellites of the IRIDIUM constellation previously mentioned, which provides global satellite telephone coverage. [1], [13] Even though the types above are the four common types of antennas used on satellites, there are a multitude of other varieties and derivations. The most notable type of antenna for the purpose of this thesis is the microstrip patch antenna. A patch antenna is a thin, lightweight antenna that is made of two conductive plates in parallel, separated by a chosen dielectric material. This type of antenna is ideal for applications on CubeSats, because they do not need to be deployed or unfolded from inside of the satellite – they can be simply attached to one of the outer surfaces of a CubeSat.[18] If the patch antenna is circularly polarized, the physical orientation of the sensor to avoid polarization disparities is not a pertinent issue; the antenna would need to be aligned, but not rotated for effective T/R operations. This simplifies what would be required by the attitude control subsystem on each satellite.

2.5 Simulation Software – Satellite Tool Kit

Satellite Tool Kit (STK), currently on version 9.1, is a comprehensive simulation software program produced by Analytical Graphics, Inc. (AGI). STK has an expansive range of capabilities, and for this reason it is widely used in the remote sensing community. STK is used by all the arenas of research and development, from university research programs, to military development operations, to commercial investment agendas.

STK is equipped with large databases of cities, as well as active (or previously active) satellites. However, users are not limited to what has been done before; it is also possible to create new satellite or object models based on individual project requirements. This flexibility makes the program extremely versatile.

STK is not restricted to satellite systems. Ground facilities and vehicles can be added to a simulation; aircrafts, missiles, and ships are also available to be inserted into scenarios. All of these objects can be equipped with sensors, radar systems, transmitters, receivers, or antennas, either with generic properties or user defined models.

The interface of STK is particularly helpful and intuitive. The program provides both a 3-dimensional view of the earth and the orbiting satellites, as well as a 2-dimensional representation. Every little detail about these projections can be altered according to preference – the images can be made simple black and white illustrations, or they can have in depth, realistic terrain models.

STK really excels in its abilities with multi-object systems. It is possible to create groups of objects in constellations, or arrange them in links. This feature was critical to the simulations in this thesis. The features in STK provide the necessary tools to determine and adjust the quality of a communications link, since they provide dynamic data on signal quality, such as the Signal to Noise Ratio (SNR), gain, and duration and location of contact.

All of the possibilities and applications of this software make amends for the steep price tag of the program. STK does not have to be a standalone software component, since it can be integrated with other mainstream programming and engineering tools. It can be outfitted to run in conjunction with MATLAB scripts, or even scripts in the C languages.

STK is an invaluable tool in satellite system design, since the time it can save in the preliminary design stages of remote sensing projects has the potential to avoid a lot of unnecessary labor and spent money. Powerful software tools such as STK are a major reason behind the exponential rate of advancement in technology, and it is difficult to imagine a scenario where one would not benefit from the utilization of a program such as STK.

CHAPTER 3 – PROBLEM DEFINITION

This thesis examines a problem involving beyond line-of-sight communications utilizing a low earth orbit picosatellite constellation. The technical area of this thesis is satellite communications, being approached from an electrical engineer's standpoint. Satellites and other remote sensing systems are a large area of interest and research for electrical engineers, since they require intimate knowledge of analog and digital communications systems, and original satellite designs depend on the capabilities of available transceivers, antennas, and other hardware components.

3.1 The General Problem

When an area of interest for the U.S. military arises, a steady communication link between that area and a home base is necessary. This link must be robust and persistent. Current solutions to this problem entail the use of satellite telephony and transmissions, static communication broadcasting towers and relays, and even physical cables for transmission of data (such as submarine communications cables for transatlantic telephony).

The High Earth Orbit satellites offer persistent coverage of an area, as long as the weather conditions are suitable for data transmission. However, the increased altitude also means that there is an increased delay, and the necessity for a strong signal. A Low Earth Orbit (LEO) system like the one proposed could possibly improve on these issues. A LEO system is more flexible and offers more coverage than the static towers, and is much easier to protect from sabotage than an exposed physical connection.

Constant monitoring of an area of interest can be extremely beneficial in a time of natural disaster or wartime conflict; having more information about an area of interest increases the likelihood of mission success. A current method of mapping an area is Synthetic Aperture Radar (SAR), which uses a series of pictures differing slightly in time and position to form a two or three dimensional, high definition map of an area. A constraint of SAR is that it is limited to mapping stationary objects and features, because SAR is traditionally implemented by an antenna on an aircraft collecting data during a single pass. If a system of satellites is used, it might be possible to continuously update the SAR rendered images in order to communicate more time-accurate maps and information to the “home-base” location.

3.2 The Specific Problem

This thesis will endeavor to design a Low-Earth Orbit CubeSat system capable of maintaining a nearly persistent low bandwidth (10 MHz) S-band (2.6 GHz) data signal. The system will be allowed to lose coverage for a total of one hour per day. The orbits of the satellites in the system can range in altitude from 200 kilometers to 400 kilometers. For the purpose of the thesis, the uplink signal will originate at the latitude and longitude coordinates 51.6731° N and 04.7097° W (Tenby, Pembrokeshire, Wales), and the downlink will be centered at a point in the continental United States that provides the optimized system. The desired signal to noise ratio (SNR) will be set at 13 dB.

There are no orbit plane constraints, and the CubeSats are assumed to be capable of attitude control as well as inter-satellite communication links. The CubeSats will be equipped with a 1 Watt transceiver, and the antenna length and type can be negotiated to provide the appropriate gain to support the required SNR. After a system capable of these requirements is established, the number of satellites in the system will be minimized. Physical cost is a major factor in designing any satellite system, and therefore minimizing the number of CubeSats is a critical component of the thesis objective.

This system will not incur the delays inherent in the HEO/GEO systems, and be more clandestine than a physical connection, and thus provide a significant benefit over these existing systems. If this system of CubeSats is successfully designed, it can potentially be applied to SAR to develop certain applications of the technology.

3.3 Statement of Hypothesis

The goal of this thesis is to establish that it is possible to design an optimized, cost-effective Low Earth Orbit satellite system, constituting solely of picosatellites using the CubeSat standard bus. This system will be capable of maintaining a nearly constant data link between Tenby, Pembrokeshire, Wales, and a tactically chosen location in the continental United States of America.

3.4 Thesis Contributions

The research developed by this thesis will have the following potential contributions:

- A model for a reliable, nearly-constant, and standalone data communication link.
- An advancement that can lead to improvements in SAR technology.
- A comparatively cheap satellite link system, using standardized picosatellites that can be launched inexpensively and frequently.

3.5 Attributes

3.5.1 Novelty

After performing a literary review, no previous instances of this specific method and approach were found. Many of the instances of CubeSat constellations, such as ESPACENET, use a larger “master” satellite to relay messages.[19, 20] Other projects utilize LEO systems, but with larger satellites, as seen with the IRIDIUM constellation.[1] The constellation in this thesis will be composed of satellites much smaller than those in IRIDIUM, and have altitudes of at least half of the larger constellations. The design proposed for this thesis will be a novel system of exclusively CubeSats with the specific purpose of a constant data communication link between two set locations.

3.5.2 Significance

The development of a CubeSat constellation capable of persistent coverage will solve a small part of the problem faced by developing Synthetic Aperture Radar technologies. Limiting the constellation to low-orbit satellites will decrease delay times and allow for higher resolution images. The system will be comprised of entirely standardized, homogenous components that will allow for simple repair and replacement, while most satellite constellations do not abide to such strict guidelines.

3.5.3 Usefulness

The CubeSat standard allows for many cost effective satellite applications. Having a small size and weight, as well as a standard launching apparatus that can be attached to virtually any spacecraft, CubeSats can be put into orbit frequently and cheaply. Many CubeSats are attached to completely unrelated spacecraft with a few extra kilograms of payload space available during launch.[20] A CubeSat constellation capable of constant coverage will be both a significant and useful tool, especially if it can indeed be applied to Synthetic Aperture Radar missions. The model of this system will be adaptable to other uplink and downlink locations. The same process developed by this thesis could potentially be used to model new applications spanning many locations of varying degrees and distances of separation.

