Cape Peninsula
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Mission design of a CubeSat constellation for in-situ monitoring applications

by

Kanyisa Sipho Mtshemla

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Supervisor: Prof. Robert Van Zyl

Bellville Campus

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DECLARATION

I, Kanyisa Sipho Mtshemla, 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

Real-time remote monitoring of Africa's resources, such as water quality, by using terrestrial sensors is impeded by the limited connectivity over the vast rural areas of the continent. Without such monitoring, the effective management of natural resources, and the response to associated disasters such as flooding, is almost impossible. A constellation of nanosatellites could provide near real-time connectivity with ground-based sensors that are distributed across the continent.

This study evaluates the high level development of a mission design for a near real-time remote monitoring CubeSat constellation and ground segment for in-situ monitoring in regions of interest on the African continent. This would facilitate management of scarce resources using a low-cost constellation. To achieve this, the design concept and operation of a Walker constellation are examined as a means of providing connectivity to a low bit rate sensor network distributed across geographic areas of interest in South Africa, Algeria, Kenya and Nigeria.

The mission requirements include the optimisation of the constellation to maintain short revisit times over South Africa and an investigation of the required communications link to perform the operations effectively. STK software is used in the design and evaluation of the constellations and the communications system. The temporal performance parameters investigated are *access* and *revisit* times of the constellations to the geographic areas mentioned. The types of constellation configurations examined, involved starting with a system level analysis of one satellite. This seed satellite has known orbital parameters. Then a gradual expansion of two to twelve satellites in one, two and three orbital planes follows. VHF, UHF and S-band communication links are considered for low data rate in-situ monitoring applications. RF link budgets and data budgets for typical applications are determined.

For South Africa, in particular, a total of 12 satellites evenly distributed in a two-plane constellation at an inclination of 39° provide the optimal solution and offer an average daily revisit time of about 5 minutes. This constellation provides average daily access time of more than 16 hours per day. A case study is undertaken that decribes a constellation for the provision of maritime vessel tracking in the Southern African oceans using the Automated Information System (AIS). This service supports the Maritime Domain Awareness (MDA) initiative implemented by the South African Government, under its Operation Phakisa.

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DEDICATION

I dedicate this thesis work to my parents, Bandile and Nodumo Mtshemla, for their continuous love and support. With the deepest appreciation, thank you.

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GLOSSARY

Acronyms and Abbreviations

AFSK	Audio Frequency Shift Keying
AGI	Analytical Graphics Inc
BER	Bit Error Rate
bps	Bits per second
BPSK	Binary Phase Shift Keying
Cal Poly	California Polytechnic State University
COTS	Commercial off the shelf
CPUT	Cape Peninsula University of Technology
DC	Direct Current
EIRP	Effective Isotropic Radiated Power
ESA	European Space Agency
FCC	Federal Communication Commission
FM	Frequency Modulation
F'SATI	French South African Institute of Technology
GENSO	Global Educational Network for Satellite Operations
GMSK	Gaussian Minimum Shift Keying
GPS	Global Positioning System
IARU	International Amateur Radio Union
IEEE	Institute of Electrical and Electronics Engineers
IESS	IntelSat Earth Station Standards
ITU	International Telecommunications Union
kHz	kilohertz
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
MATLAB	Matrix Laboratory
Mbps	Megabit per second
MHz	megahertz
NASA	National Aeronautics and Space Administration
p-p	peak to peak
ppm	parts per million
P-POD	Poly-Picosatellite Orbital Deployer
QPSK	Quadrature Phase Shift Keying
RAAN	Right Ascension of Ascending Node
SANSA	South African National Space Agency

SATCOM	Satellite Communications
SINAD	Signal in Noise Distribution
SMAD	Space Mission Analysis and Design
SNR	Signal to Noise Ratio
STK	Satellite Tool Kit
TCMD	Telecommand
TLM	Telemetry
TNC	Terminal Node Controller
TT&C	Telecommand, Telemetry and Control
UHF	Ultra High Frequency
VHF	Very High Frequency

CHAPTER 1: RESEARCH OVERVIEW

1.1 INTRODUCTION

The French South African Institute of Technology (F'SATI) was established in 2008 at the Cape Peninsula University of Technology (CPUT), offering a programme in satellite engineering. Nanosatellite platforms are utilised to give students hands-on experience with satellite technology. F'SATI launched its first 1-unit CubeSat, ZACUBE-1, on 21 November 2013. The satellite is also known as *TshepisoSAT*. Currently, a 3-unit CubeSat, ZACUBE-2, is being developed.

A CubeSat is a cubic satellite with a mass of up to 1.33 kg that conforms to the CubeSat standard. A basic CubeSat is referred to as a 1U (one unit) with dimensions 10 x 10 x 10 cm. The increasing utility of CubeSats and their multi-satellite deployment allow for LEO communication constellations of modest capability and cost relative to larger satellites.

The project baseline is to develop a feasible mission concept for low data rate in-situ monitoring using a constellation of CubeSats. In-situ sensor networks refer to sensors situated within an environment and which provide information about that environment. The remote placement of sensor nodes allows for the monitoring of desert, ocean and forest regions with the sensor data collected through CubeSat constellations in almost real-time. The objective of these monitoring services is to receive, store and transmit data gathered from distributed sensors used for in-situ measurements to a control station. Such missions have direct benefits through enhancing the management of natural resources.

1.2 STATEMENT OF RESEARCH PROBLEM

The United Nations (2006) states that "Africa is the continent most vulnerable to the impacts of climate change. Already experiencing temperature increases over much of the continent, and with predictions that temperatures will rise further, Africa is facing a wide range of impacts, including increased drought and floods".

Real-time or near real-time remote monitoring of Africa's resources, such as water quality, with terrestrial sensors is impeded through the limited connectivity in the vast rural areas of the continent. Without such monitoring, the effective management of natural resources and responses to natural disasters are challenging. In view of the detrimental effects that global warming poses to the continent, the effective management of its natural resources is clearly important to ensure the socio-economic development of the continent.

A constellation of nanosatellites can provide near real-time connectivity with ground-based sensors distributed across the continent. An example of a CubeSat mission that performs in-situ monitoring is the HumSAT constellation (HumSAT, 2013). The development of a constellation of nanosatellites providing connectivity to remote and under-developed areas, where communications infrastructure is not available, is the core initiative of HumSAT. The main application of HumSAT is the relaying of climate change measurements and other in-situ environmental information for the effective management of humanitarian initiatives.

The research addresses the satellite mission analysis and design framework of a CubeSat constellation and ground segment for in-situ monitoring of primary geographic target areas, which are South Africa, Algeria, Kenya and Nigeria on the African continent, to facilitate the management of its scarce resources. These countries are members participating in the initiative by the Regional African Satellite Communication Organisation (RASCO, n.d.). The target areas are depicted in Figure 1.1 with the ground station located in Cape Town.

