Cape Peninsula
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IN-SITU MONITORING USING NANO-SATELLITES: A SYSTEMS LEVEL APPROACH

by

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DECLARATION

I, Benjamin Deon Dixon, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

Traditional satellite systems employed for use with in-situ monitoring systems are large satellites that have a long development time, high cost and complex sub-systems. The end use of relaying data for in-situ monitoring becomes a costly application for the end user. Shifting this application to make use of nano-satellites, such as CubeSats, for data relaying will make the application more attractive to the end user when measurements are required outside existing ground based communications infrastructure. CubeSats are small, simple satellites that yield a short development time and very low cost compared to conventional satellites. Their sub-systems are generally built from off the shelf components. This keeps the designs simple, manufacture cost low with the potential for flying the latest technologies.

This research set out to analyse various scenarios related to in-situ monitoring governed by parameters such as the maximum revisit time, satellite orbit altitude, quantity of sensor nodes and data quantity relayed in the system. A systems level approach is used to analyse each designed scenario using a simulation tool called Systems Tool Kit by Agilent Graphics Incorporated.

The data acquired for each scenario through simulation was validated using theoretical approximation methods, which included parameters such as coverage potential, total node access time, communication link performance, power resources, memory resources, access time and number of ground stations. The focus was put on these parameters since they are the main constraints when designing a system using nano-satellites.

The outcome of the research was to create an analysis reference for designing an in-situ monitoring system using nano-satellites. It outlines the methods used to calculate and simulate each of the constraints governing the system. Each designed scenario showed satisfactory performance within the defined parameters and can be practically implemented as a reference for designing similar systems.

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GLOSSARY

ADC	Analog to Digital Convertor
AGI	Agilent Graphics Incorporated
ASC	Asynchronous Serial Communication
B	Bytes
b	Bits
b/s	Bits per Second
BER	Bit Error Rate
Cal Poly	California Polytechnic State University
CDMA	Code Division Multiple Access
CPU	Central Processing Unit
dBi	Decibel Isotropic
dBW	Decibel Watt
ECI	Earth-centered Inertial
EPS	Electrical Power System
FDM	Frequency Division Multiplexing
FOV	Field of View
FPGA	Field Programmable Gate Array
GB	Gigabyte
GHz	Gigahertz
GSM	Global System for Mobile Communications
I^2C	Inter-integrated Circuit
IAA	Instantaneous Access Area
IC	Integrated Circuit
IP	Internet Protocol
kb	Kilobits
kB	Kilobytes
kb/s	Kilobit per Second
kHz	Kilohertz
LEO	Low Earth Orbit
LNA	Low-Noise Amplifier
mAh	Milliamp Hour
Mb/s	Megabit per Second
MEO	Medium Earth Orbit
MHz	Megahertz
mW	Milliwatt

NORAD	North American Aerospace Defence Command
OBC	On-board Computer
PC/104	Connector Socket with 104 connections in 4 rows and 26 columns
PCB	Printed Circuit Board
P-POD	Poly Picosatellite Orbital Deployer
PV	Photovoltaic
RS232	Telecommunications Standard
SD	Secure Digital
SPI	Serial Peripheral Interface
SSC	Synchronous Serial Communication
STK	Satellite Tool Kit
TB	Terabyte
TDM	Time Division Multiplexing
TLE	Two-line Element
TMR	Triple Modular Redundancy
TT&C	Telemetry, Tracking and Control
UHF	Ultra High Frequency
USB	Universal Serial Bus
UTCG	Universal Time Code Generator
VHF	Very High Frequency
W	Watt of Power
W/m^2	Watts per Meter Squared
Wh	Watt Hour

CHAPTER ONE

INTRODUCTION

1.1 Overview

This chapter introduces the subject, the research problems and objectives associated with it, the methodology and the structure of the document.

1.2 Background

An in-situ monitoring system uses sensor nodes to collect data of the surrounding environment or variable where it exists. This is opposed to indirect monitoring methods that employ sensors which collect data about the environment or variable at a distance away, not coming in direct contact with the variable being monitored. The sensors used for in-situ monitoring are sensors such as temperature, flow, humidity, light intensity, vibration and radiation sensors to name but a few.

The sensor data is collected by converting the analogue data from the sensor into digital data by the use of analogue to digital convertors (ADC). Once data is converted into a digital format it can be processed by a central processing unit (CPU). In the case of a sensor for in-situ monitoring, extreme processing is not done locally, for light processing tasks CPUs such as Microcontrollers or Field Programmable Gate Arrays (FPGA) are used.

The sensor node requires a data storage medium to retain data until it is retrieved on a communication medium. Digital data is stored on non-volatile memory which retains the data in case of power loss to the sensor node. Non-volatile memories exist in Integrated Circuit (IC) packages containing NAND logic memory for retaining the data. The storage requirement of the memory is dependent on the digital conversion resolution, sampling period and time between data retrieval.

Various options of communication with a sensor node exist for retrieval of data. The method of data retrieval depends on the environment the sensor node exists in. In the case of the node being in an environment with an existing power and communications infrastructure, data retrieval occurs through hard wired communication such as Universal Serial Bus (USB) or the RS232 standard for wired communication. Wireless communication is also possible through Wi-Fi or GSM cellular networks.

In the case where the sensor node exists in an environment with no communications infrastructure, data retrieval methods become limited. Current methods that exist include satellite communication systems or maintenance teams physically downloading data from the sensor node (Guo *et al.*, 2012).

A focus is put on an in-situ monitoring system that exists in rural areas using a satellite communication system for data retrieval from sensor nodes. Rural areas are defined for this research as an area without an existing power or communication infrastructure.

Satellites come in various shapes and sizes; focussing on a weight category of satellites known as nano-satellites. These satellites have a weight of 1 to 10 kilograms (kg). Within this class of nano-satellites there is a form factor known as a CubeSat, these satellites are made up of cubes measuring 10cmx10cmx10cm and restricted to a weight of 1.33 kg (Cal Poly SLO, 2009). They are small and lightweight in comparison to the satellites currently used for satellite in-situ monitoring systems. The CubeSat form factor is used to wirelessly relay sensor node data to ground stations which distribute the data on existing communication infrastructure. The sensor nodes and ground stations within such a system form the ground segment, whereas the satellites used to relay the data form the space segment.

The main objective of this research is to explore the use of CubeSats for in-situ monitoring systems and operation within the constraints in the space segment that accompany the small size of nano-satellites. Through simulation and theoretical approximation analysis will be done on various scenarios governed by specified parameters. The end result will yield an analysis reference for parameter calculation or designing similar in-situ monitoring systems.

1.3 Problem Statement

In-situ monitoring in rural areas can be challenging due to the lack of a communications infrastructure. Data retrieval can be done by physical means or by a system of large conventional satellites, such as Orbcomm. The cost of conventional satellites is very large, in the order of $650,000,000 for sophisticated satellites (Abdalati, 2011), which make them inaccessible for smaller organizations. The cost to launch a conventional satellite into space is a major contributor of the total cost; it is directly related to the weight of the satellite.

Another disadvantage of conventional satellites is the long development time, which can take longer than 10 years. Depicted in the lifespan of GSat 14, launched January 2014, it has been in development for 12 years (Gunter Dirk Krebs, 2014). Nano-satellites however provide a short development time of 1 to 2 years. Their cost incurred is low compared to conventional satellites due to their small size and usage of off the shelf technologies. Figure 1.1 (Enfinio, 2014) shows that the cost to make changes in a design later in the project's life is very high compared to the early stages; taking into consideration the short development time of nano-satellites, they are more cost effective to fly latest technologies than larger satellites.

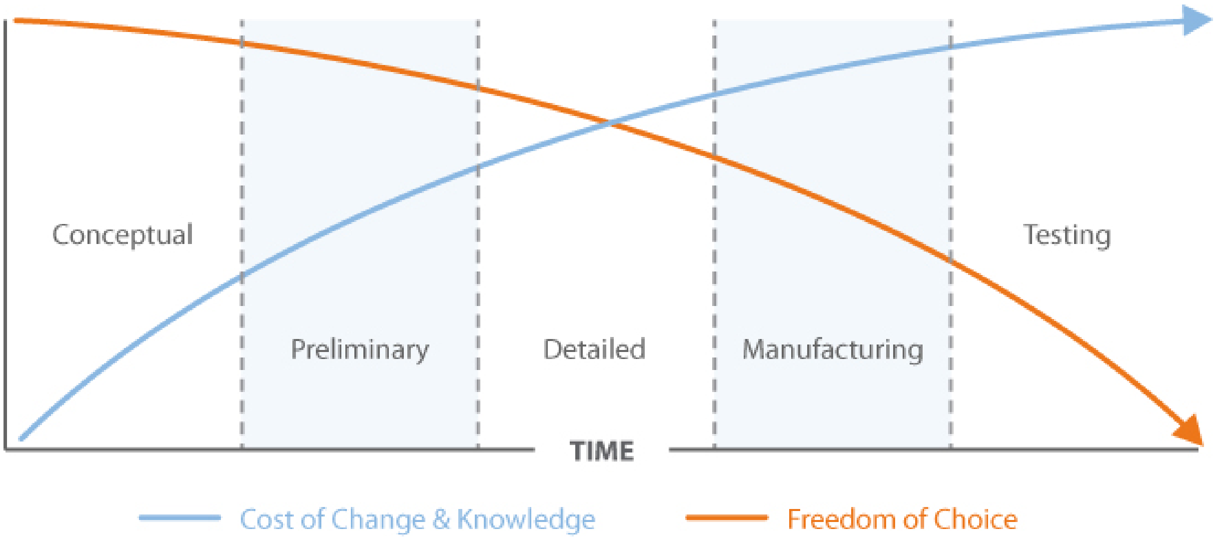


Figure 1.1: Product Design – Freedom of Choice vs. Cost of Change

The usage of nano-satellites is not without its challenges, the small size creates a design challenge regarding the use of minimal resources and an inability to implement redundancy. This normally limits nano-satellites to a specific use per mission as opposed to conventional satellites which have multiple uses. The small form factor may also create a challenge regarding communication since the available power is limited, this will limit the communication speed between nano-satellite, sensor node and ground station.

The problem is designing an in-situ monitoring system using nano-satellites within the limitations as mentioned in the previous paragraph. The resource constraints will limit the scalability of the system. This research will investigate available technologies, and their capabilities, to design realistic scenarios of in-situ monitoring for analysis.

1.4 Research Questions

In order to determine the various constraints of an in-situ monitoring system using nano-satellites, several aspects require investigation. These aspects are set out as follows:

- Communications
    - The minimum access duration to a sensor node for the given scenario?
    - The minimum access duration to a ground station for the given scenario?
    - The maximum ground coverage area of a nano-satellite?
    - The maximum revisit time for a given constellation?
    - The duration of communication for uplink and downlink above specified Bit Error Rate (BER)?
    - The maximum number of sensor nodes per ground station?
    - The maximum number of sensor nodes within satellite's Instantaneous Access Area (IAA)?

- Memory
    - The memory required on board a sensor node and satellite to store collected data?
- Power
    - How much power is available to the nano-satellite for a given scenario?

These questions will be investigated for several scenarios with varying sampling resolutions, sampling periods and revisit times which will be defined in Chapter Three.

1.5 Research Objectives

This research deals with a system point of view for specifying the requirements of an in-situ monitoring system using nano-satellites, specifically 1U - 3U CubeSats. The main objectives for this research are:

- Estimation of scenario performance characteristics using theoretical approximation methods acquired from literature studies involving space mission analysis, while staying within limitations of existing technologies. This includes parameters such as access durations to sensor nodes and ground station, ground coverage, revisit time, communication link performance, sensor node capacity, memory requirements and power requirements; it excludes parameters such as satellite orbit lifetime, component lifespan and launch determination.
- Validation of the theoretically estimated scenario parameters through use of a simulation tool, namely Satellite Tool Kit (STK).
- Compilation of scenario capabilities in accordance with parameters mentioned in research questions.

1.6 Research Methodology

The study will require thorough research into various aspects of the system to successfully determine the requirements of the system and meet the research objectives. These aspects are as follows:

- Define scenarios with varying sampling resolutions, sampling periods and revisit times.
- Research the various parameters required to accurately simulate defined scenarios.
- Theoretical analysis of scenario capabilities to serve as an estimation to validate simulation outputs.
- Analysis of scenarios using the software tool, STK, to generate accurate data on defined scenario capabilities.
- Calculation of system sensor node capacity regarding various sample rates and resolutions.

1.7 Delineation

The research will not include in-depth research into, or design into sub-systems for an in-situ monitoring system using nano-satellites. Inter-satellite communication is assumed during analysis of certain scenarios but does not form part of the in-depth research. This research focusses on a systems point of view for analysis of each scenario, which does not require component level designs.

1.8 Thesis Outline

The thesis is composed of five chapters and several appendices. Chapter Two gives a background on in-situ monitoring systems and all sub-systems involved to create a realistic scenario for analysis. Chapter Three covers the scenario designs chosen for analysis. Chapter Four is based on the simulations, theoretical approximation and results gathered during the analysis of the scenarios. Chapter Five discusses conclusions derived from analysis and recommendations for future work. Attached appendices illustrate various simulation results obtained from the simulation software, STK.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

Chapter Two sets a background on in-situ monitoring and nano-satellite systems. Various existing technologies are investigated which forms a basis upon which the parameters of the in-situ monitoring system is defined.

2.2 Space Segment: Nano-satellites

Nano-satellites are starting to make a large impact in the world, they shifted from being used merely as a learning platform for students to becoming a basis for application specific commercial systems. Through the miniaturization of electronic components and systems over the past several years the nano-satellite has become a popular form of satellite for several applications. A popular form of nano-satellite is the CubeSat, which is defined as a small satellite no larger than 10cmx10cmx10cm, weighing no more than 1.33 kg. CubeSats were originally formulated by Bob Twiggs in the late 1990's at Stanford University. They were a platform for students to use cost effective off the shelf electronic components and devices to create small satellites for educational purposes. CubeSats became attractive for commercial use through their low cost and short development time, which is normally around 12 -18 months. These also cost a fraction of the cost to launch compared to conventional satellites due to their standardized form factor (Rogers & Summers, 2010) and low orbital altitudes.

The standard for CubeSats arose for the need to lower the cost of launch and the ability to use a standardised launch and deployment platform. These standards are governed in the CubeSat Design Specification document as set up by California Polytechnic State University (Cal Poly) and Stanford University. The standardized deployment mechanism, Poly Picosatellite Orbital Deployer (P-POD), was developed by Cal Poly as part of the CubeSat program to ensure safety of the launch vehicle and provide the basis for small payload space missions. Figure 2.1 shows an example of a P-POD and CubeSats (Cal Poly SLO, 2009). Each P-POD is capable of deploying three 1U CubeSats or one 3U CubeSat. A 1U CubeSat has the dimensions of 10cmx10cmx10cm and a 3U CubeSat has the dimensions of 10cmx10cmx30cm (Cal Poly SLO, 2009). Larger CubeSats such as 4, 6 and 12U also exist, which provide more physical space for more complex systems.

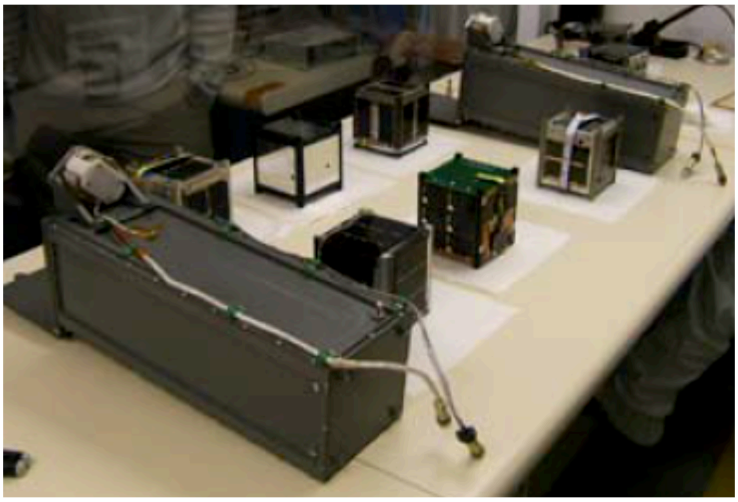


Figure 2.1: Six 1U CubeSats and P-POD Deployment Systems

Nano-satellites can form a viable basis for in-situ monitoring in remote areas where no communication infrastructure exist. This is due to their low cost and fast development time. One of the more popular methods of in-situ monitoring data acquisition in remote areas currently include data stored on board the monitoring system within non-volatile memory which is routinely acquired by maintenance teams (Guo *et al.*, 2012). This is a tedious process especially if the in-situ monitoring takes place in distant rural areas.

2.2.1 Structure

The structure of a 1U CubeSat as stated before is a cube of 10cmx10cmx10cm, this requires a frame that will from the rigid structure to encapsulate all systems. This structure is required to be strong as to withstand the forces and vibrations of the launch into space. It is also required to be as lightweight as possible. Such frames are machined from metal alloys such as aluminium alloys which are strong and lightweight (Dolengewicz *et al.*, 2010). Other multiples of the 1U exist, such as a 2U which is 10cmx10cmx20cm, 3U which is 10cmx10cmx30cm etc. Figure 2.2 (Dolengewicz *et al.*, 2010) shows an example of a 1U CubeSat frame. Currently 4, 6 and 12U CubeSats are also under development which uses a modified P-POD for deployment.

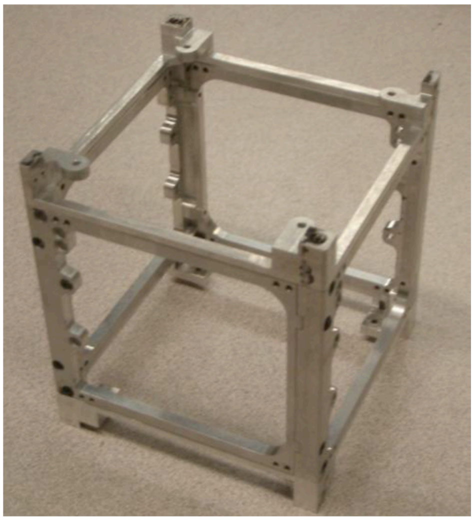


Figure 2.2: 1U Cube Frame Manufactured from Aluminium Alloy 6061

2.2.2 Subsystems

CubeSats are comprised of various sub-systems specific to the mission of the satellite. The internal systems are shaped to the same form factor of the CubeSat to fit in the 10cmx10cm dimension. The systems are connected via a PC/104 connector bus which connect all sub-system PCBs. In this section some of the commonly found systems on-board a CubeSat is discussed.

2.2.2.1 On-Board Computer

The On-Board Computer (OBC) is responsible for all house-keeping operations, task management and execution within the satellite. It features a CPU, normally in the form of a microcontroller or FPGA to do all computational operations. The communication between the various systems happen on interfaces such as the Inter-Integrated Circuit (I^2C), Synchronous Serial Communication (SSC) or Asynchronous Serial Communication (ASC) bus which is controlled and regulated by the OBC (Ahmad *et al.*, 2011). Some CubeSat designs may also implement two OBCs for redundancy such as the Belgian OUFTI-1 (De Dijcker, 2011). Figure 2.3 (Clyde Space, 2014) shows an example of an OBC manufactured by Clyde Space; note the form factor and the header on the bottom right of the board which is the PC/104 interface bus between sub-systems.

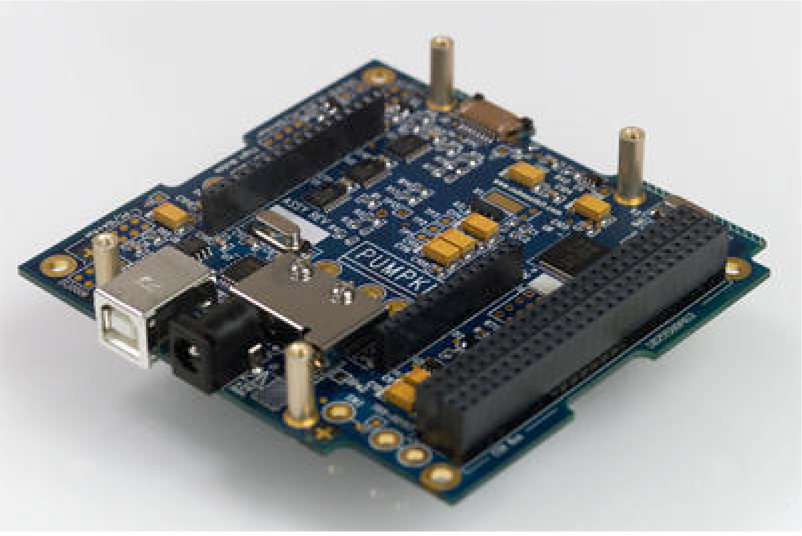


Figure 2.3: Clyde Space Pumpkin OBC

2.2.2.2 Communication Module

The communication module provides a nano-satellite with the ability to communicate wirelessly with other satellites, ground stations and sensor nodes. It provides radio modulation schemes, data encoding, error detection and power to antennas. A communication module is defined with a maximum data rate, in bits per second (b/s), operating frequency band(s) and power requirements for transmit and receive operations. The SWIFT-SLX communications module in Figure 2.4 (Tethers Unlimited, 2014) is an S-Band transmitter and dual L-Band/S-Band receiver. It is designed to fit into 0.25U of a CubeSat and kept to a low weight of only 250 grams. It features scalable power consumption for different modes of operation, the maximum power requirement for a single transmit and dual receive is 10.3W.

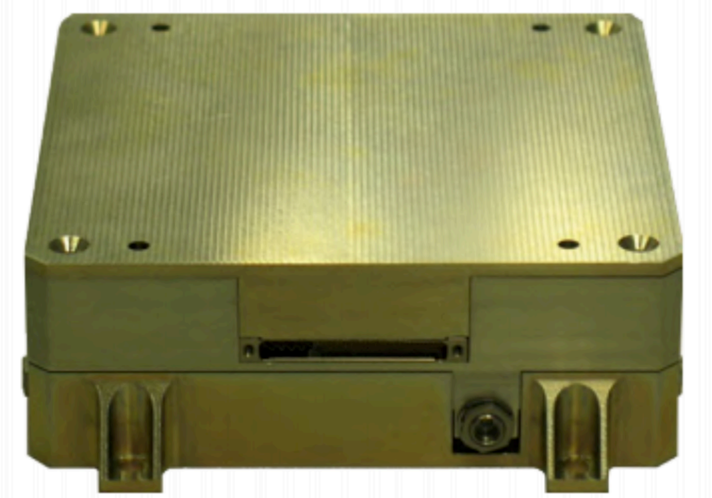


Figure 2.4: SWIFT-SLX Communications Module

2.2.2.3 Electric Power System

The electrical power system (EPS) of a CubeSat is solely responsible for power distribution and regulation within the satellite. It routes power from the batteries and/or solar cells to all sub-systems on-board the satellite through several power busses. These power busses may be regulated to 3.3V, 5V or left unregulated. The routing and housekeeping operations of the EPS are controlled by the OBC which is connected through an I^2C bus. Power generated from solar cells is used to recharge the on-board batteries, which are depleted during solar eclipse when the solar cells cannot generate any power. Figure 2.5 (Bester *et al.*, 2012) shows a general EPS block diagram for a CubeSat.

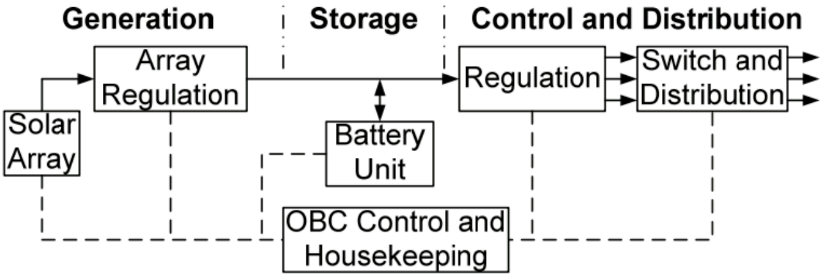


Figure 2.5: Breakdown of the Electrical Power System

2.2.2.4 Power Generation and Storage

In earth orbit the most abundant power source available is the radiated energy from the sun. This is best converted to electrical energy through means of a photovoltaic (PV) cell. A PV cell converts photons radiated from the sun to an electrical potential by means of semiconductor materials, such as silicon. Figure 2.6 (Wikipedia, 2014) shows a basic solar cell for general purpose use.

The rated power of solar cells can vary greatly between manufacturer due to the manufacturing processes used and the type of solar cell, e.g. monocrystalline or polycrystalline silicon, which varies in efficiency. During the mission design it should be established what power rating and type of panel is required. This will determine factors such as cost, size and weight.

Figure 2.6: Basic Solar Cell

Various solar panel configurations exist for CubeSats to harness electrical power from solar radiation; determined by the structure form factor such as 1U, 2U, 3U etc. Solar panels can be mounted onto the sides of the frame, additional deployable panels can be added if more power is required. Figure 2.7 (Clyde Space, 2014) shows various solar configurations available from Clyde Space for CubeSats.

Figure 2.7: CubeSat Solar Panel Configurations

Electrical power requires a storage medium to store excess power for use during the eclipse portion of the orbit. Various space compliant battery types exist, however discussion on battery types does not form part of this research. The main concern is to have a battery with sufficient capacity to supply uninterrupted power to the satellite during eclipse, therefore the mAh rating of the battery is entirely dependent on the mission requirement. The battery requirement will also determine what the final weight, size and lifetime of the battery will be, which will have to be adjusted accordingly to fit the mission specific constraints.

Many readymade battery products for CubeSats exist that can simply be purchased according to the mission specification. Figure 2.8 (GomSpace, 2014) shows an example of an available CubeSat battery product made by GomSpace, it is an 8.4V 5200mAh battery module that includes a temperature sensor and battery heater. A battery heater is required in space during the eclipse cycle to keep the batteries at nominal operating temperature and extend lifetime.

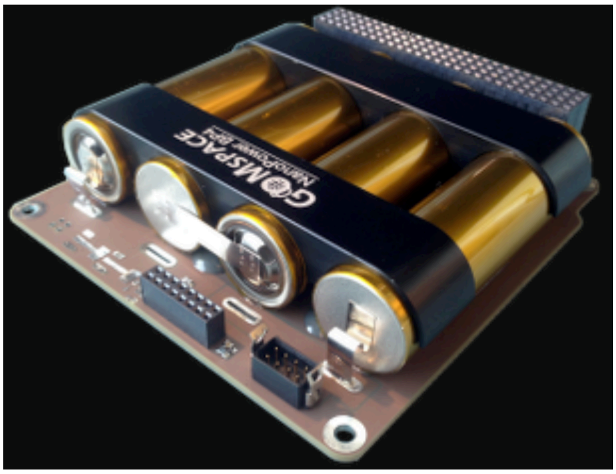
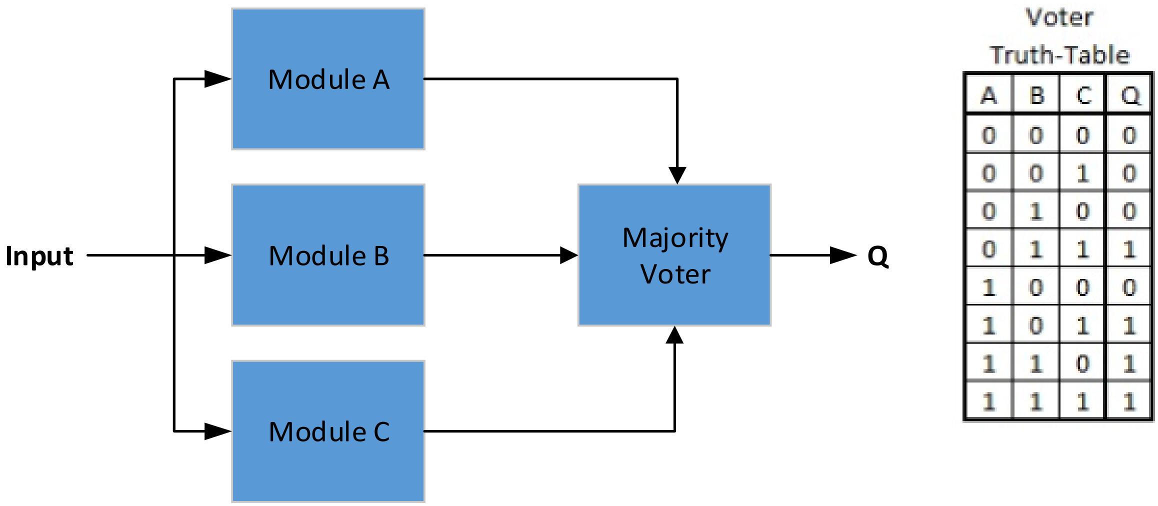


Figure 2.8: CubeSat Battery Module

2.2.2.5 Data Storage

An in-situ monitoring network will generate amounts of data that the memory on-board the microcontroller or FPGA of the OBC cannot accommodate. External data storage is required between overpasses of the ground station. A simple off the shelf solution is to store all sensor node data on a Secure Digital (SD) card. SD cards offer a viable solution for CubeSats since they are low cost, small and light weight. They are simple to interface on a Serial Peripheral Interface (SPI) bus with the OBC. They offer a large storage capacity which can accommodate an extensive in-situ monitoring network. The SDXC specification governs SD cards for capacities of 32 GB up to 2 TB (SD Group, 2013), the largest SD card currently available on the market at time of writing is 512 GB.

Off the shelf SD cards are not radiation hardened and will be susceptible to data errors through single event upset. Low earth orbit (LEO) has lower levels of radiation than satellites in higher orbits; this may offer some protection from single event upset. Nimmagadda suggests implementation of a highly reliable file system. Such a file system does error correction in case of single event upset. Triple Modular Redundancy (TMR) implementation is a form of error checking and correction by storing three copies of each file (Nimmagadda, 2008). The three files are checked and the majority of 3 bits are assumed to be correct. If two of the same bits of the three files are the same, it is taken to be the correct state, this increases the ability to withstand flipped bit errors due to single event upsets. The TMR block diagram and Voter Truth-Table in Figure 2.9, adapted from (Nimmagadda, 2008), shows how this file system is implemented in any type of memory.



A	B	C	Q
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Figure 2.9: TMR Block Diagram and Voter Truth-Table

2.3 Ground Segment: Sensor Networks

Sensors nodes located in remote locations used for in-situ monitoring require various additional sub-systems for operation compared to sensor nodes located in areas with adequate infrastructure. As stated in Chapter One, the lack of a power and communications infrastructure require that alternate methods be used. The power sub-system will be discussed in Section 2.4.2 of this chapter. Figure 2.10 shows a generic block diagram for the sensor node of an in-situ monitoring system with all relevant sub-systems.

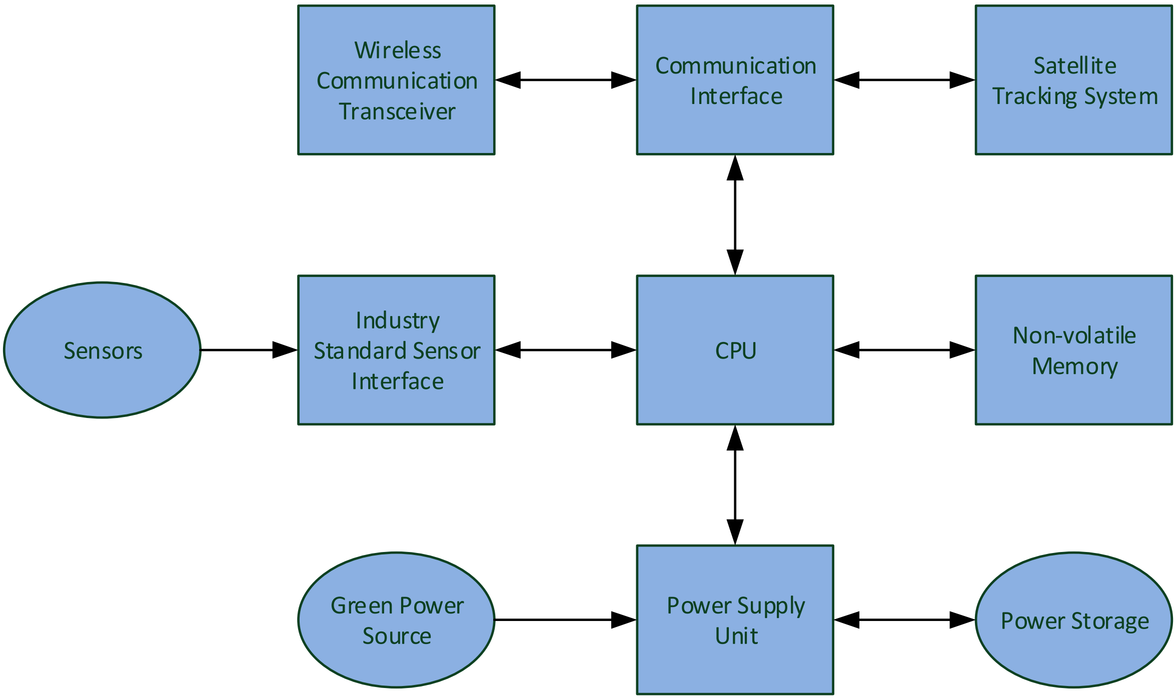


Figure 2.10: Remote Sensor Node Block Diagram

2.3.1 Communication System

Satellites, specifically nano-satellites, form the backbone of the in-situ monitoring communication system. The satellites are used to relay the sensor data to a ground station, where it is distributed to the user through existing communications infrastructure.

2.3.1.1 Wireless Transceiver

The wireless transceiver handles all wireless communication processes such as the carrier modulation, transmitting and receiving of data, error checking, input signal amplification and power signal output to the antenna. The data rate (b/s) requirement of the transceiver depends on the specific scenario of in-situ monitoring. A sensor node with a high sampling rate and resolution would require the transceiver to transmit data to the satellite at a high rate; this rate increases with the number of sensor nodes sharing the communication link. A networking method such as Time Division Multiplexing (TDM) will be required when more than one node shares the same communication link; this is discussed later in this chapter.

Since the application requires communication to occur over long distances, off the shelf modules will not suffice. Many CubeSat applications make use of amateur radio frequency bands and equipment since it is readily available (Klofas, 2013). An in-situ monitoring system that require high data rates cannot make use of this equipment and may require a proprietary transceiver design.

2.3.1.2 Satellite Tracking System

One of the constraints of a nano-satellite is the minimal power generation and power storage capacity due to the size constraint. This limits the ability to have high powered Omni-directional communication systems on-board. The use of high gain directional antennas can help to overcome this problem. In order to do this, the ground station will have to be capable of tracking the satellite through an overpass and point the antenna directly at the satellite.

Tracking of a satellite’s orbital position can be done by using two-line element (TLE) data from North American Aerospace Defence Command (NORAD) and computing the position. A TLE file consists of a satellite’s current orbital parameters; these parameters include epoch, orbital inclination, right ascension of ascending node, argument of perigee, eccentricity, mean motion and mean anomaly (Rahal *et al.*, 2012).

Extraction of TLE orbital parameters allows for the calculation of the position and speed of the satellite in the Earth-centered inertial (ECI) coordinate system using a calculation model such as the SGP4 propagator (Rahal *et al.*, 2012).

The ECI coordinate system is a Cartesian coordinate system positioned on the center of the earth. The z-axis is along the rotational axis of the earth pointing toward North, the x-axis runs along the direction of the vernal equinox and the y-axis is perpendicular to the x-axis to complete the coordinate system (Rahal *et al.*, 2012). Figure 2.11 (Rahal *et al.*, 2012) shows the ECI coordinate system.

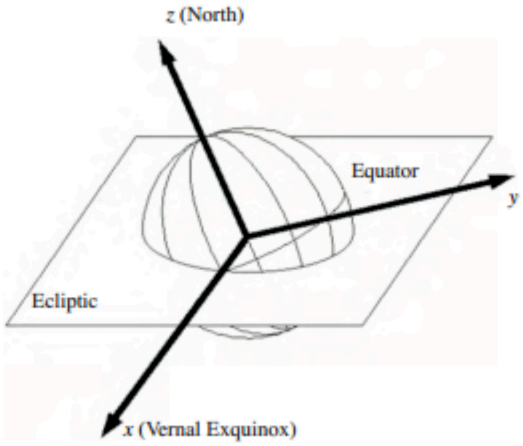


Figure 2.11: ECI coordinate system

The drawback of this method is that a connection to TLE data must be available, therefore this method can only be employed at a ground station within a communication infrastructure and is not suitable for the sensor nodes.

2.3.1.2.1 Hardware

The hardware component of the tracking system can be built with a set of motors and an actual position feedback system to point the antenna toward the satellite. The use of rotary encoders can be used to sense the rotational position of elevation and azimuth of the antenna. The signals from the rotary encoders are fed back to a controller which adjusts the motor position until the antenna is pointing toward the calculated position of the satellite. Figure 2.12 shows a basic representation of the satellite tracking hardware to control the antenna position.

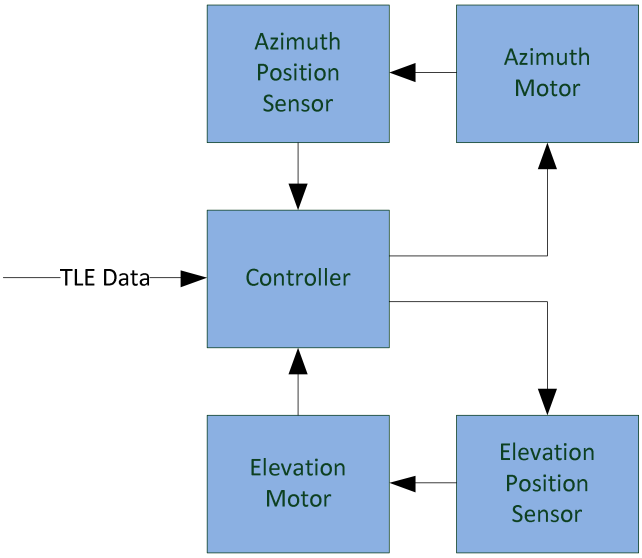


Figure 2.12: Antenna Position Controller Block Diagram

2.3.2 Networking

The system design is of such a nature that a communication link is required between multiple sensor nodes and a satellite, possibly multiple satellites with inter-satellite communication. The communication links have to be shared between the nodes within the network. Coordination within the system has to occur to avoid transmission collisions and data corruption. Spread Spectrum technologies could also be used to offer multiple transmission capabilities through code division multiplexing (CDMA).

2.3.2.1 Multiplexing

Multiplexing is a method of implementing communication with multiple nodes on a single communication medium or link. Several methods of multiplexing exist, such as Frequency Division Multiplexing (FDM) and Time Division Multiplexing (TDM). Figure 2.13 (Mahdiraji & Abas, 2010) shows a generic diagram of multiplexing where n number of channels share a single communication medium.