CHAPTER 4 – METHOD AND RESULTS

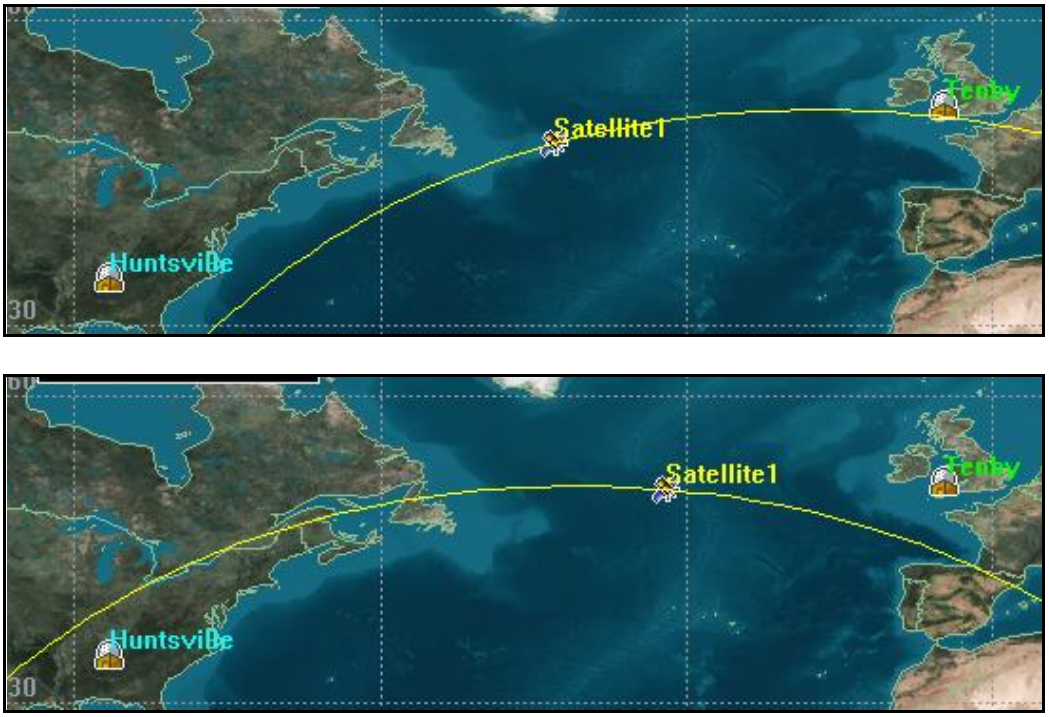
To carry out the simulations necessary for the design and development of an optimized picosatellite constellation, the software program Satellite Tool Kit (STK) was used exclusively. This software provides all the necessary tools to effectively design and evaluate a constellation of satellites, as well as the communication parameters associated with that constellation.

4.1 Initial Approach: Tenby – Huntsville

Two locations were initially chosen to develop a constellation that could maintain a line-of-sight link for a minimum of 23 out of 24 hours per day. The uplink location was chosen as an arbitrary city in the United Kingdom that was already present in the STK facility database, namely Tenby, Pembrokeshire, Wales. The downlink location, which per the specs needed to be a location in the continental United States of America, was chosen to be Huntsville, Alabama, USA (the site of the army base Redstone Arsenal, as well as NASA's Marshall Space Flight Center), a city also in the STK facility database. All simulations, unless otherwise noted, were run over the same analysis period of 24 hours, beginning on February 1st, 2010 at 0000 hours, and terminating February 2nd, 2010 at 0000 hours.

With these two locations, it became clear early on that the immense physical distance (approximately 6557 kilometers), as well as the large difference in the latitude coordinates of these two cities would present a communications problem. The latitude of Tenby is roughly 51.7° N, while the latitude of Huntsville is approximately 35.1° N. As can be seen in Figure 9, a satellite with an orbit of 400 kilometers (the maximum allowed by the provided specs), and an inclination angle equal to the latitude of Tenby (which is essentially the maximum range reached by the satellite) does not lend itself to easily communicate between the two cities. The two images in this figure were taken on two consecutive passes of the same satellite on its orbit track. By inspection, to maintain a link between Tenby and Huntsville through a multi-hop link in the satellites, it will take many satellites on this orbit track; the orbit track is close to Tenby but far from Huntsville on the first pass, but the opposite is true for the successive pass.

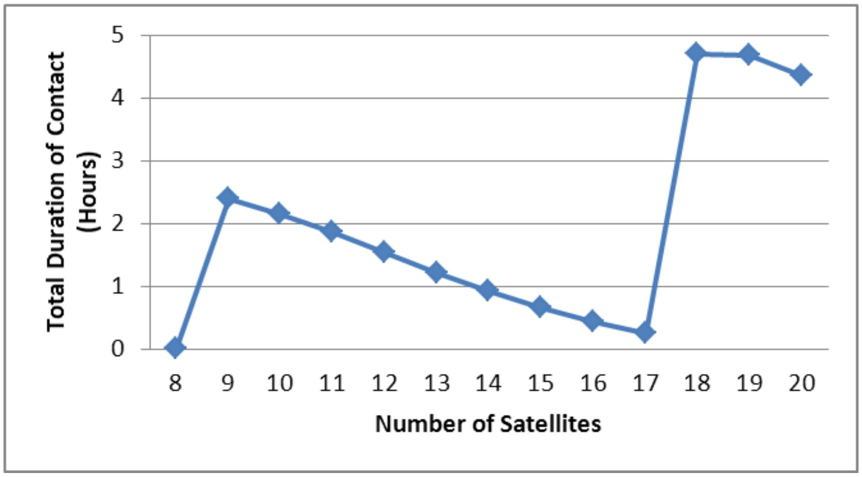
Figure 9: A 1 kg satellite in orbit at 400km, with an inclination of 51°
Top) First pass; Bottom) Subsequent pass



4.1.1 The Single Plane Experiment

As a simple concept experiment, the same satellite as in Figure 9 was used as a seed satellite to a Walker constellation. The satellite was given a 400 km orbit, a 1 kg mass, and a 51° angle of inclination (intentionally chosen for its proximity to the Tenby latitude). The Walker constellation had one plane, and increasing numbers of 1 kg satellites were tested for their line of sight communications abilities, beginning with eight satellites, since eight was the highest number of satellites unable to sustain any duration of contact. The results from this test are displayed in Figure 10.

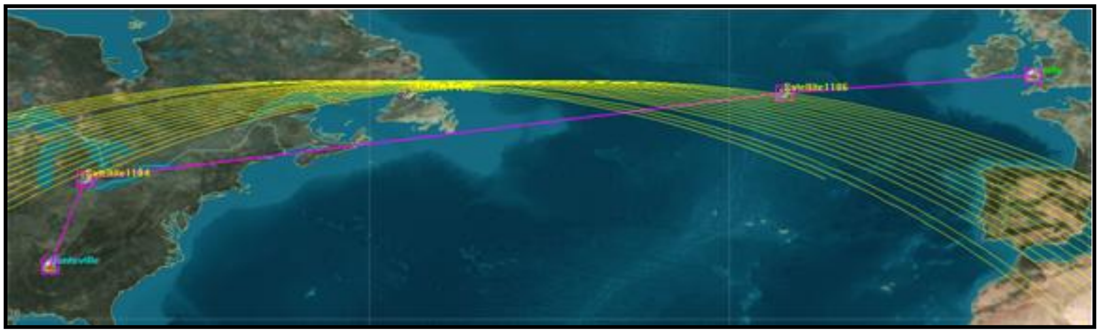
Figure 10: Total Duration of Contact vs. Number of Satellites in a Single Plane Over a 24 Hour Testing Period



From Figure 10, an interesting property is observed. Beginning with nine satellites, which is the minimum to establish any line-of-sight link, the total duration of contact between Tenby and Huntsville over the 24 hour period steadily decreases. However, once 18 satellites are in the constellation, the satellites are close enough to have favorable spacing for communications, and the duration nearly doubles from the starting point (nine satellites). Nonetheless, one must also note that after the 18 satellite threshold is met, the total duration of contact begins to decrease once more.

The reason behind this behavior is simple. To communicate between Tenby and Huntsville, a minimum of two satellite hops are required. The spacing between the satellites with 9 to 17 satellites in orbit are simply too far apart to be effective in communicating with the ground stations at Huntsville and Tenby. One must remember that although a satellite may look like it has sufficient proximity to a ground station, on a 2-D projection the altitude of the satellite is not in perspective. Satellites may *appear* to communicate amongst themselves at much greater distances than the satellites which are in contact with the ground station, but this is not the case. Once 18 satellites are in the constellation, there are enough satellites in orbit to have a more instances of immediacy to the ground stations, and this issue is no longer a problem. Figure 11 illustrates the effective distribution of satellites with an 18 satellite system, with the line-of-sight path drawn in pink.