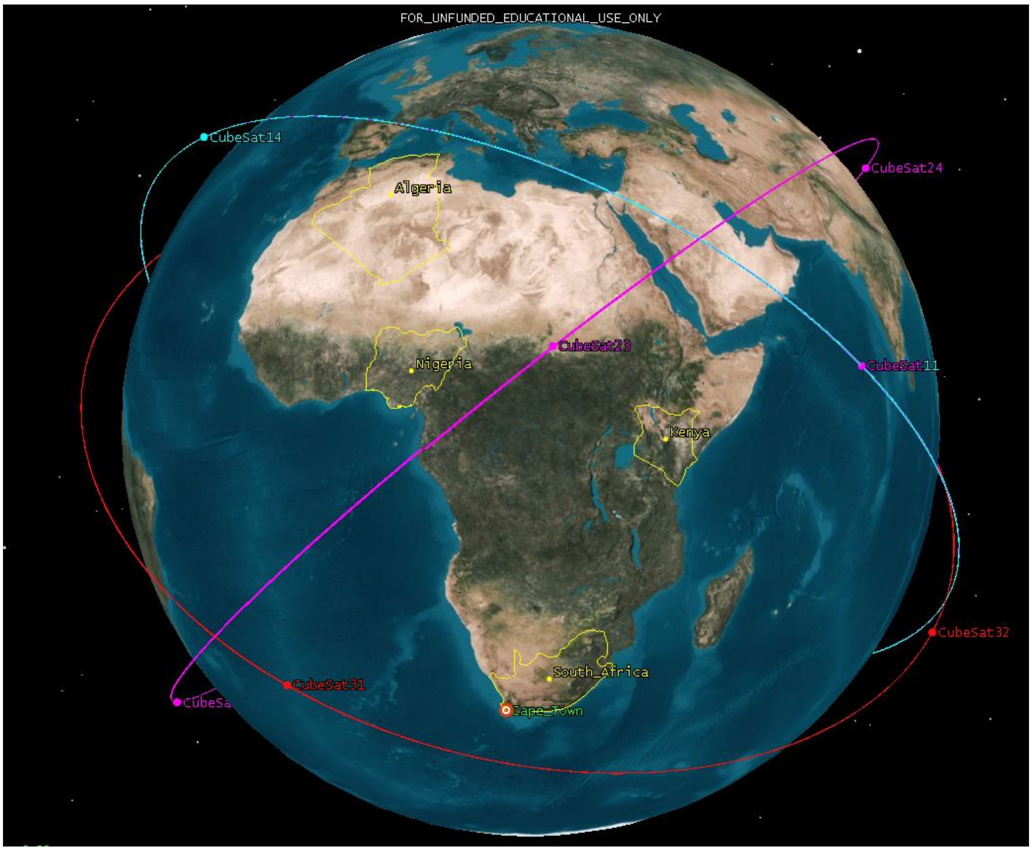

Figure 1.1: Primary geographic target areas of the constellation as defined in STK

1.3 RESEARCH OBJECTIVES

- The research proposes a systems framework for a constellation of CubeSats and the supporting ground segment that can provide near real-time low bit rate connectivity to a network of wireless remote sensors distributed across the primary target areas, which are Algeria, Kenya, Nigeria and with the ground station located in South Africa.
- The aim is the optimisation of *revisit* time to approximately 45 minutes over South Africa, while utilising a minimum number of satellites.
- In addition to revisit time, the temporal performance of the constellations is also simulated in terms of *access* time to sensors in the respective geographical areas.
- The research addresses both the constellation design and the communications systems on the satellite and on the ground.

1.4 RESEARCH QUESTIONS

- What types of services can be provided with in-situ monitoring missions?
- What is the minimum number of satellites required to maintain a frequent revisit time over South Africa, Algeria, Kenya and Nigeria?
- What are the trade-offs between revisit time, access time and number of satellites?
- Which communications links are feasible for supporting low data rate in-situ monitoring?
- How does the number of in-situ sensors, type of data and geographical distribution of sensors impact the communications system design?

1.5 SIGNIFICANCE AND CONTRIBUTIONS OF THE RESEARCH

In-situ monitoring with constellations of nanosatellites provides a viable method to monitor the natural resources of Africa. Space-based in-situ monitoring is more appropriate in rural areas where there is little or no telecommunications coverage by terrestrial means. This is especially true for the vast regions in Africa that do not benefit from radio or mobile connectivity. The enabling impact that in-situ monitoring will have on the management of our natural resources and disaster response will provide the continent with an indigenous capability to deal with the effects of global warming.

The research contribution is the utilisation of intellectual property (IP) that has been created in South Africa in nanosatellite communications systems and complete nanosatellite missions. A specific application that is being investigated is in maritime domain awareness (MDA) in support of the National Government's Operation Phakisa initiative (South Africa, 2014). The research will provide a baseline feasibility study for MDA services provided with nanosatellite constellations.

1.6 RESEARCH DELINEATION

A constellation design based on a Walker Delta Pattern is examined. The Satellite Tool Kit (STK) software program is used in this research to simulate the behaviour of the constellation and related communication parameters (Analytical Graphics Inc, n.d.).

The study only considers low bit rate data communications to interrogate several low bit rate sensors.

The deployment of the constellation will not be dealt with in-depth. The satellites are assumed to be in there "post-deployment" position. Orbital maintenance post-launch is out of the scope of this thesis.

Only the constellation and communications aspects of the mission are investigated as these are critically linked to the performance criteria of near real-time connectivity.

Space mission analysis and design (SMAD) is an iterative process. It gradually refines the requirements and methods of achieving them. In this work, some broad concepts that are part of the process are discussed.

The mission scenarios cover only the primary geographic target areas, which are Algeria, Kenya, Nigeria and South Africa, with the ground station located in Cape Town. The selected scenarios guide the analyses. This means that monitoring activity is limited to regional coverage, rather than global coverage.

Inter-satellite communications is not considered as this is still an emerging technological capability in the nanosatellite environment.

The financial feasibility of in-situ monitoring missions is a critical consideration in deploying such services. However, the focus of this research is technical and the financial analyses of developing and operating the missions are not addressed in this work. It is worth mentioning, though, that a separate study conducted by the CPUT Technology Transfer Office found that 5000 sensors distributed throughout Southern Africa will support a viable business case. Using this rough guideline, approximately 1250 sensors are assumed to be distributed in each primary target area, operating in a variety of applications mentioned in Chapter 4.

The elevation of the sensors is assumed to be relatively flat with nodes considered to be at the same height, and that no mountainous areas are monitored.

Ship tracking using the Automated Identification Service (AIS) is investigated as a case study. This service supports Operation Phakisa, which is a Government-endorsed action plan to monitor the national coastal regions (South Africa, 2014).

The sustainable exploitation of outer space is imperative. Considering that constellations of satellites eventually contribute to space debris, end of mission strategies should be put in place to remove dead satellites from orbit. Current deorbiting mechanisms available to nanosatellite platforms, such as ion thrusters and solar sails, are intended to slow the satellite down so that it falls back to Earth. Deorbiting of satellites will not be considered in this work.

1.7 RESEARCH DESIGN AND METHODOLOGY

The widely adopted Space Mission Analysis and Design (SMAD) process is generally followed. In order for the research to be carried out efficiently and expected outcomes acquired successfully, the following approach and research tools are used:

Literature survey: The SMAD process is preceded by a thorough survey of literature pertaining to constellation design; including books, reliable internet sites, journals and consulting people with expertise in the field relating to the study undertaken.

Simulations and analyses: The research is simulation-based. The STK simulation package provides the necessary tools to effectively design and analyse the performance of a constellation of satellites, including the communication links associated with the constellation. Different constellation configurations with varying number of satellites and orbital planes are evaluated over different inclinations to find the optimum constellation configuration that can be used.