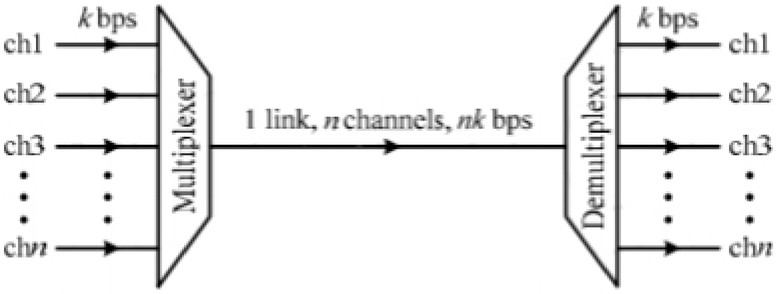


Figure 2.13: Typical Multiplexing

2.3.2.1.1 Time Division Multiplexing

TDM is a method of combining various digital signals into allocated time slots per channel within the multiplexed signal. Implementation is done by taking low bitrate digital signals and combining the individual bits into the allocated time slots to generate a high bitrate signal containing all multiplexed channels (Mahdiraji & Abas, 2010). Figure 2.14 (Mahdiraji & Abas, 2010) shows TDM of two digital channels sharing a single communication link; note the pulse widths of the respective channels, pulse width T is divided by number of channels n so that T/2 for the multiplexed signal.

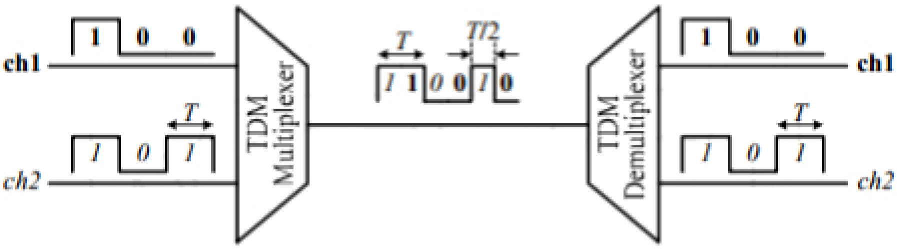


Figure 2.14: Time Division Multiplexing of Digital Two Channels

2.3.2.1.2 Frequency Division Multiplexing

FDM is a method of splitting the total bandwidth of a communication channel into several non-overlapping frequency bands to accommodate multiple channels. The use of such a system allows for simultaneous transmission of each channel, as opposed to TDM where the channels are sub divided into time slots. Figure 2.15 (Michailow *et al.*, 2012) shows how the bandwidth of the communication channel is sub-divided into separate frequencies per channel.

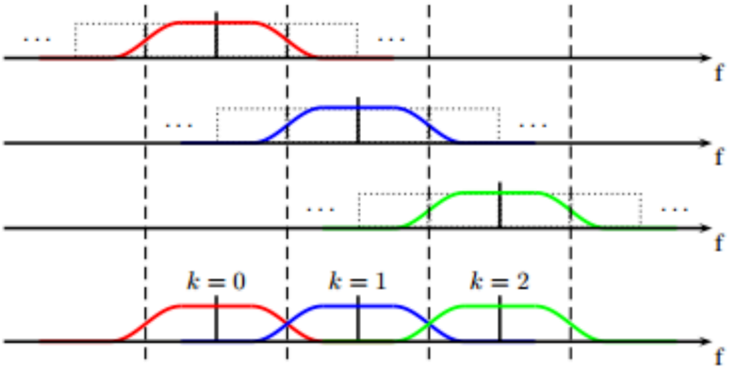
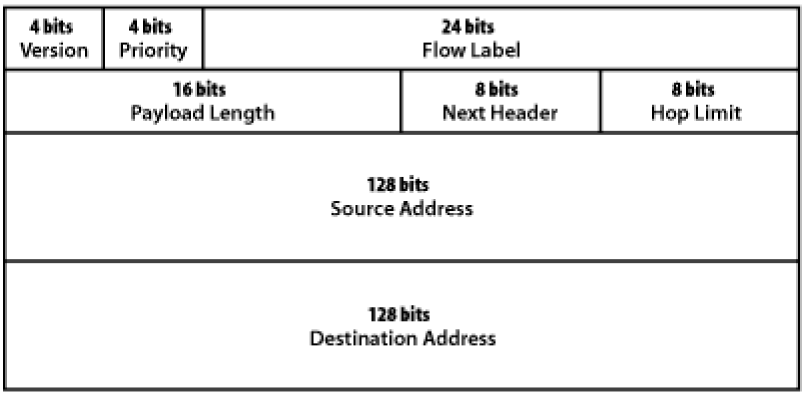


Figure 2.15: Channel Frequency Allocation of Frequency Division Multiplexing

2.3.3 Network Protocols

Large networks with several nodes require a means of identifying each node within the system and sending data packets to the correct destination. Several such network protocols exist, the most common is the Internet Protocol (IP), focussing specifically on IP version 6 (IPv6). The IPv6 header has a total of 40 bytes of data and can accommodate a payload of 65535 bytes (Wikipedia, 2014). The use of such a header for transferring data within an in-situ monitoring network would simplify the process of transferring the data from a node to the end user since it conforms to current internet protocols. Figure 2.16 (Techietek, 2014) shows the IPv6 header with the respective number of bits allocated to each section within the header.



4 bits Version
4 bits Priority
24 bits Flow Label
16 bits Payload Length
8 bits Next Header
8 bits Hop Limit
128 bits Source Address
128 bits Destination Address

Figure 2.16: IPv6 Header Including Data Quantities

2.3.4 Mesh Networking

Mesh networking is a method by which network control is done by each node in the system. Individual nodes become routers which transfer data packets within the system. Optimum routes are found within the network to relay data to the destination through the shortest path using individual nodes along the route. Link failure becomes less likely with employment of a mesh network since the network does not rely on a single link for point to point data packet transfer. In case of a link failure, data packets can be sent along a different path. A mesh network is dynamic in the sense that the optimal path between nodes is updated as the network changes. Such a network can be advantageous to an in-situ monitoring network as it can decrease the load on the link for sensor nodes that generate large amounts of data. Data can be transmitted to sensor nodes in close proximity with smaller bandwidth requirements for transmission to the satellite network. Current internet implementation of the links between routers is based on the same concept. Figure 2.17 (Silicon Labs, 2014) shows an example of a mesh network implemented with ZigBee communications modules.

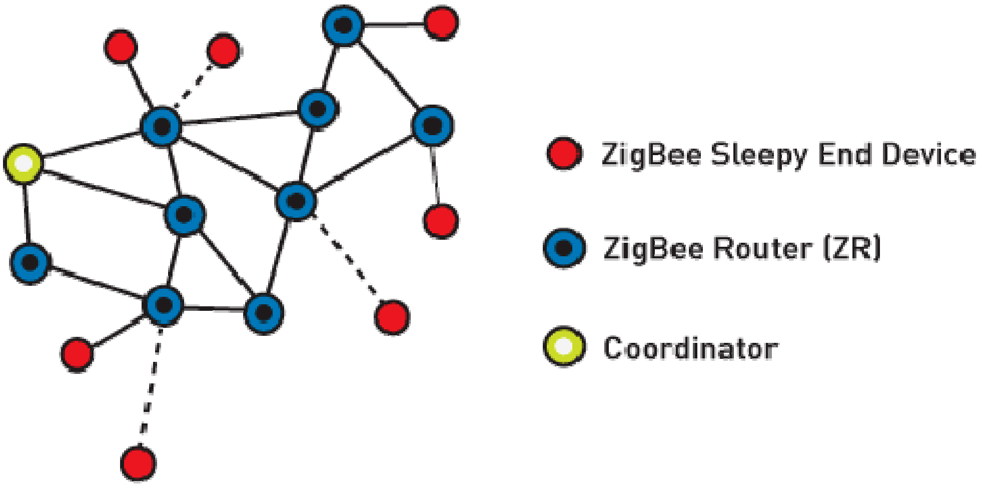


Figure 2.17: ZigBee Mesh Network

2.4 Power Systems Analysis

The power system of any device can be defined as the components or circuitry that distribute, regulate, store and generate power for the system to operate correctly. During analysis in Chapter 4 the solar panel output, storage capacity and satellite power requirement is considered to give a design reference. The system architecture considered for analysis is comprised of a typical CubeSat power architecture which includes the solar array, array regulation, battery unit, regulation, OBC control and housekeeping system as well as the switch and distribution system, see Figure 2.5 (Bester *et al.*, 2012).

2.4.1 Nano-Satellite Power Systems

The space environment that nano-satellites exist in limits the power system greatly. The power system has to be designed to be self-sustaining. In this section the power system of a nano-satellite is discussed regarding the power requirement, generation and storage. The various systems on-board a nano-satellite requiring power include systems such as the payload, OBC, communications system, attitude and orbital control system, heating systems and power regulation system.

2.4.1.1 Payload

The payload of a nano-satellite for in-situ monitoring would essentially be the communication and data storage system which relays the sensor node data between the nodes and ground station, thus the payload power requirement is not discussed as a separate entity.

2.4.1.2 On-Board Computer

The OBC power requirement of a nano-satellite is generally very low. In Table 2.1 (Thirion, 2009), modified from Thirion, an example of a nano-satellite mission is shown. The example depicts a mission with an eclipse period of 0.62 hours, sunlight period of 1.1 hours and a total orbit period of 1.72 hours. It shows that OBC1 and OBC2 together draw a maximum of 25.29 mW. According to Thirion this satellite was expected to be launched to an altitude between 350 km to 1200 km into an elliptical orbit.

Table 2.1: CubeSat Power Budget

Subsystem	Mode	Time Share (%)	Mean Instantaneous Consumption (mW)				Subtotal (mW)
			3.3 V	5 V	7.2 V	Battery	
EPS1	On	66	0.00	0.00	0.00	14.52	184.52
	On+Heater	34	0.00	0.00	0.00	170.00	
EPS2	Off	0	0.00	0.00	0.00	0.00	303.60
	Supply	99	0.00	0.00	0.00	297.00	
	Test	1	0.00	0.00	0.00	6.60	
OBC1	On	100	0.00	14.29	0.00	0.00	14.29
OBC2	On	100	11.00	0.00	0.00	0.00	11.00
Meas. System	On	100	18.33	0.00	0.00	0.00	18.33
COM	RX	95	69.67	0.00	0.00	0.00	223.05
	RX+TX	5	6.42	0.00	146.96	0.00	
Beacon	On	100	58.67	0.00	389.65	0.00	448.31

2.4.1.3 Electrical Power Supply

The power requirement of the electrical power supply (EPS) which regulates the power to all other systems on-board a nano-satellite draws a fair amount of power during the example mission shown in Table 2.1 (Thirion, 2009). EPS1 and EPS2 draws a total of 488.12mW. This is due to the requirement of battery heaters for prolonged battery life in the eclipse cycle, which uses 170 mW of power.

2.4.1.4 Communication System

The sub-system of main concern to this research is the communication system. Each case study will have different data rate requirements, which may affect power consumption. Looking at Table 2.1 (Thirion, 2009) it is observed that the communication system for the example requires 223 mW of power. The exact characteristics of the shown system, such as transmit power and data rate are unknown, therefore this is used merely as an example. The value for an in-situ monitoring mission may be much higher. Later in the research when discussing system requirements, the communication system for each case study will be the primary constraint.

2.4.1.5 Power Storage

During solar eclipse the only source of power is what is stored in the batteries. The amount of power storage capacity required is dependent on the mission and the sub-systems present in the CubeSat. A simple calculation can be done when the parameters for power requirement and eclipse duration are known. A hypothetical example for a satellite with a power requirement of 10 W and eclipse duration per orbit of 0.4625 hours is shown, see Equation 2.1 where, *B* is battery capacity, *P* is power in Watts and *t* is time in seconds.

$$B = P \times t$$ **Equation 2.1**

$$B = 4.625\ Wh$$

Equate this to power, for an 8.4 V battery, see Equation 2.2 where, *V* is volt and *I* is current in Amps.

$$P = V \times I$$ **Equation 2.2**

$$I = 550\ mAh$$

Therefore the hypothetical case would require an 8.4 V 550 mAh battery as bare minimum requirement, generally a much larger battery would be considered for safe operation.

The power calculation of a satellite is much more complex than this example, since it is dynamic and cannot be evaluated to a static case which is a constant power. The power requirement of the satellite is done by setting up a power budget of all sub-systems and analysing the result. This can then be simplified to a worst case scenario where the peak amount of power is drawn for the full duration of the orbit. A battery capacity can then be calculated which will accommodate the satellite even in a worst case. This method is however far from optimal.

2.4.1.6 Solar Cells

The solar panels are responsible for recharging the battery during the sun cycle and supplying sub-systems with power. The panels have to generate excess power to charge the batteries for the eclipse cycle when the solar panels cannot generate any power. Calculating the power output requirement of the solar panels the parameters for orbit duration, sun cycle duration and satellite power requirement is needed. Calculate for the hypothetical scenario in Section 2.4.1.5 with orbit duration of 1.61 hours, a sun cycle of 1.147 hours and a power requirement of 10 W. Power requirement, P_{Orbit}, during a single orbit for a worst case scenario is calculated, see Equation 2.3 where, t_{Orbit} is the time in hours to complete a single orbit.

$$P_{Orbit} = P \times t_{Orbit}$$ **Equation 2.3**

$$P_{Orbit} = 10 \times 1.61$$

$$P_{Orbit} = 16.1\ Wh$$

The minimum solar panel output power requirement, P_{Panel}, is calculated for the given worst case scenario by dividing the power requirement by the sun cycle duration, see Equation 2.4 where, t_{Sun} is the time in direct view of the sun in hours.

$$P_{Panel} = P_{Orbit}/t_{Sun}$$ **Equation 2.4**

$$P_{Panel} = 16.1/1.147$$

$$P_{Panel} = 14.04\ W$$

Looking at the reference in Table 2.2 (Clyde Space, 2014), modified from Clyde Space, the satellite solar panel configuration can be designed according to the power requirement that was previously calculated. The satellite in the hypothetical case would require at least a single side deployed solar panel configuration regardless of the form factor to generate 14.04 W of power per orbit. Note that Table 2.2 (Clyde Space, 2014) is only a quick reference guide by the manufacturer and actual results may vary. In depth experimentation or simulation would be required to ensure correct solar panel selection as per mission requirements.

Table 2.2: Solar Panel Configuration Reference

	1U	1.5U	2U	3U	6U
Power @ 28°C	2.1W	3.1W	5.2W	7.3W	18.78W
Single Deployed Power @ 28°C	4.2W	6.2W	10.4W	14.6W	37.5W
Two Sided Deployed	6.2W	9.4W	15.6W	21.9W	56.3W
Double Deployed Power @ 28°C	4.2W	6.2W	10.4W	14.6W	37.5W
Two Sided Deployed	8.3W	12.5W	20.8W	29.2W	75W

2.4.2 Sensor Node Power Systems

Sensor nodes have simpler design considerations compared to nano-satellites since they are based on the ground. The availability of various forms of renewable energy sources and no size constraint make it possible to generate and store any amount of required power.

2.4.2.1 Renewable Energy Sources

Renewable energy sources such as energy from wind or radiation from the sun serve as an abundant source of power on the planet. Various methods of harnessing this energy exist, the technologies applicable to the needs of this research are solar panels and wind turbines.

2.4.2.1.1 Solar Panels

In Section 2.2.2.4 solar panels for use on nano-satellites were discussed; the concepts for ground based solar panels are identical, except that it can be implemented on much larger scale. Some other constraints govern systems with ground based solar panels. During design of a system using solar power as main energy source the maximum power available and average radiated time per day have to be considered. The maximum power available is 1000 W/m^2 per hour in direct sunlight. A good approach is to calculate for 6 hours of peak power output per day and design the system accordingly (Sunforce, 2014). The following is a simple calculation showing this concept. Consider a 10 W solar panel, which is directly radiated for 6 hours per day. This is substituted into Equation 2.5 where, P_{Day} is the power generated per day and t_{Day} is the amount of direct sunlight in hours.

$$P_{Day} = P \times t_{Day}$$ **Equation 2.5**

$$P_{Day} = 10 \times 6$$

$$P_{Day} = 60\ Wh$$

Since 10 W solar panels generate 60 Wh of power, the power requirement of 60 Wh in a 24 hour period cannot be exceeded or the sensor node will shut off. Alternatively a larger solar panel and battery can be used. Figure 2.18 (Maya, 2010) shows a basic in-situ monitoring weather station powered by a solar panel.

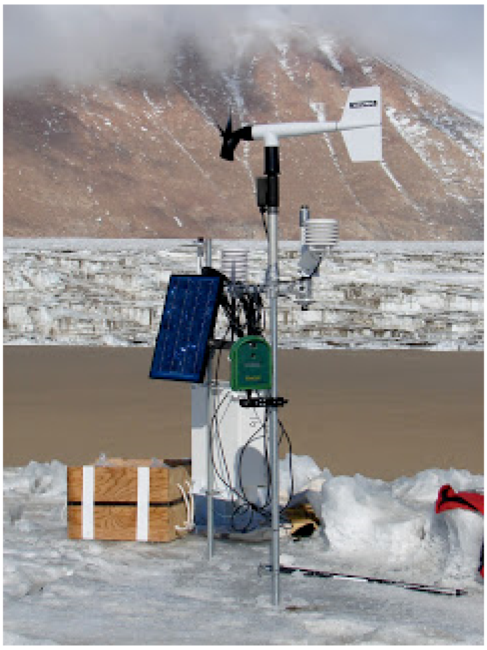


Figure 2.18: Solar Powered Weather Station

2.4.2.1.2 Wind Turbines

Wind turbines generate power by converting kinetic energy from wind into electrical energy by means of an electric generator. Wind turbines are widely used in rural areas to generate electrical power outside existing power infrastructure. They are particularly useful in areas where little solar radiation is present with large amounts of wind. Long term in-situ monitoring at the North or South Pole would be an example of this, where 6 months of the year is a constant night without any sunlight (Hauke, 2009). The obvious disadvantage of wind turbines is that they require wind to produce energy. It is critical that an environmental study be done before using wind turbines as primary source of energy. Figure 2.19 (Inforse, 2010) shows an application for wind turbines. Since telecommunication stations are better situated at high altitudes, wind turbines form a reliable source of power in these areas.

Figure 2.19: Wind Turbine Powered Telecommunication Station

2.5 Communication Subsystems

The backbone of this research lies within the communication system on-board the nano-satellite. Without a communication link capable of handling the high data rates the system may require, data from the in-situ monitoring network will not reliably transfer to the ground stations.

2.5.1 Sub-systems

The communication system consists of two sub-systems, namely a communication module, previously discussed in Section 2.2.2.2, and an antenna.

2.5.1.1 Antennas

Various types of antenna exist, which all serve specific purposes. These can be sorted into two categories, namely directional and Omni-directional antenna. Omni-directional antenna radiate equally in azimuth directions and at some angles in elevation, whereas directional antenna have a high gain in a specific direction and reject signals at other angles.

2.5.1.1.1 Dipole antenna

A dipole antenna is an Omni-directional antenna that radiates equally in all angles of azimuth. It is a simple wire antenna that is easy to construct and is designed with a length of $\lambda/2$, where λ is the wavelength of the signal. The disadvantage of a dipole antenna comes when attempting to achieve a higher gain, the antenna length must be increased to several times the wavelength. This can become too large for most applications, especially at lower frequencies with long wavelengths (Fung, 2011). Figure 2.20 (Fung, 2011) shows the characteristic radiation pattern of a dipole antenna.

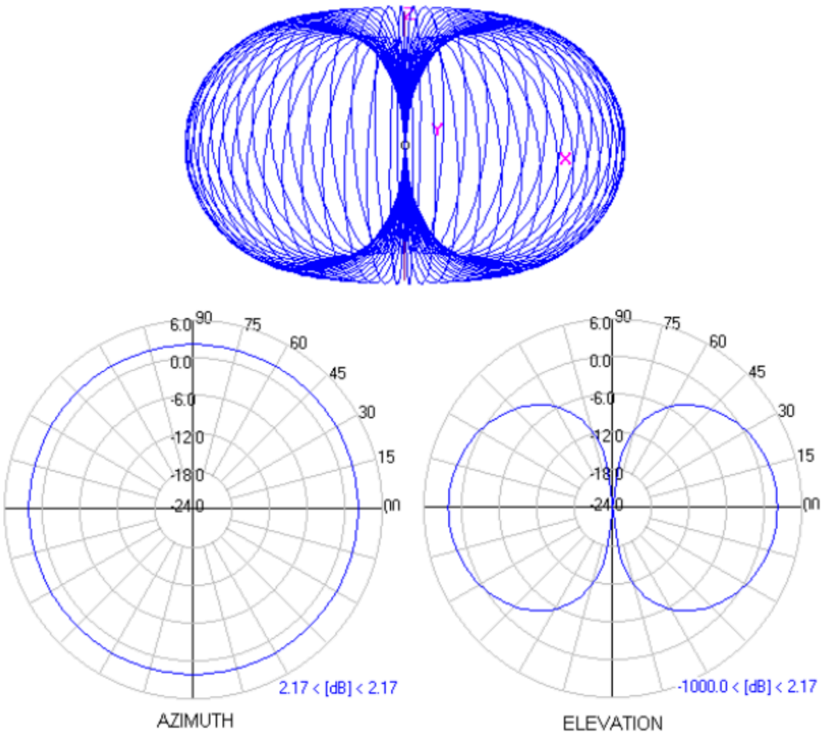


Figure 2.20: Dipole Antenna Radiation Pattern

2.5.1.1.2 Horn Antenna

A horn antenna is a directional antenna with high gain in a single direction. It consists of a conductive material in the shape of a hollow, flared horn to serve as an electromagnetic waveguide. The directivity and gain of horn antennas can be modified by varying the length of the horn. A typical horn antenna has a length that is equal to 2 - 15 times the wavelength of the carrier wave (Otasowie, 2012). Figure 2.21 (Fung, 2011) shows the basic design of a pyramid horn antenna and Figure 2.22 (openEMS, 2012) the characteristic radiation pattern for a generic horn antenna.

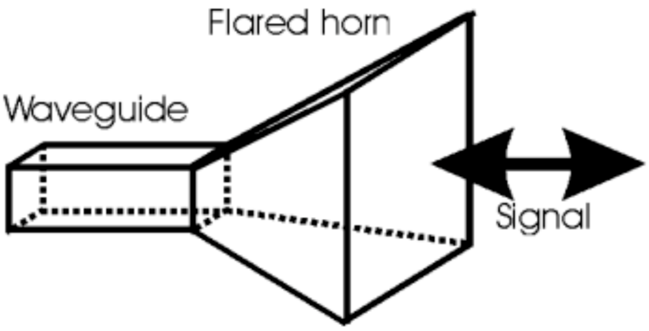


Figure 2.21: Pyramid Horn Antenna

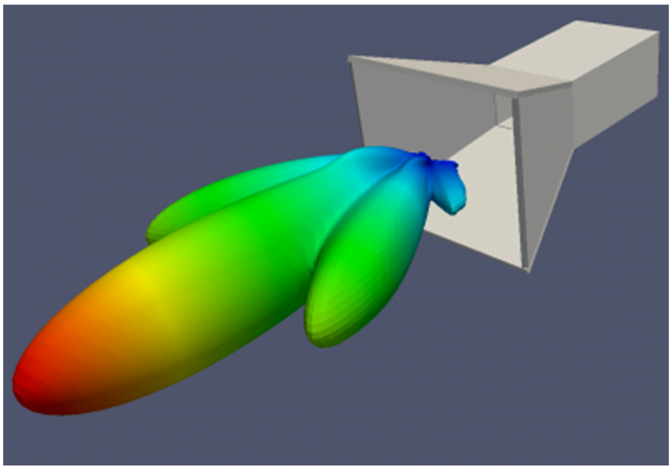


Figure 2.22: 3D Representation of Horn Antenna Radiation Pattern

2.5.1.1.3 Parabolic Antenna

A parabolic antenna consists of two parts, namely the parabolic reflector and the feed or receiver. The parabolic reflector focuses electromagnetic radiation to a convergence point known as the focal point. Alternatively if an electromagnetic feed, such as an antenna, is placed at the focal point, the electromagnetic radiation is reflected as a parallel beam (Telagarapu *et al.*, 2011).

Two types of commonly used parabolic reflectors exist, the parabolic right cylinder and the paraboloid. The most common feed for a parabolic right cylinder reflector is an antenna such as a linear dipole or array. The paraboloid reflector in turn uses a horn or conical antenna as its feed. Parabolic antenna offers high gain and narrow beam width, also known as a pencil beam (Telagarapu *et al.*, 2011). Figure 2.23 (Venusian Solutions, 2013) shows the characteristic radiation pattern for a parabolic dish antenna.

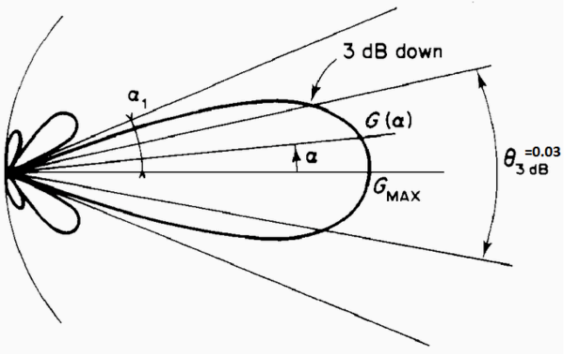


Figure 2.23: Parabolic dish radiation pattern

During the scenario design phase of this research, Chapter Three, particular types of antenna will be chosen to perform a given task in the communication system. The radiation patterns of each antenna will be considered to choose the most effective antenna to accommodate the given scenario with the least amount of design difficulty.

2.5.1.2 Nano-satellite Antennas

Compact, high gain antennas are required for use on small spacecraft such as nano-satellites. The size, weight and power constraint rule out the use of large low gain antennas. Typically found on CubeSats are Very High Frequency (VHF), Ultra High Frequency (UHF) and S-Band patch antennas.

2.5.1.2.1 VHF and UHF Antennas

VHF ranges from 30 MHz to 300 MHz, UHF ranges from 300 MHz to 3 GHz. VHF and UHF antennas are commonly used for telemetry, tracking and control (TT&C) signals, but is also used to transmit other data. These antennas are popular in the CubeSat community since they are easily interfaced with off the shelf amateur radio equipment. They are also simple to implement on a CubeSat as the design closely resembles the tape inside a tape measure which can be uncoiled from inside the satellite for deployment. Figure 2.24 (French South African Institute of Technology, 2014) shows ZACUBE-1 with its VHF and UHF antennas deployed from the sides of the satellite.

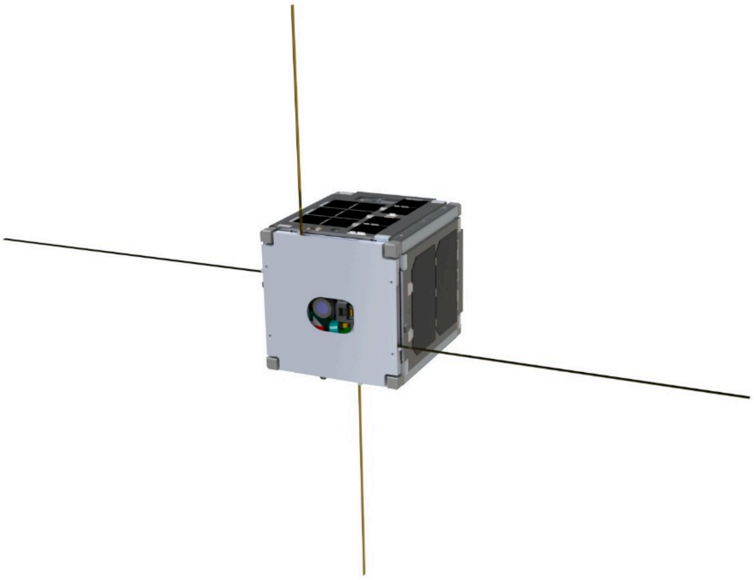


Figure 2.24: ZACUBE-1 with Deployed VHF and UHF Antennas

2.5.1.2.2 S-Band Patch Antennas

The S-Band is a frequency within the range of 2 GHZ to 4 GHz. S-Band patch antennas are ideal for CubeSats since they are compact, low profile and lightweight. They offer a directional radiation pattern which is useful for ground directed or inter-satellite communications. The operational frequency in the S-Band range is capable of high data rates which will suit the requirement for an in-situ monitoring network. Figure 2.25 (Wikipedia, 2014) shows the radiation pattern of a patch antenna.

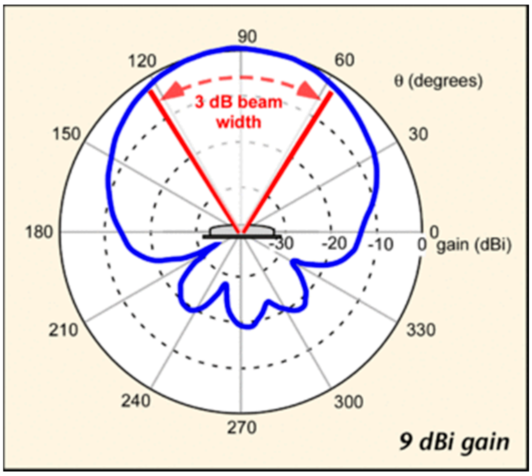


Figure 2.25: Patch Antenna Radiation Pattern

Figure 2.26 (Clyde Space, 2014) shows the S-Band Patch Antenna designed by CPUT, it features a diameter of 76 mm, height of 3.8 mm, weight of 50 g, 8 dBi gain and 2 W power output.

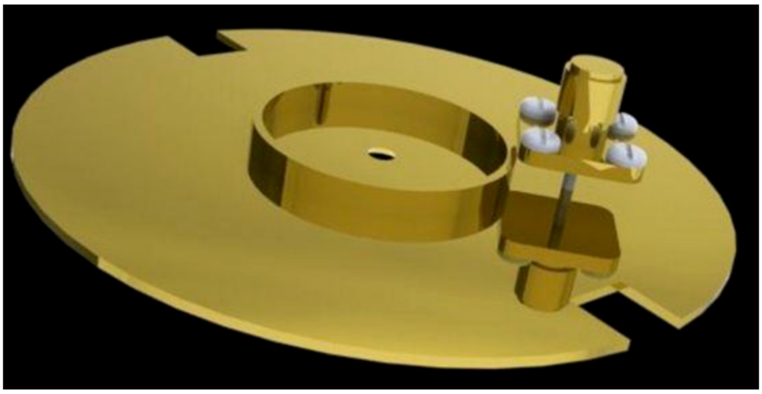


Figure 2.26: CPUT S-Band Patch Antenna

2.5.2 Wireless Communication Regulation

Regulations around space communication govern the frequency bands and types of communication that may occur within each allocated band. Various options exist within amateur and commercial bands for use with nano-satellites. Amateur radio bands offer easy access at no cost, with only a radio amateur licence required. Commercial licencing offers wider spectrum space which allows higher data rate communication, although the process to acquire licencing can be difficult and expensive compared to amateur licencing. The frequency band chosen depends greatly on the data rate required for the mission.

2.6 Orbital Dynamics

In this section various orbital parameters governing a satellite’s orbit and types of orbit are discussed.

2.6.1 Orbital Parameters

- Epoch: The point in time at which orbital parameters are defined.
- Orbital Inclination: The angle between the orbital plane and the equator, ranges from 0° to 180°. An inclination of 0° would be known as an Equatorial orbit and as it approaches 90° it becomes a Polar orbit.
- Right Ascension of Ascending Node (RAAN): Defined as the angle between the ascension node and the direction of the vernal equinox. Viewing from the north of the equatorial plane it is measured counter clockwise.
- Argument of Perigee: Other concepts have to be explained to come to terms with Argument of Perigee, such as Line of Nodes, Apogee, Perigee and the Major Axis. The Line of Nodes is the intersection between the equatorial plane and the orbital plane. Apogee is the point at which the satellite is furthest from Earth and Perigee is the point where it is closest to Earth in the orbit. Major Axis is the line between Apogee and Perigee through the ellipse. Argument of Perigee is then defined as the angle between the Line of Nodes and Major Axis.
- Eccentricity: Determines the shape of the ellipse; the elongation compared to a circle.
- Mean anomaly: The angle with respect to the perigee that points to the satellite’s position in the orbit.

2.6.2 Types of Orbit

This section describes the various types of orbits with respect to the individual classifications such as Altitude, Eccentricity, Inclination and Synchronicity.

2.6.2.1 Altitude Classification

- Low Earth Orbit (LEO): Orbits with an altitude up to 2000 km.
- Medium Earth Orbit (MEO): Orbits with an altitude between 2000 km and 35,786 km (Geosynchronous Orbit).
- High Earth Orbit: Altitudes above 35,786 km.

2.6.2.2 Eccentricity Classification

- Circular Orbit: An orbit with an eccentricity of 0 such that it is a circle.
- Elliptic Orbit: An orbit with an eccentricity greater than 0 and less than 1, so that it forms an ellipse.

2.6.2.3 Inclination Classification

- Polar Orbit: An orbit with an inclination close to 90°.
- Equatorial Orbit: An orbit with an inclination of 0°.
- Near Equatorial Orbit: An orbit with an inclination close to 0°.

2.6.2.4 Synchronicity Classification

- Synchronous Orbit: An orbit with an orbit period equal to or a multiple of the orbit period of the Earth.
- Geosynchronous Orbit: An orbit with an orbit period that is equal to a sidereal day, positioned at an altitude of 35,786 km in a circular orbit. Such an orbit will stay in position to a specified point on the Earth.

In the next chapter the methods used to identify parameters for the design of several scenarios of in-situ monitoring for simulation and the steps required to set up the scenarios in the simulation tool used for this research, namely STK, are discussed.

CHAPTER THREE

RESEARCH DESIGN

3.1 Overview

Chapter Three discusses the process used to design scenarios for analysis to answer the questions raised in Chapter One. A set of parameters will be outlined which can be used to determine the performance characteristics of each scenario.

3.2 System Specifications

The research requires a set of parameters to design a system or multiple systems for analysis. First parameters are defined that will affect the system performance, namely the minimum revisit time and the orbit altitude. The revisit time forms the main constraint which defines the design of each scenario.

3.2.1 Minimum Revisit Time

The minimum revisit time is the parameter used for the system design in this research. Focus is put on this parameter since some applications require data to be uploaded more frequently than others. This influences the constellation design with respect to the number of satellites, orbital plane definition, data throughput and memory requirements. Scenarios are therefore separated by the minimum revisit time to observe and analyse the design changes between respective systems within the limits of the CubeSat form factor. Some degree of freedom is possible during the scenario design with parameters such as the orbit altitude, number of satellites and orbital planes. The communication link throughput is limited due to limitations of existing technologies and is set to a realistic value within the scope of this research. The following minimum revisit times were selected for the systems covered in this research:

- 1 day
- 100 minutes
- Real-time (Less than 1 second)

3.2.2 Orbit Altitude

The scenarios are designed to firstly accommodate the revisit times defined in the previous section. These include the three systems repeated at two different altitudes, namely 600 and 950 km to accommodate the daily, 100 minute and real-time access constraints for minimum revisit time. The difference in altitude will provide systems with different design characteristics to analyse.

The choice of 600 km altitude is based on a common orbit used for CubeSats to limit the radiation exposure. With radiation factors in mind, the 950 km altitude is chosen in such a way to keep it below the occurrence of the Van Allen radiation belts which start at approximately 1000 km altitude, the inner region of the radiation belt being at approximately 3000 km altitude (Encyclopedia Britannica, 2014).

3.3 Scenario Design

Several scenarios were designed using a simulation tool, Systems Tool Kit (STK) from Agilent Graphics Incorporated (AGI). STK makes it possible to simulate satellite orbits, ground stations, sensors, target areas and much more. It features powerful analysis tools with which the system characteristics and performance can be determined. Software tool include simulation capabilities such as:

- Access Duration
- Ground Coverage
- Revisit Time
- Communication Link Performance
- Lighting and Eclipse Times

The satellites in each scenario have sensors attached to them with a specified cone angle which provides data for ground coverage area. The specific parameters used per scenario is described in the following sections where the scenarios are defined individually. Each sensor also has a communications module attached with a minimum elevation angle to compensate for poor communication close to the horizon.

3.3.1 Scenario Ground Locations

There are several randomly defined ground locations reoccurring in all scenarios which represent sensors for analysis and a single ground station. These locations are chosen at random such that they cover the majority of the planet to get a global scope of system performance.

3.3.1.1 Sensor Node Locations:

- Atlantic Ocean. Latitude: -16.2186° Longitude: -20°
- Australia. Latitude: -25.5852° Longitude: 134.504°
- Brazil. Latitude: -10.8105° Longitude: -52.9731°
- Canada. Latitude: 62.8329° Longitude: -95.9133°
- China. Latitude: 36.5531° Longitude: 103.975°
- Egypt. Latitude: 26.7561° Longitude: 29.8623°
- Equator/Prime Meridian. Latitude: 0° Longitude: 0°
- Europe. Latitude: 54.2612° Longitude: 17.6698°

- Greenland. Latitude: 74.3495° Longitude: -41.0899°
- India. Latitude: 23.406° Longitude: 79.4581°
- Indian Ocean. Latitude: -16° Longitude: 80°
- North Pole. Latitude: 90° Longitude: 0°
- Pacific Ocean. Latitude: 18.3425° Longitude: -150°
- Russia. Latitude: 63.1252° Longitude: 103.754°
- South Pole. Latitude: -90° Longitude: 0°
- United Kingdom. Latitude: 54.5609° Longitude: -2.21251°
- United States. Latitude: 39.4433° Longitude: -98.9573°

3.3.1.2 Ground Station Location

- Bellville, South Africa. Latitude: -33.8889° Longitude: 18.6379°

3.3.2 Scenario 1.1: 600 km Altitude, Daily Access

This scenario is designed to accommodate a system with a maximum revisit time of one day (24 Hours), see Figure 3.1 and Figure 3.2. It uses a single satellite in one orbital plane at an altitude of 600 km.