Figure 11: Communication link between Huntsville and Tenby with 18 satellites (ground tracks in yellow) in a single plane Walker constellation



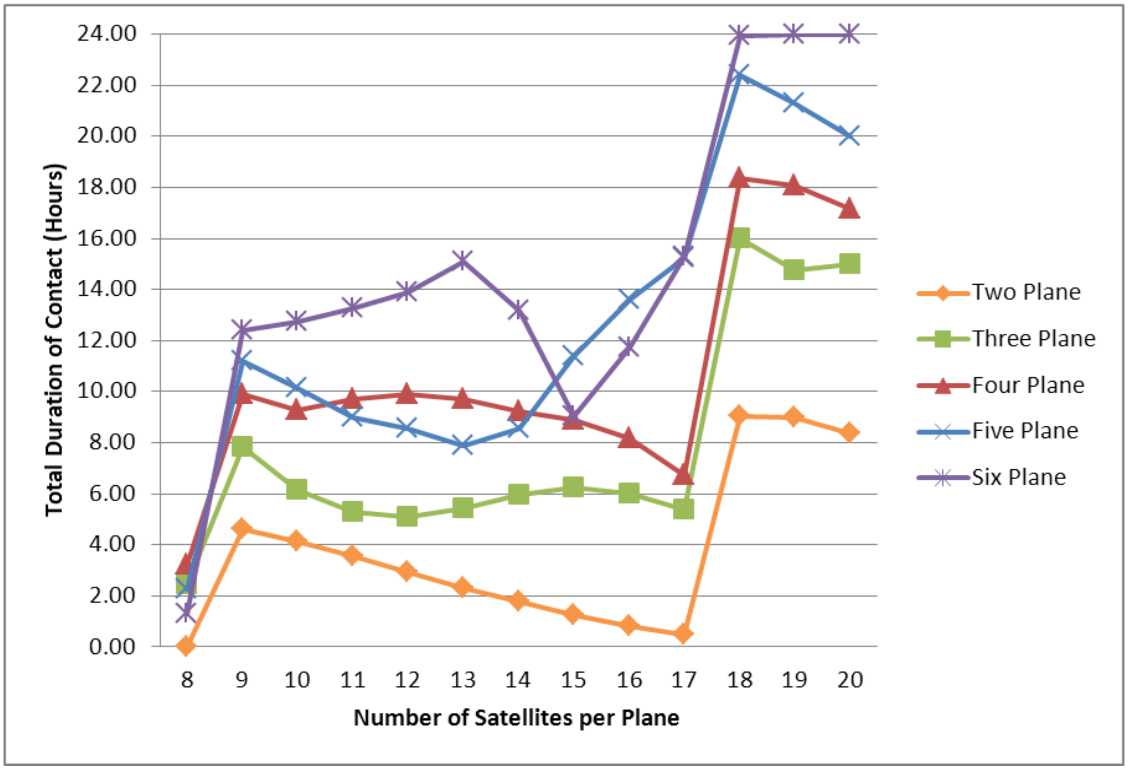
It was also observed that the duration of each individual link for the constellations with 9-17 satellites were very short – in fact, the maximum duration of a single contact over the whole 24 hours period for the constellation with 17 satellites was a mere 36.603 seconds. On the other hand, with 18 satellites in the plane, the maximum duration of contact over a 24 hour period escalates by an impressive 19712.09% to 2.004 *hours* of continuous contact. This one instance of contact accounts for almost 43% of the summed total of all contacts over the 24 hour period.

Knowing that it requires 18 satellites in a single plane for maximum contact from the satellites in the plane sets a daunting precedent. Each plane of satellites must be able to effectively maintain communications for the time when that plane is passing over the two locations. If 18 satellites per plane are required for this to be true, and the conceptual minimum number of planes is three, then the minimum number of satellites hypothetically possible becomes 54. This number is investigated further in the following sections.

4.1.2 Multi-Plane Walker Constellations

After the single plane experiment, more complex Walker constellations were tested for their efficacy in line-of-sight communications. Walker constellations with two, three, four, five and six different planes were tested with a wide range of satellites per plane (SPP). The seed satellite used in the single-plane scenario (51° inclination, 1 kg, 400 km altitude) was also used to collect the data of the multi-plane tests. A significant amount of the simulation results were compiled into Figure 12, which is a graph illustrating the data collected for each system having 8 to 20 SPP.

Figure 12: Total Duration of Contact vs. Number of SPP; 2 to 6 Plane Systems



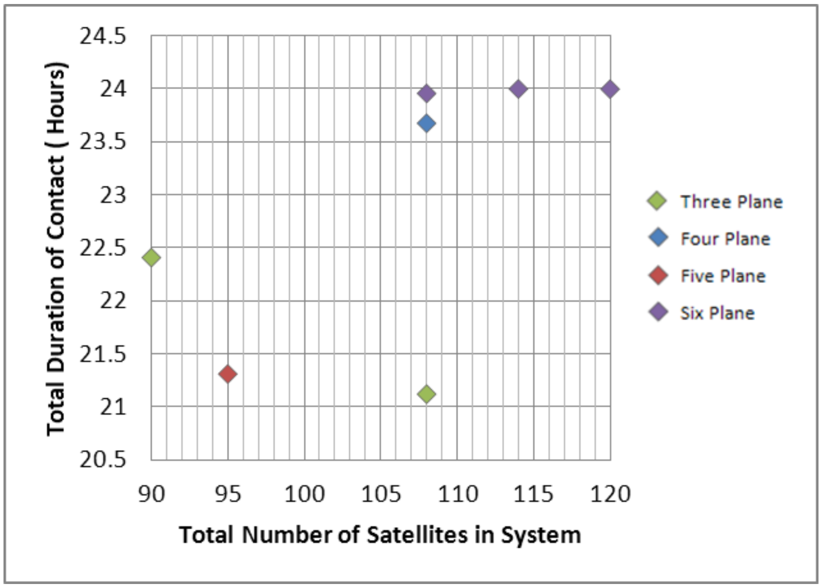
As the graph above indicates, all of the multi-plane systems with an identical seed satelllite to that used in the single-plane experiment exhibit the large jump in line-of-sight duration between having 17 SPP and 18 SPP. This strengthens the idea that, for communications between Huntsville and Tenby to be maintianed for more than 23 out of 24 hours, a minimum of 18 satellites per plane will be required.

Figure 12 only contains the data collected for 8 to 20 SPP. Since the only system that was able to attain more than 23 hours of total contact consisted of

108 satellites (6 planes, 18 SPP), the systems with fewer planes were reexamined to be sure this was the optimal system for the given ground facilities.

Systems with two to five planes were revisted, and this time the number of SPP were increased until the total number of satellites in the system approached 108 satellites. The graph in Figure 13 is the collection of data points for systems that achieved more than 20 hours of total contact; despite the multitude of tested scenarios, there were only seven systems that achieved this.

Figure 13: Total Duration of Contact vs. Total Number of System Satellites



Only four constellations were able to achieve the duration of contact specification stipulated in the design terms. The fact that all the successful systems had at least 18 SPP correlates strongly with the results from the single-plane experiment. These results suggest that any systems with more than 6 planes would follow the same trend – requiring at least 18 SPP. Logically, this means that the existence of a system with fewer than 108 satellites for Tenby – Huntsville communications is highly unlikely.

To be certain, systems with seven, eight, nine and even ten planes were simulated in STK with varying numbers of SPP. No systems with more than 108 total satellites were attempted. Just as was predicted, an acceptable system with fewer than 108 satellites was not obtained. The data supporting this statement is represented in Figure 14.