1.8 THESIS OUTLINE

Chapter 1 presents an overview of the project, the research problem, research questions, objectives and delineation, as well as methodology.

Chapter 2 provides a background on CubeSats and their capabilities. Constellation design in general is discussed.

Chapter 3 identifies and quantifies key design considerations when designing a constellation of identical CubeSats and provides the concept constellation that satisfies the required revisit time.

Chapter 4 addresses concepts of satellite communications related to low bit rate in-situ monitoring missions using amateur sensor networks.

Chapter 5 offers a case study of an AIS application for Maritime Domain Awareness in support of Operation Phakisa.

Finally, Chapter 6 submits conclusions of the complete work and proposals for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The use of satellites for remote sensing applications has brought a revolution in the field of Earth observation as they can provide information of vast areas on the Earth's surface on a continuous basis. Satellite constellations have a number of advantages over single satellite missions in terms of Earth observation utility. Some of these advantages are (Maini & Agrawal, 2007:344-345):

- continuous acquisition of data;
- frequent and regular re-visit capabilities, resulting in up-to-date information; and
- broad geographic coverage area.

2.2 CUBESAT TECHNOLOGY

Satellites can be categorised according to their mass, as summarised in Table 2.1.

Table 2.1: Satellite categories by mass

Category	Mass
Large satellite	> 1000 kg
Mini-satellite	100 - 1000 kg
Microsatellite	10 – 100 kg
Nanosatellite	1 – 10 kg
Picosatellite	< 1 kg

(From Rycroft & Crosby, 2002:2)

In this work, the focus is primarily on a specific class of nanosatellites, referred to as CubeSats. According to Marinan (2013:6), one CubeSat unit (1U) has dimensions of 10 x 10 x 10 cm. CubeSats have historically been built in 1U, 2U, 3U, or 6U sizes as shown in Figure 2.1 and Figure 2.2.

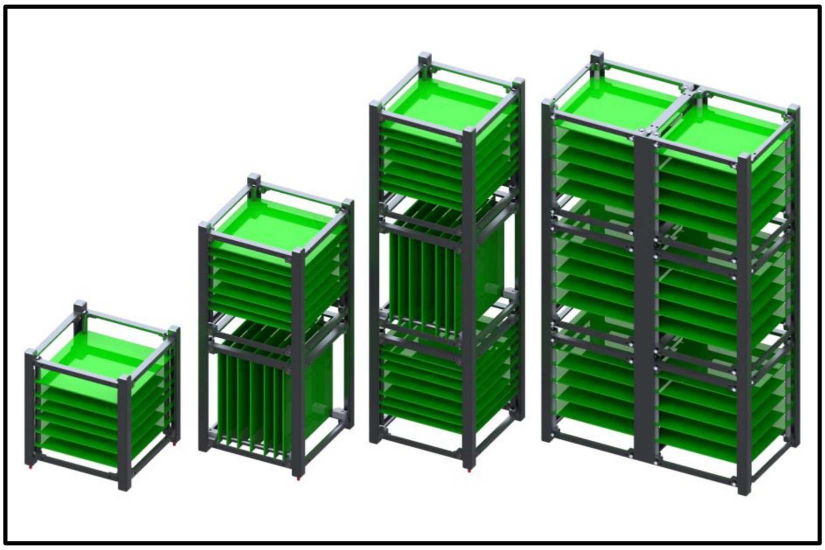

Figure 2.1: CubeSats sized by number of units

(Adapted from Radius Space, n.d.)

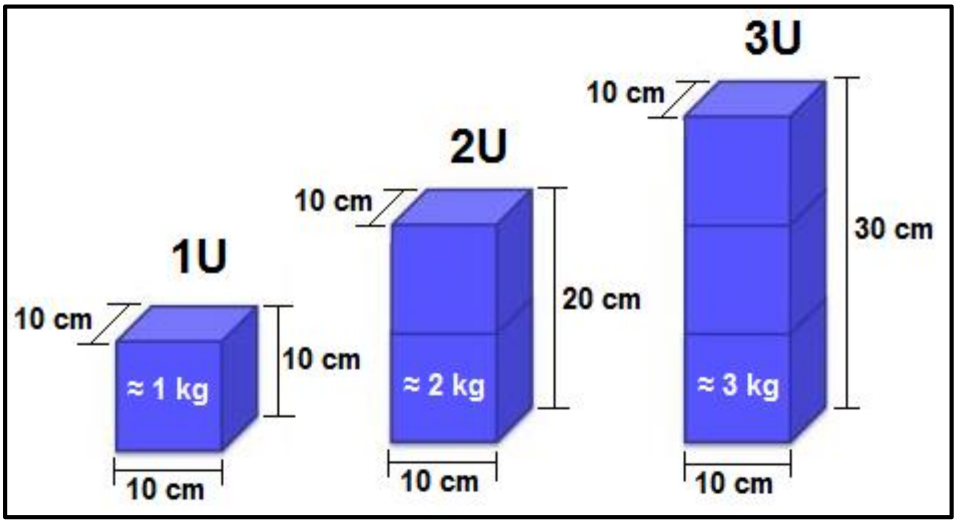

Figure 2.2: CubeSat dimensions, mass and unit type

Miniaturised instruments and components suited for CubeSats are rapidly becoming available. The components used in CubeSat development are mostly commercial-off-the-shelf (COTS), which are at a lower cost compared to those used in larger satellite systems. This results in the increased popularity of CubeSats in the field of space science and engineering and allows CubeSats to be a viable option for use in low Earth orbit constellations (Marinan, 2013:7). Figure 2.3 shows the number of nanosatellite missions launched, or planned to be launched.