3.3.2.1 Scenario Parameters

- Orbital Planes: 1
- Satellites per Plane: 1
- Satellite Sensor Cone Angle: 65.5°
- Total Satellites: 1
- Revisit Time: < 1 Day
- Ground Stations: 1
- Sensor Nodes: 17

3.3.2.2 Orbital Parameters

- Inclination: 89°
- Altitude: 600 km
- RAAN: 0°
- True Anomaly: 0°

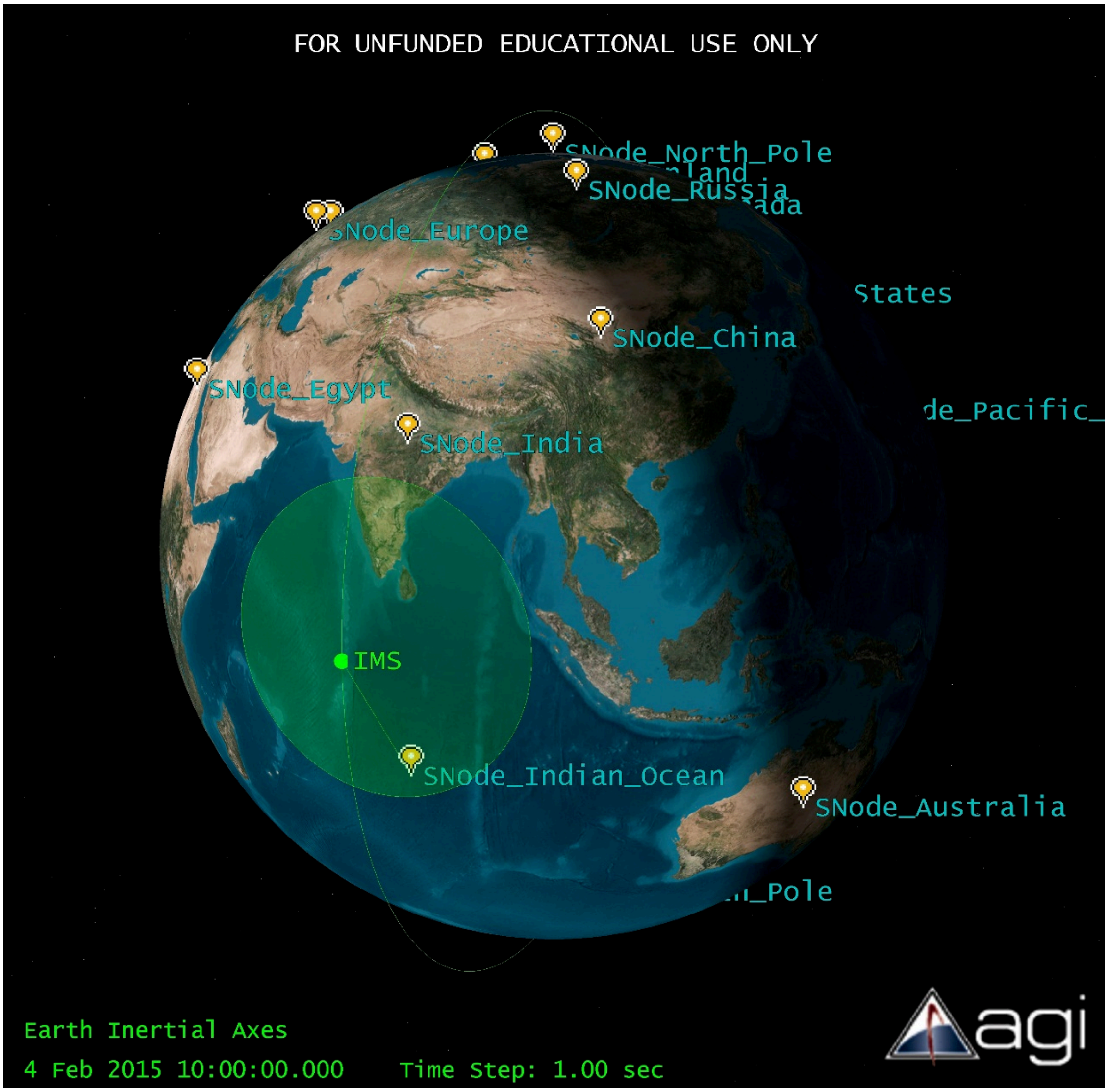


Figure 3.1: 3D Globe of Scenario 1.1

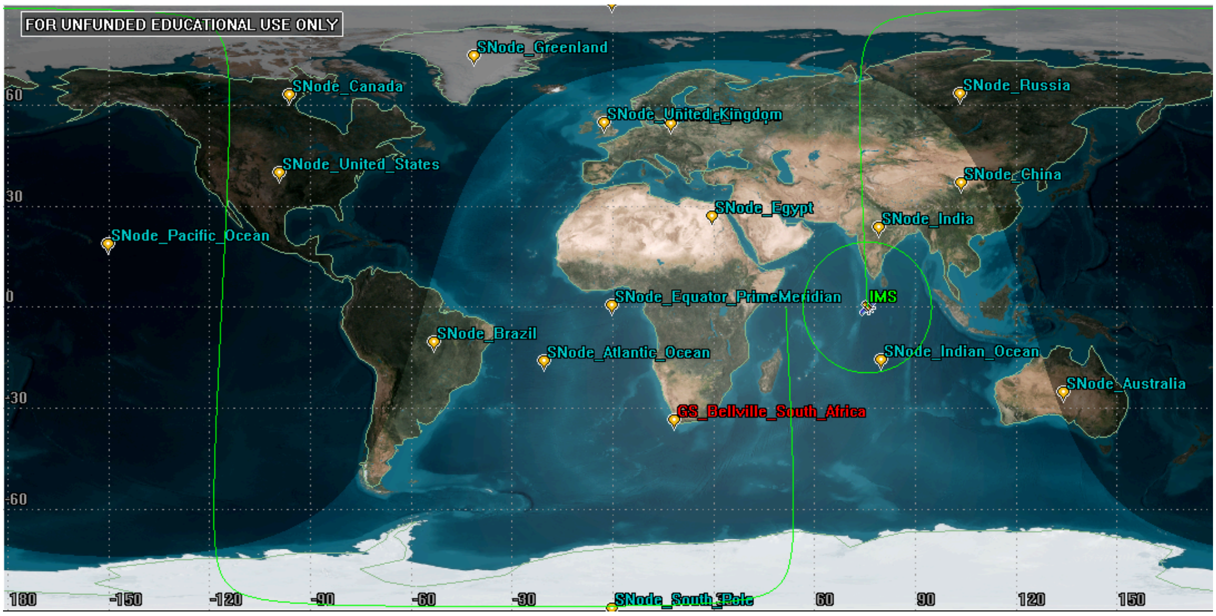


Figure 3.2: Map of Scenario 1.1

3.3.3 Scenario 1.2: 950 km Altitude, Daily Access

This scenario is designed to accommodate a system with a maximum revisit time of one day (24 Hours), see Figure 3.3 and Figure 3.4. It uses a single satellite in one orbital plane at an altitude of 950 km.

3.3.3.1 Scenario Parameters

- Orbital Planes: 1
- Satellites per Plane: 1
- Satellite Sensor Cone Angle: 62°
- Total Satellites: 1
- Revisit Time: < 1 Day
- Ground Stations: 1
- Sensor Nodes: 17

3.3.3.2 Orbital Parameters

- Inclination: 89°
- Altitude: 950 km
- RAAN: 0°
- True Anomaly: 0°

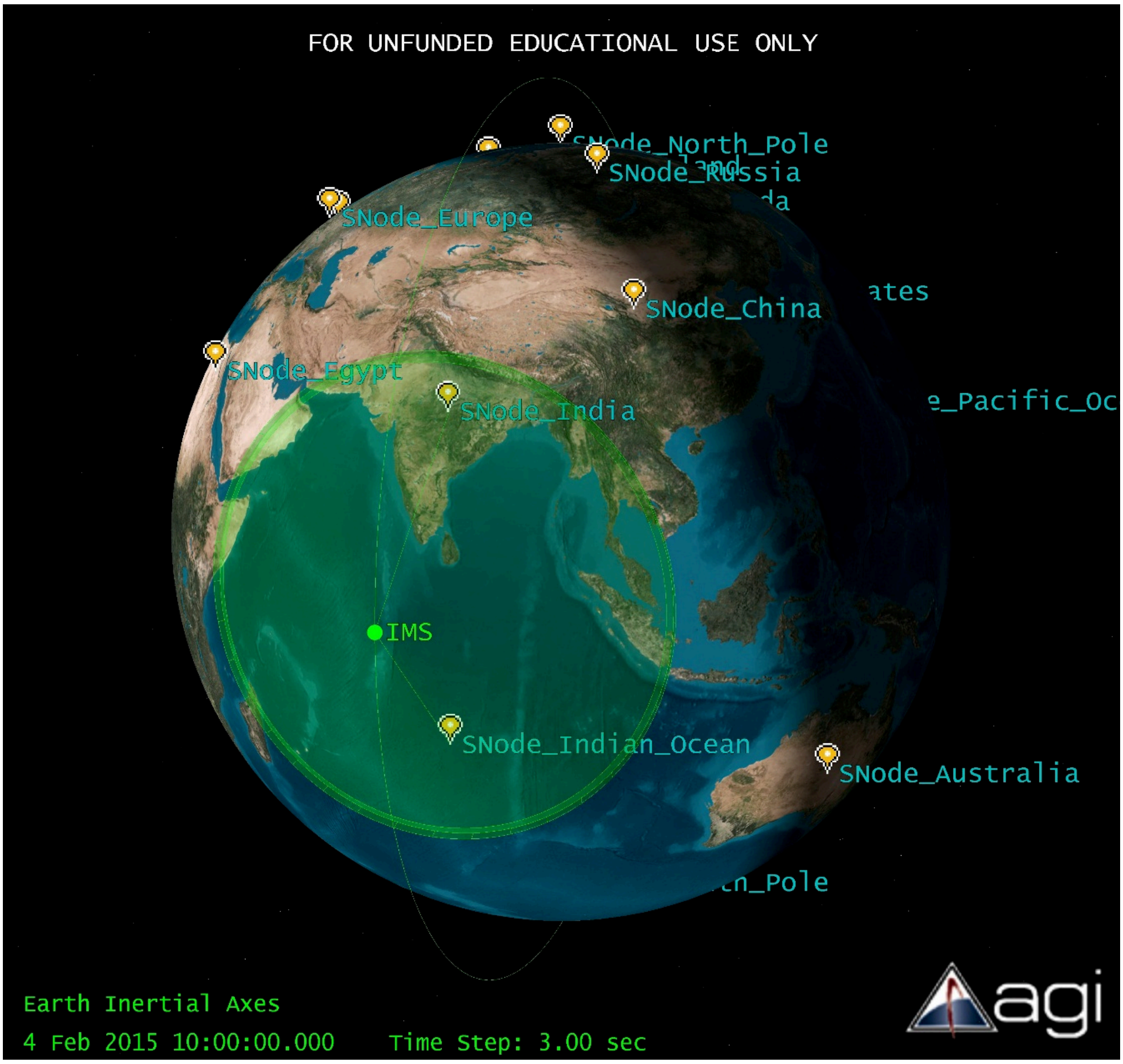


Figure 3.3: 3D Globe of Scenario 1.2

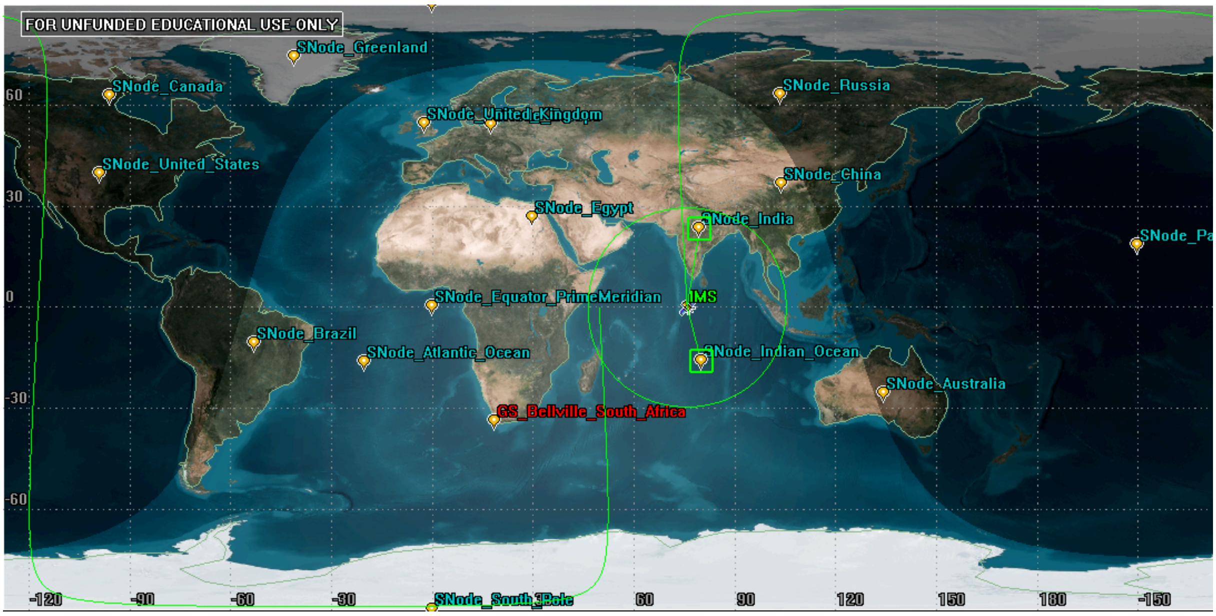


Figure 3.4: Map of Scenario 1.2

3.3.4 Scenario 2.1: 600 km Altitude, 100 Minute Access

This scenario is designed to accommodate a system with a maximum revisit time of 100 Minutes, see Figure 3.5 and Figure 3.6. It uses a total of 12 satellites in 12 orbital planes at an altitude of 600 km. The satellites are spaced equally around the equator with an orbit such that all satellites cross simultaneously at the poles. 12 satellites were required in order to cover all land mass across the equator, which is the largest area with respect to the orbit design. The satellites use inter-satellite communication to relay data to the ground station. Inter-satellite communication will not be discussed in this research, it can be assumed that the communication link is faster than the link to the ground segments and power usage is minimal since it is in a space environment with direct line of sight between satellites where less signal attenuation occurs.

3.3.4.1 Scenario Parameters

- Orbital Planes: 12
- Satellites per Plane: 1
- Satellite Sensor Cone Angle: 65.5°
- Total Satellites: 12
- Revisit Time: < 100 Minutes
- Ground Stations: 1
- Sensor Nodes: 17

3.3.4.2 Orbital Parameters for Individual Orbital Planes

- Inclination: 89°
- Altitude: 600 km
- RAAN Spacing Between Planes: 30°
- True Anomaly Increment Between Planes: 0°

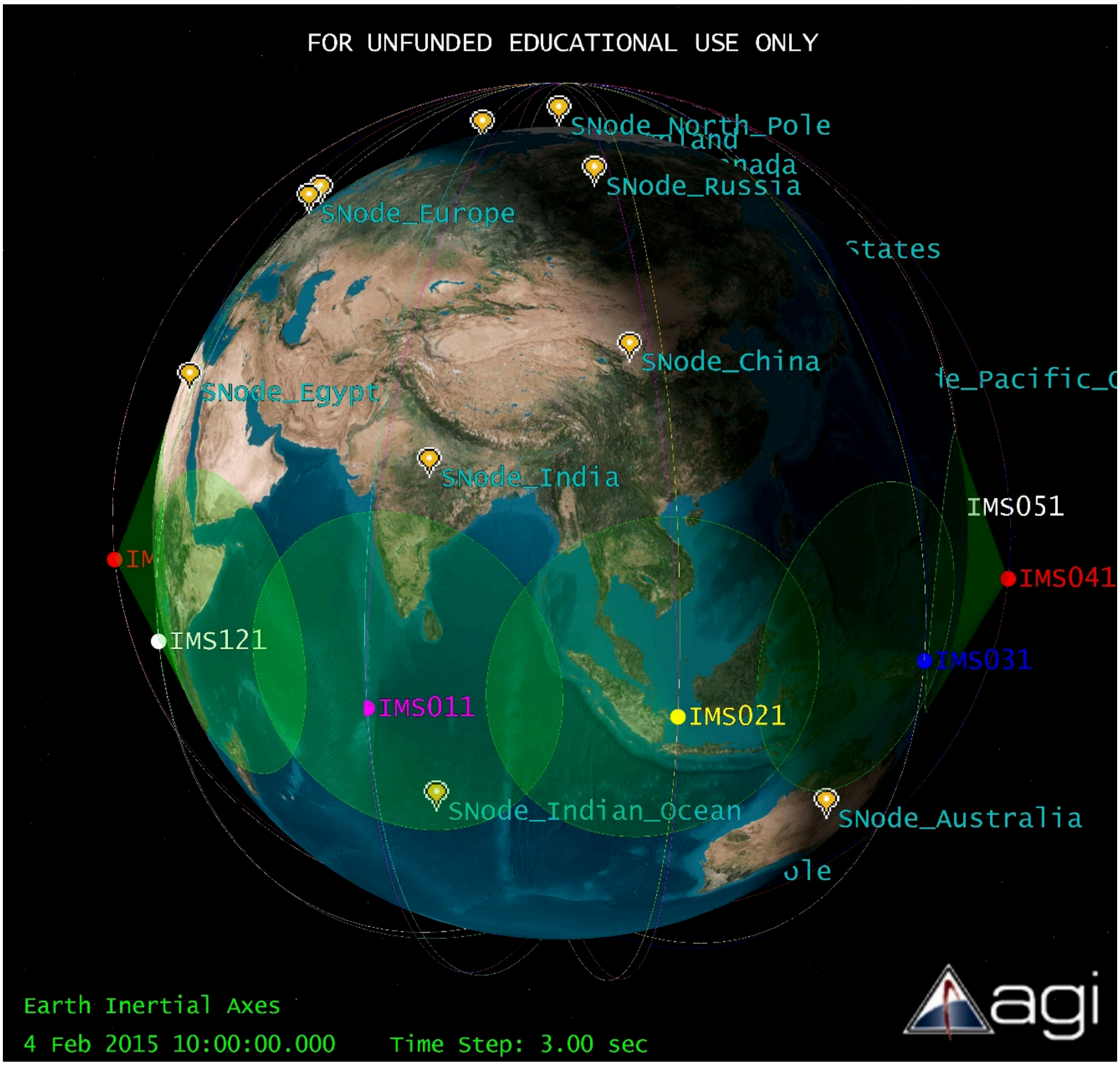


Figure 3.5: 3D Globe of Scenario 2.1

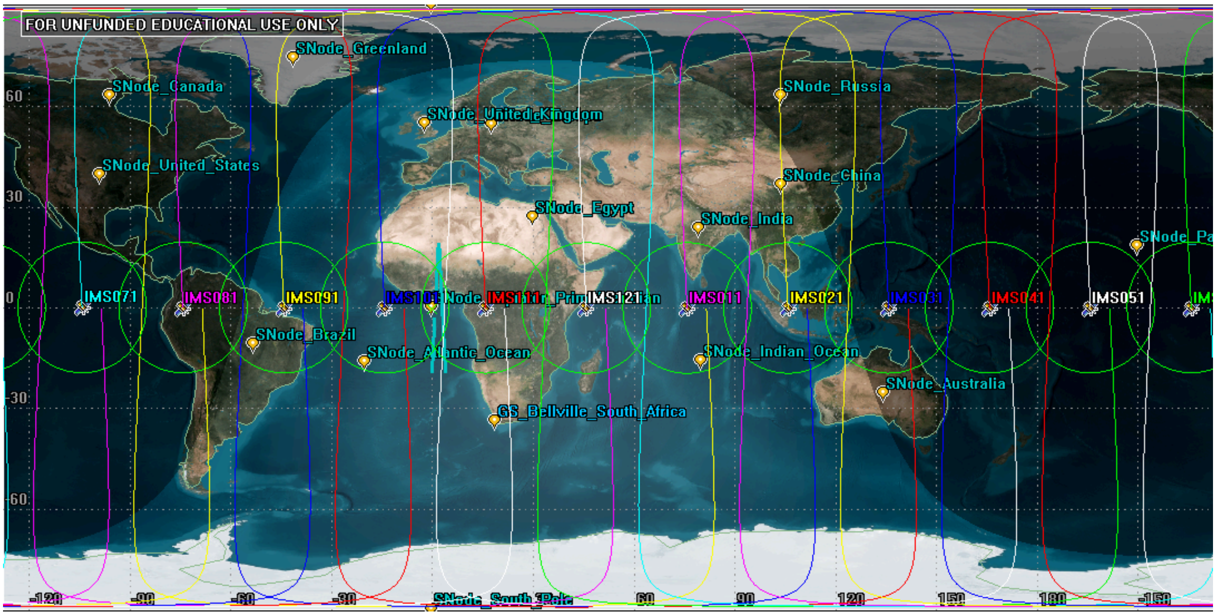


Figure 3.6: Map of Scenario 2.1

3.3.5 Scenario 2.2: 950 km Altitude, 100 Minute Access

This scenario is designed to accommodate a system with a maximum revisit time of 100 Minutes, see Figure 3.7 and Figure 3.8. It uses a total of 7 satellites in 7 orbital planes at an altitude of 950 km. The satellites are spaced equally around the equator with an orbit such that all satellites cross simultaneously at the poles. 7 satellites were required in order to cover all land mass across the equator, which is the largest area with respect to the orbit design. The satellites use inter-satellite communication to relay data to the ground station.

3.3.5.1 Scenario Parameters

- Orbital Planes: 7
- Satellites per Plane: 1
- Satellite Sensor Cone Angle: 62°
- Total Satellites: 7
- Revisit Time: < 100 Minutes
- Ground Stations: 1
- Sensor Nodes: 17

3.3.5.2 Orbital Parameters for Individual Orbital Planes

- Inclination: 89°
- Altitude: 950 km
- RAAN Spacing Between Planes: 51.43°
- True Anomaly Increment Between Planes: 0°

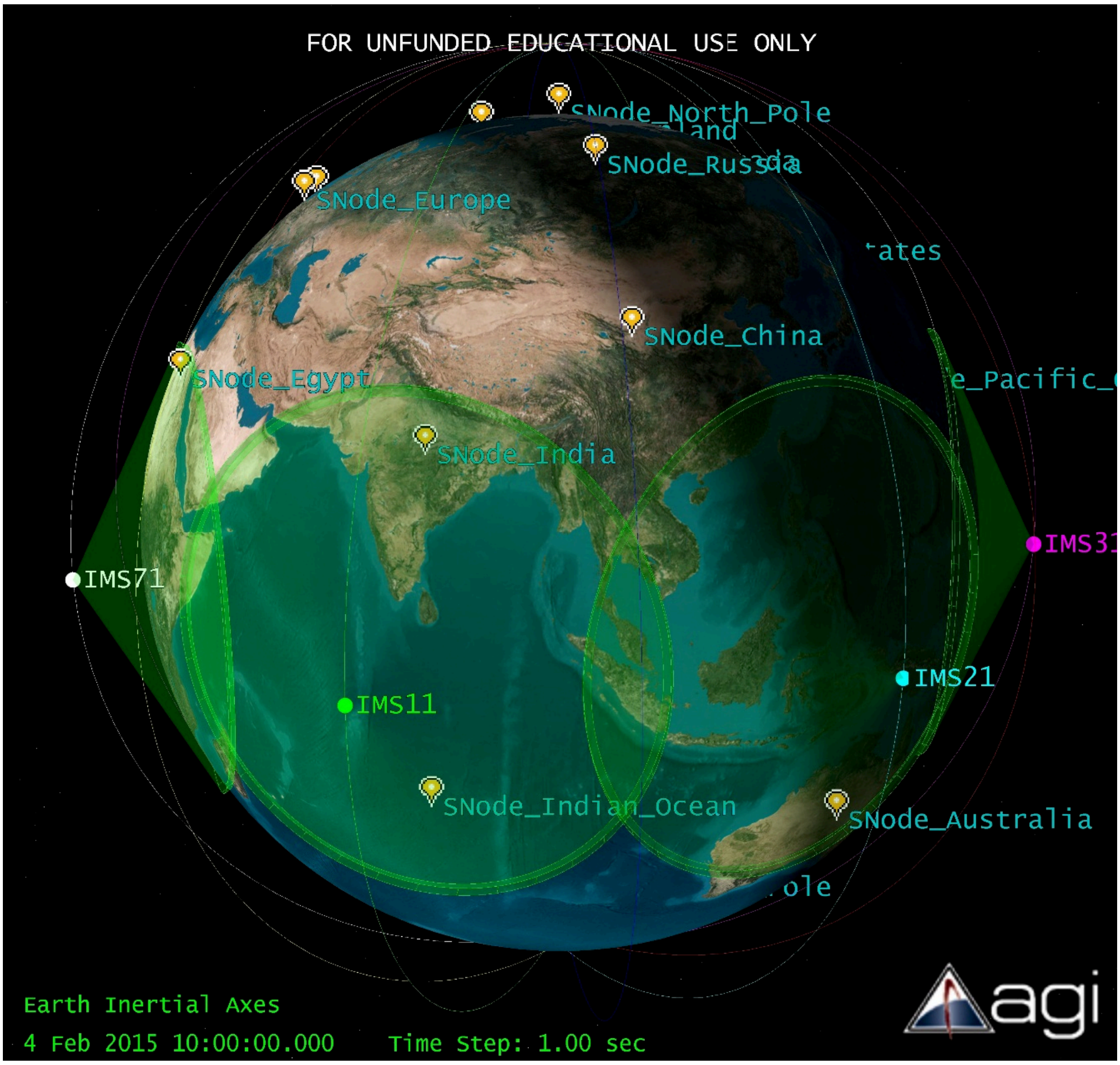


Figure 3.7: 3D Globe of Scenario 2.2

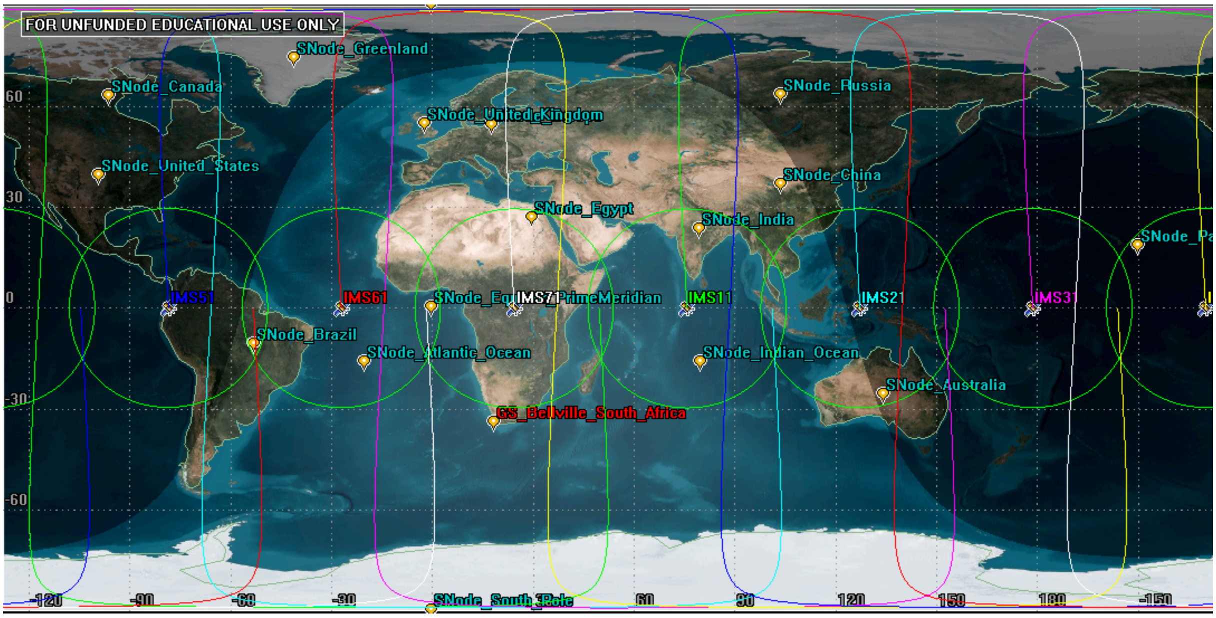


Figure 3.8: Map of Scenario 2.2

3.3.6 Scenario 3.1: 600 km Altitude, Real-time Access

This scenario is designed to accommodate a system with real-time access, see Figure 3.9 and Figure 3.10. In this research, real-time access is considered as communication with no break in relaying data from sensor node to ground station. The delays due to propagation, transmission, queuing and processing will not be considered during this research. The scenario uses a total of 77 satellites in 7 orbital planes at an altitude of 600 km. The satellites are spaced equally around the globe in such a way that all surface areas are covered simultaneously as required for real-time communication. 77 satellites were required to achieve global coverage with this orbit altitude. The satellites use inter-satellite communication to relay data to the ground station.

3.3.6.1 Scenario Parameters

- Orbital Planes: 7
- Satellites per Plane: 11
- Satellite Sensor Cone Angle: 65.5°
- Total Satellites: 77
- Revisit Time: Real-time (< 1 Second)
- Ground Stations: 1
- Sensor Nodes: 17

3.3.6.2 Orbital Parameters for Individual Orbital Planes

- Inclination: 89°
- Altitude: 600 km
- RAAN Spacing Between Planes: 25.71°
- True Anomaly Increment Between Planes: 16.36°

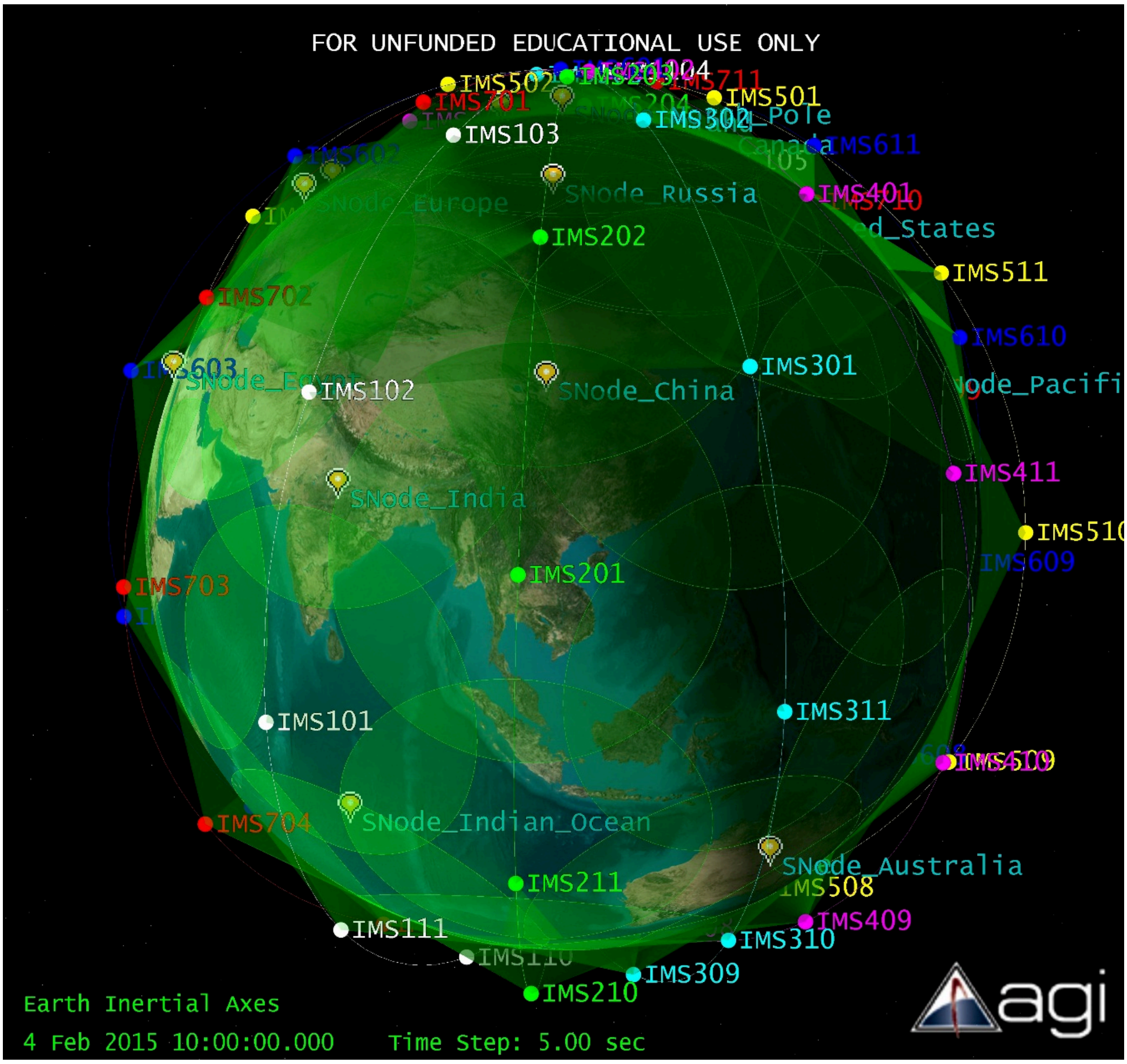


Figure 3.9: 3D Globe of Scenario 3.1

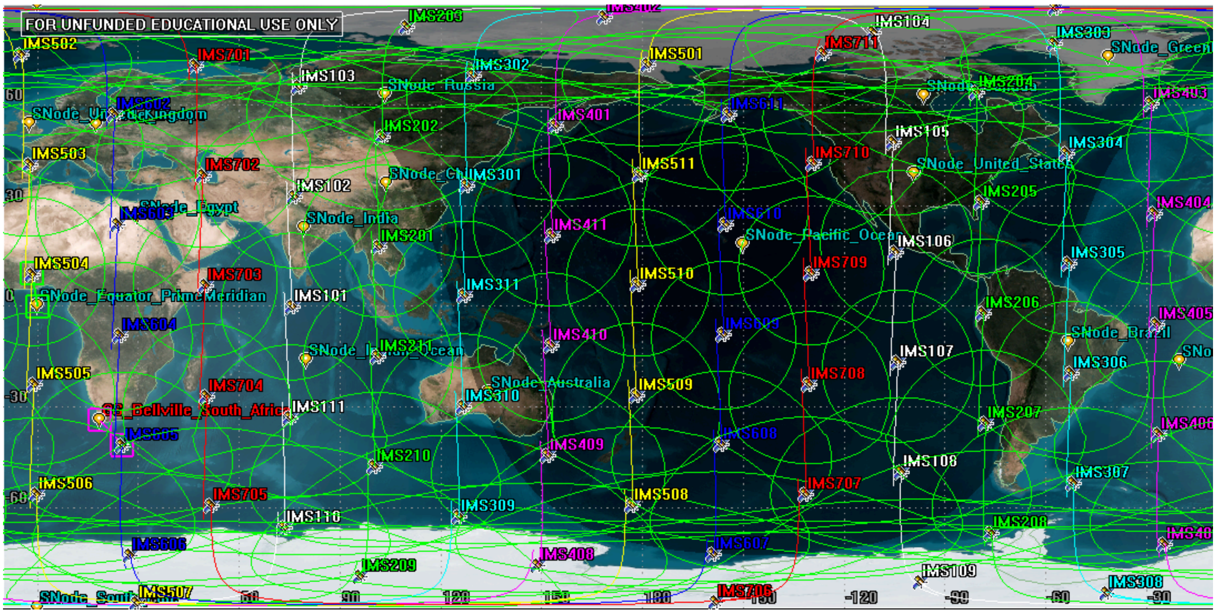


Figure 3.10: Map of Scenario 3.1

3.3.7 Scenario 3.2: 950 km Altitude, Real-time Access

This scenario is designed to accommodate a system with real-time access, see Figure 3.11 and Figure 3.12. The satellites are spaced equally around the globe in such a way that all surface areas are covered simultaneously as required for real-time communication. 48 satellites were required to achieve global coverage with this orbit altitude. Same as Scenario 3.1, inter-satellite communication will offer minimum delay.

3.3.7.1 Scenario Parameters

- Orbital Planes: 6
- Satellites per Plane: 8
- Satellite Sensor Cone Angle: 62°
- Total Satellites: 48
- Revisit Time: Real-time (< 1 Second)
- Ground Stations: 1
- Sensor Nodes: 17

3.3.7.2 Orbital Parameters for Individual Orbital Planes

- Inclination: 89°
- Altitude: 950 km
- RAAN Spacing Between Planes: 30°
- True Anomaly Increment Between Planes: 22.5°

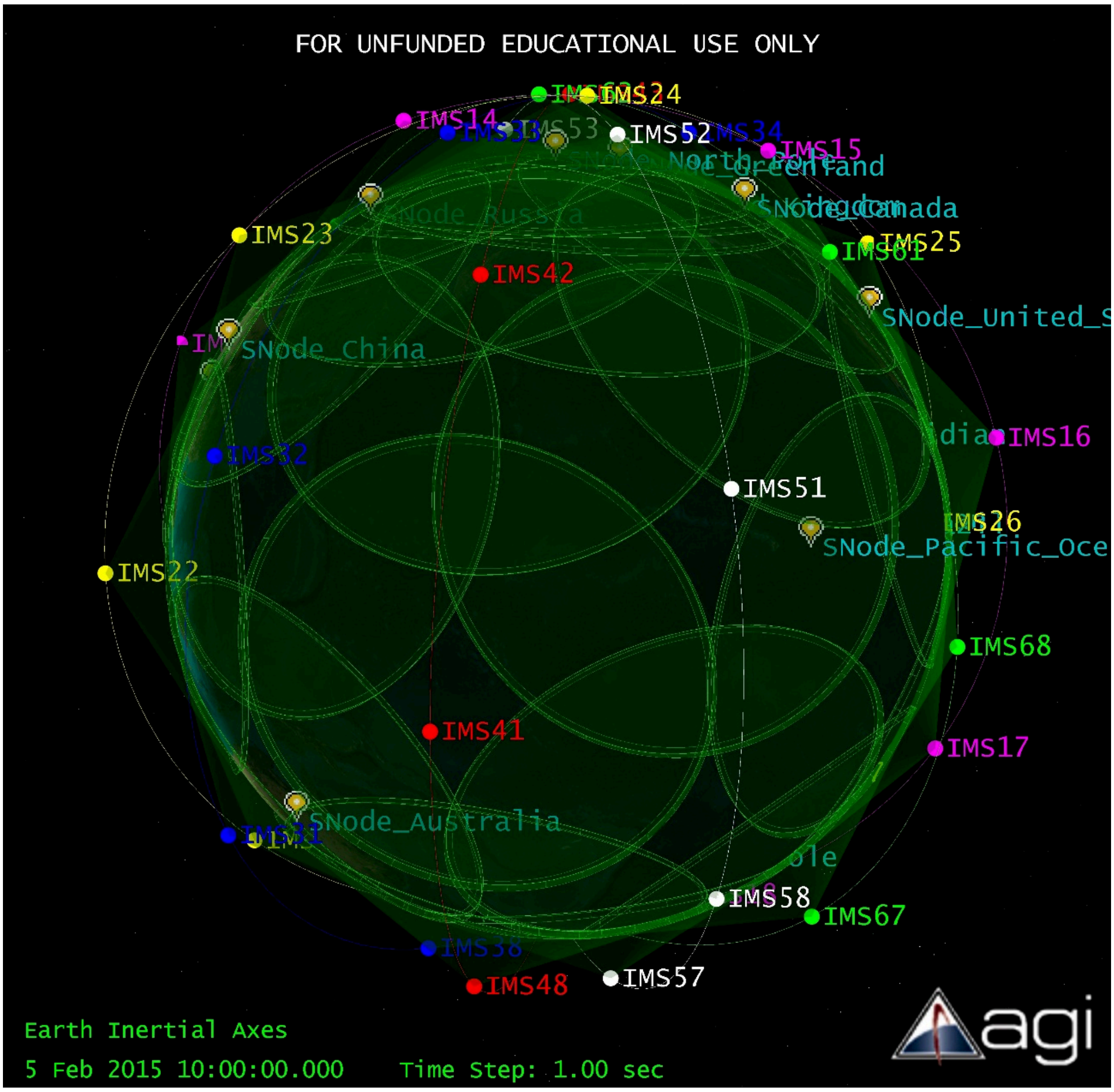


Figure 3.11: 3D Globe of Scenario 3.2

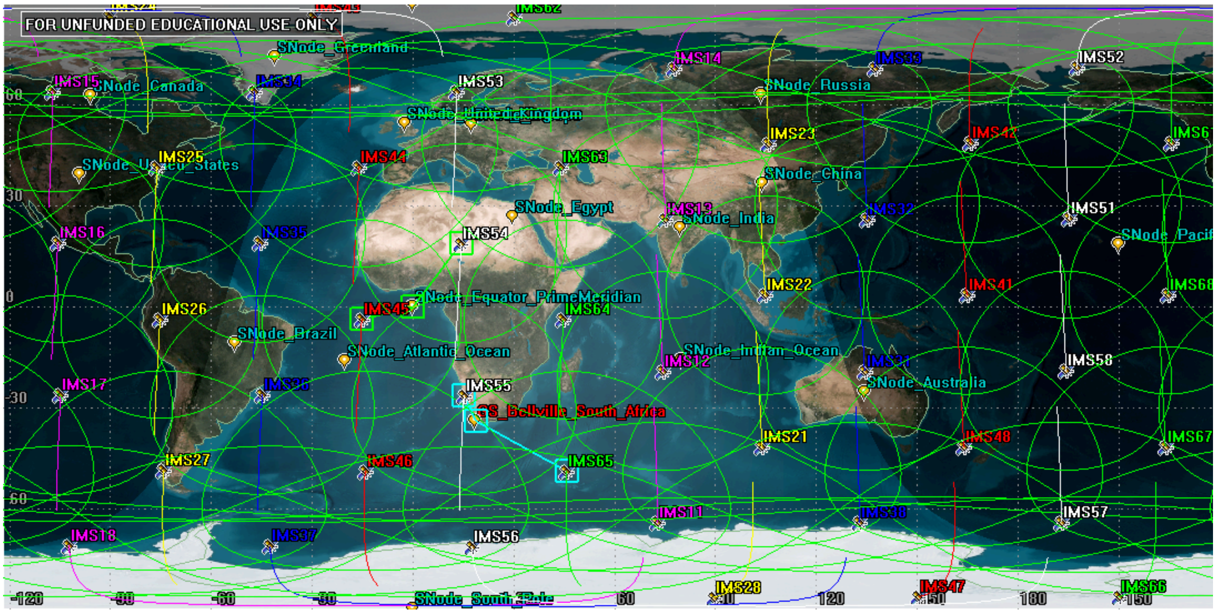


Figure 3.12: Map of Scenario 3.2

In the next Chapter all six scenarios will be analysed to determine their performance as an in-situ monitoring system. The access times, access durations, communication link quality and the quantity of data the system can handle need to be determined.