Figure 14: Total Duration of Contact vs. Number of SPP; 7 to 10 Planes

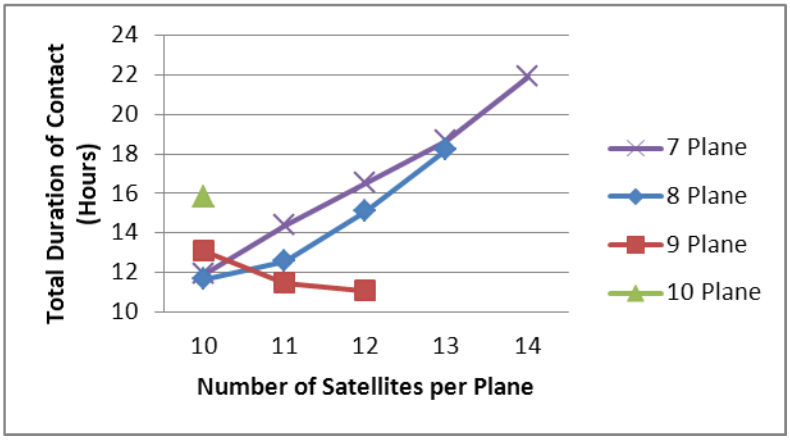


Figure 14 has four data sets, each with a different number of points. This was purposeful to avoid the unnecessary testing of systems with more than 108 total satellites, which would only be redundant and not influential on the overall optimized result.

4.2 Tenby-Huntsville Final Results

The results generated by the Tenby-Huntsville simulation did not provide an optimistic conclusion for a realistically optimized system. Many different configurations were tested, and the minimum number of satellites required to maintain a line-of-sight link for at least 23 out of 24 hours was 108. This optimum configuration consists of a 6 plane Walker constellation with 18 SPP. This number provides a point of reference from which the final system can be compared.

To be sure that this system was stable over more than a 24 hour period, it was tested over an analysis period of the entire month of February. From the STK generated data (Table 2), the daily average of the line-of-sight coverage between Tenby and Huntsville was calculated to be 23.93 hours per day.

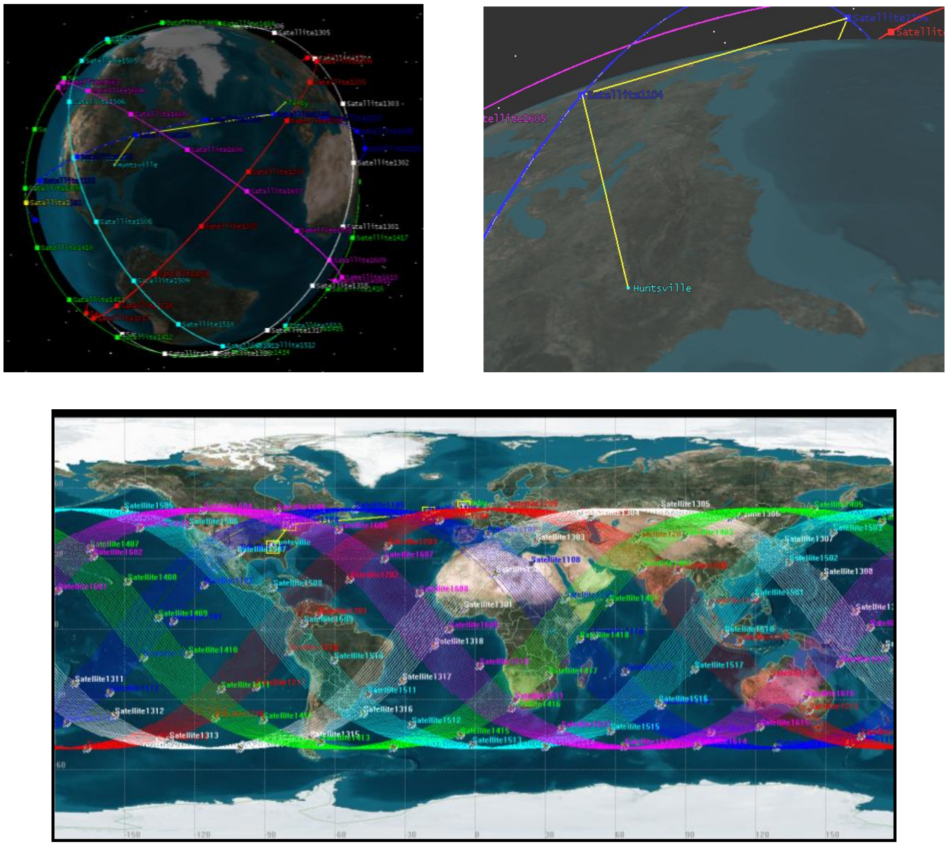
Table 2: Analysis of the Tenby-Huntsville optimized system over a month

6 Plane 18 SPP Over Month of February	Time (Seconds)	Time (Hours)
Minimum Single Duration of Contact	307.517	0.085421389
Maximum Single Duration of Contact	39481.673	10.96713139
Total Duration of Contact	2411872.169	669.9644941
Percent of Time with Line-of-Sight	**0.996970696**	**%**
Average Time/Day with Line-of-Sight	**23.92730326**	**Hours/Day**

Since the system does, on average, comply with the duration of contact specification, it is regarded as a satisfactorily optimized system for the Tenby –

Huntsville scenario. The simulation generated images of the successful Tenby – Huntsville network can be found in Figure 15. In the figure, each satellite orbit plane is acknowledged by a different color, and the communication link path is represented by a yellow line. The 2-D view shows the groundtracks of each satellite, demonstrating the variation of coverage between the satellites in the same plane.

Figure 15: The six plane Walker constellation with 18 SPP (108 Satellites) Top Left) 3-D View; Top Right) Link Path from Huntsville to closest relay; Bottom) 2-D projection



All of the scenarios evaluated in the study between Tenby and Huntsville were completed with the exact same seed satellite. All of the satellites had an inclination angle of 51°, so that the highest latitude reached by the satellites is equal to the latitude of Tenby, the city that is farther north. Pursuing this constellation any further would be a trivial exercise, despite the fact that there are several known factors that could have been adjusted to possibly secure a Tenby – Huntsville system with fewer than 108 satellites

Altering the inclination angle could possibly optimize the system further, but since the system already had 108 satellites, a number that is not realistic for an efficient system, any optimization from manipulating the inclination angle would most likely not be significant. Extensive simulations to evaluate this would ultimately be a waste of time, because a more effective parameter change would be choosing a new downlink location. This process is documented in the subsequent sections.

4.3 A Better Approach: A New Downlink Location

After a failure to design a realistic system (in terms of the total number of satellites) with the downlink location set at Huntsville, Alabama, the approach to the problem was reevaluated. The given specifications were revisited to look for a new tactic in the system design. The result was a change in the downlink location.

Given the purpose of the constellation, which is to relay data from a foreign “area of interest” (in the case of this thesis, Tenby), to a location in the United States, the specific downlink location (so long as it is within the U.S.) is not critical; the military can use a facility anywhere in the continental United

States for data analysis. Previously, the experiment was limited to a downlink in Huntsville, Alabama. To design a better system, new locales were tested.

To decrease the physical distance between the uplink and downlink locations, a downlink in the northeastern region of the United States was the obvious choice. The city of Newport, Rhode Island, which according to the STK facility database is located at 41.7901° N, 71.3128° W, was selected for its coastal location, and proximity to the ground tracks of the satellite seen above in Figure 9. Newport is approximately 5062 km away from Tenby, which is 1495 km closer than Huntsville. Newport is also only 10° of latitude away from Tenby, while Huntsville is 17° away. Both of these factors should contribute to a noticeable difference in system requirements.

The results of the downlink location change were dramatic. The very first attempted network was a Walker constellation with three planes and 18 SPP, for a total of 54 satellites. The results were extremely encouraging, since the system provided 23.42 hours of coverage over a 24 hour period, which satisfies the duration specification.

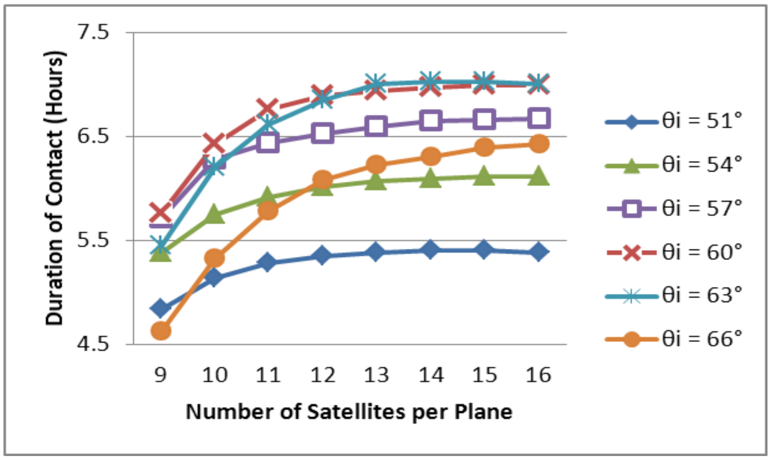
With this outcome so much more favorable than the Huntsville results, the downlink location was shifted a little farther north for a comparison test. The city in the regional northeast of the U.S. that is the farthest north and found in the STK facility database was determined to be Van Buren, Maine – a small city on the border with Canada, with coordinates of 47.1573° N, 67.9353° W. Van Buren is approximately 4495 km from Tenby, which is 567 km closer than Newport. This city was used as the new downlink position.