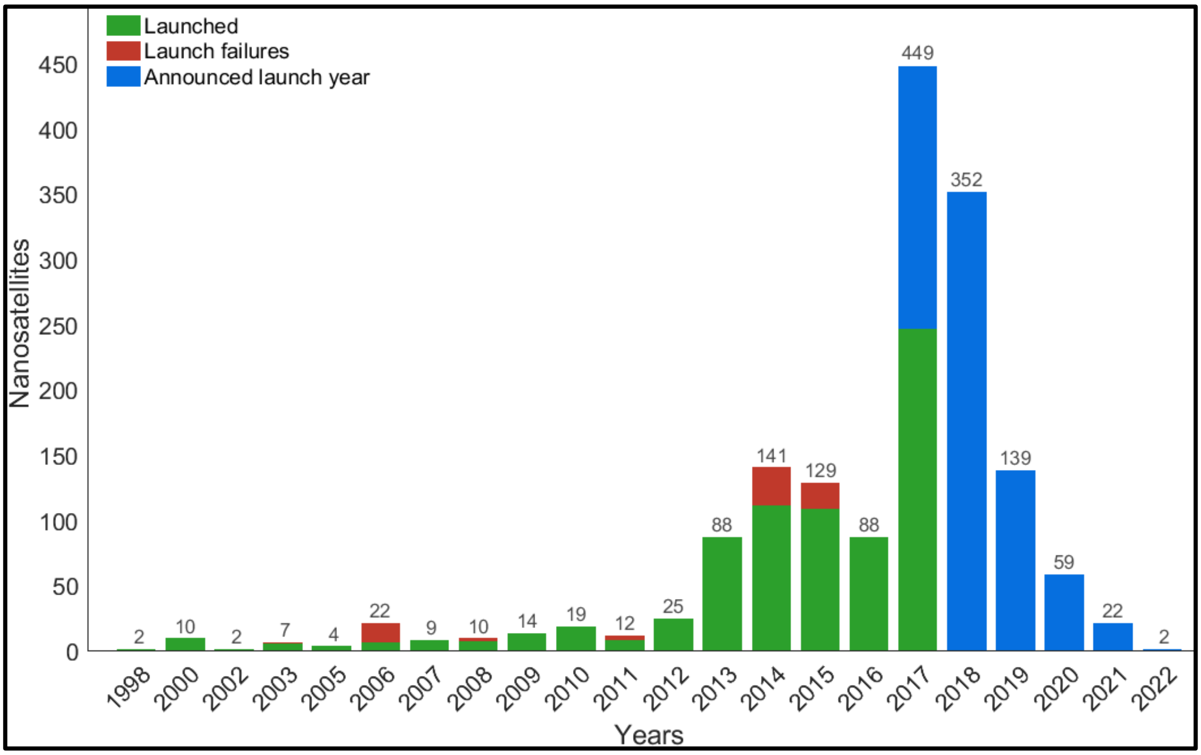

Figure 2.3: Nanosatellites by announced launch years

(Adapted from Nanosats, n.d.)

There are many applications for nanosatellites. These can range from space science, such as that carried out by “TshepisoSat”, communications, exploration, navigation and technology demonstration, which ZACUBE-2 will carry out.

With reference to the current study, it is worth noting the state-of-the-art in terms of CubeSat power and communications systems. Presently, power systems for CubeSats are capable of providing up to 50 W peak power for a 3U and up to 90 W for a 6U. Communications solutions based on IP develped at CPUT are available up to 50 Mbps (Clyde Space, 2017). In this research, CPUT products (VHF-, UHF, and S-band systems) are referenced for link budget calculations (CPUT, 2017).

2.3 SATELLITE MISSION ANALYSIS AND DESIGN PROCESS

It is appropriate to reflect on the key steps in space mission analysis and design (SMAD) to provide a framework for the work presented here.

An iterative process of analysis and design is necessary for progressively improving both the system requirements definition and approach to accomplish them. This process is summarised in Figure 2.4. Although not all steps of the SMAD process will be followed in this work, it provides a resource for future reference.

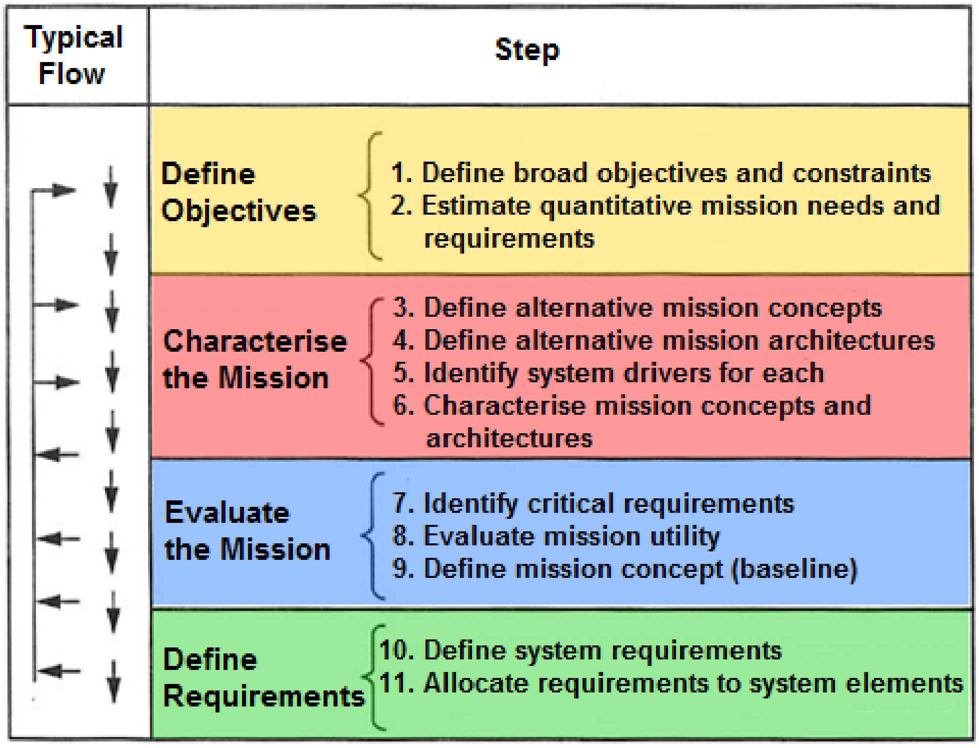

Figure 2.4: Space Mission Analysis and Design (SMAD) process flowchart

(From Larson & Wertz, 2005:2)

Each step is discussed briefly below.

Step 1: Define broad objectives and constraints

The mission objectives are defined. At this stage the objectives are obtained from the mission statement, which states the qualitative goals of the mission and the reasons behind acquiring what is aimed for. This broad aim should be returned to in order to keep track of what was initially set out to be done.

Step 2: Estimate quantitative mission needs and requirements

The level of quality is determined at which the broad objectives are desired to be accomplished with the given needs, relevant technology, and budget. A common mistake of setting requirements at fairly early stages needs to be avoided by having requirements flexible enough to change as the mission development progresses. SMAD by Larson and Wertz (2005:3) provides the necessary data for supporting these decisions. The following step is to define and characterise a space mission to meet the objectives.

Step 3: Define alternative mission concepts

Alternative mission concepts to the primary mission concept are investigated. A mission concept gives an idea of how the mission is envisioned to be implemented and operated in practice. This concerns data sensing operation and relaying of the data to end users, controlling of the mission, and schedule of the mission. Alternative mission concepts may require very different systems (Larson & Wertz, 2005:3).

Step 4: Define alternative mission architectures

Alternative mission elements, collectively referred to as the space system architecture, are described.

Step 5: Identify system drivers for each

The major cost and performance drivers for each different mission concept are analysed. In the majority of space missions, system drivers comprise of altitude, power, size and weight of instrumentation, and the number of satellites.

Step 6: Characterise mission concepts and architectures

The system capabilities and functionalities are detailed. Space and ground processing specifications are defined, and link, power and weight budgets determined.

Step 7: Identify critical requirements

The systems defined in the aforegoing phases are evaluated. The key requirements and determination of critical requirements, which impact the system cost and complexity directly, are revisited. For instance, a key requirement would be altitude, and the critical requirement would be coverage; or payload aperture would be a key requirement and resolution being the critical requirement. The relation between all these requirements should be understood, and the cost they impose on the comprehensive mission objectives be considered (Larson & Wertz, 2005:4).

Step 8: Evaluate mission utility

Mission utility looks at how well both the comprehensive objectives and the requirements are met with reference to cost or critical system design options.

Step 9: Define mission concept (baseline)

One or more baseline designs are selected, based on the evaluation of alternative designs. The baseline system design meets the majority or all of the mission objectives and is used to measure progress and offers an early milestone.

Step 10: Define system requirements

The broad mission objectives and constraints are translated into an accurately defined system requirement definition necessary for implementation. For example, it is crucial for the mission to accomplish communication at a minimum elevation angle with reference to the horizon. (In this work, link budgets are calculated for a minimum elevation of 5° above the horizon.)