STK provides all the analysis tools necessary for this task. All the required data will be gathered and the systems adapted to yield the best instance for in-situ monitoring. The primary goal is to conform to the revisit time constraint, while attempting to minimize the number of satellites used for the sake of mission simplicity and cost.

CHAPTER FOUR
SCENARIO ANALYSIS

4.1 Overview

The chapter is focused on the analysis of the scenarios set out in Chapter Three. Several analysis techniques will be used to determine the characteristics of the systems in question and clarify their given performance as an in-situ monitoring system. These characteristics include access durations to sensor nodes and ground station, ground coverage, revisit time, communication link performance, sensor node capacity, memory requirements and power requirements. These performance characteristics are required to define the overall performance of an in-situ monitoring system using nano-satellites.

4.2 Analysis Procedure

The scenarios will be analysed by the same tools to gather consistent data for cross analysis and by following the same steps. The steps for analysis outlined below will be used to determine the performance of the parameters mentioned in Section 4.1. Some calculations are omitted if calculated in a previous scenario with similar parameters. The following steps were followed to analyse each scenario for their given performance characteristics:

- Compute access times and duration with sensor nodes.
- Compute access times and duration with ground station.
- Compute ground coverage.
- Confirm maximum revisit time.
- Analyse communication uplink and downlink.
- Compute number of sensors nodes system can accommodate.
- Compute number of sensors nodes a satellite can accommodate per overpass.
- Computer memory requirement for sensor nodes and satellite(s).
- Compute power resources.

4.3 Scenario 1.1 Analysis

4.3.1 Sensor Nodes Access Duration

Theoretically an approximate value for an access with a generic sensor node on the equator of the scenario can be calculated using the following formula according to (Larson & Wertz, 2005), see Equation 4.1. Illustrated in Figure 4.1 (Larson & Wertz, 2005) we see an example of this concept.

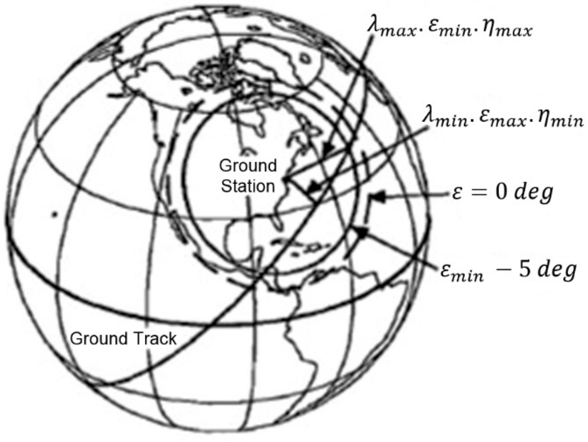


Figure 4.1: Access Duration Illustration

$$T = \left(\frac{P}{180\ deg}\right) cos^{-1}\left(\frac{cos\lambda_{max}}{cos\lambda}\right)\ Minutes \qquad \textbf{Equation 4.1}$$

Where, *P* is the orbit period in minutes, *λ* is the off ground track angle and λ_{max} is the angular radius of the Earth. Twice λ_{max} is known as the swath width. *P* is calculated with Equation 4.2, where *H*, the orbit altitude, is 600 km.

$$P = 1.658669\ \times\ 10^{-4} \times (6{,}378.14\ \times H)^{3/2} \qquad \textbf{Equation 4.2}$$

$$P =\ 96.6873\ Minutes$$

Now *T* can be calculated, where *λ* is 0°, an overpass through the centre of the satellite field of view (FOV), and λ_{max} is 66.0541°, which is the calculated angular radius for a 600 km altitude. These values are substituted into Equation 4.3.

$$T = \left(\frac{96.6873}{180\ deg}\right) cos^{-1}\left(\frac{cos(66.0541)}{cos(0)}\right) \qquad \textbf{Equation 4.3}$$

$$T = 35.4811\ Minutes$$

$$T = 2128.9\ Seconds$$

The access times and durations between the sensor nodes and the satellite can now be evaluated using the access tool in STK. See Appendix A.1 for full Access Report. The following access duration results were obtained for the scenario:

- Atlantic Ocean: 2376 Seconds
- Australia: 2771 Seconds
- Brazil: 2540 Seconds
- Canada: 6290 Seconds
- China: 3201 Seconds
- Egypt: 2559 Seconds
- Equator/Prime Meridian: 2055 Seconds
- Europe: 4668 Seconds
- Greenland: 10488 Seconds
- India: 2667 Seconds
- Indian Ocean: 2020 Seconds
- North Pole: 11784 Seconds
- Pacific Ocean: 2663 Seconds
- Russia: 6401 Seconds
- South Pole: 11784 Seconds
- United Kingdom: 4333 Seconds
- United States: 3553 Seconds

A trend can be observed with regards to the location of the sensor node, around the Equator the access time is at a minimum and around the Poles it's at a maximum. This phenomenon occurs since a Polar orbit crosses at the poles with each successive orbit, while at the equator the largest spacing between successive orbits exits. The previous theoretical calculation of a single overpass in the center of the satellite FOV correlates with similar instances in the STK simulation.

4.3.2 Ground Station Access Duration

The same process is followed for the computation of the sensor node access duration. See Appendix A.2 for full Access Report. The following access duration result was obtained for the scenario:

- Bellville, South Africa: 1928 Seconds

4.3.3 Ground Coverage

Theoretical calculation of the ground coverage also known as the Instantaneous Access Area, *IAA*, corresponds to the satellite's FOV. In (Larson & Wertz, 2005) this is defined by Equation 4.4.

$$IAA = K_A(1 - cos\lambda) \qquad \textbf{Equation 4.4}$$

Where K_A is 2.56x10^{14}, half the surface area of Earth, and λ is 23.95°, the angle for the true outer horizon of the satellite's FOV. Equation 4.4 can be reduced to:

$$IAA = 2.2 \times 10^{13}\ m^2$$

To establish the time taken for 100% coverage the Longitude increment, *ΔL*, of each successive orbit is calculated. Which is defined by Equation 4.5 according to (Larson & Wertz, 2005).

$$\Delta L = \frac{P}{1436\ minutes} \times 360° \qquad \textbf{Equation 4.5}$$

Where *P* is the orbit period calculated in Section 4.3.1. Equation 4.5 is reduced to:

$$\Delta L = 24.24°$$

Next the angle is required for the true outer horizon if a 5° elevation constraint is added. The angle can be calculated by using the trigonometry law of sines for calculation of *ρ*, the Earth Angular Radius, which denotes the angle between the satellite and the outer horizon, defined by Equation 4.6. Illustrated in Figure 4.2 (Larson & Wertz, 2005) for calculation of Earth's Angular Radius.

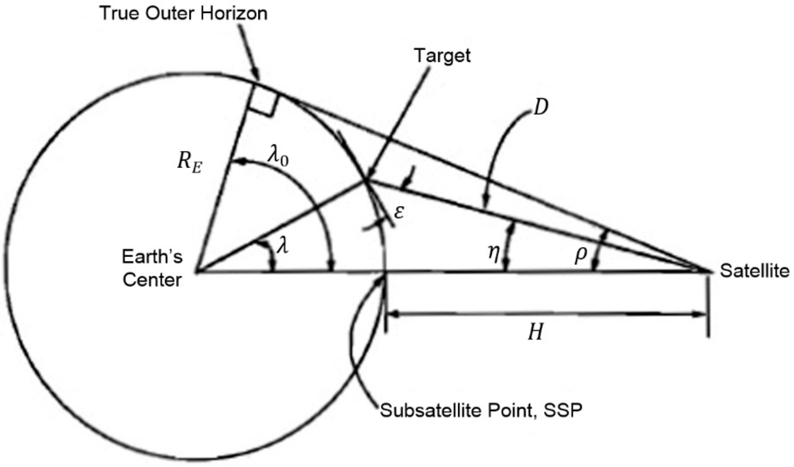


Figure 4.2: Illustration of Earth's Angular Radius Calculation

$$\rho = sin^{-1}\left(\frac{R_E.sin(95°)}{R_E + H}\right) \qquad \textbf{Equation 4.6}$$

Where *R$_E$*, Earth's radius in km, is 6.371 x 10^6 km and *H*, the satellite's orbit altitude in km, is 600 km. Equation 4.6 is reduced to:

$$\rho = 65.57°$$

λ can now be calculated by the summing of the angles inside a triangle. See Equation 4.7.

$$\lambda = 180° - 95° - \rho \qquad \textbf{Equation 4.7}$$

$$\lambda = 19.43°$$

Now *λ* denotes the degrees in longitude accessed by the satellite with respect to the ground with each successive orbit. Note that it will be calculate for half of the Earth, using 180°, since the satellite will cover two areas in longitude with each orbit, spaced by 180°. It must be considered that the initial area covered will be 19.43° as calculated and thereafter the swath width, 2λ, will be covered by each successive overpass. Since each orbit will be spaced by 24.24° and the swath width is 38.86°, there will be an overlap in access area with the previous orbit. Therefore the calculation is done by considering the initial access area denoted by 19.43° and add 19.43° for each successive orbit, disregarding the overlap. The N_{Orbits}, number of orbits to cover 180° is calculated as follows in Equation 4.8.

$$N_{Orbits} = \frac{180 - \lambda}{\Delta L}$$

Equation 4.8

$$N_{Orbits} = \frac{180 - 19.43}{24.24}$$

$$N_{Orbits} = 6.62\ Orbits$$

Finally the time in hours, T_{100}, for 100% coverage is calculated Equation 4.9.

$$T_{100} = \frac{P.N_{Orbits}}{60\ minutes}$$

Equation 4.9

$$T_{100} = 10.675\ Hours$$

This equates to 10 Hours 40 minutes for 100% coverage.

The ground coverage percentage was computed with STK by first defining a coverage region in Latitude and Longitude. The coverage region was chosen for a Latitude from 90 to -90 degrees and a Longitude from 180 to -180 degrees with 1 degree increments, effectively covering the whole globe. Figure 4.3 shows that the coverage percentage reaches 100% in a period of 10 Hours and 35 Minutes, which closely matches the theoretical estimation.

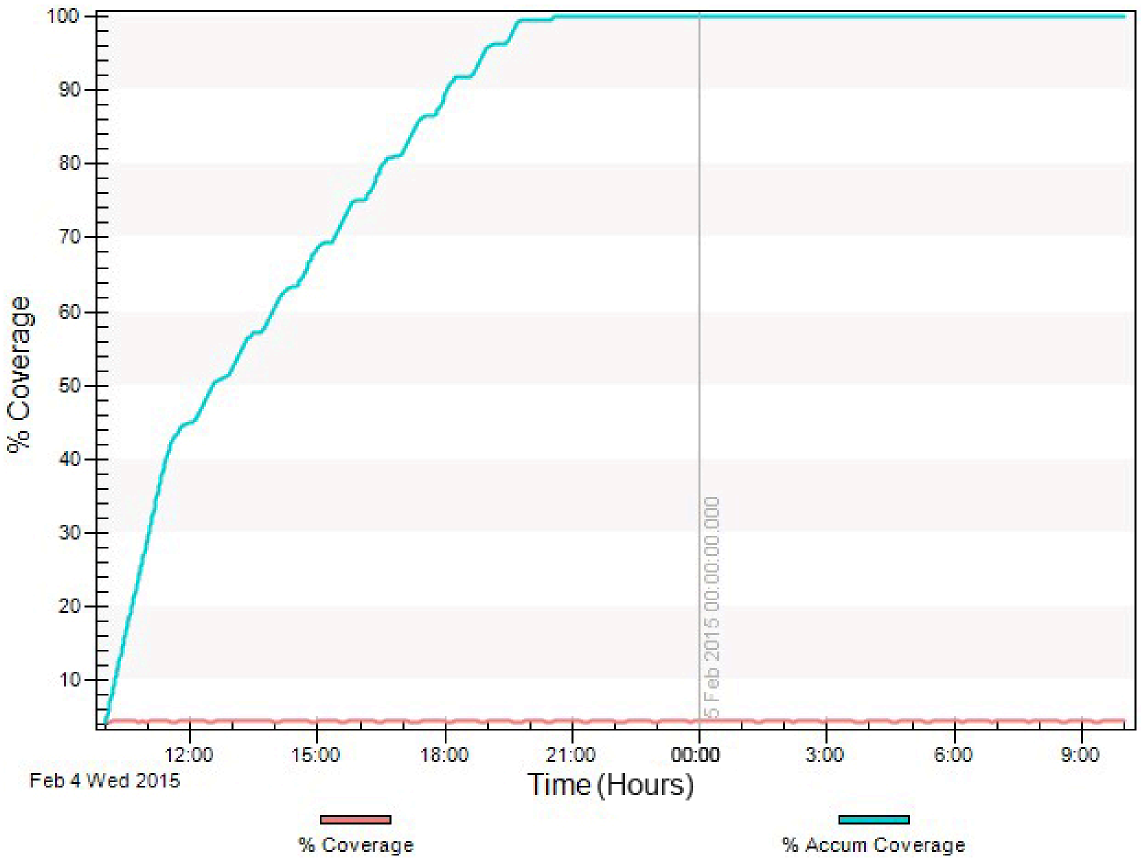


Figure 4.3: Scenario 1.1 Coverage Percentage over Time (STK Simulation)

4.3.4 Maximum Revisit Time

A theoretical approximation of the maximum revisit time to a point is done by calculating the time in seconds taken for N_{Orbits} in 180° Longitude subtracted with the N_{Orbits} within the swath width, 2λ, of the satellite. Denoted by Equation 4.10.

$$Gap_{Max} = P \times 60\ Seconds\ \times \left(\frac{180°}{\Delta L} - \frac{2\lambda}{\Delta L}\right) \qquad \textbf{Equation 4.10}$$

$$Gap_{Max} =\ 96.69\ Minutes \times 60\ Seconds\ \times \left(\frac{180°}{24.24°} - \frac{38.86°}{24.24°}\right)$$

$$Gap_{Max} = 33.778\ Seconds$$

The maximum revisit time calculated in STK is done by using a Gaps Summary report, which will give data on the period between satellite accesses of a specified point on Earth. Scenario 1.1 requires a revisit time of less than 86400 seconds. See Appendix A.3 for full Gaps Summary report. The calculated maximum gap in STK is 38343 seconds, which satisfies the constraint and correlates with the theoretical approximation. The data from STK Gaps Summary report for access gaps as per location:

4.3.4.1 Ground Station

- Bellville, South Africa: 38343 Seconds

4.3.4.2 Sensor Nodes

- Atlantic Ocean: 32253 Seconds
- Australia: 36237 Seconds
- Brazil: 37464 Seconds
- Canada: 22098 Seconds
- China: 32738 Seconds
- Egypt: 36246 Seconds
- Equator/Prime Meridian: 37214 Seconds
- Europe: 23795 Seconds
- Greenland: 5265 Seconds
- India: 37843 Seconds
- Indian Ocean: 37636 Seconds
- North Pole: 5024 Seconds
- Pacific Ocean: 37678 Seconds
- Russia: 17531 Seconds
- South Pole: 5024 Seconds
- United Kingdom: 29462 Seconds
- United States: 32766 Seconds

4.3.5 Uplink and Downlink Analysis

The radio communication links in the system has to be analysed to establish if they provide a stable connection with few bit errors. A Bit Error Rate (BER) of 1×10^{-6} is practically acceptable with forward error correction being applied to received data.

4.3.5.1 Uplink

The Uplink is considered as the link between sensor node and the satellite, which is transmitted from the sensor node at 10 dBW from a half wave dipole antenna. The RF carrier is set at 145 MHz in the Amateur Radio frequency band and bit rate at 100 kb/s.

A theoretical maximum range for the Uplink at the given BER of 1×10^{-6} can be calculated using the Noise Power Density, N_O, Bit Energy, E_B, Power Received, P_R, and the Free Space Loss, L_{FS}. The maximum range can then be calculated for a given carrier frequency corresponding to the loss in free space. N_O is governed by Equation 4.11.

$$N_O = K.t_e$$ **Equation 4.11**

With the Boltsmann's constant $K = 1.38 \times 10^{-23}$ and the Equivalent Noise Temperature $t_e = 300$ typical for a satellite receiver pointing toward Earth. Reducing Equation 4.11 to:

$$N_O = 4.14 \times 10^{-21}$$

The calculation for E_B is dependent on the modulation scheme used, which in this case is Quadrature Phase Shift Keying (QPSK). The calculation of BER for QPSK is shown in Equation 4.12 (Singhal *et al.*, 2012).

$$BER = \frac{1}{2} erfc \sqrt{\frac{E_B}{N_O}}$$ **Equation 4.12**

Equation 4.12 can be manipulated to get E_B in Equation 4.13.

$$E_B = N_O\left(erfc^{-1}(2BER)\right)^2$$ **Equation 4.13**

$$E_B = 4.68 \times 10^{-20}$$

Equation 4.14 is used to calculate P_R where the Bit Rate, R_B, is equal to 100 kb/s.

$$P_R = E_B.R_B$$ **Equation 4.14**

$$P_R = -143.3\, dB$$

The Free Space Loss L_{FS} can now be calculated with Equation 4.15.

$$L_{FS}(dB) = P_T + G_T - \eta_T + G_R - \eta_R - P_R$$ **Equation 4.15**

With Transmitted Power, P_T = 10 dBW, Transmitter Antenna Gain, G_T = 0 dB, Transmitter Efficiency, η_T = 4.56 dB, Receiver System Gain, G_R = 20 dB, Receiver Efficiency, η_R = 4.56 dB. Reducing Equation 4.15 to:

$$L_{FS} = 2.62 \times 10^{16}$$

The Wavelength (λ) of the Carrier Frequency, f, is governed by Equation 4.16.

$$\lambda = \frac{c}{f}$$ **Equation 4.16**

$$\lambda = 2.07\, Meters$$

Finally the maximum range, r, for a BER of $1\text{x}10^{-6}$ is given by Equation 4.17.

$$r = \frac{\sqrt{L_{FS}} \times \lambda}{4\pi}$$ **Equation 4.17**

$$r = 26{,}635\, km$$

The link is analysed within STK by selecting the transmitter on the sensor node positioned at the Prime Meridian/Equator using the access button and then generating a Link Budget report with respect to the receiver on the satellite. See Appendix A.4 for full Link Budget report.

The transmitter was set up with an elevation constraint of 5° to compensate for a bad connection as the satellite comes over the horizon. Using the data from the Link Budget report, it was discovered that a poor link also exists when the satellite passes directly overhead of the sensor node, this is due to the radiation pattern of a dipole antenna, see Section 2.5.1.1.1. The total time the link is stable, defined as a BER better than $1\text{x}10^{-6}$, was found to be 1157 seconds. This is disregarding the time that the link was below the BER constraint.

4.3.5.2 Downlink

The Downlink is considered the link between satellite and ground station, which is transmitted from the satellite at 10 dBW from a half wave dipole antenna. The receiver on the ground station is a high gain Yagi antenna with narrow beam width and tracking capability. The RF carrier is set at 145 MHz in the Amateur Radio frequency band and bit rate at 100 kb/s.

The link is analysed within STK by selecting the transmitter on the satellite, using the access button and then generating a Link Budget report with respect to the receiver on the ground station. See Appendix A.5 for full Link Budget report.

The receiver was set up with an elevation constraint of 5° to compensate for a bad connection as the satellite comes over the horizon. Using the data from the Link Budget report it was discovered that the total time the link is stable, defined as a BER better than $1\text{x}10^{-6}$, is 1990 seconds. This is disregarding the time that the link was below the BER constraint.

4.3.6 System Capability Calculation

The system capability calculation will establish an approximation of the amount of sensor nodes each ground station can accommodate. The calculation is done by using approximate values of the system's data quantity since many different sensor configurations may exist.

The first step is to calculate the amount of data that can be downloaded to the ground station within a 24 hour period. The total amount of access time, *Acc*, to the ground station was found to be 1990 seconds (See Section 4.3.5.2). The total data transfer capacity, D_{Cap}, is calculated using Equation 4.18 with link speed, L_{Speed}, set to 100 kb/s (0.1 Mb/s).

$$D_{Cap} = L_{Speed} \times Acc \qquad \textbf{Equation 4.18}$$

$$D_{Cap} = 24.875\ MB$$

The next step is to use this data to calculate the system capacity, D_{Quant}. An example calculation is performed using a sensor node with 8 bit resolution, *Res*, and 1 Hz sampling rate, *Samp*. Equation 4.19 is used to calculate D_{Quant} for this scenario with an 86400 second revisit time, t_{Rev}.

$$D_{Quant} = \frac{Res \times t_{Rev}}{Samp}$$ **Equation 4.19**

$$D_{Quant} = 86400\ Bytes$$

Impact on data quantity needs to be considered when making use of network protocols. In Section 2.3.3 it is discussed that the IPv6 header uses 40 bytes of data and has a capacity to package 65535 bytes of data. Data usage can be minimized by using a single time stamp per data packet by including the time of the first measured data in the packet and sensor sampling period in the header. The end user can recover the time stamp for all measurements in a packet by using the header values and decompressing the data. Irregular sampling will require time stamps attached to each sample or to a set of samples.

The total data quantity can be recalculated by determining the number of packets, *Pkts*, and adding the result times 40 bytes for header size, H_{Size}, to the original value. Equation 4.20 is used to recalculate considering the network packet headers where, packet size, $\mathrm{Pkt}_{\mathrm{Size}}$, is 65535 Bytes.

$$Pkts = \frac{D_{Quant}}{Pkt_{Size}}$$ **Equation 4.20**

$$Pkts = 1.32$$

Round up to 2 packets and evaluate the final data quantity in Equation 4.20.

$$D_{Quant} = D_{Quant} + (Pkts\ \times H_{Size})$$ **Equation 4.21**

$$D_{Quant} = 86480\ Bytes$$

Calculate the system capacity, *Sys*, in Equation 4.22.

$$Sys = \frac{D_{Cap} \times\ 1024^2}{D_{Quant}}$$ **Equation 4.22**

$$Sys = 301\ Sensor\ Nodes$$

The example system is capable of accommodating 301 sensor nodes per ground station (See result obtained from Equation 4.22) when these parameters are considered.

This computational method can be used to set up a quick reference table of possible system capabilities per ground station. Table 4.1 indicates the number of sensor nodes the system can accommodate with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.1: Scenario 1.1 System Capability Quick Reference

Sampling Period (Seconds)

	s b	3600	60	1	0.1	0.05
Resolution (Bit)	**8**	407552	17623	301	30	15
	12	343201	11856	201	20	10
	16	296401	8932	150	15	7
	24	232886	5982	100	10	5
	32	191789	4497	75	7	3

4.3.7 Satellite Sensor Node Capacity

The satellite sensor node capacity is the amount of sensor nodes a single satellite can support within its IAA. The calculation is similar to the previous section where the system capability is calculated. Instead *Acc* is used as 1157 seconds and other variables remain unchanged, see calculation starting at Equation 4.18.

The example satellite is capable of accommodating 175 sensor nodes in the IAA when the same parameters as for system capability calculation in Section 4.3.6 are considered.

The computational method is used to set up a quick reference table of possible sensor node capacities per satellite overpass. Table 4.2 indicates the number of sensor nodes the satellite can accommodate in its IAA with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.2: Scenario 1.1 Satellite Capacity Quick Reference

Sampling Period (Seconds)

	s b	3600	60	1	0.1	0.05
Resolution (Bit)	**8**	236953	10246	175	17	8
	12	199539	6893	116	11	5
	16	172329	5193	87	8	4
	24	135402	3478	58	5	2
	32	111507	2614	43	4	2

4.3.8 Memory Resource Calculation

The satellites and sensor nodes in the system each require memory to store the data between collection and transmission. The calculations can be done with the data previously acquired from the scenario analysis.

4.3.8.1 Sensor Node Memory Requirement

The memory requirement is calculated using the parameters for sampling period, *Samp*, resolution, *Res*, and revisit time, t_{Rev}. The example calculation will be done using a sensor node with 8 bit resolution and 1 Hz sampling rate or alternatively for this calculation, a period of 1 second. Equation 4.23 the calculation for this scenario is done with 86400 second revisit time.

$$D_{Quant} = \frac{Res \times t_{Rev}}{Samp} \qquad \textbf{Equation 4.23}$$

$$D_{Quant} = 86400\,Bytes$$

The memory required to store the data between overpasses for this example is 86400 Bytes or alternatively, 84.375 kB. This equation can be used to set up a quick reference table of possible sensor node memory requirements. Table 4.3 indicates the sensor node memory requirement, in kB, with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.3: Scenario 1.1 Sensor Node Memory Requirement Quick Reference

		Sampling Period (Seconds)				
	s **b**	**3600**	**60**	**1**	**0.1**	**0.05**
Resolution (Bit)	**8**	0.02	1.41	84.38	843.75	1687.5
	12	0.04	2.11	126.56	1265.63	2531.25
	16	0.05	2.81	168.75	1687.5	3375
	24	0.07	4.22	253.13	2531.25	5062.5
	32	0.09	5.63	337.5	3375	6750

4.3.8.2 Satellite Memory Requirement

The satellite memory requirement directly correlates with the quantity calculated in Equation 4.18. The satellite has to have a minimum storage capability of $24.875\,MB$ as calculated in Section 4.3.6, which is the total downlink capacity.

4.3.9 Power Resource Calculation

The simulation tool offers a method to simulate the amount of time the satellite is in direct sunlight. This tool can be used to gather data that can assist in calculating the power available use on-board the satellite. A Lighting Times Report can be simulated by, within STK, selecting the satellite in question, opening the Report and Graph Manager and generating a Lighting Times Report. The report gives a duration for the total amount of lighting time per orbit, for worst case scenario 65 minutes is used, see Appendix A.6 for full report.

This data can be used to calculate the power requirement of a satellite. First the power requirement, P_{Req}, is calculated per orbit with Equation 4.24.

$$P_{Req} = P \times t$$ **Equation 4.24**

Where P is the power consumption of the satellite in Watts and t is the time for a single orbit in hours. Using a 5 W continuous requirement for P, this is an average hypothetical value as a satellite's power requirement will greatly vary depending on communication usage. t is 96.69 minutes or 1.61 hours, as calculated in Equation 4.3. Reducing Equation 4.24 to:

$$P_{Req} = 8.05\ Wh$$

With the power requirement the minimum solar panel capacity can be evaluated. This can be done by using the same equation and calculating for P and equating t to the sunlight time, which is 1.08 Hours. This is shown in Equation 4.25.

$$P = \frac{P_{Req}}{t}$$ **Equation 4.25**

$$P = 7.45\ W$$

This value is useful in selecting appropriate solar panels for the given mission. Clyde Space provides a table of solar panel configurations and the respective power outputs for quick reference, see Section 2.4.1.6. This example, for a 3U satellite, would require at least a single side with a deployed solar panel. The calculation holds true for all scenarios in this document with a 600 km altitude and will not be recalculated.

4.4 Scenario 1.2 Analysis

4.4.1 Sensor Nodes Access Duration

Since the validity of STK has already been verified in the previous section, the access times and durations between the sensor nodes and the satellite can simply be calculated using the access tool in STK. See Appendix B.1 for full Access Report. The following access duration results were obtained for the scenario:

- Atlantic Ocean: 3985 Seconds
- Australia: 4189 Seconds
- Brazil: 3881 Seconds
- Canada: 10914 Seconds
- China: 4793 Seconds
- Egypt: 4054 Seconds
- Equator/Prime Meridian: 3706 Seconds
- Europe: 7039 Seconds
- Greenland: 13501 Seconds
- India: 3967 Seconds
- Indian Ocean: 3198 Seconds
- North Pole: 14498 Seconds
- Pacific Ocean: 3695 Seconds
- Russia: 11022 Seconds
- South Pole: 14432 Seconds
- United Kingdom: 7140 Seconds
- United States: 4998 Seconds

A trend can be observed with regards to the location of the sensor node, around the Equator the access time is at a minimum and around the Poles it’s at a maximum. It is also observed that the increase in altitude compared to the previous scenario gives longer access durations.

4.4.2 Ground Station Access Duration

The same process is followed as computation of the sensor node access duration. See Appendix B.2 for full Access Report. The following access duration result was obtained for the scenario:

- Bellville, South Africa: 4266 Seconds

4.4.3 Ground Coverage

The same process to evaluate ground coverage as per Section 4.3.3 is used. Figure 4.4 shows that the coverage percentage reaches 100% in a period of 10 Hours and 20 Minutes, which is slightly faster than the Scenario 1.1 with 600 km orbital altitude.

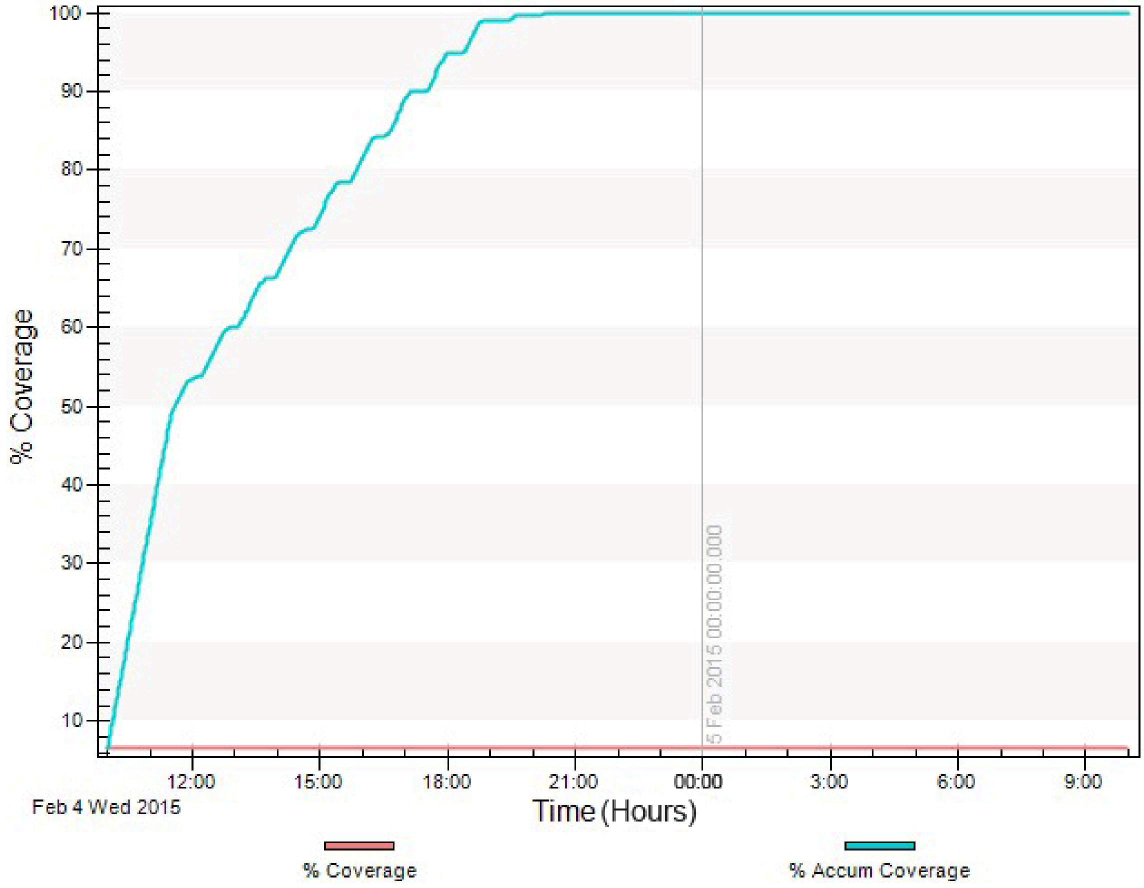


Figure 4.4: Scenario 1.2 Coverage Percentage over Time (STK Simulation)

4.4.4 Maximum Revisit Time

The same process to evaluate maximum revisit time as per Section 4.3.4 is used. Scenario 1.2 requires a revisit time of less than 86400 seconds. See Appendix B.3 for full report. The maximum gap experienced is 34868 seconds, which satisfies the constraint. Maximum access gaps as per location:

4.4.4.1 Ground Station

- Bellville, South Africa: 34703 Seconds

4.4.4.2 Sensor Nodes

- Atlantic Ocean: 34244 Seconds
- Australia: 32639 Seconds
- Brazil: 34096 Seconds
- Canada: 5902 Seconds

- China: 34779 Seconds
- Egypt: 32722 Seconds
- Equator/Prime Meridian: 33797 Seconds
- Europe: 21395 Seconds
- Greenland: 5442 Seconds
- India: 34372 Seconds
- Indian Ocean: 34338 Seconds
- North Pole: 5216 Seconds
- Pacific Ocean: 34210 Seconds
- Russia: 5871 Seconds
- South Pole: 5216 Seconds
- United Kingdom: 19084 Seconds
- United States: 34868 Seconds

4.4.5 Uplink and Downlink Analysis

The same process to analyse the communication links as per Section 4.3.5 is used.

4.4.5.1 Uplink

The total time the link is stable, defined as a BER better than $1x10^{-6}$, was found to be 1664 seconds. See Appendix B.4 for full Link Budget report. This is disregarding the time that the link was below the BER constraint. A significant difference in access time can be seen between this scenario and scenario 1.1 which exhibited an access period of 1157 seconds.

4.4.5.2 Downlink

The total time the link is stable, defined as a BER better than $1x10^{-6}$, was found to be 2689 seconds. This is disregarding the time that the link was below the BER constraint. See Appendix B.5 for full Link Budget report. A significant difference in access time can also be seen between this scenario and scenario 1.1 which exhibited an access period of 1990 seconds.

4.4.6 System Capability Calculation

The system capability calculation is done in the same manner as in Section 4.3.6 starting with Equation 4.18. The quick reference table is calculated using the total amount of access time to the ground station that was found to be 2685 seconds (See Section 4.4.5.2) and a revisit time of 86400 seconds. Table 4.4 indicates the number of sensor nodes the system can accommodate with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.4: Scenario 1.2 System Capability Quick Reference

Sampling Period (Seconds)

	s b	3600	60	1	0.1	0.05
Resolution (Bit)	**8**	549888	23778	406	40	20
	12	463063	15996	271	27	13
	16	399918	12052	203	20	10
	24	314221	8071	135	13	6
	32	258770	6067	101	10	5

4.4.7 Satellite Sensor Node Capacity

The satellite sensor node capacity calculation is done in the same manner as in Section 4.3.6 starting with Equation 4.18. The quick reference table is calculated using total amount of access time to the ground station that was found to be 1157 seconds (See Section 4.4.5.1) and a revisit time of 86400 seconds. Table 4.5 indicates the number of sensor nodes the satellite can accommodate in its IAA with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.5: Scenario 1.2 Satellite Capacity Quick Reference

Sampling Period (Seconds)

	s b	3600	60	1	0.1	0.05
Resolution (Bit)	**8**	340787	14736	252	25	12
	12	286978	9913	168	16	8
	16	247845	7469	126	12	6
	24	194735	5002	84	8	4
	32	160370	3760	63	6	3

4.4.8 Memory Resource Calculation

The satellites and sensor nodes in the system each require memory to store the data between collection and transmission. The calculations can be done with the data previously acquired from the scenario analysis.

4.4.8.1 Sensor Node Memory Requirement

The sensor node memory requirement calculation is done in the same manner as in Section 4.3.8 starting with Equation 4.23. The quick reference table is calculated using the revisit time of 86400 seconds. Calculation yields Table 4.6 which illustrates the sensor node memory requirement, in kB, with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.6: Scenario 1.2 Sensor Node Memory Requirement Quick Reference

		Sampling Period (Seconds)				
	s b	3600	60	1	0.1	0.05
Resolution (Bit)	8	0.02	1.41	84.38	843.75	1687.5
	12	0.04	2.11	126.56	1265.63	2531.25
	16	0.05	2.81	168.75	1687.5	3375
	24	0.07	4.22	253.13	2531.25	5062.5
	32	0.09	5.63	337.5	3375	6750

4.4.8.2 Satellite Memory Requirement

The satellite memory requirement is calculated using Equation 4.18. The total amount of access time to the ground station that was found to be 2685 seconds (See Section 4.4.5.2) and link speed of 100 kb/s is used. The result is that the satellite has to have a minimum storage capability of 33.563 MB.

4.4.9 Power Resource Calculation

Following the same method for the power resource calculation as used in Section 4.3.9, starting at Equation 4.24. The lighting times report gives a duration for the total amount of lighting time per orbit, for worst case scenario 74 minutes is used for calculation, see Appendix B.6 for full report. The result is a power requirement of 7.05 W. This value is useful in selecting appropriate solar panels for the given mission from the Clyde Space table in Section 2.4.1.6. This calculation, for a 3U satellite, would require solar panels on all long faces. The calculation holds true for all scenarios in this document with a 950 km altitude and will not be recalculated.