Using the same testing scenario as the Newport experiment, the Tenby – Van Buren link sustained line-of-sight for 23.82 hours, which is an improvement of 0.4 hours. Due to this improvement, Van Buren was selected as the ideal city for the final optimized system.

4.4 Tenby-Van Buren System Design Method

To establish the optimal design, it was first necessary to determine the best incidence angle for the system. To ascertain this value, a single plane system was evaluated at different angles. By looking at the geography between Van Buren and Tenby, it can be deduced that the best path would extend higher than the latitude of Tenby. For this reason, the angles tested were increased steadily by 3° until a clear change in the direction of growth was observed, which in this instance, occurred between $\theta_i = 63°$ (teal) and $\theta_i = 66°$ (orange), as seen in Figure 16. The data was then evaluated to determine the best inclination angle. From the data in the graph, $\theta_i = 60°$ was chosen as the ideal angle at which to design the system, since it had the best performance for the lower SPP systems.

Figure 16: Contact Duration vs. Number of SPP; For Incidence Angle Design



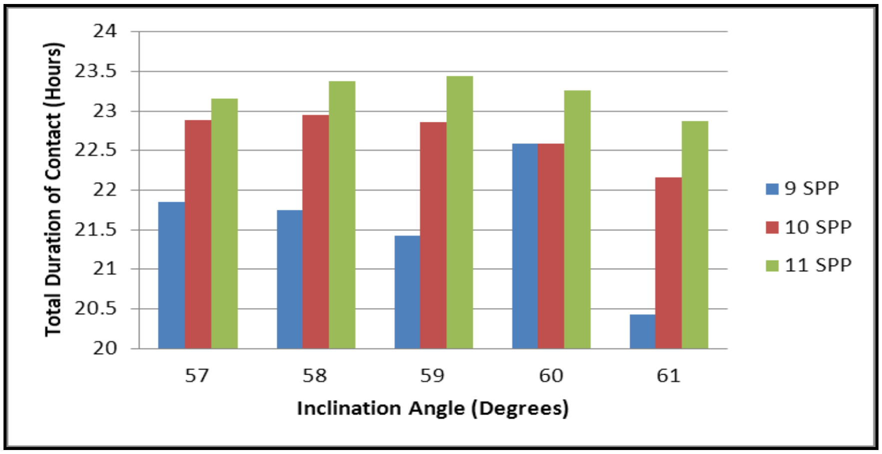
Since the total duration of contact for the single plane system with the inclination angle of 60° was the largest (or comparatively similar) for all of varying numbers of satellites per plane, it can be concluded that this is the inclination angle that would provide an optimal system. Therefore, a satellite with a 1 kg mass, a 400 km altitude, and an inclination of 60° was used as the seed satellite for the Tenby – Van Buren constellation. The results of the tests on the systems with varying numbers of SPP can be seen in Table 3.

Table 3: Simulation results: 3 plane constellation with a seed having θ_i = 60°

Number of SPP	Total Duration of Contact (Hours)
9	21.00706528
10	22.58758194
11	23.25490167
12	23.41898083
13	23.42153528

From the table it is evident that the Tenby-Van Buren system achieves the communication duration spec for a system with 3 planes, and 11 SPP. However, it must be verified that the inclination angle used is indeed the optimum choice, so a minor comparison study was conducted. In this study, three plane systems (as opposed to the single plane systems previously evaluated) were tested while the inclination angle was gradually changed by 1° until the most effective angle was assertively evident. The data analyzed during this process can be seen in Figure 17.

Figure 17: Detailed Inclination Angle Study



Since none of the systems with 9 or 10 SPP achieved more than 23 hours of contact, it is clear that it is not possible to design a Walker constellation system with less than 33 satellites while maintaining the duration of contact specification. The graph indicates that the longest duration is achieved by a system with an inclination angle of 59°, and 11 SPP.

4.5 Tenby-Van Buren Line-of-Sight Results

From the simulations and tests conducted, it can be concluded that the optimized constellation to maintain line-of-sight between Tenby, Pembrokeshire, Wales, and Van Buren, Maine, USA consists of a Walker configuration of 33 satellites. The seed satellite of this constellation has a mass of 1 kg, an altitude of 400 km, and an inclination angle of 59°, and is replicated into a three plane system with 11 satellites per plane.

To be confident of the result, the simulation was extended over an analysis period of the entire month of February, instead of the 24 hour period that begins on February 1st, 2010 at 0000 hours and terminates on February 2nd, 2010 at 0000 hours. The simulation data from the month long analysis period provided the necessary information to determine the average duration of contact each day, and is related in Table 4.

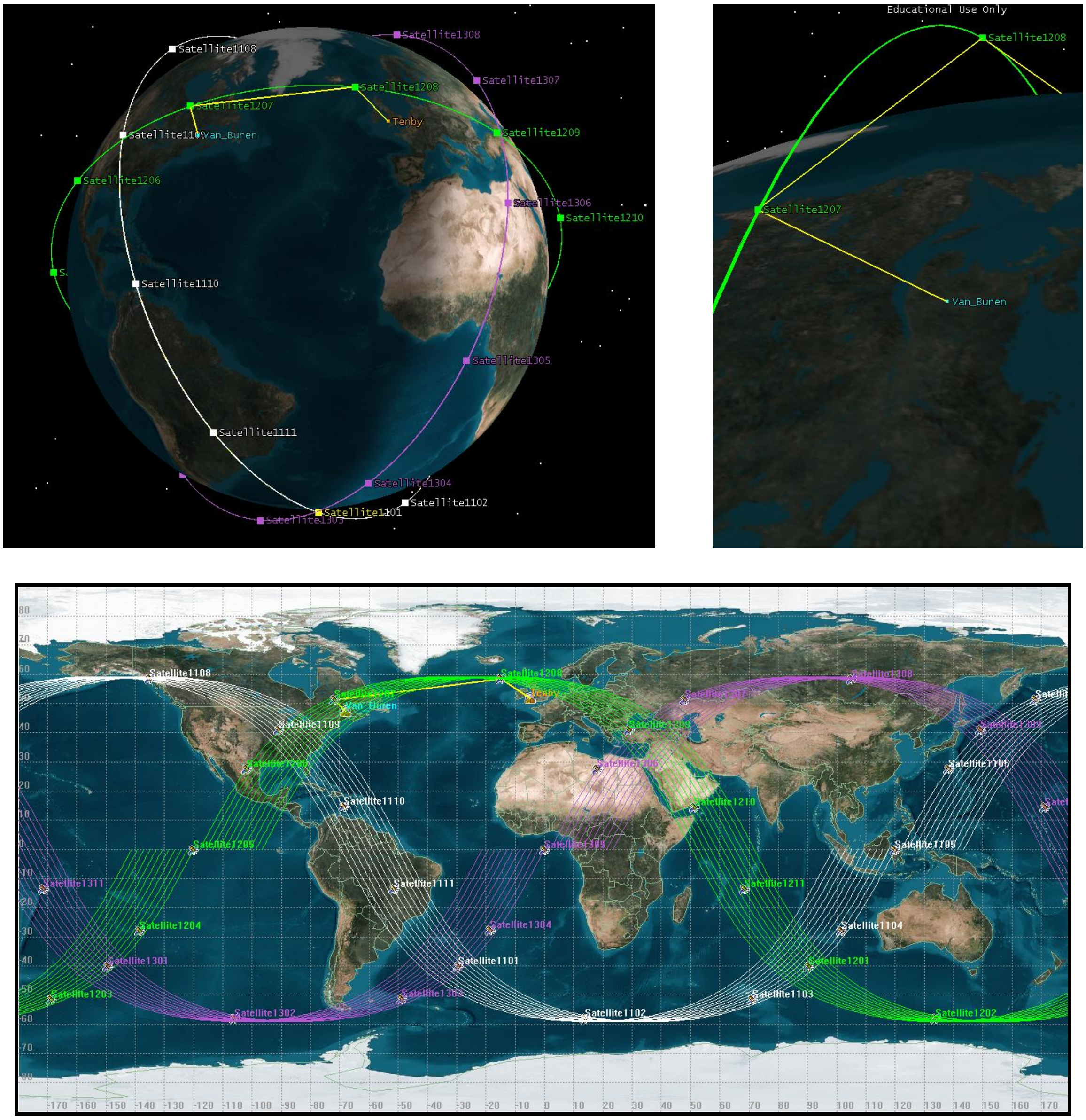
Table 4: Average line-of-sight coverage/day for optimized 33 satellite system