Step 11: Allocate requirements to system elements

The final space mission components are allocated numerical requirements. The quality of the SMAD process, design and resource allocation are determined by the final list of requirements (Larson & Wertz, 2005:5).

The following section is a discussion of the communications systems and constellation design. For a low bit rate constellation network, these are key design drivers of the solution.

2.4 SATELLITE COMMUNICATIONS

In general, amateur radio frequency bands are used for CubeSat communications. The ground sensors “uplink” their data to the next visible satellite. The data is then transmitted to the ground station when the satellite is in view, in a typical store and forward configuration.

A brief overview of concepts related to amateur communications systems is described in this section.

2.4.1 Link budget

Signal transmission between a transmitter and receiver module is referred to as a communications link. With reference to a satellite and a ground station there are both *uplink* and *downlink* communications; *uplink* referring to a transmitter being located at the ground station and the receiver on the satellite.

Signal strength and system noise are the primary system parameters influencing the performance of the communications link. To account for signal strength and noise is a fundamental part of communications system design and is referred to as determining the *link budget*. In the link budget, a *link margin* determines the performance of the link.

In this section, the basic concepts and components of link budgets are reviewed. The calculation of the link margin is also discussed.

Antenna Gain

Antenna gain is a measure of how much power is transmitted in a certain direction as compared to an omni-directional antenna with the same input power. For aperture antennas the antenna gain G is given by (Pozar, 2005:639-641):

$$G = \eta(\pi D/\lambda)^2 \tag{2.1}$$

Where

D : Antenna diameter;

η : Efficiency of the antenna; and

$\lambda = c/f$ is the wavelength of the RF signal with frequency *f*.

The gain of an omni-directional antenna is 0 dBi, which means it radiates in all directions the same. A directive antenna will have *G* > 0 because it radiates more power in a certain direction than the omni-directional antenna.

Aperture antennas require very big cross-sectional areas at UHF and VHF, which make them impractical to implement on nanosatellites. Even on the ground they are not used. Wire antennas are generally used at these frequencies, for example the half-wave dipole antenna. The gain of the dipole antenna is 2.15 dBi (Balanis, 2005:183).

Antenna gain is inversely proportional to the antenna beamwidth. High antenna gain comes at the expense of having a small beamwidth, resulting in a requirement of accurate antenna pointing.

Effective Isotropic Radiated Power

The *effective isotropic radiated power* (*EIRP*) of a transmitter is the equivalent power transmitted through an ideal isotropic antenna to produce the same amount of power at the receiving end as the actual transmitter with a directional antenna (Pozar, 2005:648). *EIRP* is calculated as:

$$EIRP = P_{tx} + G_{tx} \text{ [dB]} \tag{2.2}$$

Where

P_{tx} : Transmitter power, in dBW; and

G_{tx} : Gain of transmit antenna, in dBi.

Antenna Noise Temperature

Taking account of noise in communication systems is done in terms of the equivalent temperature of a body (a resistor) that would create similar amounts of noise over the relevant range of frequencies. This is referred to as the *noise temperature*. Thermal effects are the main sources of natural noise. An antenna on a satellite pointing towards Earth would pick up significant noise from thermal and man-made sources. A ground station antenna pointing up into cold space will pick up lower noise levels. Balanis (2005:106) states that the *brightness temperature* at which the different sources emit, is intercepted by antennas and it appears at their terminals as an *antenna temperature*. The combined temperature produced by the brightness emitted from external sources captured at the antenna and the self-generated antenna thermal noise is the equivalent temperature, referred to as the *antenna noise temperature* (Pozar, 2005:644).

Satellites in low Earth orbit pass over the ground station. The movement of the satellite has to be tracked by the ground station antenna. Thus, the elevation angle of the antenna also varies with this movement (Cakaj *et al.*, 2011:2). The background temperature that the antenna points to, referred to as the sky temperature, versus frequency and elevation angle is depicted in Figure 2.5. Lowest noise occurs in the frequency range of 1 to 12 GHz. The sky temperature rises rapidly as the frequency decreases below 400 MHz, and the curve continues the rapid rise at the same slope for lower frequencies (Milligan, 2005:31), irrespective of inclination. It is evident that when the satellite is directly overhead, the antenna temperature is the lowest for frequencies above 400 MHz. At VHF and UHF it can be assumed that the antenna temperature is independent of inclination.

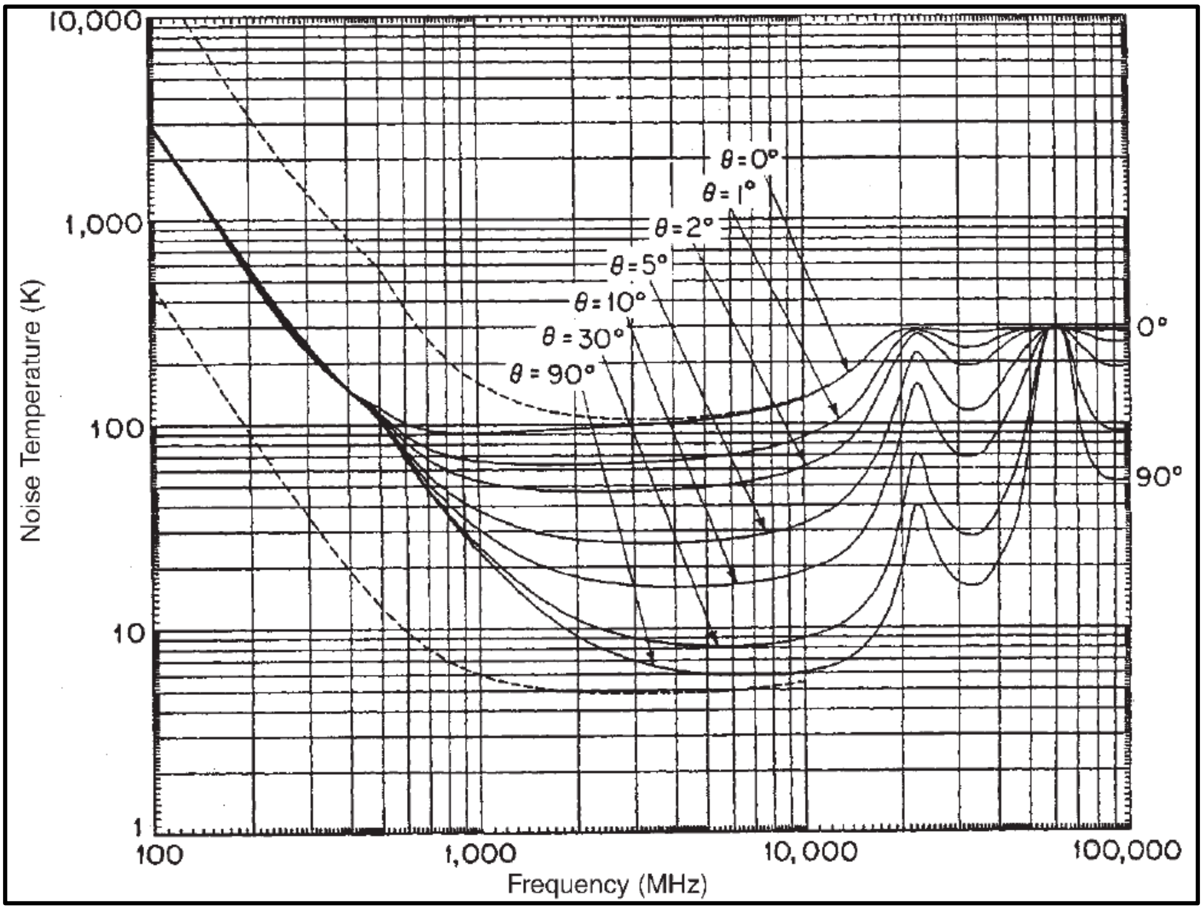

Figure 2.5: Antenna sky temperature for an antenna located on the ground as a function of frequency for different beam elevation angles