4.5 Scenario 2.1 Analysis

Some assumptions have to be made for the inter-satellite communications to continue analysis in Scenario 2.1, 2.2, 3.1 and 3.2. It is assumed that the inter-satellite links yield higher data rates than the space to ground communications due to less signal attenuation in a space environment with the use of high gain directional antennas. A ring network topology can be assumed between the satellites for Scenarios 2.1 and 2.2. Whereas a topology similar to internet operation can be assumed for Scenarios 3.1 and 3.2; packets are routed through the network and attempts the shortest possible path with least congestion.

4.5.1 Sensor Nodes Access Duration

Since the validity of STK was already verified in Section 4.3 the access times and durations between the sensor nodes and satellite will only be computed using the access tool in STK. During the analysis of the first scenario only the sensor node at Equator/Prime Meridian and the Ground station at Bellville, South Africa was used. Simplification will be done by only using these points of interest in all further analysis. Within STK to do analysis with a constellation of satellites it must defined as such. This is done by adding a constellation item and placing all satellites in the constellation. A chain must be added and defined as the Equator/Prime Meridian sensor node and the satellite constellation. This is done to gather access data on accesses between the satellite constellation and the sensor node in question. See Appendix C.1 for full Access Report. The following total access duration result was obtained for the scenario over a 24 hour simulation period:

- Equator/Prime Meridian: 17510 Seconds

This value is used to work out the average per 100 minute period by dividing the total access by 1440 minutes (24 hours) times 100 minutes, which gives an average access duration of 1215 seconds.

4.5.2 Ground Station Access Duration

The same process is followed as computation of the sensor node access duration. See Appendix C.2 for full Access Report. The following total access duration result was obtained for the scenario over a 24 hour simulation period:

- Bellville, South Africa: 20817 Seconds

Calculating the average in the same manner as the previous section, an average access duration of 1445 seconds over a 100 minute period is obtained.

4.5.3 Ground Coverage

The same process to evaluate ground coverage as per Section 4.3.3 is used. Figure 4.5 shows that the coverage percentage reaches 100% in a period of 1 Hour and 26 Minutes.

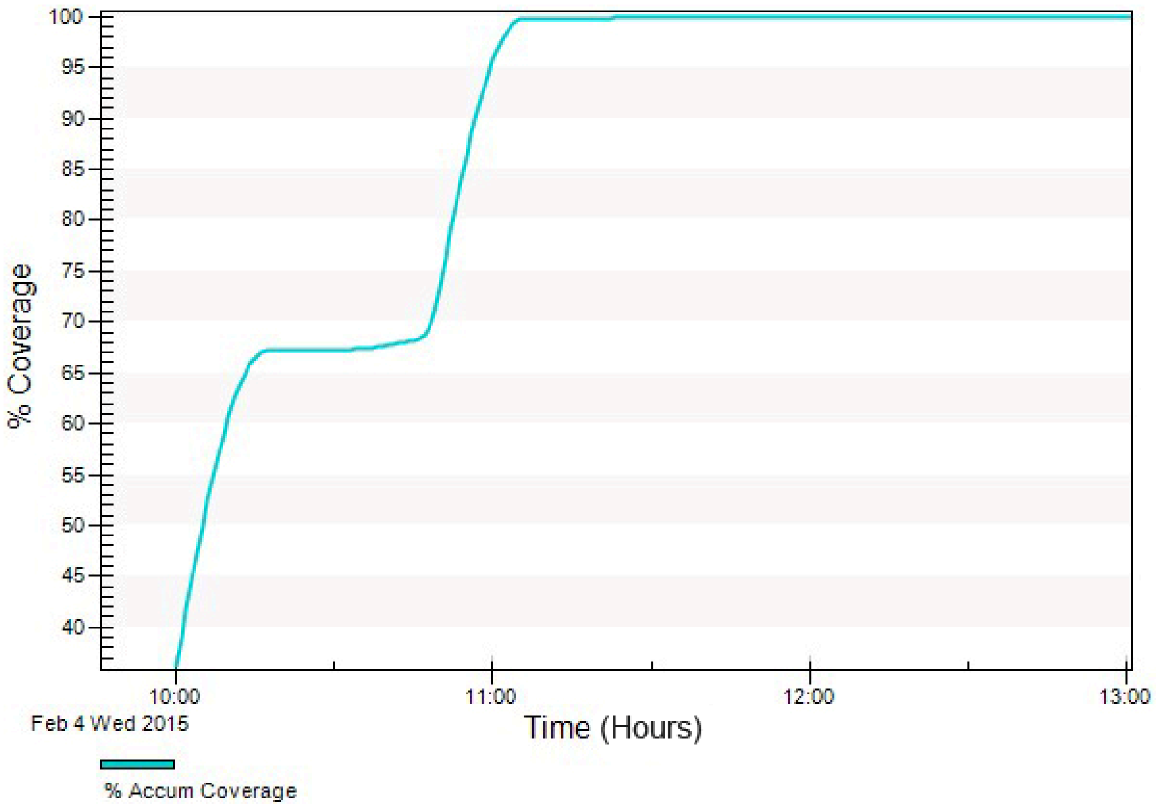


Figure 4.5: Scenario 2.1 Coverage Percentage over Time (STK Simulation)

4.5.4 Maximum Revisit Time

The maximum revisit time is calculated differently than with the single satellite scenario, since it is a constellation, calculation is done only for the Equator/Prime Meridian sensor node. First a constraint is set on the constellation to show when none of the satellites has access to the node, then a graph is plotted of the accesses to the chain as defined earlier. This gives a graph where the maximum gap can be visualised. This gives the maximum period between accesses. Scenario 2.1 requires a revisit time of less than 6000 seconds. The maximum gap experienced is 5288 seconds, which satisfies the constraint. See Figure 4.6 below for visualisation of the maximum gap experienced, the gap is illustrated in green.

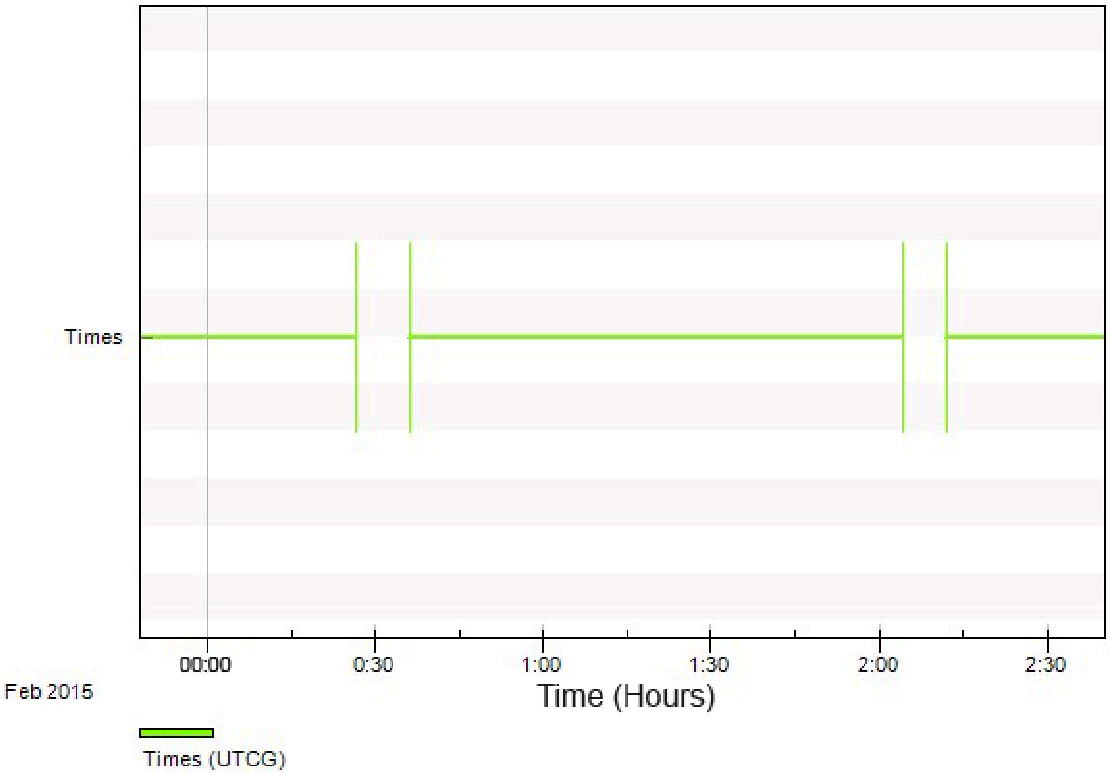


Figure 4.6: Scenario 2.1 Maximum Access Gap (STK Simulation)

4.5.5 Uplink and Downlink Analysis

STK does not provide a means to analyse the link between a sensor node and the defined constellation, therefore one satellite will be analysed and an approximate value will be extrapolated. All other parameters remain unchanged from method used in Section 4.3.5.

4.5.5.1 Uplink

Data obtained in Scenario 1.1 is used since it is the same for this analysis. The total time the link is stable, defined as a BER better than 1x10^{-6}, was found to be 1157 seconds. This is disregarding the time that the link was below the BER constraint. See Appendix A.4 for full Link Budget report with a single satellite. An approximate value can be calculated by multiplying this value by the number of satellites, which is 11 for Scenario 2.1, and calculating an average value for a 100 minute period, since the time was calculated over a 24 hour simulation period. The average value then equates to 883 seconds, where the link is above 1x10^{-6} BER.

4.5.5.2 Downlink

Similar to the uplink calculation, the data obtained in Scenario 1.1 can be used since it is the same for this scenario. The total time the link is stable, defined as a BER better than 1x10^{-6}, was found to be 1990 seconds. This is disregarding the time that the link was below the BER constraint. See Appendix A.5 for full Link Budget report with a single satellite. An approximate value can be calculated by multiplying this value by the number of satellites, which is 11 for Scenario 2.1, and calculating an average value for a 100 minute period, since the time was calculated over a 24 hour simulation period. The average value then equates to 1520 seconds, where the link is above 1x10^{-6} BER.

4.5.6 System Capability Calculation

The system capability calculation is done in the same manner as in Section 4.3.6 starting with Equation 4.18. The quick reference table is calculated using the total amount of access time to the ground station that was found to be 1520 seconds (See Section 4.5.5.2) and a revisit time of 6000 seconds. Table 4.7 indicates the number of sensor nodes the system can accommodate with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.7: Scenario 2.1 System Capability Quick Reference

		Sampling Period (Seconds)				
	s b	**3600**	**60**	**1**	**0.1**	**0.05**
Resolution (Bit)	**8**	478150	142306	3298	331	165
	12	468775	104857	2203	221	110
	16	459760	83012	1654	165	82
	24	442732	58596	1104	110	55
	32	426920	45279	828	82	41

4.5.7 Memory Resource Calculation

The satellites and sensor nodes in the system each require memory to store the data between collection and transmission. The calculations can be done with the data previously acquired from the scenario analysis.

4.5.7.1 Sensor Node Memory Requirement

The sensor node memory requirement calculation is done in the same manner as in Section 4.3.8 starting with Equation 4.23. The quick reference table is calculated using the revisit time of 6000 seconds. Calculation yields Table 4.8 indicates the sensor node memory requirement, in Bytes, with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.8: Scenario 2.1 Sensor Node Memory Requirement Quick Reference

		Sampling Period (Seconds)				
	s b	3600	60	1	0.1	0.05
Resolution (Bit)	**8**	0.17	10	600	6000	12000
	12	0.25	15	900	9000	18000
	16	0.33	20	1200	12000	24000
	24	0.5	30	1800	18000	36000
	32	0.67	40	2400	24000	48000

4.5.7.2 Satellite Memory Requirement

The satellite memory requirement is calculated using Equation 4.18. The total amount of access time to the ground station, that was found to be 1520 seconds (See Section 4.5.5.2), and link speed of 100 kb/s is used. The result is that the satellite has to have a minimum storage capability of 19 MB.

4.6 Scenario 2.2 Analysis

4.6.1 Sensor Nodes Access Duration

The same method as Section 4.5.1 is used to evaluate the sensor node access duration. See Appendix D.1 for full Access Report. The following total access duration result was obtained for the scenario over a 24 hour simulation period:

- Equator/Prime Meridian: 18852 Seconds

This value is used to work out the average per 100 minute period by dividing the total access by 1440 minutes (24 hours) times 100 minutes, which gives us an average access duration of 1309 seconds.

4.6.2 Ground Station Access Duration

The same process is followed as computation of the sensor node access duration. See Appendix D.2 for full Access Report. The following total access duration result was obtained for the scenario over a 24 hour simulation period:

- Bellville, South Africa: 21443 Seconds

Calculating the average in the same manner as the previous section, an average access duration of 1489 seconds over a 100 minute period is obtained.

4.6.3 Ground Coverage

The same process to evaluate ground coverage as per Section 4.3.3 is used. Figure 4.7 shows that the coverage percentage reaches 100% in a period of 1 Hour and 10 Minutes, which is slightly faster than the Scenario 2.1 with 950 km orbital altitude.

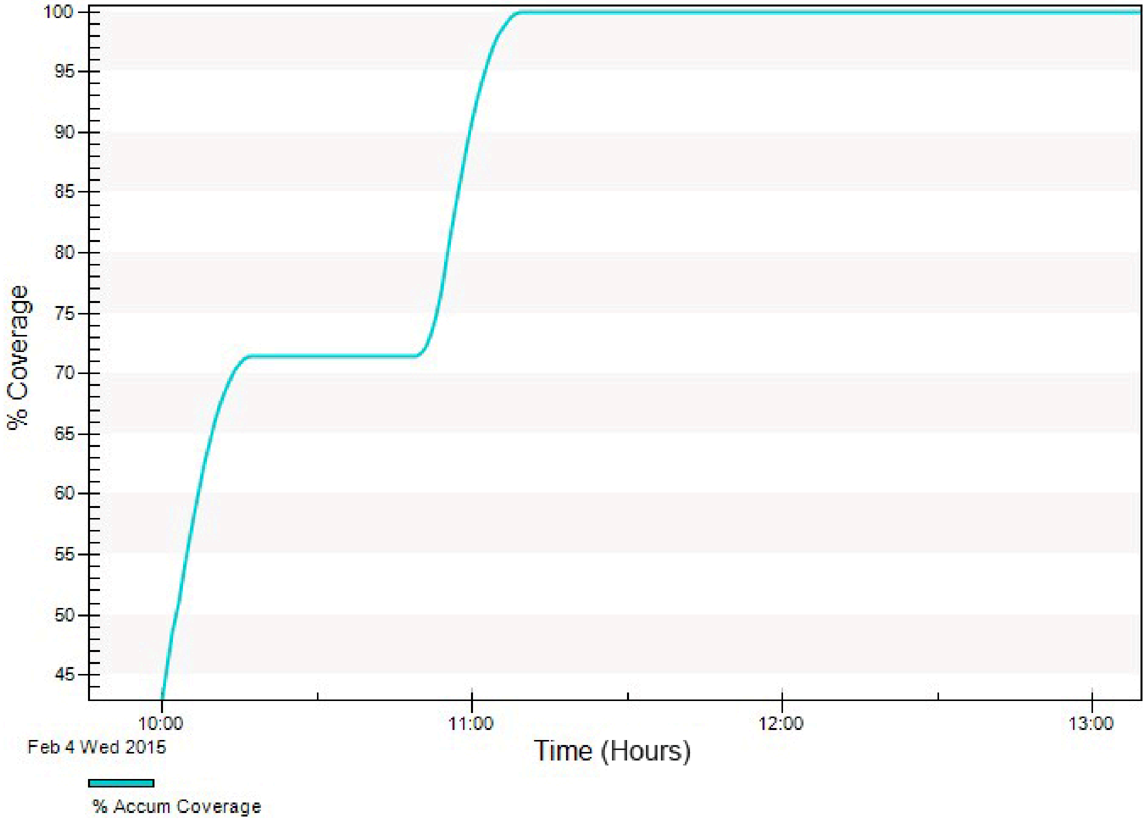


Figure 4.7: Scenario 2.2 Coverage Percentage over Time (STK Simulation)

4.6.4 Maximum Revisit Time

The same method to calculate maximum revisit time in Section 4.5.4 is used. Scenario 2.2 requires a revisit time of less than 6000 seconds. The maximum gap experienced is 2634 seconds, which is well under the value to satisfy the constraint. See Figure 4.8 below for visualisation of the maximum gap experienced, the gap is illustrated in green.

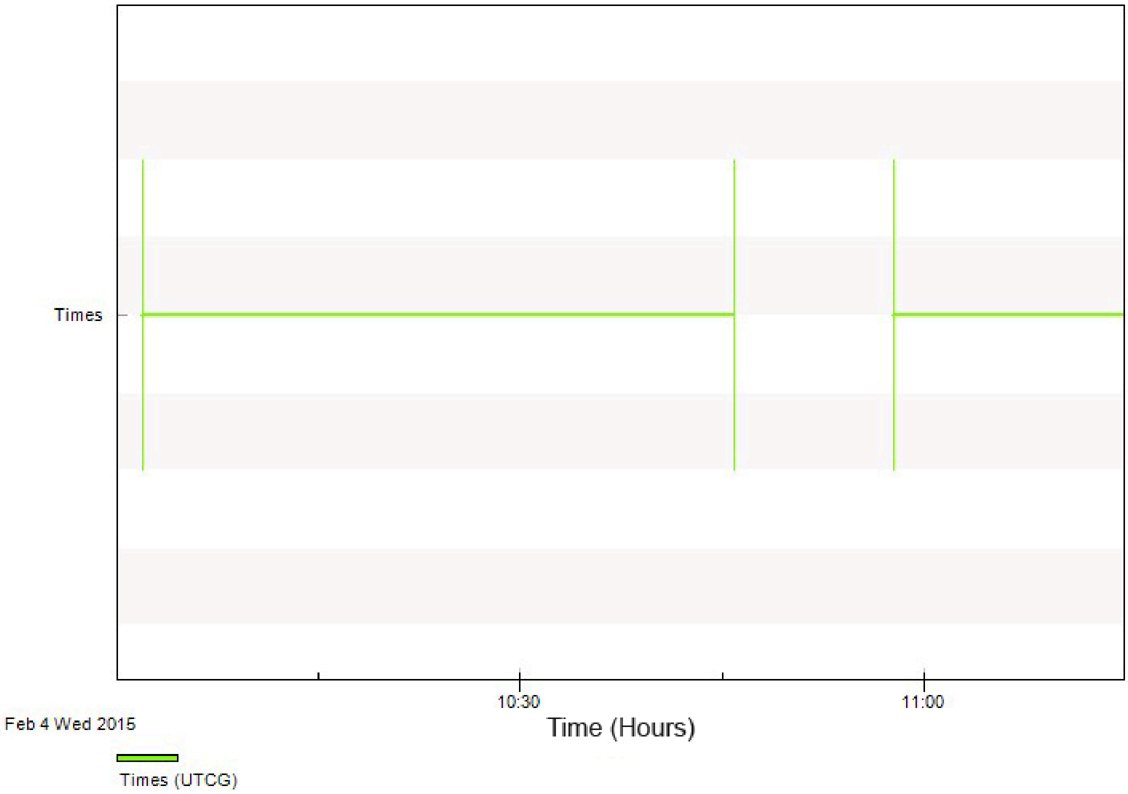


Figure 4.8: Scenario 2.2 Maximum Access Gap (STK Simulation)

4.6.5 Uplink and Downlink Analysis

STK does not provide a means to analyse the link between a sensor node and the defined constellation, therefore one satellite will be analysed and an approximate value will be extrapolated. All other parameters remain unchanged from method used in Section 4.3.5.

4.6.5.1 Uplink

Data obtained in Scenario 1.2 is used since it is the same for this analysis. The total time the link is stable, defined as a BER better than $1\text{x}10^{-6}$, was found to be 1664 seconds. This is disregarding the time that the link was below the BER constraint. See Appendix B.4 for full Link Budget report with a single satellite. An approximate value can be calculated by multiplying this value by the number of satellites, which is 7 for Scenario 2.2, and calculating an average value for a 100 minute period, since the time was calculated over a 24 hour simulation period. The average value then equates to 808 seconds, where the link is above $1\text{x}10^{-6}$ BER.

4.6.5.2 Downlink

Similar to the uplink calculation, the data obtained in Scenario 1.2 can be used since it is the same for this scenario. The total time the link is stable, defined as a BER better than $1\text{x}10^{-6}$, was found to be 2689 seconds. This is disregarding the time that the link was below the BER constraint. See Appendix B.5 for full Link Budget report with a single satellite. An approximate value can be calculated by multiplying this value by the number of satellites, which is 7 for Scenario 2.2, and calculating an average value for a 100 minute period, since the time was calculated over a 24 hour simulation period. The average value then equates to 1307 seconds, where the link is above $1x10^{-6}$ BER.

4.6.6 System Capability Calculation

The system capability calculation is done in the same manner as in Section 4.3.6 starting with Equation 4.18. The quick reference table is calculated using the total amount of access time to the ground station that was found to be 1307 seconds (See Section 4.6.5.2) and a revisit time of 6000 seconds. Table 4.9 indicates the number of sensor nodes the system can accommodate with a variation of sampling periods and resolutions that may be typical parameters for a sensor node.

Table 4.9: Scenario 2.2 System Capability Quick Reference

		Sampling Period (Seconds)				
	s b	3600	60	1	0.1	0.05
Resolution (Bit)	8	411146	122365	2836	285	142
	12	403084	90163	1895	190	95
	16	395333	71379	1422	142	71
	24	380691	50385	949	95	47
	32	367095	38934	712	71	35

4.6.7 Memory Resource Calculation

The satellites and sensor nodes in the system each require memory to store the data between collection and transmission. The calculations can be done with the data previously acquired from the scenario analysis.

4.6.7.1 Sensor Node Memory Requirement

The sensor node memory requirement calculation is done in the same manner as in Section 4.3.8 starting with Equation 4.23. It was established in Scenario 1.2 that the orbit altitude does not affect the sensor node memory requirement, this will not be recalculated since it was calculated in Scenario 2.1.

4.6.7.2 Satellite Memory Requirement

The satellite memory requirement is calculated using Equation 4.18. Total amount of access time to the ground station, that was found to be 1307 seconds (See Section 4.6.5.2), and link speed of 100 kb/s is used. The result is that the satellite has to have a minimum storage capability of 16.338 MB.

4.7 Scenario 3.1 Analysis

4.7.1 Sensor Nodes Access Duration

Since validity of STK was already verified in Section 4.3, access times and durations between the sensor nodes and the satellite will only be computed using the access tool in STK. Within STK to do analysis with a constellation of satellites it must be defined as such. Do this by adding a constellation item and placing all satellites in the constellation. A chain must be added, where it is defined as the chain between the Equator/Prime Meridian sensor node and the satellite constellation. A real time system must have constant access to the satellite constellation, thus it should be evaluated to see if the system meets this requirement instead of simulating access duration. In the simulation a graph of constellation access is generated, which shows no gap in access, this meets the requirement for real time access. See Figure 4.9 for sensor node access graph, access indicated in green.

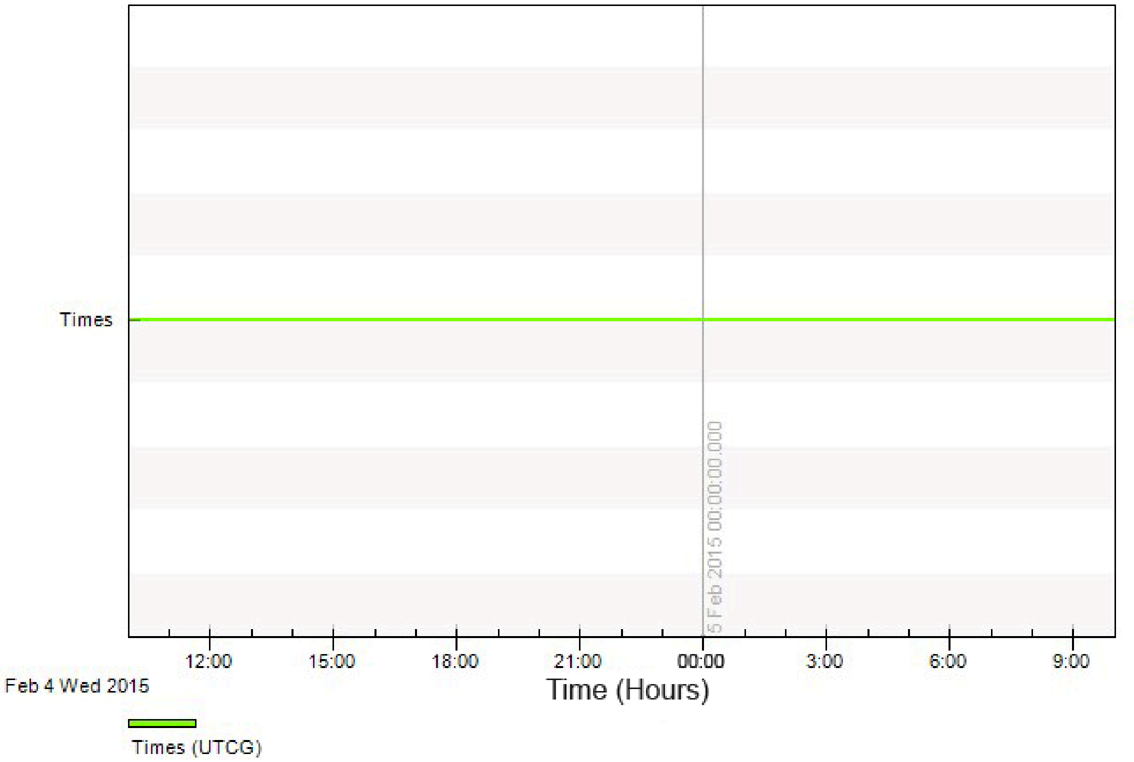


Figure 4.9: Scenario 3.1 Equator/Prime Meridian Sensor Node Access Graph (STK Simulation)

4.7.2 Ground Station Access Duration

The same procedure is followed as for the sensor node calculation. The requirement for real time communication must also be applied to the ground station. A graph is generated to allow for observation of access gaps. From the generated graph below no gaps in access are observed, which satisfies the requirement for real time communication. See Figure 4.10 for ground station access graph, access indicated in green.

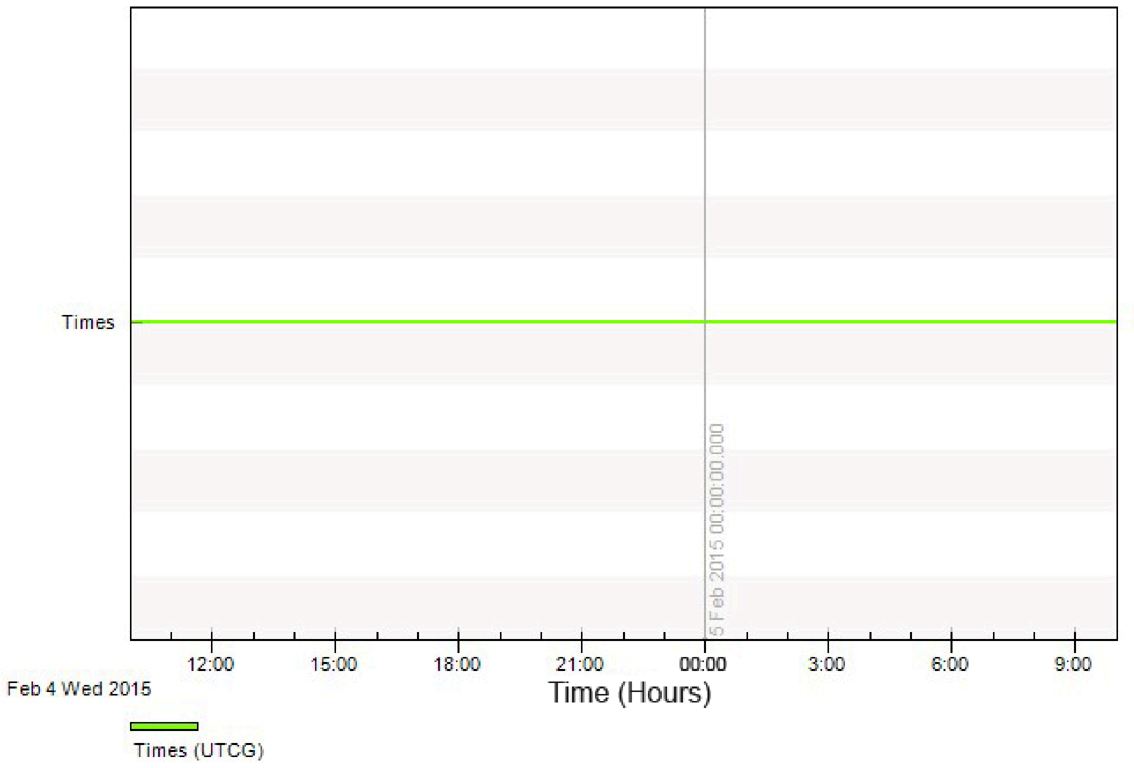


Figure 4.10: Scenario 3.1 Ground Station Access Graph (STK Simulation)

4.7.3 Ground Coverage

The same process to evaluate ground coverage as per Section 4.3.3 is used. Figure 4.11 shows that the coverage percentage is 100% from the start, which is expected for a real time system.

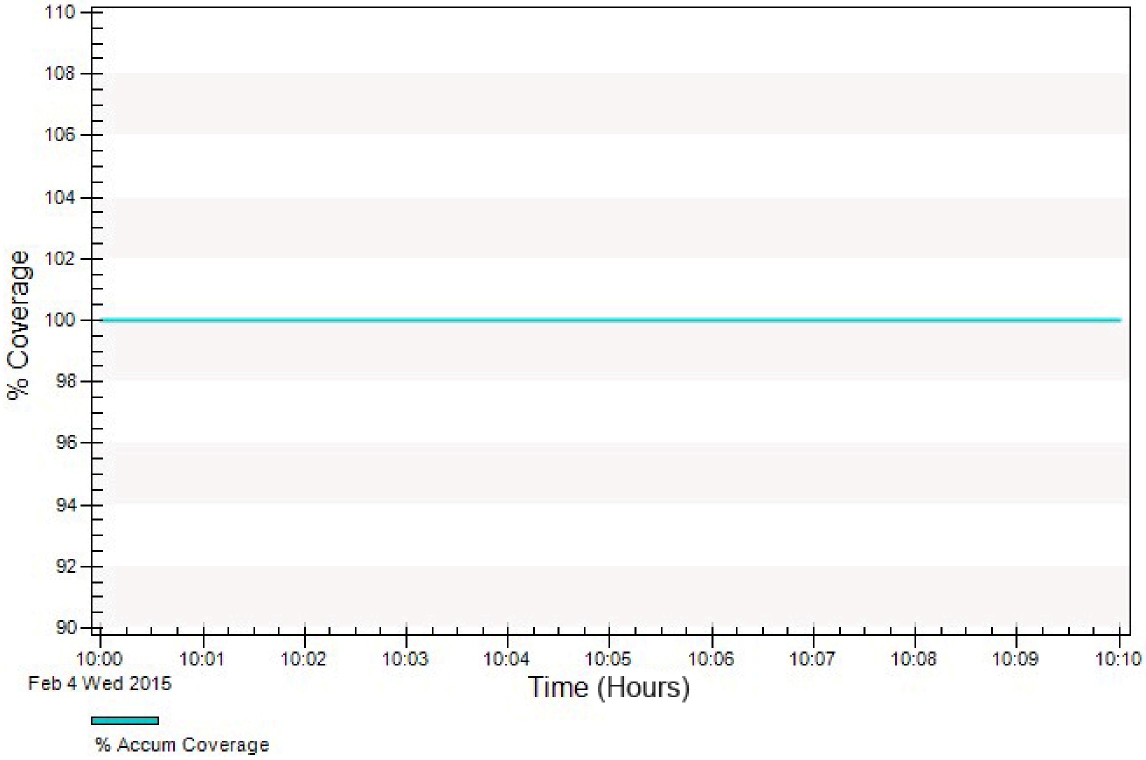


Figure 4.11: Scenario 3.1 Coverage Percentage over Time (STK Simulation)

4.7.4 Uplink and Downlink Analysis

The link for up and downlink has been previously analysed and proven to give a maximum BER of $1x10^{-6}$ for a scenario with satellites at 600 km altitude if measured at a minimum elevation of 5°, see Section 4.3.5. The only poor link experienced was with an overpass directly over the sensor node, due to the radiation pattern of a dipole antenna. The time when the poor link occurs is minimal and can be disregarded.

A real time communication system will constantly relay the data to the ground station(s) as it is transmitted from the sensor nodes. Essentially the system will be a large network with the satellites acting as routers of data in the network. The only limitation in terms of capacity becomes the downlink to the ground station.

4.7.5 System Capability Calculation

The system capability calculation is done in the same manner as in Section 4.3.6 starting with Equation 4.18. The quick reference table is calculated using the total amount of access time to the ground station as 1 second and a revisit time as 1 second, due to real time access. Within such a system the limiting factor is the downlink to the ground station. Table 4.10 indicates the number of sensor nodes the system can accommodate with a variation of sampling periods and resolutions that may be typical parameters for a sensor node. Since this is a real time system, for sensor sampling slower than 1 Hz, it is difficult to estimate a maximum value. All sensors may sample at different intervals, which is most likely the case, or simultaneously in a worst case scenario. The values given is a worst case scenario approximation.

Table 4.10: Scenario 3.1 System Capability Quick Reference

		Sampling Rate (Seconds)				
	s b	**3600**	**60**	**1**	**0.1**	**0.05**
Resolution (Bit)	**8**	327	327	319	262	218
	12	327	327	315	238	187
	16	327	327	312	218	163
	24	327	327	304	187	131
	32	327	327	297	163	109

4.8 Scenario 3.2 Analysis

4.8.1 Sensor Nodes Access Duration

Following the same procedure as Section 4.7.1 a graph of constellation access is generated, which shows no gap in access, which meets the requirement for real time access. See Figure 4.12 for sensor node access graph, access indicated in green.

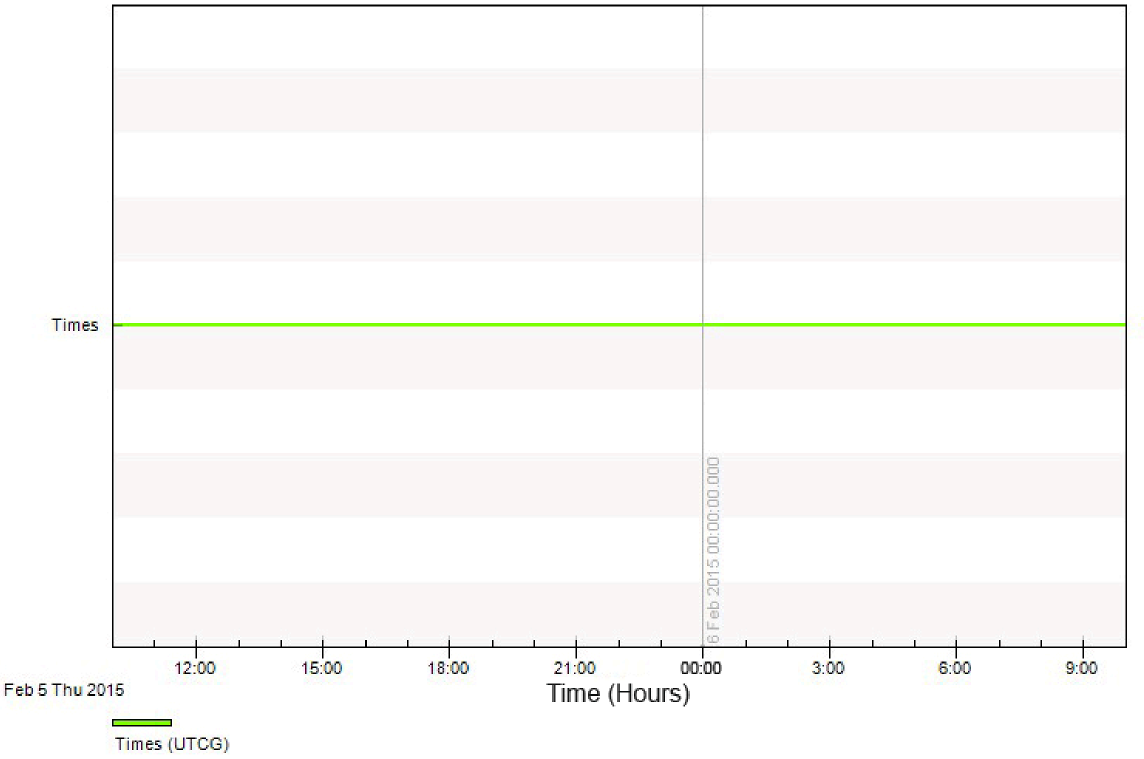


Figure 4.12: Scenario 3.2 Equator/Prime Meridian Sensor Node Access Graph (STK Simulation)

4.8.2 Ground Station Access Duration

The same procedure as for the sensor node calculation is used. The requirement for real time communication must also be applied to the ground station. A graph is generated to allow for observation of access gaps. From the generated graph below it is observed that there are almost no gaps in access. Upon close inspection shows only a small gap of less than 1 second that occurs randomly and very infrequently. This small gap can be neglected for practical purposes. The only way to compensate for these small gaps is the addition of satellites. The addition of satellites is impractical, it will constitute in a large increase in cost with very little change to the system performance. See Figure 4.13 for ground station access graph, access indicated in green.