3 Plane 11 SPP Over Month of February	Time (Seconds)	Time (Hours)
Minimum Single Duration of Contact	396.941	0.110261389
Maximum Single Duration of Contact	3157.148	0.876985556
Total Duration of Contact	2362785.389	656.3292747
Percent of Time with Line-of-Sight	**0.976680468**	**%**
Average Time/Day with Line-of-Sight	**23.44033124**	**Hours/Day**

On average, the constellation achieves line-of-sight contact for 23.44 hours per day. As a comparison, the same network with a seed satellite having an inclination angle of 60° was analyzed over the month of February. The results indicated an average of 23.262 hours of line-of-sight contact per day, which is 0.178 hours less than the 59° inclination system. Although the 1° difference does not reduce the number of satellites in the system, the minor duration of contact improvement is a small bonus to the value of the network.

Given the trends in the simulation data, it is safe to declare this constellation the optimized network for an uplink location at Tenby and a downlink location at Van Buren; this constellation is shown in Figure 18.

Figure 18: Optimized Tenby – Van Buren constellation with 33 satellites
Top Left) 3-D view; Top Right) View from Van Buren; Bottom) 2-D Projection



CHAPTER 5 – CONCLUSIONS AND FURTHER RESEARCH

When designing a satellite constellation for beyond line-of-of sight communications, there are many factors that need to be considered. Collecting data from a specific area of interest (uplink location) requires strategic placement of the downlink location as a critical element in network optimization. This was demonstrated clearly in the difference between the Tenby – Huntsville system as compared to the Tenby – Van Buren.

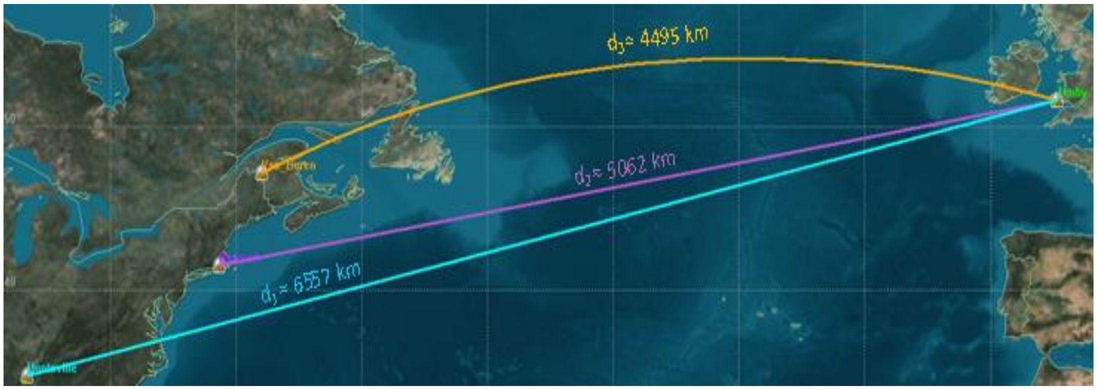
5.1 Line-of-Sight Comprehensive Conclusions

The optimal constellation for the Tenby – Huntsville scenario consisted of 108 satellites (6 planes, 18 SPP). Having such a high number of satellites in a single constellation is not a realistic situation, even if the satellites being used are CubeSats. Even though the total collective mass of all the satellites in the constellation would be less than 108 kg, a low weight in comparison to some single satellite missions (such as the Tropical Rainfall Measuring Mission satellite, TRMM, which by itself had a launch mass of 2394 kg), the shear multitude is problematic. Having so many objects in relatively close orbit could cause a collision hazard or possibly interfere with other systems in orbit.

Conversely, the Tenby – Van Buren scenario successfully accomplished the duration specification with a network of only 33 satellites (3 planes, 11 SPP), which is a mere 30.6% of the satellites of the Tenby – Huntsville system. This network, with a collective mass of only 33 kg, is a much more manageable model. Since the CubeSat standard necessitates the P-POD launch vehicle, all 33 satellites in the constellation could be placed into orbit with only 11 P-PODS; the Tenby-Huntsville system would require 36 P-PODS.

After some study and logical deduction, the cause for the vast difference in the number of satellites between the different networks becomes evident. Figure 19 illustrates the variances in distance, calculated as great arc lengths along the surface of the earth, which contribute to the different satellite network requirements. The significant curvature of the arc between Van Buren and Tenby is the result of the "stretching" of the 2-D projection; the viewpoint of the other two vectors causes a straighter appearance of path, despite the fact that all three are great arc lengths.

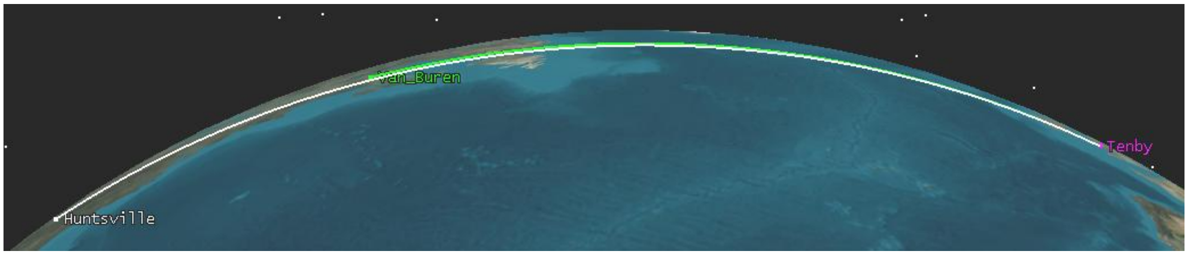
Figure 19: Great arc length between the three downlink locations and Tenby



The distance between Van Buren and Tenby (4495 km) is roughly 68.6% of the distance between Huntsville and Tenby (6557 km). If distance alone was the issue, one would not assume an improvement 75 satellites between the two networks. The fact of the matter is that the earth is an oblique spheroid. The

Huntsville – Tenby network has to overcome more actual arcing than the Van Buren – Tenby network, which is farther north. This concept is illustrated further in Figure 20.