(From Milligan, 2005:31)

System Noise

From the perspective of the radio receiver, the overall system noise temperature T_s is a combination of the noise temperature of the antenna plus the noise temperature of the cascaded transmission line connecting the antenna with the receiver, and the receiver itself. This noise temperature of both the transmission line and receiver is defined at the antenna terminals as (Pozar, 2005:653):

$$T_s = \eta_{rad} T_b + (1 - \eta_{rad}) T_p + (L_T - 1) T_p + L_T T_{REC} \quad [\text{K}] \qquad (2.3)$$

Where

η_{rad} : Radiation efficiency of the antenna;

T_b : Equivalent brightness temperature of the background seen by the antenna beam, in K (such as given in Figure 2.5);

T_p : Physical temperature of the antenna, in K;

L_T : Losses in the transmission line connecting the antenna to receiver, converted to linear units; and

T_{REC} : Equivalent noise temperature of the receiver, in K.

Take note that the noise temperature of the system is dependent on where the antenna is pointing as well as the noise contribution of the receiver electronics.

Figure of Merit

The ratio of the antenna gain to the station's equivalent noise temperature at the receiving frequency gives the Figure of Merit G/T (measured in dBK) of the receiver (Orfanidis, 2008:9):

$$G/T = G_{rx} - T_s \text{ [dBK]} \tag{2.4}$$

Where

G_{rx} : Gain of the receive antenna, in dBi; and

T_s : System noise temperature, in dBK.

Signal Losses

Several mechanisms contribute to the total signal loss L in the link budget, for instance (Cowley & Glover, 2008:3):

$$L = FSL + AAL + TFL + AML + PL + IL \text{ [dB]} \tag{2.5}$$

Where, in units of dB

FSL : Free space loss;

AAL : Atmospheric absorption loss;

TFL, RFL : Tansmitter (or Receiver) feeder loss;

AML : Antenna alignment (pointing) loss;

PL : Polarisation loss; and

IL : Insertion loss.

Distance and frequency determine the free space loss:

$$FSL = 32.45 + 20log\,(R) + 20\log(f) \text{ [dB]} \tag{2.6}$$

Where

R : Link distance, in kilometre; and

f : Frequency, in MHz.

The free space loss is proportional to the square of both the frequency and link distance.

Link Budget Equation

The relation between the quantities described above is critical to designing a satellite communications system. This relation is referred to as the link budget and relates to all communications links. The *link equation* is given by (Cowley & Glover, 2008:4):

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L \text{ [dB]} \tag{2.7}$$

Where

P_{tx} : Power transmitted, in dBW;

G_{tx} : Gain of the transmit antenna, in dBi;

G_{rx} : Gain of the receive antenna, in dBi; and

L : Total link losses.

The energy received per bit equates to the energy received per second divided by the number of bits per second; for a digital system with a bit rate of r_b bps,

$$E_b = P_{rx}/r_b\ . \tag{2.8}$$

The energy per bit (E_b) is used because it allows for comparison between different modulation schemes.

The link performance can be determined by taking the ratio of the received energy per bit to system noise spectral density, E_b/N_o (Yuen, 2013:9):

$$E_b/N_o = P_{tx}(dBW) + G_{tx}(dBi) + G_{rx}(dBi) - L(dB) - 10log\, r_b - 10log\, k - 10log\, T_S \tag{2.9}$$

Where

N_0 : System noise spectral density = kT_s, in W/Hz;

k *:* Boltzmann’s constant; and

T_s : System noise temperature, in K.

Associating all relevant quantities results in (Cowley & Glover, 2008:4):

$$E_b/N_o = EIRP(dBW) + G/T(dBK) - L(dB) - 10log\, r_b - 10log\, k\ . \tag{2.10}$$

For a digital communications system, the E_b/N_o may be regarded as a signal-to-noise ratio. The bit error rate (BER) of a communications link that is based on a certain modulation scheme is related to the E_b/N_o as shown in Figure 2.6.

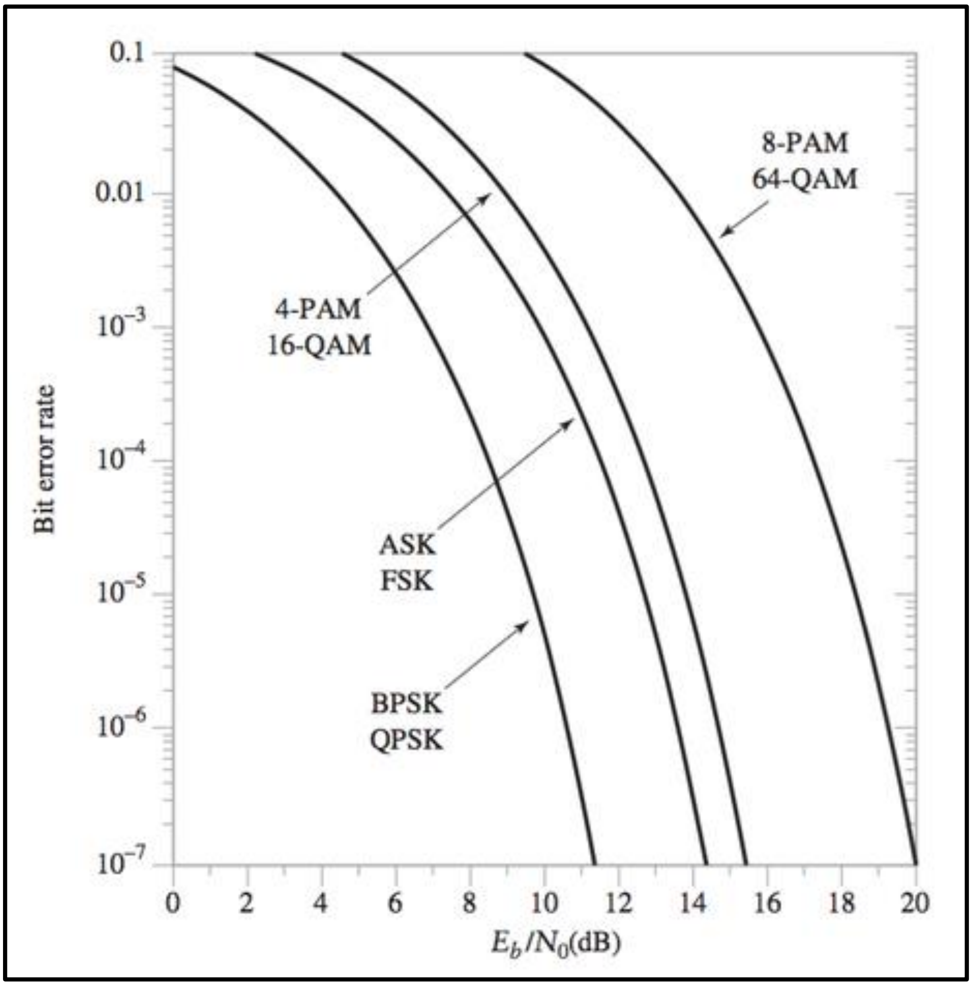

Figure 2.6: Bit Error Rate vs *E_b/N_o* for different modulation schemes

(From Sklar, 2001:218)

The E_b/N_o ratio is, therefore, particularly useful when comparing the BER performance of different modulation schemes. The communication links for this work are based on phase modulation. Gaussian Minimum Shift Keying (GMSK) for the uplink and Quadrature Phase Shift Keying (QPSK) for the downlink are assumed for link budget purposes, and in line with the available radios from CPUT. One reason is that these give superior BER with similar E_b/N_o than other modulation schemes. QPSK is implemented in the radios developed in-house at CPUT as it is a popular modulation scheme in amateur communications.