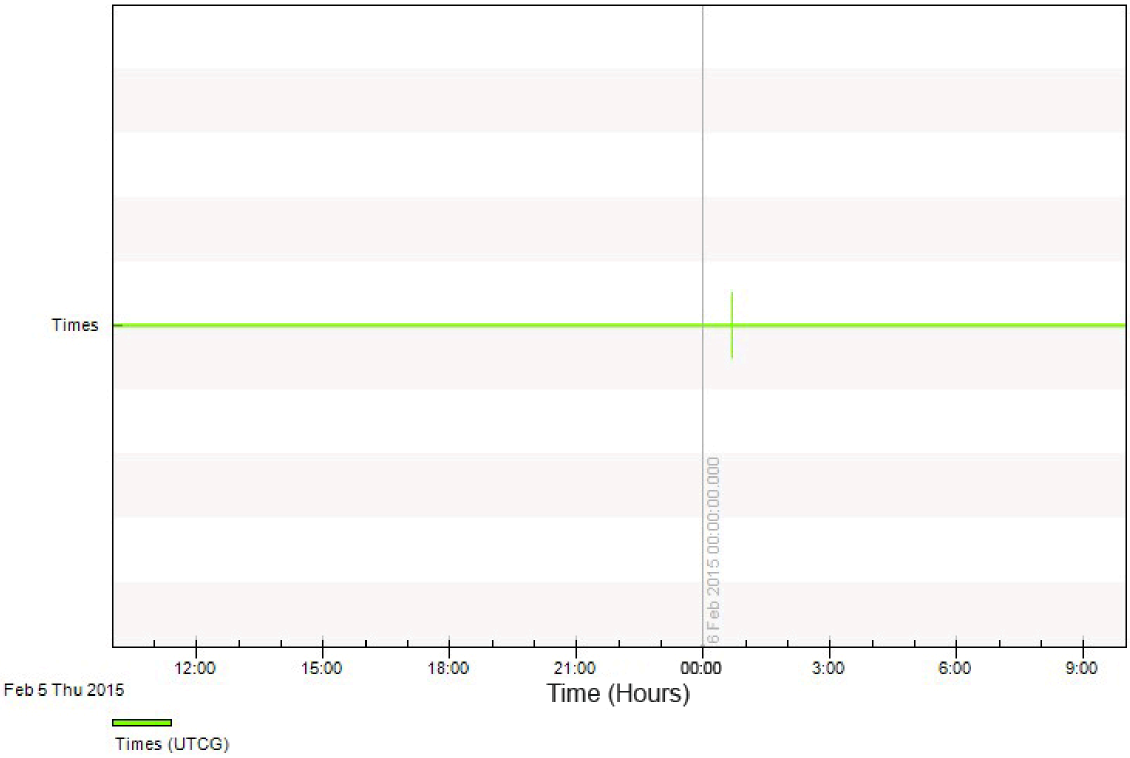


Figure 4.13: Scenario 3.2 Ground Station Access Graph (STK Simulation)

4.8.3 Ground Coverage

The same process to evaluate ground coverage as per Section 4.3.3 is used. Figure 4.14 shows that the coverage percentage is 100% from the start, which is expected for a real time system.

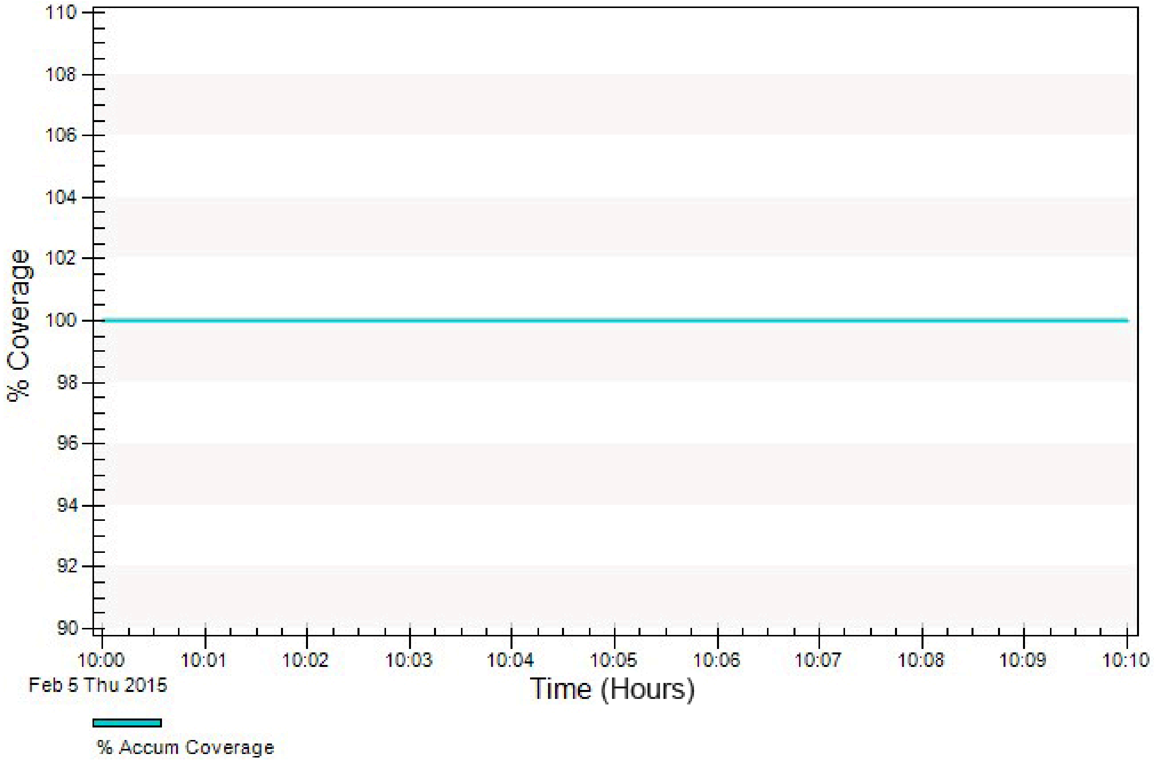


Figure 4.14: Scenario 3.2 Coverage Percentage over Time (STK Simulation)

4.8.4 Uplink and Downlink Analysis

The up and downlink for a system at 950 km altitude is governed by the same characteristics as for the 600 km altitude system, refer to Section 4.7.4.

4.8.5 System Capability Calculation

The system capability calculation is done in the same manner as in Section 4.3.6 starting with Equation 4.18. The quick reference table is calculated using the total amount of access time to the ground station as 1 second and a revisit time as 1 second, due to real time access. Within such a system the limiting factor is the downlink to the ground station. Table 4.11 indicates the number of sensor nodes the system can accommodate with a variation of sampling periods and resolutions that may be typical parameters for a sensor node. Since this is a real time system, for sensor sampling slower than 1 Hz, it is difficult to estimate a maximum value. All sensors may sample at different intervals, which is most likely the case, or simultaneously in a worst case scenario. The values given is a worst case scenario approximation.

Table 4.11: Scenario 3.2 System Capacity Quick Reference

Sampling Period (Seconds)

	s b	**3600**	**60**	**1**	**0.1**	**0.05**
Resolution (Bit)	**8**	327	327	319	262	218
	12	327	327	315	238	187
	16	327	327	312	218	163
	24	327	327	304	187	131
	32	327	327	297	163	109

4.9 Scenario Meta-Analysis

This section serves as a side by side analysis of data gathered during analysis of each scenario. Since the scenarios work on different time frames for revisit time, the meta analysis is done by using the revisit time for the first scenario at 24 hours so that an equal cross comparison can be established. System capability and memory requirement comparisons were all selected to use a 16 bit resolution with 60 second sampling period for equality. Table 4.12 illustrates a collection of data gathered during analysis of various scenarios of in-situ monitoring systems.

Table 4.12: Meta-Analysis Cross Comparison

Scenario Number

		1.1	1.2	2.1	2.2	3.1	3.2
Analysis Type	Sensor Node Access Duration (Seconds)	2055	3706	17510	18852	86400	86400
	Ground Station Access Duration (Seconds)	1928	4266	20817	21443	86400	86400
	Time till 100% Ground Coverage (Seconds)	38100	37200	5160	4200	0	0
	Uplink Analysis (Seconds)	1157	1664	12727	11648	86400	86400
	Downlink Analysis (Seconds)	1990	2689	21890	18823	86400	86400
	System Capability (Total Nodes)	8932	12052	83012	71397	327	327
	Sensor Node Memory Requirement (kB)	2.81	2.81	0.3	0.3	N/A	N/A
	Satellite Memory Requirement (MB)	24.88	33.56	19	16.34	N/A	N/A

4.9.1 Sensor Node Access Duration

The sensor node used in Table 4.12 is situated at the Equator/Prime Meridian. The data shows that increasing the orbital altitude has a larger impact on the single satellite scenarios than on the constellation scenarios. This can be attributed to the fact that there is an overlap in ground track area for the satellites in the constellation. Furthermore it is expected to see an increase in access duration with the number of satellites in the constellation. Scenario 2.2 appears to have overall better performance than scenario 2.1. It only has 7 satellites compared to scenario 2.1 with 11 satellites, but the increase in altitude from 600 km to 950 km yields a longer access duration even with less satellites in the constellation. Scenarios 3.1 and 3.2 are difficult to compare due to their real time communication and will not be further discussed for ground station access duration, communication link analysis and memory resource calculation since they are similarly affected.

4.9.2 Ground Station Access Duration

Table 4.12 shows that a similar conclusion can be reached as in Section 4.9.1. This trend can also be extended to conclude that the outcome for ground coverage and maximum revisit time will have a similar performance, they will therefore not be discussed separately.

4.9.3 Uplink and Downlink Analysis

The up and downlink analysis in Table 4.12 showed that there was a comparable link performance difference between orbit altitudes with the single satellite scenarios 1.1 and 1.2. The same performance increase should occur with scenarios 2.1 and 2.2; however, the analysis shows a decrease in performance which can be attributed to the decrease in satellites from 11 in scenario 2.1 to 7 in scenario 2.2.

4.9.4 System Capability Calculation

In Table 4.12 the effects of changing orbit altitude is clearly visible between scenarios 1.1 and 1.2 with a 34.9% increase in capability. Looking at scenarios 2.1 and 2.2 a decrease in capability is observed, this can be attributed to the fact that there are less satellites at the higher altitude scenario and thus can serve less nodes at a given instant in time. The low number associated with scenarios 3.1 and 3.2 is due to it being analysed as a worst case scenario with sensors sampling simultaneously within the real time system, this number would be much higher than all of the previous scenarios when samples occur randomly such as it would realistically.

4.9.5 Memory Resource Calculation

It is observed with the sensor node memory requirement in Table 4.12 that an increase in altitude does not affect the data. It may be slightly affected if the maximum gap time between overpasses are taken into account, which will cause scenario 1.2 to require less memory due to the increase in IAA size. During analysis a worst case scenario was implemented by using the maximum revisit time constraint for calculation, which disregards the larger IAA.

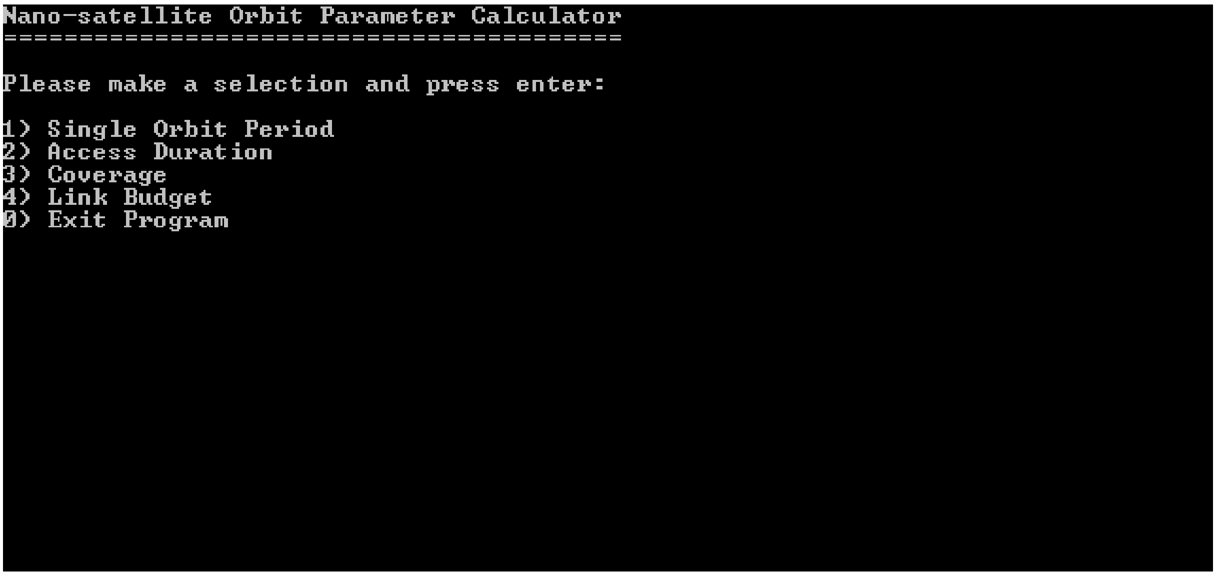
The satellite memory requirement is observed in Table 4.12 to increase proportionally with the amount of access time available to the ground station with scenario 1.1 and 1.2. This can be attributed to the fact that the downlink to ground station is the limiting factor within the system. Scenario 2.1 and 2.2, the amount of satellites also limits the amount of data that can be sent through the downlink, therefore scenario 2.2 has a lower memory requirement than scenario 2.1 due to less satellites in the constellation.

4.10 Software Tool

The research has led to the development of a supporting software tool for in-situ monitoring satellite calculations. The calculator is a simple, easy to use interface for calculation based on the theoretical approximation methods used during the scenario calculations earlier in this chapter. The software is run from an executable file, which presents the user with an interface to select the calculation required. The functions available for calculation are:

- Single Orbit Period
- Access Duration
- Coverage
- Link Budget

Figure 4.15 depicts the selection menu which appears at software start.

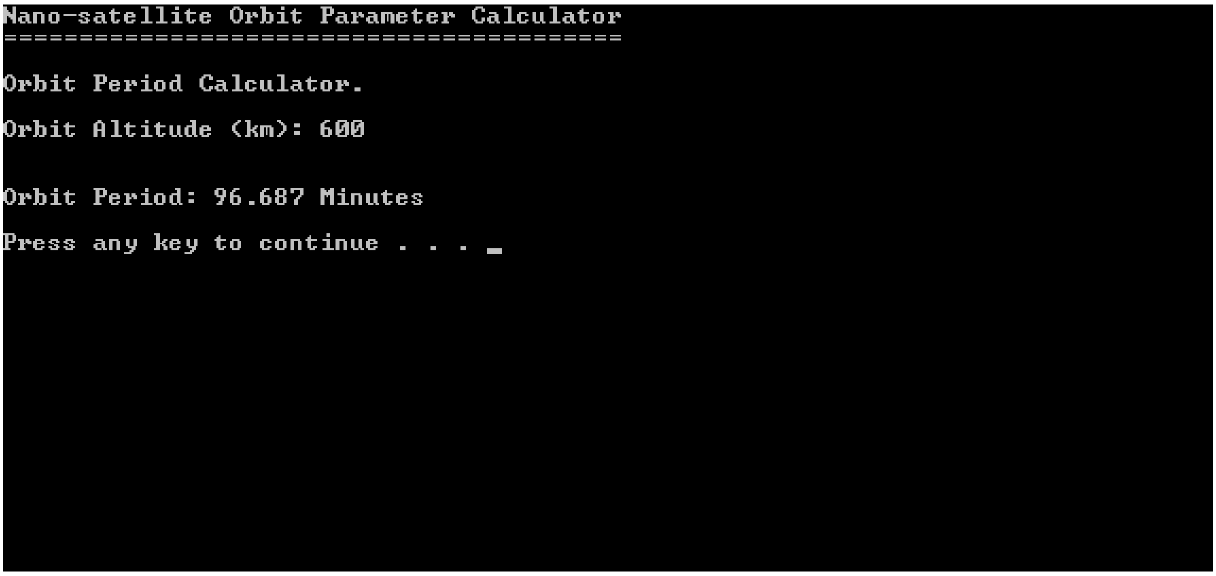


```
Nano-satellite Orbit Parameter Calculator
=========================================

Please make a selection and press enter:

1) Single Orbit Period
2) Access Duration
3) Coverage
4) Link Budget
0) Exit Program
```

Figure 4.15: Software Tool Main Menu

4.10.1 Single Orbit Period Calculation

The menu shown in Figure 4.16 depicts the single orbit period calculation. The user is prompted to enter the orbit altitude in km, which then gives the orbit period in minutes. The example shown in Figure 4.16 is for a 600 km orbit altitude which yields a 96.687 minute orbit period.

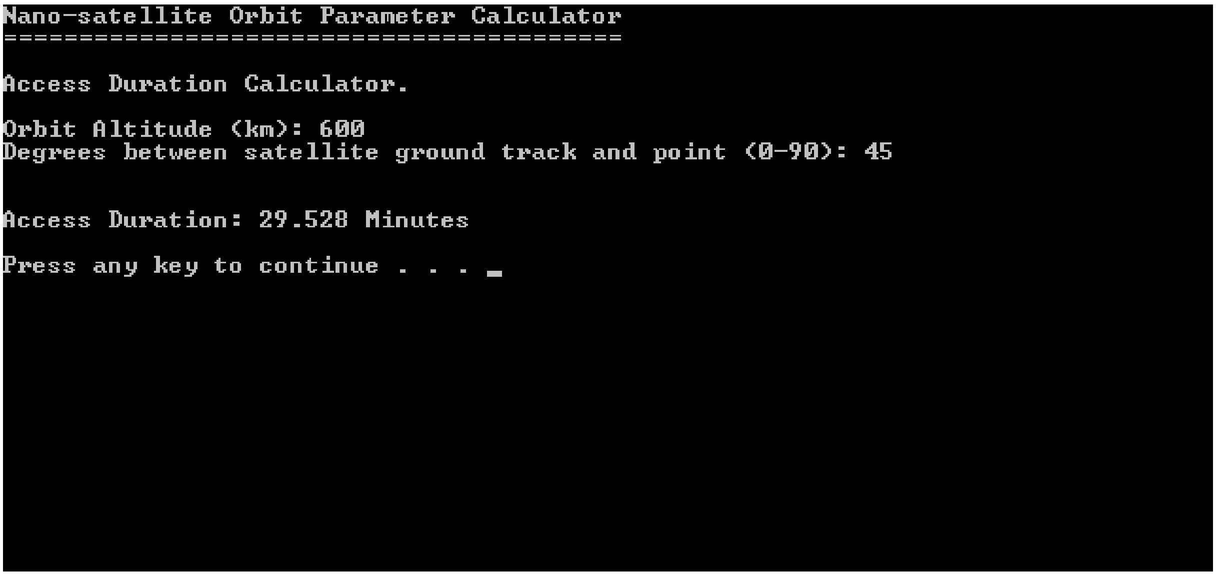


```
Nano-satellite Orbit Parameter Calculator
=========================================

Orbit Period Calculator.

Orbit Altitude (km): 600


Orbit Period: 96.687 Minutes

Press any key to continue . . .
```

Figure 4.16: Single Orbit Period Calculation Menu

4.10.2 Access Duration Calculation

The menu shown in Figure 4.17 depicts the access duration calculation. The user is prompted to enter the orbit altitude in km as well as the angle between satellite ground track and point of interest in degrees, this is the angle at which the point first enters the edge of the satellite's IAA during an overpass. The calculator then gives the access time in minutes. The example shown in Figure 4.17 is for a 600 km orbit altitude with 45 degree angle which yields a 29.528 minute access duration.



```
Nano-satellite Orbit Parameter Calculator
=========================================

Access Duration Calculator.

Orbit Altitude (km): 600
Degrees between satellite ground track and point (0-90): 45


Access Duration: 29.528 Minutes

Press any key to continue . . . _
```

Figure 4.17: Access Duration Calculation Menu

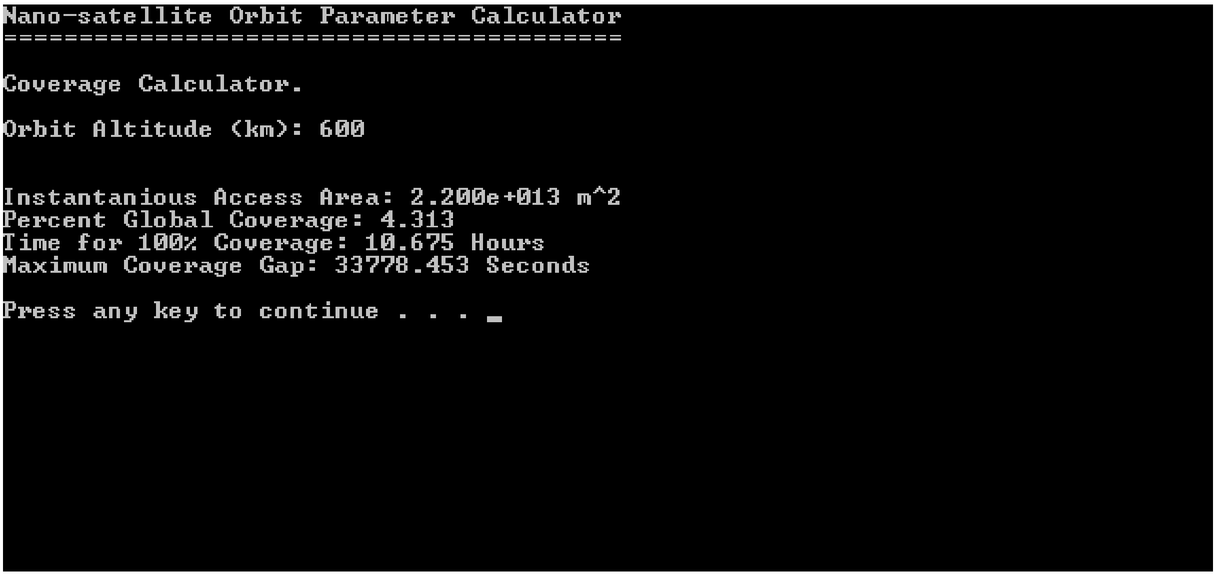
4.10.3 Coverage Calculation

The menu shown in Figure 4.18 depicts the coverage calculation. The user is prompted to enter orbit altitude to calculate the following:

- IAA
- Percent global coverage (Covered by IAA)
- Time for 100% coverage
- Maximum coverage gap

The example shown in Figure 4.18 is for a 600 km orbit altitude which gives the following results:

- IAA: 2.2 x 10^{13} m^2
- Percent global coverage: 4.313%
- Time for 100% coverage: 10.675 Hours
- Maximum coverage gap: 33778 Seconds



```
Nano-satellite Orbit Parameter Calculator
=========================================

Coverage Calculator.

Orbit Altitude (km): 600


Instantanious Access Area: 2.200e+013 m^2
Percent Global Coverage: 4.313
Time for 100% Coverage: 10.675 Hours
Maximum Coverage Gap: 33778.453 Seconds

Press any key to continue . . .
```

Figure 4.18: Coverage Calculation Menu

4.10.4 Link Budget Calculator

The menu shown in Figure 4.19 depicts the link budget calculation. The calculator uses a maximum limit of 10^{-6} BER to calculate parameters. The calculation is used to establish a maximum communications distance for quick reference purposes. The user is prompted to enter the following parameters:

- Bitrate in b/s
- Transmit power in dBW
- Transmit antenna and LNA gain in dB
- Transmit antenna efficiency in percent
- Receive antenna and LNA gain in dB
- Receive antenna efficiency in percent
- Carrier frequency in Hz

The calculator yields the following results:

- Power received in dBW
- Freespace loss in dB
- Maximum range in meters
- Eb/No in dB

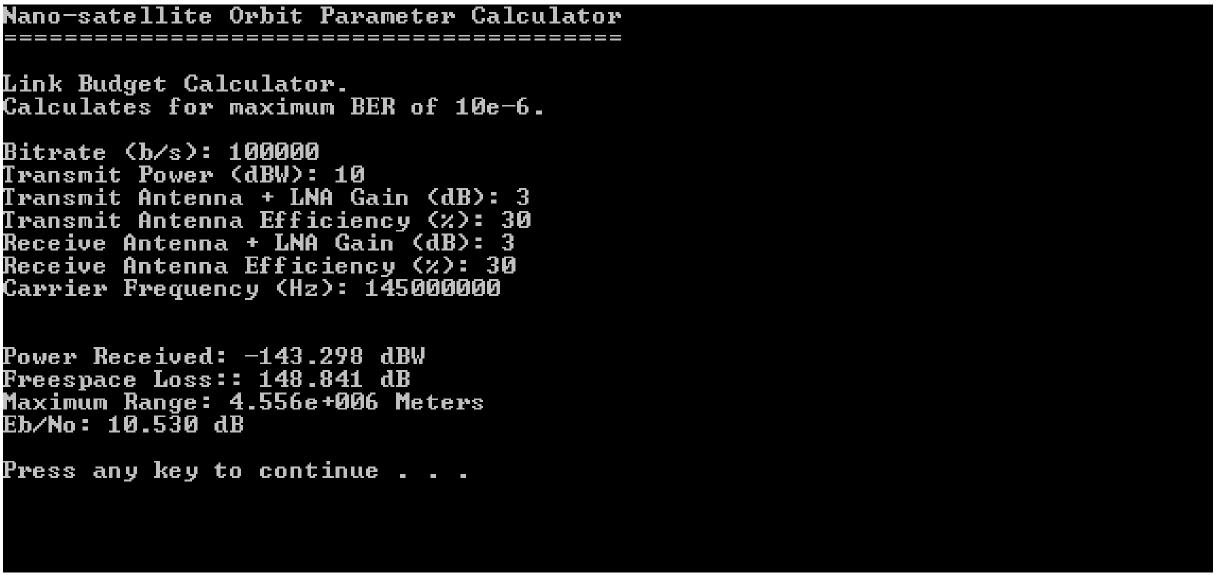
The example shown in Figure 4.19 is for the following parameters:

- Bitrate: 100 kb/s
- Transmit power: 10 dBW
- Transmit antenna and LNA gain: 3 dB

- Transmit antenna efficiency: 30%
- Receive antenna and LNA gain: 3 dB
- Receive antenna efficiency: 30%
- Carrier frequency: 145 MHz

The results obtained are as follows:

- Power received: -143 dBW
- Freespace loss: 149 dB
- Maximum range: 4556 km
- Eb/No: 10.53 dB



```
Nano-satellite Orbit Parameter Calculator
=========================================

Link Budget Calculator.
Calculates for maximum BER of 10e-6.

Bitrate (b/s): 100000
Transmit Power (dBW): 10
Transmit Antenna + LNA Gain (dB): 3
Transmit Antenna Efficiency (%): 30
Receive Antenna + LNA Gain (dB): 3
Receive Antenna Efficiency (%): 30
Carrier Frequency (Hz): 145000000


Power Received: -143.298 dBW
Freespace Loss:: 148.841 dB
Maximum Range: 4.556e+006 Meters
Eb/No: 10.530 dB

Press any key to continue . . .
```

Figure 4.19: Link Budget Calculation Menu

The calculator is in essence a quick reference tool that uses simplified calculations for ease of use. It is in no way developed to handle the full complexity of an in-situ monitoring system and the corresponding orbital parameters. It is recommended to use theoretical approximation equations outlined earlier in this chapter or simulation software if more accurate solutions are required.

The next chapter will conclude the research and provide a summary of findings with recommendations and possibilities for future research to be conducted around this topic.

CHAPTER FIVE

CONCLUSION

5.1 Summary and Conclusions

The main objective of this research was to establish the performance characteristics of an in-situ monitoring system using nano-satellites and provide an easy method to analyse various scenarios.

The first steps required for this thesis was to establish the various parameters governing an in-situ monitoring system using nano-satellites by reviewing literature and current technologies. Emphasis was put on researching the communication systems currently used on nano-satellites and the orbital dynamics implemented in most CubeSat missions. The concept was to gather the relevant information from literature needed to create realistic scenarios representing in-situ monitoring missions with various specifications. These scenarios are then analysed theoretically and through simulation, applying similar analysis methods across scenarios to obtain accurate data. The use of a combination of theoretical estimation and simulation data gives us the assurance that the data is feasible for analysis. Finally six scenarios were created and analysed, these consisted of missions which vary in orbit altitude and revisit time. The analysis as outlined in Chapter Four of this document show the obtained results.

During the analysis it was proven that theoretical calculation, used for satellite mission analysis and design, align with the results obtained with the simulation tool, namely STK. The simulation data was therefore deemed accurate and used for analysis throughout the following scenarios. The theoretical calculation only provides an estimate of mission parameters, whereas the simulation tool can provide more accurate data when given correct input parameters.

The focus of creating an in-situ monitoring system using nano-satellites places emphasis on the communication sub-systems that transfer the data from sensor node to satellite and from satellite to ground station. The communication sub-system was made the main objective for analysis to establish its performance characteristics and had to be capable of relaying all the data generated by the sensor nodes to the ground station(s) within the revisit time constraint.

The most apparent constraints limiting the communication system was the lack of bandwidth, considering radio bands allocated for amateur use, and the available transmit power. Operating within these constraints, the communication sub-system was limited to using a transmit power of 10 dBW at a RF carrier of 145 MHz, amateur allocated frequency, and a data rate of 100 kb/s. For further reduction of bandwidth usage the analysis was done with a

QPSK modulation scheme in the communication simulations, which limits the bandwidth usage to 50 kHz.

The scenario analysis has shown that staying within the amateur radio bands limited data rate, which greatly affects the performance of the in-situ monitoring system. Radio regulation does not allow for wide band communication in the amateur radio bands and therefore the data rate is directly affected and cannot be increased further. The only way to overcome the constraint is to shift the system into a commercial radio band, which requires more involved licencing and increases cost.

Analysis of the variations in scenario parameters done with different revisit times and orbit altitudes show how the performance characteristics and system capability is affected with these individual changes. In the analysis of Scenario 1.1 and 1.2 it became apparent how the access duration and IAA increases with orbit altitude. It could also be observed how the latitude position of ground station(s) and sensor nodes affect the duration of an access, being shorter at the Equator and longer at the Poles.

Scenario 2.1 and 2.2 analysis presented data that suggested that increasing the orbit altitude, decreases the number of satellites required to conform to the revisit time constraint, since the access area is increased per satellite. It was noted that for Scenario 2.2 the system capability was negatively affected by decreasing the number of satellites. Although the IAA was greater compared to the Scenario 2.1 at a lower altitude, allowing the decrease in satellites, the limit in data rate of 100 kb/s allowed less data to be transferred during the simulated access duration.

Real time Scenarios 3.1 and 3.2 had the lowest sensor node capacity of all simulated scenarios. This data can be attributed to the fact that a real time system does not store data, it relies solely on the data link transfer rate to move data between sensor nodes and ground station(s). The low link speed of 100 kb/s simply does not provide enough transfer speed to accommodate a large number of sensor nodes. It must be noted that the calculation was done with a worst case scenario in mind, where all sensor nodes are uploading data simultaneously, in practice this is unlikely. In a real world implementation with sensors transferring data intermittently, the sensor node capacity will be greater.

5.2 Recommendations

The simulations were all done with transmitter powers of 10 dBW, which ensured proper communication between sensor node and satellite, as well as satellite and ground station. During all simulations a 5° minimum inclination for communication was taken into account. The scenarios all presented with a maximum BER of 10^{-6} throughout the overpass above the inclination constraint, except for directly overhead a sensor node, which is due to a dipole antenna's radiation pattern. The data suggests that a 10 dBW transmitter is possibly more powerful than required for such an in-situ monitoring system and could be scaled down. Investigation into a different antenna for sensor nodes to eliminate the poor communication area directly overhead the sensor node is also recommended.

5.3 Future Work

The research was focussed on keeping the system within amateur radio bands for research and non-commercial purposes. Unfortunately as stated earlier in this chapter, the data rate is greatly limited by remaining in amateur radio bands. Future work may include investigation into shifting the operational frequencies of the system into commercial radio bands. The research will include adjusting the data rates to higher values to accommodate a system with a greater capacity for sensor nodes. These adjustments will require an increase in transmit power to maintain the practical maximum BER of 10^{-6}. The research did not include investigation into the inter-satellite communication links as required in Scenario 2 and 3. Future work can include investigation into the power requirements, data rates and link quality of the inter-satellite communication links.

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APPENDICES

Appendix A.1: Scenario 1.1 Sensor Node Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS-Sensor-Comms_Cone-Transmitter-Transmitter2-To-Place-SNode_Atlantic_Ocean-Sensor-
Comms_Cone2-Receiver-Receiver4, Receiver-Receiver5, Receiver-Receiver6, Receiver-Receiver7, Receiver-
Receiver8, Receiver-Receiver9, Receiver-Receiver3, Receiver-Receiver10, Receiver-Receiver19, Receiver-
Receiver18, Receiver-Receiver17, Receiver-Receiver16, Receiver-Receiver15, Receiver-Receiver14, Receiver-
Receiver13, Receiver-Receiver12, Receiver-Receiver11:  Access Summary Report


Transmitter2-To-Receiver4
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 14:43:54.828    4 Feb 2015 14:48:06.448           251.620
                       2    4 Feb 2015 16:16:27.875    4 Feb 2015 16:29:20.413           772.538
                       3    4 Feb 2015 17:58:01.738    4 Feb 2015 17:59:59.359           117.621
                       4    5 Feb 2015 02:57:31.286    5 Feb 2015 03:05:23.096           471.810
                       5    5 Feb 2015 04:31:22.706    5 Feb 2015 04:44:05.866           763.159

Global Statistics
-----------------
Min Duration           3    4 Feb 2015 17:58:01.738    4 Feb 2015 17:59:59.359           117.621
Max Duration           2    4 Feb 2015 16:16:27.875    4 Feb 2015 16:29:20.413           772.538
Mean Duration                                                                             475.350
Total Duration                                                                           2376.749


Transmitter2-To-Receiver5
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 17:16:51.747    4 Feb 2015 17:28:40.842           709.095
                       2    4 Feb 2015 18:53:47.361    4 Feb 2015 19:05:03.808           676.447
                       3    5 Feb 2015 05:09:00.035    5 Feb 2015 05:20:50.959           710.924
                       4    5 Feb 2015 06:45:50.670    5 Feb 2015 06:57:05.897           675.226

Global Statistics
-----------------
Min Duration           4    5 Feb 2015 06:45:50.670    5 Feb 2015 06:57:05.897           675.226
Max Duration           3    5 Feb 2015 05:09:00.035    5 Feb 2015 05:20:50.959           710.924
Mean Duration                                                                             692.923
Total Duration                                                                           2771.692


Transmitter2-To-Receiver6
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 17:55:07.732    4 Feb 2015 18:07:22.213           734.481
                       2    4 Feb 2015 19:32:51.800    4 Feb 2015 19:42:29.487           577.687
                       3    5 Feb 2015 06:06:53.176    5 Feb 2015 06:19:31.046           757.870
                       4    5 Feb 2015 07:45:57.053    5 Feb 2015 07:53:47.971           470.918

Global Statistics
-----------------
Min Duration           4    5 Feb 2015 07:45:57.053    5 Feb 2015 07:53:47.971           470.918
Max Duration           3    5 Feb 2015 06:06:53.176    5 Feb 2015 06:19:31.046           757.870
Mean Duration                                                                             635.239
Total Duration                                                                           2540.956


Transmitter2-To-Receiver7
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:25:05.774    4 Feb 2015 10:37:19.776           734.002
                       2    4 Feb 2015 12:02:20.432    4 Feb 2015 12:11:03.275           522.843
                       3    4 Feb 2015 18:19:21.130    4 Feb 2015 18:26:46.910           445.779
                       4    4 Feb 2015 19:52:28.101    4 Feb 2015 20:04:09.671           701.570
                       5    4 Feb 2015 21:28:05.988    4 Feb 2015 21:41:10.107           784.119
                       6    4 Feb 2015 23:06:09.520    4 Feb 2015 23:18:00.598           711.078
                       7    5 Feb 2015 00:46:53.348    5 Feb 2015 00:54:35.617           462.269
                       8    5 Feb 2015 05:47:01.763    5 Feb 2015 05:54:24.251           442.488
                       9    5 Feb 2015 07:23:35.162    5 Feb 2015 07:35:17.654           702.492
                      10    5 Feb 2015 09:00:25.123    5 Feb 2015 09:13:29.310           784.187

Global Statistics
-----------------
Min Duration           8    5 Feb 2015 05:47:01.763    5 Feb 2015 05:54:24.251           442.488
Max Duration          10    5 Feb 2015 09:00:25.123    5 Feb 2015 09:13:29.310           784.187
Mean Duration                                                                             629.083
Total Duration                                                                           6290.826


Transmitter2-To-Receiver8
-------------------------
```

```
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:09:35.866    4 Feb 2015 10:11:50.787           134.921
                       2    4 Feb 2015 18:37:21.492    4 Feb 2015 18:47:18.426           596.934
                       3    4 Feb 2015 20:13:02.271    4 Feb 2015 20:25:49.961           767.691
                       4    4 Feb 2015 21:52:49.882    4 Feb 2015 21:57:29.840           279.958
                       5    5 Feb 2015 07:03:06.924    5 Feb 2015 07:14:28.768           681.844
                       6    5 Feb 2015 08:39:10.019    5 Feb 2015 08:51:30.519           740.500

Global Statistics
-----------------
Min Duration           1    4 Feb 2015 10:09:35.866    4 Feb 2015 10:11:50.787           134.921
Max Duration           3    4 Feb 2015 20:13:02.271    4 Feb 2015 20:25:49.961           767.691
Mean Duration                                                                            533.641
Total Duration                                                                          3201.848


Transmitter2-To-Receiver9
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 11:40:17.665    4 Feb 2015 11:48:54.905           517.239
                       2    4 Feb 2015 13:14:24.796    4 Feb 2015 13:27:13.035           768.239
                       3    4 Feb 2015 23:31:18.324    4 Feb 2015 23:39:45.087           506.763
                       4    5 Feb 2015 01:06:08.170    5 Feb 2015 01:18:55.641           767.471

Global Statistics
-----------------
Min Duration           3    4 Feb 2015 23:31:18.324    4 Feb 2015 23:39:45.087           506.763
Max Duration           2    4 Feb 2015 13:14:24.796    4 Feb 2015 13:27:13.035           768.239
Mean Duration                                                                            639.928
Total Duration                                                                          2559.712


Transmitter2-To-Receiver3
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 14:44:06.307    4 Feb 2015 14:56:52.580           766.273
                       2    4 Feb 2015 16:23:59.949    4 Feb 2015 16:29:57.343           357.394
                       3    5 Feb 2015 02:50:10.482    5 Feb 2015 03:03:01.714           771.232
                       4    5 Feb 2015 04:31:44.142    5 Feb 2015 04:34:25.163           161.021

Global Statistics
-----------------
Min Duration           4    5 Feb 2015 04:31:44.142    5 Feb 2015 04:34:25.163           161.021
Max Duration           3    5 Feb 2015 02:50:10.482    5 Feb 2015 03:03:01.714           771.232
Mean Duration                                                                            513.980
Total Duration                                                                          2055.920


Transmitter2-To-Receiver10
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 11:48:07.688    4 Feb 2015 11:56:58.432           530.745
                       2    4 Feb 2015 13:21:54.352    4 Feb 2015 13:34:41.870           767.518
                       3    4 Feb 2015 14:59:19.488    4 Feb 2015 15:11:24.274           724.786
                       4    4 Feb 2015 16:41:29.270    4 Feb 2015 16:46:16.747           287.477
                       5    4 Feb 2015 23:22:51.181    4 Feb 2015 23:31:12.483           501.302
                       6    5 Feb 2015 00:58:41.880    5 Feb 2015 01:11:27.655           765.775
                       7    5 Feb 2015 02:35:39.754    5 Feb 2015 02:47:49.233           729.479
                       8    5 Feb 2015 04:14:04.675    5 Feb 2015 04:20:06.383           361.707

Global Statistics
-----------------
Min Duration           4    4 Feb 2015 16:41:29.270    4 Feb 2015 16:46:16.747           287.477
Max Duration           2    4 Feb 2015 13:21:54.352    4 Feb 2015 13:34:41.870           767.518
Mean Duration                                                                            583.599
Total Duration                                                                          4668.788