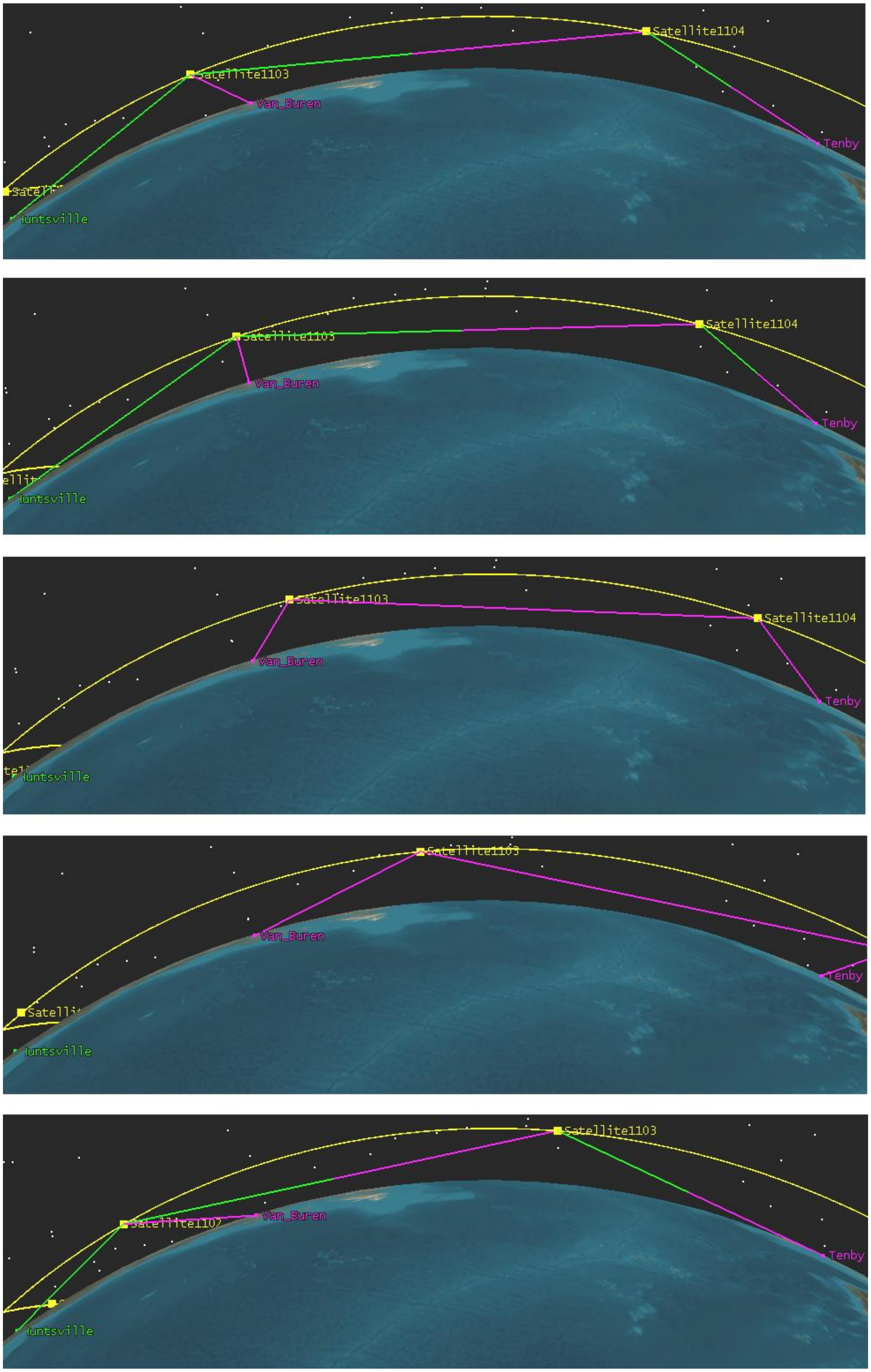
Figure 20: Illustration of earth curvature variances between cities



In the above figure, the surface arc between Huntsville and Tenby is drawn in white, and the arc between Van Buren and Tenby is depicted in green. Even though both networks need a minimum of two satellite hops to cover the distance, the geometry between the Tenby – Van Buren network permits a greater range of view; satellites in LEO are generally lost over the horizon in a matter of minutes, so it is critical that the two satellites in relay can see each other for the maximum allowable amount of time.

To demonstrate this concept further, a line-of-sight link for both scenarios were simulated simultaneously, using the optimized constellation from the Tenby – Van Buren scenario. Using the same viewpoint as Figure 20, successive images were taken with a time step of 60 seconds; these images can be seen on the following page, in Figure 21. In these images, the link between Van Buren and Tenby is illustrated in pink, while the link between Huntsville and Tenby is represented in green. The images where captured at the following times (h:m:s), respectively: 00:00:00; 00:01:00; 00:02:00; 00:03:00; 00:04:30; 00:07:00.

Figure 21: Demonstration of line-of-sight limitations incurred by curvature



Resolutely, the parameters of the optimum system to provide line-of-sight between an uplink location at Tenby, Pembrokeshire, Wales (51.6731° N, 4.7097° W), and a downlink location at a strategically chosen site in the continental United States are as follows:

- Downlink location: Van Buren, Maine, USA (47.1573° N, 67.9353° W)
- Walker Delta Configuration
- Seed Satellite:
  - 1 kg mass
  - 400 km altitude
  - 59° inclination angle
- Number of planes: 3
- Number of satellites per plane: 11

The design specifications mandated an orbit altitude ranging between 200 km and 400 km. The upper limit of this spec was chosen to provide the maximum instantaneous field of view for all satellites, but if deemed necessary, it could be possible that a lower altitude could be used while still maintaining over 23 hours of line of sight.

5.2 Further Research

Due to the time constraints imposed on this thesis, the conclusions of the project were limited to an optimized line-of-sight network. Further research will be conducted to aptly conclude the design specifications of the communications components of the CubeSats in the system.

5.2.1 Design of Communications Hardware Components

STK is equipped to analyze and evaluate constellation communications scenarios, with highly customizable reports that output almost every aspect of the link, including the SNR, bit error rate (BER), flux density, T/R power, and gains, just to name a few. This is accomplished by equipping transmitters and receivers to each of the satellites in the constellation, as well as to the ground facilities (transmitter to the uplink facility, and receiver to the downlink).

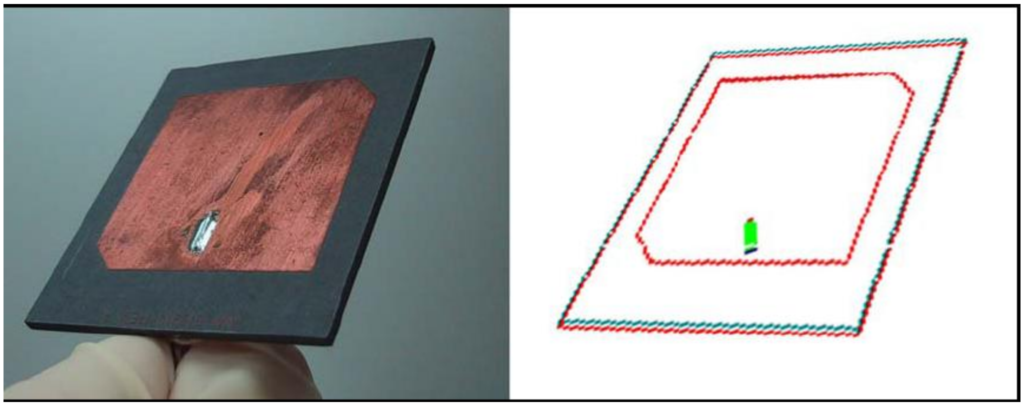
The T/R components can be combined into their own constellation, much like the satellites were for the line-of-sight tests. A link is then specified from the uplink location, through the constellation of T/R components, and then to the downlink receiver. If the communications scenario does in fact make contact, the STK report will identify the times of access, along with all of the data required or specified to analyze the validity of the link.

The STK databases provide basic T/R models that are customizable to the situation at hand. There are simple models, for use from the systems engineering standpoint, as well as a variety of more complex options. The complex models allow for the declaration of antenna type, which is particularly useful in very specific scenarios.

From the research conducted in this thesis, it was determined that the best choice in antenna type is a circularly polarized microstrip patch antenna. In

[18], a patch antenna is evaluated for very similar communications conditions. In this paper, the antenna is being used for a CubeSat called *NarcisSat*, which stipulates a 1 W transceiver, for an operational frequency of 2.4 GHz), with a weight restriction of 100 g, and a size restriction of 10 cm by 10 cm. A COTS patch antenna, shown in Figure 22 (image from [18]), was tested and found suitable for the design needs.

Figure 22: Patch antenna used on *NarcisSat*



This indicates that it is highly probable that there is a COTS patch antenna that operates in the slightly higher frequency range required by the 2.6 GHz signal being used by the constellation of this thesis. Unfortunately, the STK database is not equipped with patch antenna models, and thus using the complex T/R models was an impractical option, given the limited time involved in the system design.

In all attempts to create the STK communications analysis model using the simple T/R models, an output matching the design specs was not attained. For a reason that has not yet been determined, the total SNR of the system diverges upon the satellite-satellite hop. A sample of the report data from one of the communication strands is shown in Table 5 , which is a condensed table of data taken directly from the STK Bent Pipe Communications Link report.

Table 5: Abridged STK Bent Pipe Comm Report for Van Buren Constellation

Time (UTCG)	00:32.1	00:33.9
Xmtr Power1 (dBW)	1	1
EIRP1 (dBW)	14	14
Prop Loss1 (dB)	-168.1227	-168.0838
Rcvd. Frequency1 (GHz)	2.600049	2.600049
Flux Density1 (dBW/m^2)	-124.367589	-124.3287
g/T1 (dB/K)	13	13
C/No1 (dB*Hz)	87.476398	87.515296
Bandwidth1 (kHz)	40000	40000
C/N1 (dB)	11.4558	11.4947
BER1	3.10E-17	2.25E-17
Xmtr Power2 (dBW)	-37.368	-37.329
EIRP2 (dBW)	-37.368	-37.329
Prop Loss2 (dB)	-165.3584	-165.396
Rcvd. Frequency2 (GHz)	1.900015	1.900014
C/No2 (dB*Hz)	-9999.99	-9999.99
C/N Tot.2 (dB)	-9999.99	-9999.99
BER Tot.2	5.00E-01	5.00E-01

Since the transmitter power in the second instance of transmission (Xmtr Power2) is calculated by STK to be -37.368 dBW (which is a mere 183 μW), it is deduced that the problem in communications is the result of the inter-satellite links. With no transmitted power, the received power, which is for all intents and purposes the signal itself, is nullified, and therefore the SNR becomes -9999.99 dB (the smallest value used by STK for this element), which is 0 on the non-dB scale.