Link Margin

The margin between the actual E_b/N_o value and the desired E_b/N_o value to accomplish a certain bit error rate (BER) is referred to as the *link margin* (Cowley & Glover, 2008:4). Typical required margins for adequate communication links are greater than 3 dB.

2.4.2 Antennas

Antenna types typically used on CubeSats are reviewed, such as the deployable UHF and VHF dipoles shown in Figure 2.7. These are designed to provide omni-directional communication and compensates for a tumbling satellite (no steering of the beam is required).

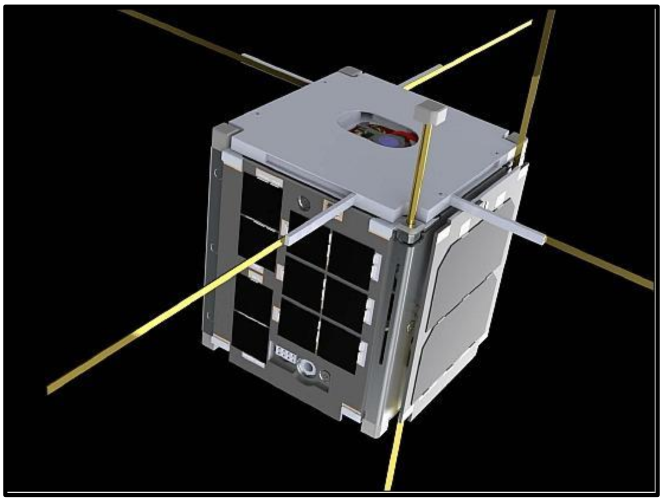

Figure 2.7: Physical implementation of deployable UHF and VHF antennas on ZACUBE-1

(From AMSAT-UK, n.d)

2.4.2.1 Dipole antenna

One of the most basic and commonly used antenna types is the dipole antenna. It has the omni-directional features required for most CubeSats that do not have advanced attitude determination and control system (ADCS) functionalities. It has a gain of about 1.64 (or G = 2.15 dBi). A simple dipole antenna utilises two elements, as shown in Figure 2.8, with a combined electrical length of $\lambda/2$ at the operating frequency. It has a radiation resistance of about 73 Ω, which is close to the characteristic impedance of popular transmission lines (50 Ω or 75 Ω). This simplifies impedance matching of the antenna to the transmission line at resonance (Iwami, 2010:31). A balun (balanced to unbalanced transformer) is required to drive the centre-fed, balanced antenna with a co-axial cable (Balanis, 2005:539).

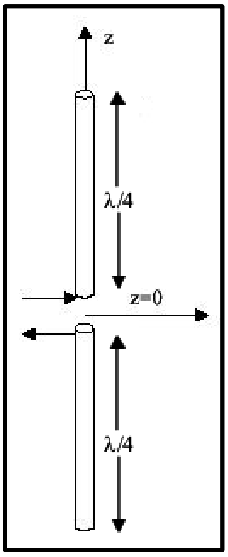

Figure 2.8: Half-wave dipole antenna

(Adapted from Kim, 2000:1)

The radiation pattern of a typical dipole antenna is shown in Figure 2.9.

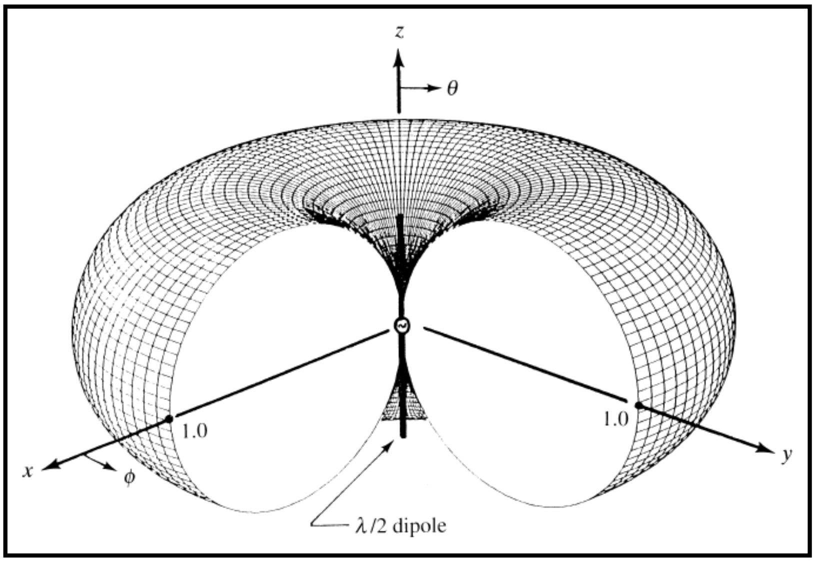

Figure 2.9: Three-dimensional radiation pattern of a half-wave dipole antenna

(Adapted from Balanis, 2005:183)

2.4.2.2 Monopole antenna

When a quarter-wave monopole antenna is positioned over a conducting ground plane and a source is applied at the base, as shown in Figure 2.10, it exhibits the same radiation pattern in the section above the ground plane as a half-wave dipole in free space. The gain of the quarter-wave monopole is twice that of the gain of the half-wave dipole

(Balanis, 2005:217), or 5.15 dB. The conducting plane can be substituted with the image of a quarter-wave monopole as depicted in Figure 2.10. However, the radiation of the monopole occurs only above the ground plane; hence, its radiation impedance is 36.5 Ω. Note that the monopole antenna can accommodate a single-ended signal feed and can be driven without a balun.