Transmitter2-To-Receiver19
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:20:41.681    4 Feb 2015 10:30:40.402           598.721
                       2    4 Feb 2015 11:56:00.473    4 Feb 2015 12:05:31.546           571.073
                       3    4 Feb 2015 13:30:44.436    4 Feb 2015 13:41:03.171           618.735
                       4    4 Feb 2015 15:05:31.751    4 Feb 2015 15:17:13.256           701.505
                       5    4 Feb 2015 16:41:01.653    4 Feb 2015 16:53:48.409           766.756
                       6    4 Feb 2015 18:17:35.445    4 Feb 2015 18:30:41.317           785.873
                       7    4 Feb 2015 19:55:17.381    4 Feb 2015 20:07:52.010           754.629
                       8    4 Feb 2015 21:33:54.042    4 Feb 2015 21:45:27.371           693.329
                       9    4 Feb 2015 23:12:50.294    4 Feb 2015 23:23:39.010           648.717
                      10    5 Feb 2015 00:51:23.418    5 Feb 2015 01:02:27.089           663.671
                      11    5 Feb 2015 02:29:16.945    5 Feb 2015 02:41:19.886           722.942
                      12    5 Feb 2015 04:06:39.621    5 Feb 2015 04:19:34.275           774.654
                      13    5 Feb 2015 05:43:41.661    5 Feb 2015 05:56:45.222           783.561
                      14    5 Feb 2015 07:20:26.775    5 Feb 2015 07:32:48.009           741.233
                      15    5 Feb 2015 08:56:51.742    5 Feb 2015 09:07:54.430           662.688
```

```
Global Statistics
-----------------
Min Duration           2    4 Feb 2015 11:56:00.473    4 Feb 2015 12:05:31.546           571.073
Max Duration           6    4 Feb 2015 18:17:35.445    4 Feb 2015 18:30:41.317           785.873
Mean Duration                                                                            699.206
Total Duration                                                                         10488.087


Transmitter2-To-Receiver18
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:00:00.000    4 Feb 2015 10:12:37.756           757.756
                       2    4 Feb 2015 20:18:29.912    4 Feb 2015 20:27:15.977           526.064
                       3    4 Feb 2015 21:53:26.046    4 Feb 2015 22:06:06.984           760.939
                       4    5 Feb 2015 08:36:49.892    5 Feb 2015 08:47:22.791           632.899

Global Statistics
-----------------
Min Duration           2    4 Feb 2015 20:18:29.912    4 Feb 2015 20:27:15.977           526.064
Max Duration           3    4 Feb 2015 21:53:26.046    4 Feb 2015 22:06:06.984           760.939
Mean Duration                                                                            669.415
Total Duration                                                                          2677.659


Transmitter2-To-Receiver17
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:00:00.000    4 Feb 2015 10:02:01.423           121.423
                       2    4 Feb 2015 20:29:16.609    4 Feb 2015 20:38:44.617           568.008
                       3    4 Feb 2015 22:04:11.675    4 Feb 2015 22:16:35.589           743.914
                       4    5 Feb 2015 08:26:16.776    5 Feb 2015 08:36:03.572           586.796

Global Statistics
-----------------
Min Duration           1    4 Feb 2015 10:00:00.000    4 Feb 2015 10:02:01.423           121.423
Max Duration           3    4 Feb 2015 22:04:11.675    4 Feb 2015 22:16:35.589           743.914
Mean Duration                                                                            505.035
Total Duration                                                                          2020.140


Transmitter2-To-Receiver16
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:17:39.464    4 Feb 2015 10:30:45.084           785.619
                       2    4 Feb 2015 11:54:28.555    4 Feb 2015 12:07:34.183           785.628
                       3    4 Feb 2015 13:31:17.654    4 Feb 2015 13:44:23.276           785.622
                       4    4 Feb 2015 15:08:06.749    4 Feb 2015 15:21:12.368           785.620
                       5    4 Feb 2015 16:44:55.844    4 Feb 2015 16:58:01.464           785.620
                       6    4 Feb 2015 18:21:44.935    4 Feb 2015 18:34:50.563           785.628
                       7    4 Feb 2015 19:58:34.033    4 Feb 2015 20:11:39.653           785.620
                       8    4 Feb 2015 21:35:23.129    4 Feb 2015 21:48:28.748           785.619
                       9    4 Feb 2015 23:12:12.219    4 Feb 2015 23:25:17.847           785.628
                      10    5 Feb 2015 00:49:01.316    5 Feb 2015 01:02:06.941           785.626
                      11    5 Feb 2015 02:25:50.414    5 Feb 2015 02:38:56.033           785.620
                      12    5 Feb 2015 04:02:39.504    5 Feb 2015 04:15:45.128           785.624
                      13    5 Feb 2015 05:39:28.599    5 Feb 2015 05:52:34.227           785.628
                      14    5 Feb 2015 07:16:17.698    5 Feb 2015 07:29:23.319           785.620
                      15    5 Feb 2015 08:53:06.794    5 Feb 2015 09:06:12.413           785.619

Global Statistics
-----------------
Min Duration           1    4 Feb 2015 10:17:39.464    4 Feb 2015 10:30:45.084           785.619
Max Duration          13    5 Feb 2015 05:39:28.599    5 Feb 2015 05:52:34.227           785.628
Mean Duration                                                                            785.623
Total Duration                                                                         11784.341


Transmitter2-To-Receiver15
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 12:14:23.312    4 Feb 2015 12:26:16.262           712.950
                       2    4 Feb 2015 13:51:25.831    4 Feb 2015 14:02:12.047           646.216
                       3    5 Feb 2015 00:30:09.561    5 Feb 2015 00:42:37.912           748.351
                       4    5 Feb 2015 02:08:30.741    5 Feb 2015 02:17:46.770           556.029

Global Statistics
-----------------
Min Duration           4    5 Feb 2015 02:08:30.741    5 Feb 2015 02:17:46.770           556.029
Max Duration           3    5 Feb 2015 00:30:09.561    5 Feb 2015 00:42:37.912           748.351
Mean Duration                                                                            665.886
Total Duration                                                                          2663.546


Transmitter2-To-Receiver14
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
```

```
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:12:17.439    4 Feb 2015 10:23:32.464           675.025
                       2    4 Feb 2015 11:53:34.874    4 Feb 2015 12:00:04.279           389.404
                       3    4 Feb 2015 16:52:14.831    4 Feb 2015 17:01:02.006           527.175
                       4    4 Feb 2015 18:28:56.491    4 Feb 2015 18:41:12.585           736.094
                       5    4 Feb 2015 20:05:49.073    4 Feb 2015 20:18:50.173           781.099
                       6    4 Feb 2015 21:42:51.025    4 Feb 2015 21:54:05.076           674.051
                       7    4 Feb 2015 23:20:18.779    4 Feb 2015 23:26:48.217           389.438
                       8    5 Feb 2015 04:04:24.108    5 Feb 2015 04:06:28.827           124.720
                       9    5 Feb 2015 05:35:18.369    5 Feb 2015 05:44:55.332           576.962
                      10    5 Feb 2015 07:09:30.629    5 Feb 2015 07:22:04.161           753.532
                      11    5 Feb 2015 08:46:05.847    5 Feb 2015 08:59:00.330           774.483

Global Statistics
-----------------
Min Duration           8    5 Feb 2015 04:04:24.108    5 Feb 2015 04:06:28.827           124.720
Max Duration           5    4 Feb 2015 20:05:49.073    4 Feb 2015 20:18:50.173           781.099
Mean Duration                                                                            581.998
Total Duration                                                                          6401.983


Transmitter2-To-Receiver13
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 11:06:04.011    4 Feb 2015 11:19:09.631           785.619
                       2    4 Feb 2015 12:42:53.102    4 Feb 2015 12:55:58.730           785.628
                       3    4 Feb 2015 14:19:42.198    4 Feb 2015 14:32:47.825           785.626
                       4    4 Feb 2015 15:56:31.296    4 Feb 2015 16:09:36.916           785.620
                       5    4 Feb 2015 17:33:20.388    4 Feb 2015 17:46:26.011           785.624
                       6    4 Feb 2015 19:10:09.482    4 Feb 2015 19:23:15.110           785.628
                       7    4 Feb 2015 20:46:58.581    4 Feb 2015 21:00:04.202           785.621
                       8    4 Feb 2015 22:23:47.676    4 Feb 2015 22:36:53.296           785.619
                       9    5 Feb 2015 00:00:36.767    5 Feb 2015 00:13:42.395           785.628
                      10    5 Feb 2015 01:37:25.863    5 Feb 2015 01:50:31.489           785.626
                      11    5 Feb 2015 03:14:14.961    5 Feb 2015 03:27:20.581           785.620
                      12    5 Feb 2015 04:51:04.052    5 Feb 2015 05:04:09.676           785.624
                      13    5 Feb 2015 06:27:53.147    5 Feb 2015 06:40:58.775           785.628
                      14    5 Feb 2015 08:04:42.246    5 Feb 2015 08:17:47.866           785.620
                      15    5 Feb 2015 09:41:31.341    5 Feb 2015 09:54:36.961           785.619

Global Statistics
-----------------
Min Duration          15    5 Feb 2015 09:41:31.341    5 Feb 2015 09:54:36.961           785.619
Max Duration          13    5 Feb 2015 06:27:53.147    5 Feb 2015 06:40:58.775           785.628
Mean Duration                                                                            785.623
Total Duration                                                                         11784.350


Transmitter2-To-Receiver12
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 13:24:07.163    4 Feb 2015 13:34:11.179           604.016
                       2    4 Feb 2015 14:58:39.274    4 Feb 2015 15:11:38.301           779.027
                       3    4 Feb 2015 16:36:43.139    4 Feb 2015 16:48:11.518           688.378
                       4    5 Feb 2015 00:59:13.236    5 Feb 2015 01:08:59.516           586.280
                       5    5 Feb 2015 02:35:23.992    5 Feb 2015 02:48:22.329           778.337
                       6    5 Feb 2015 04:12:30.979    5 Feb 2015 04:24:06.824           695.845
                       7    5 Feb 2015 05:51:45.049    5 Feb 2015 05:55:06.973           201.924

Global Statistics
-----------------
Min Duration           7    5 Feb 2015 05:51:45.049    5 Feb 2015 05:55:06.973           201.924
Max Duration           2    4 Feb 2015 14:58:39.274    4 Feb 2015 15:11:38.301           779.027
Mean Duration                                                                            619.115
Total Duration                                                                          4333.807


Transmitter2-To-Receiver11
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:31:48.618    4 Feb 2015 10:43:03.024           674.406
                       2    4 Feb 2015 19:49:08.716    4 Feb 2015 19:55:56.684           407.969
                       3    4 Feb 2015 21:21:55.241    4 Feb 2015 21:34:48.696           773.455
                       4    4 Feb 2015 23:00:42.027    4 Feb 2015 23:10:28.120           586.094
                       5    5 Feb 2015 07:32:45.211    5 Feb 2015 07:38:24.176           338.966
                       6    5 Feb 2015 09:06:49.035    5 Feb 2015 09:19:41.359           772.324

Global Statistics
-----------------
Min Duration           5    5 Feb 2015 07:32:45.211    5 Feb 2015 07:38:24.176           338.966
Max Duration           3    4 Feb 2015 21:21:55.241    4 Feb 2015 21:34:48.696           773.455
Mean Duration                                                                            592.202
Total Duration                                                                          3553.213
```

Appendix A.2: Scenario 1.1 Ground Station Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS-Sensor-Comms_Cone-Transmitter-Transmitter2-To-Place-GS_Bellville_South_Africa-Sensor-
Sensor1-Receiver-Receiver2:  Access Summary Report


Transmitter2-To-Receiver2
-------------------------
                  Access      Start Time (UTCG)          Stop Time (UTCG)        Duration (sec)
                  ------   ------------------------   ------------------------   --------------
                       1   4 Feb 2015 12:59:56.751    4 Feb 2015 13:09:02.407           545.655
                       2   4 Feb 2015 14:37:04.635    4 Feb 2015 14:44:58.563           473.927
                       3   5 Feb 2015 01:24:01.350    5 Feb 2015 01:33:51.521           590.171
                       4   5 Feb 2015 03:03:18.811    5 Feb 2015 03:08:37.908           319.097

Global Statistics
-----------------
Min Duration           4   5 Feb 2015 03:03:18.811    5 Feb 2015 03:08:37.908           319.097
Max Duration           3   5 Feb 2015 01:24:01.350    5 Feb 2015 01:33:51.521           590.171
Mean Duration                                                                           482.213
Total Duration                                                                         1928.851
```

Appendix A.3: Scenario 1.1 Gaps Summary

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS-Sensor-Comms_Cone-Transmitter-Transmitter2-To-Place-GS_Bellville_South_Africa-Sensor-
Sensor1-Receiver-Receiver2, Receiver-Receiver4, Receiver-Receiver5, Receiver-Receiver6, Receiver-
Receiver7, Receiver-Receiver8, Receiver-Receiver9, Receiver-Receiver3, Receiver-Receiver10, Receiver-
Receiver19, Receiver-Receiver18, Receiver-Receiver17, Receiver-Receiver16, Receiver-Receiver15, Receiver-
Receiver14, Receiver-Receiver13, Receiver-Receiver12, Receiver-Receiver11


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        1    4 Feb 2015 13:09:02.407    4 Feb 2015 14:37:04.635          5282.229
Max Duration        2    4 Feb 2015 14:44:58.563    5 Feb 2015 01:24:01.350         38342.787
Mean Duration                                                                       16894.230
Total Duration                                                                      84471.149


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        4    5 Feb 2015 03:05:23.096    5 Feb 2015 04:31:22.706          5159.610
Max Duration        3    4 Feb 2015 17:59:59.359    5 Feb 2015 02:57:31.286         32251.927
Mean Duration                                                                       14003.875
Total Duration                                                                      84023.251


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        3    5 Feb 2015 05:20:50.959    5 Feb 2015 06:45:50.670          5099.711
Max Duration        2    4 Feb 2015 19:05:03.808    5 Feb 2015 05:09:00.035         36236.227
Mean Duration                                                                       16725.662
Total Duration                                                                      83628.308


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        1    4 Feb 2015 18:07:22.213    4 Feb 2015 19:32:51.800          5129.587
Max Duration        2    4 Feb 2015 19:42:29.487    5 Feb 2015 06:06:53.176         37463.689
Mean Duration                                                                       16771.809
Total Duration                                                                      83859.044


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:25:05.774          1505.774
Max Duration        2    4 Feb 2015 12:11:03.275    4 Feb 2015 18:19:21.130         22097.856
Mean Duration                                                                        7282.652
Total Duration                                                                      80109.174


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:09:35.866           575.866
Max Duration        4    4 Feb 2015 21:57:29.840    5 Feb 2015 07:03:06.924         32737.084
Mean Duration                                                                       11885.450
Total Duration                                                                      83198.152


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        1    4 Feb 2015 11:48:54.905    4 Feb 2015 13:14:24.796          5129.891
Max Duration        2    4 Feb 2015 13:27:13.035    4 Feb 2015 23:31:18.324         36245.289
Mean Duration                                                                       16768.058
Total Duration                                                                      83840.288


                  Gap      Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------
```

```
Global Statistics
-----------------
Min Duration        1    4 Feb 2015 14:56:52.580    4 Feb 2015 16:23:59.949          5227.369
Max Duration        2    4 Feb 2015 16:29:57.343    5 Feb 2015 02:50:10.482         37213.139
Mean Duration                                                                       16868.816
Total Duration                                                                      84344.080


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        6    5 Feb 2015 01:11:27.655    5 Feb 2015 02:35:39.754          5052.099
Max Duration        4    4 Feb 2015 16:46:16.747    4 Feb 2015 23:22:51.181         23794.434
Mean Duration                                                                        9081.246
Total Duration                                                                      81731.212


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:20:41.681          1241.681
Max Duration        9    4 Feb 2015 23:23:39.010    5 Feb 2015 00:51:23.418          5264.408
Mean Duration                                                                        4744.495
Total Duration                                                                      75911.913


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        4    5 Feb 2015 08:47:22.791    5 Feb 2015 10:00:00.000          4357.209
Max Duration        3    4 Feb 2015 22:06:06.984    5 Feb 2015 08:36:49.892         37842.908
Mean Duration                                                                       20930.585
Total Duration                                                                      83722.341


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        4    5 Feb 2015 08:36:03.572    5 Feb 2015 10:00:00.000          5036.428
Max Duration        1    4 Feb 2015 10:02:01.423    4 Feb 2015 20:29:16.609         37635.186
Mean Duration                                                                       21094.965
Total Duration                                                                      84379.860


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:17:39.464          1059.464
Max Duration        7    4 Feb 2015 20:11:39.653    4 Feb 2015 21:35:23.129          5023.475
Mean Duration                                                                        4663.479
Total Duration                                                                      74615.659


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        1    4 Feb 2015 12:26:16.262    4 Feb 2015 13:51:25.831          5109.569
Max Duration        2    4 Feb 2015 14:02:12.047    5 Feb 2015 00:30:09.561         37677.514
Mean Duration                                                                       16747.291
Total Duration                                                                      83736.454


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:12:17.439           737.439
Max Duration        2    4 Feb 2015 12:00:04.279    4 Feb 2015 16:52:14.831         17530.552
Mean Duration                                                                        6666.501
Total Duration                                                                      79998.017


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration       15    5 Feb 2015 09:54:36.961    5 Feb 2015 10:00:00.000           323.039
```

```
Max Duration       14    5 Feb 2015 08:17:47.866    5 Feb 2015 09:41:31.341           5023.475
Mean Duration                                                                         4663.478
Total Duration                                                                       74615.650

                  Gap       Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        5    5 Feb 2015 02:48:22.329    5 Feb 2015 04:12:30.979           5048.650
Max Duration        3    4 Feb 2015 16:48:11.518    5 Feb 2015 00:59:13.236          29461.718
Mean Duration                                                                        10258.274
Total Duration                                                                       82066.193

                  Gap       Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:31:48.618           1908.618
Max Duration        1    4 Feb 2015 10:43:03.024    4 Feb 2015 19:49:08.716          32765.692
Mean Duration                                                                        11835.255
Total Duration                                                                       82846.787
```

Appendix A.4: Scenario 1.1 Uplink Link Budget

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Place-SNode_Equator_PrimeMeridian-Sensor-Comms_Cone1-Transmitter-Transmitter1-To-Satellite-IMS-Sensor-
Comms_Cone-Receiver-Receiver1:  Link Budget - Short Form


      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)        BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 14:45:19.839                 0.145003                  -135.647    3.648516e-012
4 Feb 2015 14:46:19.000                 0.145003                  -134.156    1.075857e-015
4 Feb 2015 14:47:19.000                 0.145003                  -132.512    1.565749e-020
4 Feb 2015 14:48:19.000                 0.145003                  -130.921    4.451055e-025
4 Feb 2015 14:49:19.000                 0.145002                  -130.252    9.456058e-021
4 Feb 2015 14:50:19.000                 0.145000                  -131.967    4.237090e-008
4 Feb 2015 14:51:19.000                 0.144998                  -130.628    7.686407e-016
4 Feb 2015 14:52:19.000                 0.144997                  -130.493    1.410093e-027
4 Feb 2015 14:53:19.000                 0.144997                  -131.923    6.757211e-026
4 Feb 2015 14:54:19.000                 0.144997                  -133.589    1.503790e-020
4 Feb 2015 14:55:19.000                 0.144997                  -135.155    7.814530e-016
4 Feb 2015 14:55:39.161                 0.144997                  -135.647    1.611333e-014

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)        BER
-----------------------    ---------------------    ----------------------    -------------
5 Feb 2015 02:51:23.320                 0.145003                  -135.649    3.741033e-014
5 Feb 2015 02:52:23.000                 0.145003                  -134.123    8.511944e-019
5 Feb 2015 02:53:23.000                 0.145003                  -132.441    5.253734e-025
5 Feb 2015 02:54:23.000                 0.145003                  -130.812    9.645190e-030
5 Feb 2015 02:55:23.000                 0.145002                  -130.450    7.430096e-019
5 Feb 2015 02:56:23.000                 0.145001                  -138.589    1.488602e-001
5 Feb 2015 02:57:23.000                 0.144998                  -131.957    2.845140e-008
5 Feb 2015 02:58:23.000                 0.144997                  -130.329    5.124259e-029
5 Feb 2015 02:59:23.000                 0.144997                  -131.692    3.866330e-029
5 Feb 2015 03:00:23.000                 0.144997                  -133.401    1.315615e-022
5 Feb 2015 03:01:23.000                 0.144997                  -135.007    6.766585e-017
5 Feb 2015 03:01:48.896                 0.144997                  -135.649    5.982915e-015
```

Appendix A.5: Scenario 1.1 Downlink Link Budget

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Place-GS_Bellville_South_Africa-Sensor-Sensor1-Receiver-Receiver2-To-Satellite-IMS-Sensor-Comms_Cone-
Transmitter-Transmitter2:  Link Budget - Short Form


      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)        BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 12:59:42.283                 0.145003                  -136.711    2.272737e-009
4 Feb 2015 13:00:42.000                 0.145003                  -135.401    2.998775e-018
4 Feb 2015 13:01:42.000                 0.145002                  -134.067    1.000000e-030
4 Feb 2015 13:02:42.000                 0.145002                  -132.868    1.000000e-030
4 Feb 2015 13:03:42.000                 0.145001                  -132.069    1.000000e-030
4 Feb 2015 13:04:42.000                 0.145000                  -131.863    1.000000e-030
4 Feb 2015 13:05:42.000                 0.144999                  -132.271    1.000000e-030
4 Feb 2015 13:06:42.000                 0.144998                  -133.234    1.000000e-030
4 Feb 2015 13:07:42.000                 0.144997                  -134.507    3.941527e-021
4 Feb 2015 13:08:42.000                 0.144997                  -135.851    4.357151e-009
4 Feb 2015 13:09:08.846                 0.144997                  -136.441    9.999998e-007

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)        BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 14:36:48.498                 0.145003                  -136.709    1.723130e-012
4 Feb 2015 14:37:48.000                 0.145002                  -135.567    8.310244e-026
4 Feb 2015 14:38:48.000                 0.145002                  -134.502    1.000000e-030
4 Feb 2015 14:39:48.000                 0.145001                  -133.679    1.000000e-030
4 Feb 2015 14:40:48.000                 0.145000                  -133.279    1.000000e-030
4 Feb 2015 14:41:48.000                 0.144999                  -133.408    1.000000e-030
4 Feb 2015 14:42:48.000                 0.144998                  -134.030    1.000000e-030
4 Feb 2015 14:43:48.000                 0.144998                  -134.990    1.000000e-030
4 Feb 2015 14:44:48.000                 0.144997                  -136.109    2.802057e-025
4 Feb 2015 14:45:14.548                 0.144997                  -136.620    1.071526e-018

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)        BER
-----------------------    ---------------------    ----------------------    -------------
5 Feb 2015 01:24:58.066                 0.145003                  -134.864    9.999513e-007
5 Feb 2015 01:25:58.000                 0.145003                  -133.255    2.348848e-016
5 Feb 2015 01:26:58.000                 0.145003                  -131.789    1.000000e-030
5 Feb 2015 01:27:58.000                 0.145002                  -131.273    1.000000e-030
5 Feb 2015 01:28:58.000                 0.145000                  -131.813    1.000000e-030
5 Feb 2015 01:29:58.000                 0.144998                  -131.244    1.000000e-030
5 Feb 2015 01:30:58.000                 0.144997                  -131.944    1.000000e-030
5 Feb 2015 01:31:58.000                 0.144997                  -133.457    3.776470e-008
5 Feb 2015 01:32:08.971                 0.144997                  -133.753    1.000002e-006

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)        BER
-----------------------    ---------------------    ----------------------    -------------
5 Feb 2015 03:02:54.846                 0.145002                  -136.633    1.000000e-030
5 Feb 2015 03:03:54.000                 0.145001                  -135.928    1.000000e-030
5 Feb 2015 03:04:54.000                 0.145001                  -135.437    1.000000e-030
5 Feb 2015 03:05:54.000                 0.145000                  -135.254    1.000000e-030
5 Feb 2015 03:06:54.000                 0.144999                  -135.416    1.000000e-030
5 Feb 2015 03:07:54.000                 0.144999                  -135.888    1.000000e-030
5 Feb 2015 03:08:54.000                 0.144998                  -136.590    1.000000e-030
5 Feb 2015 03:09:02.216                 0.144998                  -136.698    1.000000e-030
```

Appendix A.6: Scenario 1.1 Lighting Times Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS:  Lighting


Sunlight Times
--------------
                     Start Time (UTCG)           Stop Time (UTCG)       Duration (min)
                  -----------------------    -----------------------    --------------
                  4 Feb 2015 10:00:00.000    4 Feb 2015 10:26:50.051            26.834
                  4 Feb 2015 10:58:03.525    4 Feb 2015 12:03:39.415            65.598
                  4 Feb 2015 12:34:53.964    4 Feb 2015 13:40:28.779            65.580
                  4 Feb 2015 14:11:44.400    4 Feb 2015 15:17:18.143            65.562
                  4 Feb 2015 15:48:34.835    4 Feb 2015 16:54:07.506            65.545
                  4 Feb 2015 17:25:25.265    4 Feb 2015 18:30:56.872            65.527
                  4 Feb 2015 19:02:15.692    4 Feb 2015 20:07:46.234            65.509
                  4 Feb 2015 20:39:06.114    4 Feb 2015 21:44:35.599            65.491
                  4 Feb 2015 22:15:56.534    4 Feb 2015 23:21:24.965            65.474
                  4 Feb 2015 23:52:46.951    5 Feb 2015 00:58:14.328            65.456
                  5 Feb 2015 01:29:37.365    5 Feb 2015 02:35:03.693            65.439
                  5 Feb 2015 03:06:27.777    5 Feb 2015 04:11:53.060            65.421
                  5 Feb 2015 04:43:18.182    5 Feb 2015 05:48:42.425            65.404
                  5 Feb 2015 06:20:08.586    5 Feb 2015 07:25:31.791            65.387
                  5 Feb 2015 07:56:58.987    5 Feb 2015 09:02:21.156            65.369
                  5 Feb 2015 09:33:49.384    5 Feb 2015 10:00:00.000            26.177

Global Statistics
-----------------
Min Duration      5 Feb 2015 09:33:49.384    5 Feb 2015 10:00:00.000            26.177
Max Duration      4 Feb 2015 10:58:03.525    4 Feb 2015 12:03:39.415            65.598
Mean Duration                                                                   60.611
Total Duration                                                                 969.774
```

Appendix B.1: Scenario 1.2 Sensor Node Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS-Sensor-Comms_Cone-Transmitter-Transmitter1-To-Place-SNode_Atlantic_Ocean-Sensor-Sensor2-
Receiver-Receiver4, Receiver-Receiver2, Receiver-Receiver5, Receiver-Receiver6, Receiver-Receiver7,
Receiver-Receiver8, Receiver-Receiver9, Receiver-Receiver10, Receiver-Receiver11, Receiver-Receiver12,
Receiver-Receiver13, Receiver-Receiver14, Receiver-Receiver15, Receiver-Receiver16, Receiver-Receiver17,
Receiver-Receiver18, Receiver-Receiver19:  Access Summary Report


Transmitter1-To-Receiver4
-------------------------
                  Access      Start Time (UTCG)          Stop Time (UTCG)        Duration (sec)
                  ------    ------------------------    ------------------------    --------------
                       1    4 Feb 2015 15:00:49.813    4 Feb 2015 15:14:52.883           843.070
                       2    4 Feb 2015 16:43:37.508    4 Feb 2015 17:00:08.166           990.658
                       3    5 Feb 2015 02:30:51.309    5 Feb 2015 02:39:44.888           533.579
                       4    5 Feb 2015 04:10:03.543    5 Feb 2015 04:27:07.548          1024.005
                       5    5 Feb 2015 05:57:55.089    5 Feb 2015 06:07:49.318           594.230

Global Statistics
-----------------
Min Duration           3    5 Feb 2015 02:30:51.309    5 Feb 2015 02:39:44.888           533.579
Max Duration           4    5 Feb 2015 04:10:03.543    5 Feb 2015 04:27:07.548          1024.005
Mean Duration                                                                            797.108
Total Duration                                                                          3985.542


Transmitter1-To-Receiver2
-------------------------
                  Access      Start Time (UTCG)          Stop Time (UTCG)        Duration (sec)
                  ------    ------------------------    ------------------------    --------------
                       1    4 Feb 2015 16:08:41.776    4 Feb 2015 16:17:43.383           541.607
                       2    4 Feb 2015 17:47:43.681    4 Feb 2015 18:04:46.106          1022.425
                       3    4 Feb 2015 19:34:36.180    4 Feb 2015 19:46:49.623           733.443
                       4    5 Feb 2015 04:50:47.917    5 Feb 2015 05:06:12.211           924.294
                       5    5 Feb 2015 06:34:27.097    5 Feb 2015 06:50:34.899           967.802

Global Statistics
-----------------
Min Duration           1    4 Feb 2015 16:08:41.776    4 Feb 2015 16:17:43.383           541.607
Max Duration           2    4 Feb 2015 17:47:43.681    4 Feb 2015 18:04:46.106          1022.425
Mean Duration                                                                            837.914
Total Duration                                                                          4189.571


Transmitter1-To-Receiver5
-------------------------
                  Access      Start Time (UTCG)          Stop Time (UTCG)        Duration (sec)
                  ------    ------------------------    ------------------------    --------------
                       1    4 Feb 2015 16:48:40.162    4 Feb 2015 16:58:39.748           599.586
                       2    4 Feb 2015 18:29:13.704    4 Feb 2015 18:46:16.261          1022.557
                       3    4 Feb 2015 20:17:27.294    4 Feb 2015 20:24:49.378           442.084
                       4    5 Feb 2015 05:53:04.432    5 Feb 2015 06:09:35.208           990.775
                       5    5 Feb 2015 07:38:23.283    5 Feb 2015 07:52:09.657           826.373

Global Statistics
-----------------
Min Duration           3    4 Feb 2015 20:17:27.294    4 Feb 2015 20:24:49.378           442.084
Max Duration           2    4 Feb 2015 18:29:13.704    4 Feb 2015 18:46:16.261          1022.557
Mean Duration                                                                            776.275
Total Duration                                                                          3881.375


Transmitter1-To-Receiver6
-------------------------
                  Access      Start Time (UTCG)          Stop Time (UTCG)        Duration (sec)
                  ------    ------------------------    ------------------------    --------------
                       1    4 Feb 2015 10:25:20.624    4 Feb 2015 10:41:46.591           985.967
                       2    4 Feb 2015 12:09:29.130    4 Feb 2015 12:22:45.365           796.236
                       3    4 Feb 2015 13:53:16.949    4 Feb 2015 14:01:41.545           504.596
                       4    4 Feb 2015 15:35:17.490    4 Feb 2015 15:40:58.465           340.975
                       5    4 Feb 2015 17:14:03.175    4 Feb 2015 17:23:43.548           580.373
                       6    4 Feb 2015 18:53:23.673    4 Feb 2015 19:07:39.338           855.664
                       7    4 Feb 2015 20:34:59.052    4 Feb 2015 20:51:50.417          1011.365
                       8    4 Feb 2015 22:19:09.534    4 Feb 2015 22:36:10.282          1020.748
                       9    5 Feb 2015 00:06:02.335    5 Feb 2015 00:20:43.585           881.250
                      10    5 Feb 2015 01:55:17.160    5 Feb 2015 02:05:55.498           638.338
                      11    5 Feb 2015 03:44:17.120    5 Feb 2015 03:53:19.921           542.802
                      12    5 Feb 2015 05:30:22.650    5 Feb 2015 05:42:58.947           756.297
                      13    5 Feb 2015 07:15:10.554    5 Feb 2015 07:31:14.973           964.420
                      14    5 Feb 2015 08:59:36.277    5 Feb 2015 09:16:51.339          1035.062

Global Statistics
-----------------
Min Duration           4    4 Feb 2015 15:35:17.490    4 Feb 2015 15:40:58.465           340.975
Max Duration          14    5 Feb 2015 08:59:36.277    5 Feb 2015 09:16:51.339          1035.062
Mean Duration                                                                            779.578
Total Duration                                                                         10914.092
```

```
Transmitter1-To-Receiver7
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:06:12.915    4 Feb 2015 10:16:51.832           638.917
                       2    4 Feb 2015 17:34:10.793    4 Feb 2015 17:39:18.349           307.556
                       3    4 Feb 2015 19:14:01.698    4 Feb 2015 19:30:40.931           999.233
                       4    4 Feb 2015 20:58:26.405    4 Feb 2015 21:13:51.640           925.235
                       5    5 Feb 2015 06:53:30.229    5 Feb 2015 07:08:52.293           922.064
                       6    5 Feb 2015 08:36:37.600    5 Feb 2015 08:53:18.437          1000.838

Global Statistics
-----------------
Min Duration           2    4 Feb 2015 17:34:10.793    4 Feb 2015 17:39:18.349           307.556
Max Duration           6    5 Feb 2015 08:36:37.600    5 Feb 2015 08:53:18.437          1000.838
Mean Duration                                                                            798.974
Total Duration                                                                          4793.842


Transmitter1-To-Receiver8
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 11:45:17.597    4 Feb 2015 11:59:38.543           860.946
                       2    4 Feb 2015 13:27:43.527    4 Feb 2015 13:44:27.276          1003.750
                       3    4 Feb 2015 22:49:48.926    4 Feb 2015 22:55:54.661           365.734
                       4    5 Feb 2015 00:29:19.844    5 Feb 2015 00:46:16.789          1016.945
                       5    5 Feb 2015 02:14:33.607    5 Feb 2015 02:28:00.566           806.959

Global Statistics
-----------------
Min Duration           3    4 Feb 2015 22:49:48.926    4 Feb 2015 22:55:54.661           365.734
Max Duration           4    5 Feb 2015 00:29:19.844    5 Feb 2015 00:46:16.789          1016.945
Mean Duration                                                                            810.867
Total Duration                                                                          4054.334


Transmitter1-To-Receiver9
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 13:23:25.155    4 Feb 2015 13:34:03.364           638.209
                       2    4 Feb 2015 15:04:00.375    4 Feb 2015 15:20:59.925          1019.550
                       3    4 Feb 2015 16:54:10.090    4 Feb 2015 16:58:16.712           246.621
                       4    5 Feb 2015 02:21:32.973    5 Feb 2015 02:38:04.934           991.961
                       5    5 Feb 2015 04:06:51.084    5 Feb 2015 04:20:21.455           810.370

Global Statistics
-----------------
Min Duration           3    4 Feb 2015 16:54:10.090    4 Feb 2015 16:58:16.712           246.621
Max Duration           2    4 Feb 2015 15:04:00.375    4 Feb 2015 15:20:59.925          1019.550
Mean Duration                                                                            741.342
Total Duration                                                                          3706.712


Transmitter1-To-Receiver10
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:17:21.132    4 Feb 2015 10:21:37.339           256.206
                       2    4 Feb 2015 11:53:51.126    4 Feb 2015 12:08:03.981           852.855
                       3    4 Feb 2015 13:35:31.012    4 Feb 2015 13:52:39.648          1028.637
                       4    4 Feb 2015 15:20:57.710    4 Feb 2015 15:36:46.010           948.300
                       5    4 Feb 2015 17:11:09.822    4 Feb 2015 17:19:56.150           526.328
                       6    4 Feb 2015 22:37:47.991    4 Feb 2015 22:48:21.388           633.398
                       7    5 Feb 2015 00:21:15.259    5 Feb 2015 00:37:35.170           979.910
                       8    5 Feb 2015 02:05:26.243    5 Feb 2015 02:22:23.886          1017.643
                       9    5 Feb 2015 03:50:08.606    5 Feb 2015 04:03:25.072           796.466

Global Statistics
-----------------
Min Duration           1    4 Feb 2015 10:17:21.132    4 Feb 2015 10:21:37.339           256.206
Max Duration           3    4 Feb 2015 13:35:31.012    4 Feb 2015 13:52:39.648          1028.637
Mean Duration                                                                            782.194
Total Duration                                                                          7039.744


Transmitter1-To-Receiver11
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:20:18.345    4 Feb 2015 10:34:53.598           875.253
                       2    4 Feb 2015 12:02:38.266    4 Feb 2015 12:16:54.160           855.895
                       3    4 Feb 2015 13:44:30.843    4 Feb 2015 13:59:33.530           902.686
                       4    4 Feb 2015 15:26:38.814    4 Feb 2015 15:42:55.591           976.777
                       5    4 Feb 2015 17:09:42.547    4 Feb 2015 17:26:51.160          1028.612
                       6    4 Feb 2015 18:54:02.405    4 Feb 2015 19:11:14.987          1032.582
                       7    4 Feb 2015 20:39:37.071    4 Feb 2015 20:56:09.758           992.687
                       8    4 Feb 2015 22:26:00.463    4 Feb 2015 22:41:44.023           943.560
```

```
                       9    5 Feb 2015 00:12:25.418    5 Feb 2015 00:27:59.525           934.107
                      10    5 Feb 2015 01:58:14.348    5 Feb 2015 02:14:29.079           974.731
                      11    5 Feb 2015 03:43:21.296    5 Feb 2015 04:00:24.318          1023.022
                      12    5 Feb 2015 05:27:54.806    5 Feb 2015 05:45:10.494          1035.688
                      13    5 Feb 2015 07:12:00.043    5 Feb 2015 07:28:38.531           998.488
                      14    5 Feb 2015 08:55:34.340    5 Feb 2015 09:11:01.557           927.217

Global Statistics
-----------------
Min Duration           2    4 Feb 2015 12:02:38.266    4 Feb 2015 12:16:54.160           855.895
Max Duration          12    5 Feb 2015 05:27:54.806    5 Feb 2015 05:45:10.494          1035.688
Mean Duration                                                                            964.379
Total Duration                                                                         13501.305


Transmitter1-To-Receiver12
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:00:00.000    4 Feb 2015 10:15:13.071           913.071
                       2    4 Feb 2015 11:49:03.208    4 Feb 2015 11:54:01.559           298.351
                       3    4 Feb 2015 21:02:04.490    4 Feb 2015 21:18:46.056          1001.566
                       4    4 Feb 2015 22:46:57.675    4 Feb 2015 23:01:07.283           849.608
                       5    5 Feb 2015 08:33:58.487    5 Feb 2015 08:49:02.948           904.461

Global Statistics
-----------------
Min Duration           2    4 Feb 2015 11:49:03.208    4 Feb 2015 11:54:01.559           298.351
Max Duration           3    4 Feb 2015 21:02:04.490    4 Feb 2015 21:18:46.056          1001.566
Mean Duration                                                                            793.411
Total Duration                                                                          3967.057


Transmitter1-To-Receiver13
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:00:00.000    4 Feb 2015 10:03:47.714           227.714
                       2    4 Feb 2015 11:35:46.899    4 Feb 2015 11:41:10.230           323.330
                       3    4 Feb 2015 21:13:28.096    4 Feb 2015 21:30:17.951          1009.855
                       4    4 Feb 2015 22:59:36.090    4 Feb 2015 23:12:23.970           767.880
                       5    5 Feb 2015 08:22:28.932    5 Feb 2015 08:36:59.044           870.112