It is also interesting to note the change in the received frequencies, which decreases by 0.7 GHz between the satellite to satellite hop. This is most likely due to the DFS, and calculations must be made to determine if the situation requires filters to rectify the issue, similar to the study conducted in [15].

Currently, the method required to fix the matter of the invalid transmitted power from satellite to satellite has not been identified. More research and simulations are required to determine the best method to rectify the LEO-LEO link to provide an acceptable solution.

Despite this setback, it is still believed that a system of 33 CubeSats would be able to achieve the desired goal; it is simply a matter of utilizing STK to its full potential. Future attempts will be made to use the complex T/R models to simulate patch antenna patterns, equipped with the appropriate filters to lessen the evident DFS concern.

5.2.2 Synthetic Aperture Radar

One of the main motivations behind the constellation design is an application with Synthetic Aperture Radar (SAR). There have been many attempts to develop SAR-type systems onboard satellites, without losing resolution from altitude. One such study is described in [21], which developed a chirp scaling algorithm for use in a formation flying satellite interferometric synthetic aperture radar (InSAR) system.

SAR is a method of high resolution mapping from aerial measurements. Using an antenna mounted on a moving aircraft or satellite, successive radar images are collected and correlated to produce high resolution images. "A good SAR might have a resolution in range and cross-range of one meter, but it can be much less if desired." [22] SAR is traditionally only useful for stationary objects, as a result of the method by which the images are collected and combined. This is not always a concern, though, since the goal of a SAR is usually the development of a terrain map, rather than target identification.

One of the more well-known SAR system is onboard NASA's DC-8 aircraft, called AirSAR, which is unofficially dubbed the flying science laboratory. This system was developed by NASA's Dryden Flight Research Center, and has been used for a wide variety of scientific applications, in fields varying from cryospheric science, to physical oceanography, to terrestrial ecology, and hydrology. [23]

InSAR, on the other hand, makes use of the phase angle data that is disregarded by SAR systems. This extra element contributes two new elements to the system output: the ability to detect moving targets, and “the height of the object within a pixel.” [22] The height measurement is especially useful for mapping applications, since it permits the construction of 3-D terrain maps in the form of detailed digital elevation maps.

The largest problem with SAR is the long delay between image updates. To generate one image takes the entire pass of the aircraft or spacecraft. If continuously updated images are required, it is inefficient to make multiple passes in aircraft such as AirSAR, since large jets tend to be heavy on fuel consumption.

This is why using a constellation of satellites in LEO might prove useful for monitoring an “area of interest.” Although it would not be realistic for the CubeSats themselves to be equipped with the full SAR systems, since they greatly exceed the 1 kg weight limit requisite by the CubeSat standard, and it would be extremely expensive to outfit each individual CubeSat with full blown SAR, using the CubeSats for data collection and transmission might one day be possible. Further investigation and research will be placed in adapting CubeSat constellations to SAR applications, in the hopes of improving on the current methods used.

REFERENCES

[1] S. R. Pratt, R. A. Raines, C. E. Fossa Jr., and M. A. Temple, "An operational and performance overview of the IRIDIUM low earth orbit satellite system," *IEEE Communications Surveys,* vol. 2, 1999.

[2] H. J. Kramer and A. P. Cracknell, "An overview of small satellites in remote sensing," *International Journal of Remote Sensing,* vol. 29, pp. 4285-4337, 2008.

[3] A. C. Clarke, "Extra -Terrestrial Relay: Can Rocket Stations Give World-wide Radio Coverage? ," *Wireless World,* pp. 305-308, 1945.

[4] "Technical Report on Space Debris," Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, New York A/AC. 105/720, 1999.

[5] S. Waydo, D. Henry, and M. Campbell, "CubeSat design for LEO-based Earth science missions," in *Aerospace Conference Proceedings, 2002. IEEE*, 2002, pp. 1-435-1-445 vol.1.

[6] C. Clark, A. Chin, P. Karuza, D. Rumsey, and D. Hinkley, "CubeSat communications transceiver for increased data throughput," in *Aerospace conference, 2009 IEEE*, 2009, pp. 1-5.

[7] T. Vladimirova, X. Wu, K. Sidibeh, D. Barnhart, and A. H. Jallad, "Enabling Technologies for Distributed Picosatellite Missions in LEO," in *Adaptive Hardware and Systems, 2006. AHS 2006. First NASA/ESA Conference on*, 2006, pp. 330-337.

[8] J. Bai, X. Lu, Z. Lu, and W. Peng, "Compact explicit multi-path routing for LEO satellite networks," in *Workshop on High Performance Switching and Routing, 2005. HPSR.* , 2005, pp. 386-390.

[9] A. Valdez, C. Hu, C. Kitts, M. Breiling, A. Slaughterbeck, J. Ota, D. Hadi, T. Kuhlman, and S. Lyons, "The Artemis project: Picosatellites and the feasibility of the smaller, faster, cheaper approach," in *Aerospace Conference, 1999. Proceedings. 1999 IEEE*, 1999, pp. 235-243 vol.2.

[10] S. S. Sung, J. D. Roque, B. T. Murakami, G. S. Shiroma, R. Y. Miyamoto, and W. A. Shiroma, "Retrodirective antenna technology for CubeSat networks," in *Wireless Communication Technology, 2003. IEEE Topical Conference on*, 2003, pp. 220-221.

[11] S. M. Azizi and K. Khorasani, "Cooperative fault accommodation in formation flying satellites," in *Control Applications, 2008. CCA 2008. IEEE International Conference on*, 2008, pp. 1127-1132.

[12] R. A. Serway and J. W. Jewett Jr., *Physics for Scientists and Engineers*, 6 ed. vol. 1. Belmont, CA: David Harris, 2004.

[13] T. Pratt, C. W. Bostian, and J. E. Allnutt, *Satellite Communications*, 2 ed.: John Wiley & Sons, 2003.

[14] "NASA Safety Standard: Guidelines and Assessment Procedures for Limiting Orbital Debris," Washington D.C. NSS 1740.14, 1995.

[15] E. Duca, "Background noise limitations on optical intersatellite links for data relay applications," in *11th International Conference on Transparent Optical Networks, 2009. ICTON '09.* , 2009, pp. 1-4.

[16] S. J. Orfanidis, "Chapter 18: Aperture Antennas," in *Electromagnetic Waves and Antennas*, 2010.

[17] "Telecommunications: Glossary of Telecommunication Terms," N. T. I. A, Ed. Arlington: Gerneral Services Administration Information Technology Service, 1996.

[18] K. Doerksen, J.-F. Levesque, and I. Mas, "Design, Modeling and Evaluation of a 2.4 GHz FHSS Communications System for *NarcisSat*," in *17th AIAA/USU Conference on Small Satellites* Logan, Utah, 2003.

[19] E. Duca, "Background noise limitations on optical intersatellite links for data relay applications," in *Transparent Optical Networks, 2009. ICTON '09. 11th International Conference on*, 2009, pp. 1-4.

[20] N. Haridas, T. Arslan, and A. T. Erdogan, "Multiband Antenna for Space Based Reconfigurable Satellite Sensor Node," in *Wideband, Multiband Antennas and Arrays for Defence or Civil Applications, 2008 Institution of Engineering and Technology Seminar on*, 2008, pp. 195-202.

[21] Q.-l. Zhang and Y.-b. Lu, "The study on imaging algorithm of formation flying satellites InSAR system," in *Synthetic Aperture Radar, 2007. APSAR 2007. 1st Asian and Pacific Conference on*, 2007, pp. 27-31.

[22] M. I. Skolnik, *Introduction to Radar Systems*, 3rd ed. New York: McGraw-Hill, 2001.

[23] M. Curry, "DC-8 Airborne Laboratory: Dryden Flight Research Center," Edwards, CA: NASA, 2004.