Global Statistics
-----------------
Min Duration           1    4 Feb 2015 10:00:00.000    4 Feb 2015 10:03:47.714           227.714
Max Duration           3    4 Feb 2015 21:13:28.096    4 Feb 2015 21:30:17.951          1009.855
Mean Duration                                                                            639.778
Total Duration                                                                          3198.892


Transmitter1-To-Receiver14
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:17:24.893    4 Feb 2015 10:34:40.501          1035.608
                       2    4 Feb 2015 12:01:35.681    4 Feb 2015 12:18:51.289          1035.608
                       3    4 Feb 2015 13:45:46.469    4 Feb 2015 14:03:02.077          1035.607
                       4    4 Feb 2015 15:29:57.258    4 Feb 2015 15:47:12.862          1035.604
                       5    4 Feb 2015 17:14:08.046    4 Feb 2015 17:31:23.650          1035.604
                       6    4 Feb 2015 18:58:18.838    4 Feb 2015 19:15:34.437          1035.600
                       7    4 Feb 2015 20:42:29.626    4 Feb 2015 20:59:45.225          1035.600
                       8    4 Feb 2015 22:26:40.414    4 Feb 2015 22:43:56.014          1035.600
                       9    5 Feb 2015 00:10:51.202    5 Feb 2015 00:28:06.802          1035.600
                      10    5 Feb 2015 01:55:01.990    5 Feb 2015 02:12:17.590          1035.600
                      11    5 Feb 2015 03:39:12.778    5 Feb 2015 03:56:28.378          1035.600
                      12    5 Feb 2015 05:23:23.566    5 Feb 2015 05:40:39.166          1035.600
                      13    5 Feb 2015 07:07:34.354    5 Feb 2015 07:24:49.954          1035.600
                      14    5 Feb 2015 08:51:45.143    5 Feb 2015 09:09:00.742          1035.600

Global Statistics
-----------------
Min Duration           6    4 Feb 2015 18:58:18.838    4 Feb 2015 19:15:34.437          1035.600
Max Duration           2    4 Feb 2015 12:01:35.681    4 Feb 2015 12:18:51.289          1035.608
Mean Duration                                                                           1035.602
Total Duration                                                                         14498.429


Transmitter1-To-Receiver15
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 12:22:40.712    4 Feb 2015 12:39:20.174           999.461
                       2    4 Feb 2015 14:07:42.066    4 Feb 2015 14:21:33.803           831.737
                       3    4 Feb 2015 23:51:43.597    5 Feb 2015 00:06:33.180           889.583
                       4    5 Feb 2015 01:34:45.587    5 Feb 2015 01:51:00.378           974.792

Global Statistics
-----------------
Min Duration           2    4 Feb 2015 14:07:42.066    4 Feb 2015 14:21:33.803           831.737
Max Duration           1    4 Feb 2015 12:22:40.712    4 Feb 2015 12:39:20.174           999.461
```

```
Mean Duration                                                                            923.893
Total Duration                                                                          3695.573


Transmitter1-To-Receiver16
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:11:23.084    4 Feb 2015 10:27:12.739           949.655
                       2    4 Feb 2015 11:59:49.949    4 Feb 2015 12:12:07.122           737.172
                       3    4 Feb 2015 13:49:17.513    4 Feb 2015 13:58:30.775           553.262
                       4    4 Feb 2015 15:36:21.459    4 Feb 2015 15:47:38.677           677.218
                       5    4 Feb 2015 17:21:28.670    4 Feb 2015 17:36:35.700           907.030
                       6    4 Feb 2015 19:06:00.847    4 Feb 2015 19:23:08.274          1027.427
                       7    4 Feb 2015 20:50:19.695    4 Feb 2015 21:07:01.440          1001.746
                       8    4 Feb 2015 22:34:28.612    4 Feb 2015 22:48:23.016           834.403
                       9    5 Feb 2015 00:18:17.980    5 Feb 2015 00:27:38.456           560.477
                      10    5 Feb 2015 02:00:40.114    5 Feb 2015 02:06:45.164           365.050
                      11    5 Feb 2015 03:39:49.975    5 Feb 2015 03:49:02.750           552.774
                      12    5 Feb 2015 05:19:02.947    5 Feb 2015 05:32:51.192           828.245
                      13    5 Feb 2015 07:00:20.706    5 Feb 2015 07:16:59.805           999.098
                      14    5 Feb 2015 08:44:09.740    5 Feb 2015 09:01:18.382          1028.642

Global Statistics
-----------------
Min Duration          10    5 Feb 2015 02:00:40.114    5 Feb 2015 02:06:45.164           365.050
Max Duration          14    5 Feb 2015 08:44:09.740    5 Feb 2015 09:01:18.382          1028.642
Mean Duration                                                                            787.300
Total Duration                                                                         11022.200


Transmitter1-To-Receiver17
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 11:09:30.287    4 Feb 2015 11:26:45.894          1035.606
                       2    4 Feb 2015 12:53:41.076    4 Feb 2015 13:10:56.679          1035.603
                       3    4 Feb 2015 14:37:51.867    4 Feb 2015 14:55:07.467          1035.600
                       4    4 Feb 2015 16:22:02.655    4 Feb 2015 16:39:18.255          1035.600
                       5    4 Feb 2015 18:06:13.444    4 Feb 2015 18:23:29.043          1035.600
                       6    4 Feb 2015 19:50:24.232    4 Feb 2015 20:07:39.831          1035.600
                       7    4 Feb 2015 21:34:35.020    4 Feb 2015 21:51:50.620          1035.600
                       8    4 Feb 2015 23:18:45.808    4 Feb 2015 23:36:01.408          1035.600
                       9    5 Feb 2015 01:02:56.596    5 Feb 2015 01:20:12.196          1035.600
                      10    5 Feb 2015 02:47:07.384    5 Feb 2015 03:04:22.984          1035.600
                      11    5 Feb 2015 04:31:18.172    5 Feb 2015 04:48:33.772          1035.600
                      12    5 Feb 2015 06:15:28.960    5 Feb 2015 06:32:44.560          1035.600
                      13    5 Feb 2015 07:59:39.749    5 Feb 2015 08:16:55.348          1035.600
                      14    5 Feb 2015 09:43:50.537    5 Feb 2015 10:00:00.000           969.463

Global Statistics
-----------------
Min Duration          14    5 Feb 2015 09:43:50.537    5 Feb 2015 10:00:00.000           969.463
Max Duration           1    4 Feb 2015 11:09:30.287    4 Feb 2015 11:26:45.894          1035.606
Mean Duration                                                                           1030.876
Total Duration                                                                         14432.270


Transmitter1-To-Receiver18
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 11:58:46.363    4 Feb 2015 12:07:05.741           499.377
                       2    4 Feb 2015 13:37:08.593    4 Feb 2015 13:52:30.030           921.438
                       3    4 Feb 2015 15:19:44.190    4 Feb 2015 15:36:57.125          1032.936
                       4    4 Feb 2015 17:06:07.374    4 Feb 2015 17:20:57.157           889.783
                       5    4 Feb 2015 18:57:58.388    4 Feb 2015 19:03:29.117           330.729
                       6    5 Feb 2015 00:21:32.370    5 Feb 2015 00:34:13.673           761.303
                       7    5 Feb 2015 02:05:18.135    5 Feb 2015 02:22:10.953          1012.818
                       8    5 Feb 2015 03:49:35.649    5 Feb 2015 04:06:05.914           990.265
                       9    5 Feb 2015 05:34:28.602    5 Feb 2015 05:46:10.656           702.054

Global Statistics
-----------------
Min Duration           5    4 Feb 2015 18:57:58.388    4 Feb 2015 19:03:29.117           330.729
Max Duration           3    4 Feb 2015 15:19:44.190    4 Feb 2015 15:36:57.125          1032.936
Mean Duration                                                                            793.412
Total Duration                                                                          7140.704


Transmitter1-To-Receiver19
--------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 10:32:28.510    4 Feb 2015 10:47:59.574           931.064
                       2    4 Feb 2015 20:29:07.094    4 Feb 2015 20:44:42.824           935.730
                       3    4 Feb 2015 22:12:23.932    4 Feb 2015 22:29:05.554          1001.622
                       4    5 Feb 2015 00:02:56.136    5 Feb 2015 00:09:56.489           420.353
                       5    5 Feb 2015 07:24:06.861    5 Feb 2015 07:35:30.075           683.214
                       6    5 Feb 2015 09:06:27.474    5 Feb 2015 09:23:33.778          1026.305
```

```
Global Statistics
-----------------
Min Duration           4    5 Feb 2015 00:02:56.136    5 Feb 2015 00:09:56.489           420.353
Max Duration           6    5 Feb 2015 09:06:27.474    5 Feb 2015 09:23:33.778          1026.305
Mean Duration                                                                            833.048
Total Duration                                                                          4998.287
```

Appendix B.2: Scenario 1.2 Ground Station Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS-Sensor-Comms_Cone-Transmitter-Transmitter1-To-Place-GS_Bellville_South_Africa-Sensor-
Sensor1-Receiver-Receiver3:  Access Summary Report


Transmitter1-To-Receiver3
-------------------------
                  Access       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ------    -----------------------    -----------------------    --------------
                       1    4 Feb 2015 11:29:26.363    4 Feb 2015 11:37:06.393           460.030
                       2    4 Feb 2015 13:10:05.276    4 Feb 2015 13:27:00.475          1015.199
                       3    4 Feb 2015 14:54:53.993    4 Feb 2015 15:09:19.889           865.896
                       4    5 Feb 2015 00:47:42.782    5 Feb 2015 01:03:35.964           953.182
                       5    5 Feb 2015 02:31:30.784    5 Feb 2015 02:47:42.614           971.830

Global Statistics
-----------------
Min Duration           1    4 Feb 2015 11:29:26.363    4 Feb 2015 11:37:06.393           460.030
Max Duration           2    4 Feb 2015 13:10:05.276    4 Feb 2015 13:27:00.475          1015.199
Mean Duration                                                                            853.227
Total Duration                                                                          4266.136
```

Appendix B.3: Scenario 1.2 Gaps Summary

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS-Sensor-Comms_Cone-Transmitter-Transmitter1-To-Place-GS_Bellville_South_Africa-Sensor-
Sensor1-Receiver-Receiver3, Receiver-Receiver4, Receiver-Receiver2, Receiver-Receiver5, Receiver-
Receiver6, Receiver-Receiver7, Receiver-Receiver8, Receiver-Receiver9, Receiver-Receiver10, Receiver-
Receiver11, Receiver-Receiver12, Receiver-Receiver13, Receiver-Receiver14, Receiver-Receiver15, Receiver-
Receiver16, Receiver-Receiver17, Receiver-Receiver18, Receiver-Receiver19


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        2    4 Feb 2015 13:27:00.475    4 Feb 2015 14:54:53.993          5273.518
Max Duration        3    4 Feb 2015 15:09:19.889    5 Feb 2015 00:47:42.782         34702.893
Mean Duration                                                                       13688.977
Total Duration                                                                      82133.864


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        1    4 Feb 2015 15:14:52.883    4 Feb 2015 16:43:37.508          5324.626
Max Duration        2    4 Feb 2015 17:00:08.166    5 Feb 2015 02:30:51.309         34243.142
Mean Duration                                                                       13735.743
Total Duration                                                                      82414.458


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        4    5 Feb 2015 05:06:12.211    5 Feb 2015 06:34:27.097          5294.886
Max Duration        3    4 Feb 2015 19:46:49.623    5 Feb 2015 04:50:47.917         32638.294
Mean Duration                                                                       13701.738
Total Duration                                                                      82210.429


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        4    5 Feb 2015 06:09:35.208    5 Feb 2015 07:38:23.283          5328.076
Max Duration        3    4 Feb 2015 20:24:49.378    5 Feb 2015 05:53:04.432         34095.054
Mean Duration                                                                       13753.104
Total Duration                                                                      82518.625


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:25:20.624          1520.624
Max Duration       10    5 Feb 2015 02:05:55.498    5 Feb 2015 03:44:17.120          5901.622
Mean Duration                                                                        5032.394
Total Duration                                                                      75485.908


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:06:12.915           372.915
Max Duration        4    4 Feb 2015 21:13:51.640    5 Feb 2015 06:53:30.229         34778.589
Mean Duration                                                                       11658.023
Total Duration                                                                      81606.158


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        1    4 Feb 2015 11:59:38.543    4 Feb 2015 13:27:43.527          5284.984
Max Duration        2    4 Feb 2015 13:44:27.276    4 Feb 2015 22:49:48.926         32721.650
Mean Duration                                                                       13724.278
Total Duration                                                                      82345.666


                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------
```

```
Global Statistics
-----------------
Min Duration        4    5 Feb 2015 02:38:04.934    5 Feb 2015 04:06:51.084          5326.150
Max Duration        3    4 Feb 2015 16:58:16.712    5 Feb 2015 02:21:32.973         33796.261
Mean Duration                                                                       13782.215
Total Duration                                                                      82693.288

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:17:21.132          1041.132
Max Duration        9    5 Feb 2015 04:03:25.072    5 Feb 2015 10:00:00.000         21394.928
Mean Duration                                                                        7936.026
Total Duration                                                                      79360.256

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:20:18.345          1218.345
Max Duration        8    4 Feb 2015 22:41:44.023    5 Feb 2015 00:12:25.418          5441.396
Mean Duration                                                                        4859.913
Total Duration                                                                      72898.695

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        5    5 Feb 2015 08:49:02.948    5 Feb 2015 10:00:00.000          4257.052
Max Duration        4    4 Feb 2015 23:01:07.283    5 Feb 2015 08:33:58.487         34371.204
Mean Duration                                                                       16486.589
Total Duration                                                                      82432.943

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        5    5 Feb 2015 08:36:59.044    5 Feb 2015 10:00:00.000          4980.956
Max Duration        2    4 Feb 2015 11:41:10.230    4 Feb 2015 21:13:28.096         34337.866
Mean Duration                                                                       16640.222
Total Duration                                                                      83201.108

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:17:24.893          1044.893
Max Duration        6    4 Feb 2015 19:15:34.437    4 Feb 2015 20:42:29.626          5215.188
Mean Duration                                                                        4793.438
Total Duration                                                                      71901.571

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        3    5 Feb 2015 00:06:33.180    5 Feb 2015 01:34:45.587          5292.406
Max Duration        2    4 Feb 2015 14:21:33.803    4 Feb 2015 23:51:43.597         34209.795
Mean Duration                                                                       16540.885
Total Duration                                                                      82704.427

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:11:23.084           683.084
Max Duration        3    4 Feb 2015 13:58:30.775    4 Feb 2015 15:36:21.459          5870.684
Mean Duration                                                                        5025.187
Total Duration                                                                      75377.800

                  Gap       Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
                  ---    -----------------------    -----------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 11:09:30.287          4170.287
```

```
Max Duration        4    4 Feb 2015 16:39:18.255    4 Feb 2015 18:06:13.444           5215.188
Mean Duration                                                                         5140.552
Total Duration                                                                       71967.730

                  Gap       Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                  ---    ------------------------    ------------------------    --------------

Global Statistics
-----------------
Min Duration        2    4 Feb 2015 13:52:30.030    4 Feb 2015 15:19:44.190           5234.159
Max Duration        5    4 Feb 2015 19:03:29.117    5 Feb 2015 00:21:32.370          19083.253
Mean Duration                                                                         7925.930
Total Duration                                                                       79259.296

                  Gap       Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                  ---    ------------------------    ------------------------    --------------

Global Statistics
-----------------
Min Duration        0    4 Feb 2015 10:00:00.000    4 Feb 2015 10:32:28.510           1948.510
Max Duration        1    4 Feb 2015 10:47:59.574    4 Feb 2015 20:29:07.094          34867.520
Mean Duration                                                                        11628.816
Total Duration                                                                       81401.713
```

Appendix B.4: Scenario 1.2 Uplink Link Budget

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Place-SNode_Equator_PrimeMeridian-Sensor-Sensor8-Transmitter-Transmitter8-To-Satellite-IMS-Sensor-
Comms_Cone-Receiver-Receiver1:  Link Budget - Short Form


      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 13:27:49.172                 0.145000                  -137.611    9.999902e-007
4 Feb 2015 13:28:49.000                 0.145000                  -137.533    1.682706e-007
4 Feb 2015 13:28:57.296                 0.145000                  -137.538    1.000001e-006

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 15:05:20.787                 0.145003                  -138.082    2.492555e-008
4 Feb 2015 15:06:20.000                 0.145003                  -137.079    8.232945e-010
4 Feb 2015 15:07:20.000                 0.145003                  -136.035    1.949970e-011
4 Feb 2015 15:08:20.000                 0.145003                  -135.024    8.870807e-013
4 Feb 2015 15:09:20.000                 0.145003                  -134.215    8.981541e-013
4 Feb 2015 15:10:20.000                 0.145002                  -134.060    9.285224e-010
4 Feb 2015 15:10:53.789                 0.145002                  -134.631    9.992680e-007

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 15:14:07.399                 0.144998                  -134.591    9.998641e-007
4 Feb 2015 15:15:07.000                 0.144998                  -134.000    4.955189e-011
4 Feb 2015 15:16:07.000                 0.144997                  -134.538    3.940398e-012
4 Feb 2015 15:17:07.000                 0.144997                  -135.470    3.183344e-011
4 Feb 2015 15:18:07.000                 0.144997                  -136.507    9.696076e-010
4 Feb 2015 15:19:07.000                 0.144997                  -137.540    2.720896e-008
4 Feb 2015 15:19:39.317                 0.144997                  -138.081    1.351931e-007

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
5 Feb 2015 02:24:04.042                 0.145003                  -136.997    9.998370e-007
5 Feb 2015 02:25:04.000                 0.145003                  -136.027    1.086474e-007
5 Feb 2015 02:26:04.000                 0.145003                  -135.112    9.507667e-009
5 Feb 2015 02:27:04.000                 0.145002                  -134.370    1.077299e-009
5 Feb 2015 02:28:04.000                 0.145002                  -133.977    4.118712e-010
5 Feb 2015 02:29:04.000                 0.145001                  -133.987    8.572592e-010
5 Feb 2015 02:30:04.000                 0.145000                  -134.032    1.634426e-009
5 Feb 2015 02:31:04.000                 0.144999                  -133.946    5.897693e-010
5 Feb 2015 02:32:04.000                 0.144998                  -134.111    1.846749e-010
5 Feb 2015 02:33:04.000                 0.144998                  -134.694    2.621643e-010
5 Feb 2015 02:34:04.000                 0.144997                  -135.541    1.303632e-009
5 Feb 2015 02:35:04.000                 0.144997                  -136.497    1.108163e-008
5 Feb 2015 02:36:04.000                 0.144997                  -137.474    1.017896e-007
5 Feb 2015 02:36:41.510                 0.144997                  -138.076    3.830732e-007

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
5 Feb 2015 04:12:21.485                 0.145001                  -136.215    9.999873e-007
5 Feb 2015 04:13:21.000                 0.145000                  -136.057    1.793744e-010
5 Feb 2015 04:14:21.000                 0.145000                  -136.120    1.648007e-010
5 Feb 2015 04:15:14.313                 0.144999                  -136.338    9.999961e-007
```

Appendix B.5: Scenario 1.2 Downlink Link Budget

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS-Sensor-Comms_Cone-Transmitter-Transmitter1-To-Place-GS_Bellville_South_Africa-Sensor-
Sensor1-Receiver-Receiver3:  Link Budget - Short Form


      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 13:13:32.964                 0.145003                  -137.788    9.997850e-007
4 Feb 2015 13:14:32.000                 0.145003                  -136.817    6.784509e-012
4 Feb 2015 13:15:32.000                 0.145002                  -135.983    8.973441e-025
4 Feb 2015 13:16:32.000                 0.145002                  -135.567    1.000000e-030
4 Feb 2015 13:17:32.000                 0.145001                  -135.885    1.000000e-030
4 Feb 2015 13:18:32.000                 0.145000                  -136.427    1.000000e-030
4 Feb 2015 13:19:32.000                 0.144999                  -135.996    1.000000e-030
4 Feb 2015 13:20:32.000                 0.144998                  -135.564    1.000000e-030
4 Feb 2015 13:21:32.000                 0.144998                  -135.881    2.284269e-017
4 Feb 2015 13:22:32.000                 0.144997                  -136.672    1.515398e-007
4 Feb 2015 13:22:41.603                 0.144997                  -136.822    9.997916e-007

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
4 Feb 2015 14:56:33.614                 0.145002                  -139.834    6.457955e-011
4 Feb 2015 14:57:33.000                 0.145002                  -139.082    2.660175e-017
4 Feb 2015 14:58:33.000                 0.145002                  -138.376    3.326801e-029
4 Feb 2015 14:59:33.000                 0.145001                  -137.768    1.000000e-030
4 Feb 2015 15:00:33.000                 0.145001                  -137.310    1.000000e-030
4 Feb 2015 15:01:33.000                 0.145000                  -137.042    1.000000e-030
4 Feb 2015 15:02:33.000                 0.145000                  -137.014    1.000000e-030
4 Feb 2015 15:03:33.000                 0.144999                  -137.237    1.000000e-030
4 Feb 2015 15:04:33.000                 0.144999                  -137.658    1.000000e-030
4 Feb 2015 15:05:33.000                 0.144998                  -138.236    1.000000e-030
4 Feb 2015 15:06:33.000                 0.144998                  -138.923    1.379562e-026
4 Feb 2015 15:07:33.000                 0.144998                  -139.670    8.927514e-017
4 Feb 2015 15:07:40.556                 0.144998                  -139.767    6.748759e-016

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
5 Feb 2015 00:49:10.024                 0.145003                  -139.776    1.685096e-007
5 Feb 2015 00:50:10.000                 0.145003                  -138.870    1.663350e-011
5 Feb 2015 00:51:10.000                 0.145002                  -137.973    1.722497e-019
5 Feb 2015 00:52:10.000                 0.145002                  -137.135    1.000000e-030
5 Feb 2015 00:53:10.000                 0.145002                  -136.435    1.000000e-030
5 Feb 2015 00:54:10.000                 0.145001                  -135.955    1.000000e-030
5 Feb 2015 00:55:10.000                 0.145000                  -135.722    1.000000e-030
5 Feb 2015 00:56:10.000                 0.145000                  -135.736    1.000000e-030
5 Feb 2015 00:57:10.000                 0.144999                  -135.993    1.000000e-030
5 Feb 2015 00:58:10.000                 0.144998                  -136.499    1.000000e-030
5 Feb 2015 00:59:10.000                 0.144998                  -137.219    5.886040e-024
5 Feb 2015 01:00:10.000                 0.144998                  -138.069    1.541790e-012
5 Feb 2015 01:01:10.000                 0.144997                  -138.972    2.571510e-007
5 Feb 2015 01:01:20.710                 0.144997                  -139.135    1.000003e-006

      Time (UTCG)          Rcvd. Frequency (GHz)    Rcvd. Iso. Power (dBW)         BER
-----------------------    ---------------------    ----------------------    -------------
5 Feb 2015 02:33:50.356                 0.145003                  -138.989    9.997649e-007
5 Feb 2015 02:34:50.000                 0.145002                  -138.094    2.493930e-011
5 Feb 2015 02:35:50.000                 0.145002                  -137.241    2.081081e-021
5 Feb 2015 02:36:50.000                 0.145002                  -136.508    1.000000e-030
5 Feb 2015 02:37:50.000                 0.145001                  -135.983    1.000000e-030
5 Feb 2015 02:38:50.000                 0.145001                  -135.707    1.000000e-030
5 Feb 2015 02:39:50.000                 0.145000                  -135.655    1.000000e-030
5 Feb 2015 02:40:50.000                 0.144999                  -135.840    1.000000e-030
5 Feb 2015 02:41:50.000                 0.144998                  -136.261    1.000000e-030
5 Feb 2015 02:42:50.000                 0.144998                  -136.915    1.000000e-030
5 Feb 2015 02:43:50.000                 0.144998                  -137.724    4.741506e-022
5 Feb 2015 02:44:50.000                 0.144997                  -138.606    8.412311e-013
5 Feb 2015 02:45:50.000                 0.144997                  -139.505    3.396435e-008
5 Feb 2015 02:46:13.347                 0.144997                  -139.853    4.568734e-007
```

Appendix B.6: Scenario 1.2 Lighting Times Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Satellite-IMS:  Lighting


Sunlight Times
--------------
                        Start Time (UTCG)           Stop Time (UTCG)        Duration (min)
                    ------------------------    ------------------------    --------------
                    4 Feb 2015 10:00:00.000     4 Feb 2015 10:31:09.041             31.151
                    4 Feb 2015 11:00:11.930     4 Feb 2015 12:15:19.937             75.133
                    4 Feb 2015 12:44:24.464     4 Feb 2015 13:59:30.832             75.106
                    4 Feb 2015 14:28:36.995     4 Feb 2015 15:43:41.727             75.079
                    4 Feb 2015 16:12:49.519     4 Feb 2015 17:27:52.624             75.052
                    4 Feb 2015 17:57:02.034     4 Feb 2015 19:12:03.521             75.025
                    4 Feb 2015 19:41:14.548     4 Feb 2015 20:56:14.423             74.998
                    4 Feb 2015 21:25:27.057     4 Feb 2015 22:40:25.324             74.971
                    4 Feb 2015 23:09:39.562     5 Feb 2015 00:24:36.226             74.944
                    5 Feb 2015 00:53:52.061     5 Feb 2015 02:08:47.126             74.918
                    5 Feb 2015 02:38:04.556     5 Feb 2015 03:52:58.032             74.891
                    5 Feb 2015 04:22:17.047     5 Feb 2015 05:37:08.935             74.865
                    5 Feb 2015 06:06:29.532     5 Feb 2015 07:21:19.841             74.838
                    5 Feb 2015 07:50:42.013     5 Feb 2015 09:05:30.750             74.812
                    5 Feb 2015 09:34:54.488     5 Feb 2015 10:00:00.000             25.092

Global Statistics
-----------------
Min Duration        5 Feb 2015 09:34:54.488     5 Feb 2015 10:00:00.000             25.092
Max Duration        4 Feb 2015 11:00:11.930     4 Feb 2015 12:15:19.937             75.133
Mean Duration                                                                       68.725
Total Duration                                                                    1030.876
```

Appendix C.1: Scenario 2.1 Sensor Node Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Chain-GS_Equator:  Chain Access Data


   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 14:45:19.846    4 Feb 2015 14:55:39.169           619.323
5 Feb 2015 02:51:23.327    5 Feb 2015 03:01:48.904           625.576

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 16:22:41.428    4 Feb 2015 16:32:04.547           563.119
4 Feb 2015 18:00:44.275    4 Feb 2015 18:07:00.552           376.277
5 Feb 2015 04:28:34.076    5 Feb 2015 04:38:24.957           590.881
5 Feb 2015 06:07:48.439    5 Feb 2015 06:12:08.883           260.444

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 18:00:43.203    4 Feb 2015 18:07:49.943           426.739
4 Feb 2015 19:36:15.383    4 Feb 2015 19:45:16.415           541.033
5 Feb 2015 06:06:18.175    5 Feb 2015 06:14:27.709           489.534
5 Feb 2015 07:42:44.426    5 Feb 2015 07:51:00.251           495.826

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 21:12:33.048    4 Feb 2015 21:22:44.852           611.803
5 Feb 2015 07:45:15.773    5 Feb 2015 07:49:17.567           241.794
5 Feb 2015 09:18:48.720    5 Feb 2015 09:28:42.273           593.552

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 10:43:17.525    4 Feb 2015 10:53:33.074           615.549
4 Feb 2015 22:49:19.776    4 Feb 2015 22:59:43.979           624.203

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 12:20:42.647    4 Feb 2015 12:29:54.251           551.604
4 Feb 2015 13:58:25.402    4 Feb 2015 14:05:10.538           405.135
5 Feb 2015 00:26:33.690    5 Feb 2015 00:36:16.243           582.552
5 Feb 2015 02:05:21.105    5 Feb 2015 02:10:27.397           306.292

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 13:58:51.740    4 Feb 2015 14:05:32.507           400.767
4 Feb 2015 15:34:05.160    4 Feb 2015 15:43:18.696           553.536
5 Feb 2015 02:04:23.149    5 Feb 2015 02:12:13.855           470.706
5 Feb 2015 03:40:32.233    5 Feb 2015 03:49:04.599           512.366

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 17:10:27.628    4 Feb 2015 17:20:43.887           616.259
5 Feb 2015 03:43:44.089    5 Feb 2015 03:46:41.449           177.359
5 Feb 2015 05:16:42.108    5 Feb 2015 05:26:42.623           600.516

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 18:47:18.520    4 Feb 2015 18:57:40.768           622.248
5 Feb 2015 06:53:23.209    5 Feb 2015 07:03:49.359           626.150

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 10:00:00.000    4 Feb 2015 10:03:22.798           202.798
4 Feb 2015 20:24:36.970    4 Feb 2015 20:34:10.495           573.525
4 Feb 2015 22:03:02.246    4 Feb 2015 22:08:45.688           343.442
5 Feb 2015 08:30:31.131    5 Feb 2015 08:40:29.519           598.387

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 10:00:00.000    4 Feb 2015 10:03:17.721           197.721
4 Feb 2015 11:31:59.646    4 Feb 2015 11:41:24.352           564.706
4 Feb 2015 22:02:33.074    4 Feb 2015 22:10:03.253           450.178
4 Feb 2015 23:38:24.919    4 Feb 2015 23:47:12.147           527.228
```

Appendix C.2: Scenario 2.1 Ground Station Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Chain-GS_Bellville:  Chain Access Data


   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 12:59:42.280    4 Feb 2015 13:09:16.612           574.331
4 Feb 2015 14:36:48.497    4 Feb 2015 14:45:14.555           506.058
5 Feb 2015 01:23:48.442    5 Feb 2015 01:34:04.647           616.206
5 Feb 2015 03:02:54.848    5 Feb 2015 03:09:02.223           367.376

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 14:37:14.121    4 Feb 2015 14:45:08.149           474.028
4 Feb 2015 16:13:07.090    4 Feb 2015 16:22:55.659           588.569
5 Feb 2015 03:01:12.010    5 Feb 2015 03:10:35.535           563.525
5 Feb 2015 04:38:17.084    5 Feb 2015 04:46:56.979           519.896

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 16:15:37.363    4 Feb 2015 16:19:58.226           260.863
4 Feb 2015 17:49:43.604    4 Feb 2015 18:00:09.647           626.044
5 Feb 2015 04:39:05.331    5 Feb 2015 04:46:45.085           459.754
5 Feb 2015 06:14:21.547    5 Feb 2015 06:24:18.373           596.826

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 19:26:34.271    4 Feb 2015 19:37:00.720           626.449
4 Feb 2015 21:05:31.028    4 Feb 2015 21:10:21.129           290.101
5 Feb 2015 06:17:58.062    5 Feb 2015 06:22:04.360           246.298
5 Feb 2015 07:50:52.882    5 Feb 2015 08:01:21.428           628.546

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 10:53:52.274    4 Feb 2015 11:01:26.943           454.669
4 Feb 2015 21:03:39.485    4 Feb 2015 21:13:28.723           589.238
4 Feb 2015 22:41:02.328    4 Feb 2015 22:49:00.487           478.159
5 Feb 2015 09:27:47.036    5 Feb 2015 09:38:10.194           623.158

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 10:53:25.849    4 Feb 2015 11:02:06.361           520.512
4 Feb 2015 12:29:38.245    4 Feb 2015 12:39:02.612           564.367
4 Feb 2015 22:41:04.067    4 Feb 2015 22:49:28.794           504.726
5 Feb 2015 00:17:15.577    5 Feb 2015 00:26:48.871           573.294

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 12:31:41.619    4 Feb 2015 12:37:58.270           376.651
4 Feb 2015 14:05:57.192    4 Feb 2015 14:16:14.762           617.570
5 Feb 2015 00:19:06.501    5 Feb 2015 00:24:42.074           335.574
5 Feb 2015 01:53:48.723    5 Feb 2015 02:04:09.009           620.285

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 15:42:40.855    4 Feb 2015 15:53:11.283           630.428
5 Feb 2015 03:30:36.564    5 Feb 2015 03:41:06.473           629.909
5 Feb 2015 05:10:17.376    5 Feb 2015 05:13:34.590           197.215

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 17:19:47.257    4 Feb 2015 17:29:53.976           606.719
4 Feb 2015 18:58:19.594    4 Feb 2015 19:05:17.210           417.616
5 Feb 2015 05:07:38.610    5 Feb 2015 05:17:41.760           603.150
5 Feb 2015 06:45:22.973    5 Feb 2015 06:52:44.253           441.279

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 18:57:18.375    4 Feb 2015 19:06:20.863           542.488
4 Feb 2015 20:33:56.391    4 Feb 2015 20:43:01.654           545.262
5 Feb 2015 06:44:58.303    5 Feb 2015 06:53:51.079           532.777
5 Feb 2015 08:21:29.646    5 Feb 2015 08:30:43.437           553.791

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 20:35:23.148    4 Feb 2015 20:42:23.189           420.041
4 Feb 2015 22:10:09.616    4 Feb 2015 22:20:18.605           608.989
5 Feb 2015 08:22:48.436    5 Feb 2015 08:29:20.935           392.498
5 Feb 2015 09:57:58.924    5 Feb 2015 10:00:00.000           121.076
```

Appendix D.1: Scenario 2.2 Sensor Node Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Chain-EquatorSense:  Chain Access Data


   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 13:26:17.196    4 Feb 2015 13:31:13.003           295.807
4 Feb 2015 15:05:20.797    4 Feb 2015 15:19:39.327           858.530
5 Feb 2015 02:22:56.885    5 Feb 2015 02:36:41.520           824.636
5 Feb 2015 04:08:42.503    5 Feb 2015 04:18:28.751           586.247

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 16:54:01.943    4 Feb 2015 17:00:09.115           367.172
4 Feb 2015 18:33:42.665    4 Feb 2015 18:47:57.873           855.208
5 Feb 2015 05:51:13.321    5 Feb 2015 06:05:05.874           832.553
5 Feb 2015 07:37:18.534    5 Feb 2015 07:46:32.116           553.583

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 10:45:54.669    4 Feb 2015 10:57:45.137           710.469
4 Feb 2015 20:21:52.837    4 Feb 2015 20:28:57.030           424.193
4 Feb 2015 22:02:04.317    4 Feb 2015 22:16:15.370           851.053
5 Feb 2015 09:19:29.435    5 Feb 2015 09:33:28.974           839.539

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 12:29:52.528    4 Feb 2015 12:42:53.966           781.438
4 Feb 2015 14:14:24.808    4 Feb 2015 14:25:54.944           690.137
4 Feb 2015 23:49:47.950    4 Feb 2015 23:57:40.483           472.533
5 Feb 2015 01:30:26.758    5 Feb 2015 01:44:32.779           846.021

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 15:58:06.841    4 Feb 2015 16:11:20.861           794.020
4 Feb 2015 17:42:57.123    4 Feb 2015 17:54:04.856           667.733
5 Feb 2015 03:17:46.976    5 Feb 2015 03:26:21.785           514.808
5 Feb 2015 04:58:50.746    5 Feb 2015 05:12:50.766           840.021

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 19:26:22.839    4 Feb 2015 19:39:48.282           805.443
4 Feb 2015 21:11:31.426    4 Feb 2015 21:22:14.466           643.039
5 Feb 2015 06:45:49.638    5 Feb 2015 06:55:01.887           552.250
5 Feb 2015 08:27:16.205    5 Feb 2015 08:41:09.186           832.980

   Start Time (UTCG)           Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------    --------------
4 Feb 2015 10:00:00.000    4 Feb 2015 10:02:00.686           120.686
4 Feb 2015 11:36:58.232    4 Feb 2015 11:51:19.218           860.986
4 Feb 2015 22:54:39.857    4 Feb 2015 23:08:15.500           815.642
5 Feb 2015 00:40:06.829    5 Feb 2015 00:50:22.754           615.925
```

Appendix D.2: Scenario 2.2 Ground Station Access Report

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Chain-GS_Bellville:  Chain Access Data


   Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------   --------------
4 Feb 2015 13:11:28.344    4 Feb 2015 13:25:38.871          850.526
4 Feb 2015 14:56:33.600    4 Feb 2015 15:07:40.546          666.945
5 Feb 2015 00:49:10.013    5 Feb 2015 01:02:08.223          778.210
5 Feb 2015 02:32:58.295    5 Feb 2015 02:46:13.337          795.042

   Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------   --------------
4 Feb 2015 16:39:47.741    4 Feb 2015 16:54:02.270          854.530
4 Feb 2015 18:25:00.703    4 Feb 2015 18:35:49.374          648.672
5 Feb 2015 04:17:23.664    5 Feb 2015 04:30:33.023          789.359
5 Feb 2015 06:01:25.809    5 Feb 2015 06:14:29.607          783.798

   Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------   --------------
4 Feb 2015 20:08:06.473    4 Feb 2015 20:22:24.618          858.145
4 Feb 2015 21:53:28.267    4 Feb 2015 22:03:56.533          628.265
5 Feb 2015 07:45:37.235    5 Feb 2015 07:58:56.538          799.303
5 Feb 2015 09:29:53.133    5 Feb 2015 09:42:45.250          772.117

   Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------   --------------
4 Feb 2015 10:56:15.350    4 Feb 2015 11:08:22.246          726.896
4 Feb 2015 12:39:08.357    4 Feb 2015 12:52:57.814          829.458
4 Feb 2015 21:58:02.389    4 Feb 2015 21:59:00.502           58.113
4 Feb 2015 23:36:25.488    4 Feb 2015 23:50:46.851          861.363
5 Feb 2015 01:21:57.643    5 Feb 2015 01:32:02.630          604.987

   Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------   --------------
4 Feb 2015 14:24:27.712    4 Feb 2015 14:36:48.058          740.346
4 Feb 2015 16:07:34.377    4 Feb 2015 16:21:16.884          822.508
5 Feb 2015 01:25:04.811    5 Feb 2015 01:28:47.297          222.485
5 Feb 2015 03:04:45.690    5 Feb 2015 03:19:09.689          863.999
5 Feb 2015 04:50:29.348    5 Feb 2015 05:00:08.353          579.005

   Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------   --------------
4 Feb 2015 17:52:41.468    4 Feb 2015 18:05:14.808          753.340
4 Feb 2015 19:36:01.891    4 Feb 2015 19:49:36.498          814.606
5 Feb 2015 04:52:49.283    5 Feb 2015 04:57:54.223          304.939
5 Feb 2015 06:33:07.220    5 Feb 2015 06:47:33.090          865.871
5 Feb 2015 08:19:02.656    5 Feb 2015 08:28:13.986          551.330

   Start Time (UTCG)          Stop Time (UTCG)       Duration (sec)
-----------------------    -----------------------   --------------
4 Feb 2015 11:28:05.811    4 Feb 2015 11:39:29.992          684.181
4 Feb 2015 21:20:55.846    4 Feb 2015 21:33:41.901          766.056
4 Feb 2015 23:04:30.176    4 Feb 2015 23:17:55.618          805.442
5 Feb 2015 08:20:45.985    5 Feb 2015 08:26:49.942          363.957
```