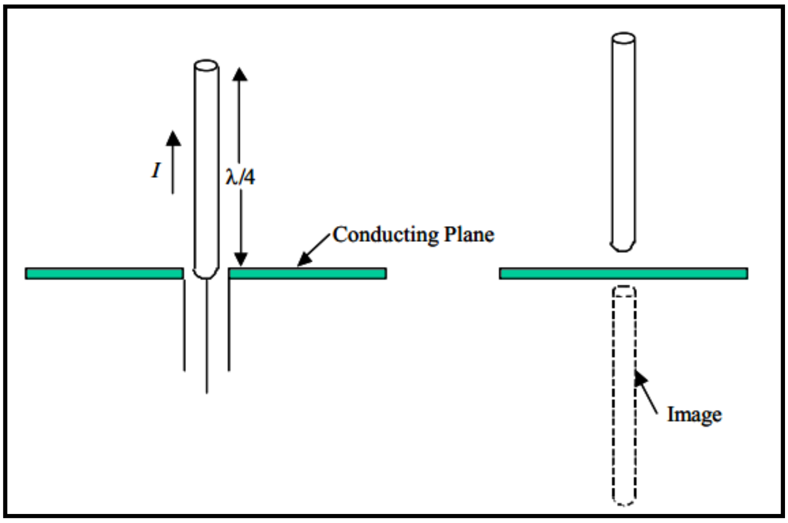

Figure 2.10: Quarter-wave monopole antenna and equivalent half-wave dipole antenna

(Adapted from Kim, 2000:3)

2.4.3 AX.25 protocol

The majority of CubeSats operate in the amateur radio frequency bands with equipment that utilises the AX.25 protocol for digital communications. The AX.25 protocol and framing format are typically used for sharing information, for example position and weather data, among radio amateurs.

A frame of AX.25 generally has three types of structures, namely (Beech *et al*., 1998:6):

- Information (I frame);
- Supervisory (S frame); and
- Unnumbered (U frame).

Each frame is made up of smaller groups, called *fields*. Figure 2.11 illustrates the construction of these fields in their frames. Assuming an overhead size of *n* bytes, the resulting maximum package size is 256 – *n* bytes (Bahr, 2016:9).

Flag	Address	Control	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	N*8 Bits	16 Bits	01111110

U and S frame construction.

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	8 Bits	N*8 Bits	16 Bits	01111110

Information frame construction.

Figure 2.11: Field types in AX.25 frame construction

(From Beech *et al*., 1998:6)

The different fields represent the following:

- Flag – start and end of packet;
- Address – sending station, receiving station;
- Control – type of frame, used for link supervision and retransmission;
- Info – user data or text;
- FCS – Frame Check Sequence error detection; and
- PID – Identifies the type of layer 3 protocol used, if it has been used.

The AX.25 protocol is commonly used in the amateur radio community although it has its limitations (Behrendt and Gottscheber, n.d.). It has gained popularity over the last few years due to its simple architecture and use of the Automatic Packet Reporting System (APRS). These two features have directed many suppliers of radios to develop cost-effective, low power transmitters that are suitable for university satellite projects.

Although the main limiting factor for these low power transmitters is the large amount of overhead that is inclusive of the AX.25 packet, they are still popular. The large amount of data overhead often limits the baud rate to 9600 bps. The data rates for AX.25 are usually either 1200 bps or 9600 bps (Gronstad, 2010:12). This data is specific to the usage of the AX.25 Transfer Frame. Another limitation is that the maximum size of the Information field is 256 bytes (Castello, 2012:9). The Information field contains the user data or text.

2.4.4 Amateur frequency bands

The growth in the amateur radio community has led to regulation by organisations, such as the Federal Communication Commission (FCC) and the International Amateur Radio Union (IARU), to ensure the fair use of these bands. OSCAR 1 was one of the first satellites to use amateur radio frequencies in space (Bilsing, n.d.). Almost every CubeSat operates in the amateur VHF (144 – 146 MHz) or UHF (430 – 440 MHz) bands. In this project, amateur radio frequencies will be assumed for the up- and downlinks since the research is limited to low bit rate in-situ monitoring.

Higher bit rate nanosatellite downlinks can be designed for the S-band frequency range. S-band transmitters used for CubeSat missions feature support for commercial (2.2 – 2.3 GHz) and amateur (2.4 – 2.45 GHz) bands (Clyde Space, 2017). A major advantage of higher frequencies for CubeSats is that the antenna aperture decreases, while maintaining similar gain. This advantage also applies to the ground system. The major disadvantage is that absorption by the atmosphere and path loss becomes greater at higher frequencies and therefore requires higher transmit power (NASA, 2016).

2.4.5 Ground sensor nodes

An overview of amateur sensor nodes and typical applications are given for the communications uplink of ground sensor data to satellites. Figure 2.12 shows the topology of a typical ground sensor node.

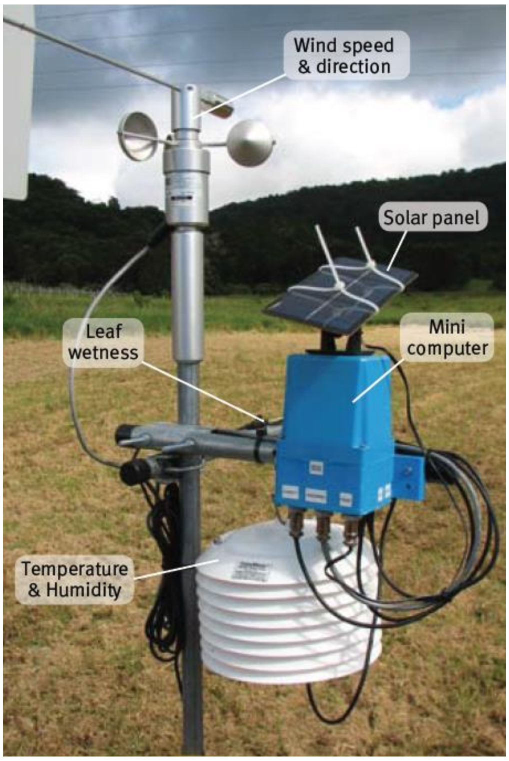

Figure 2.12: Topology of a ground sensor node used to measure wind speed and direction, leaf wetness, relative humidity and temperature

(From Springbrook Rescue Project, n.d.)

The ground sensor nodes can have several sensors plugged into them. Each node has its sensors activated and sampling the environment at suitable intervals. Figure 2.13 illustrates more examples of in-situ monitoring nodes and sensors.

Figure 2.13: Ground sensor nodes deployed and performing measurements

(From Springbrook Rescue Project, n.d.)

Types of low data rate services

Emergency services:

Deployment of sensor networks in target areas can be beneficial to gathering important information from the field, and provide support when other terrestrial systems are unavailable. Services providing information transfer can be used by rescue teams to assist victims affected by disastrous events. Satellite communications enhance the capability for the transmission of essential information. This improvement leads to better efforts and tasks performed by rescue teams responding to, and during, emergencies (Wang & Liu, 2011:657).

Border control:

Monitoring and control of countries' borders are provided through sensor networks that are strategically distributed for the prevention of illegal activities, such as smuggling (Sun *et al.*, 2011:469).

Environmental and atmospheric monitoring:

Environmental sensor networks can typically be used for (1) fluvial observation and flood warning using sensors measuring water temperature, conductivity, and level; (2)

measurement of soil and water contaminants with soil temperature sensors, soil CO_2 sensors and nitrate flux; and (3) habitat monitoring using sensors measuring air temperature, relative humidity, light levels, nutrient flux, river gauges, etc. (Hart & Martinez, 2006:180).

Figure 2.14 depicts typical examples of data buoys that measure and transmit autonomously to satellites. With advantages of relatively low operating cost and ease of deployment, reliable measurements of the atmosphere and conditions of the surface of the ocean are obtained.

Also, a study supported by NASA introduces a lightning detection method inside a hurricane, enabling the forecasting of the strength of approaching storms (NASA, 2007). Figure 2.15 shows the lightning sensor used for this measurement.

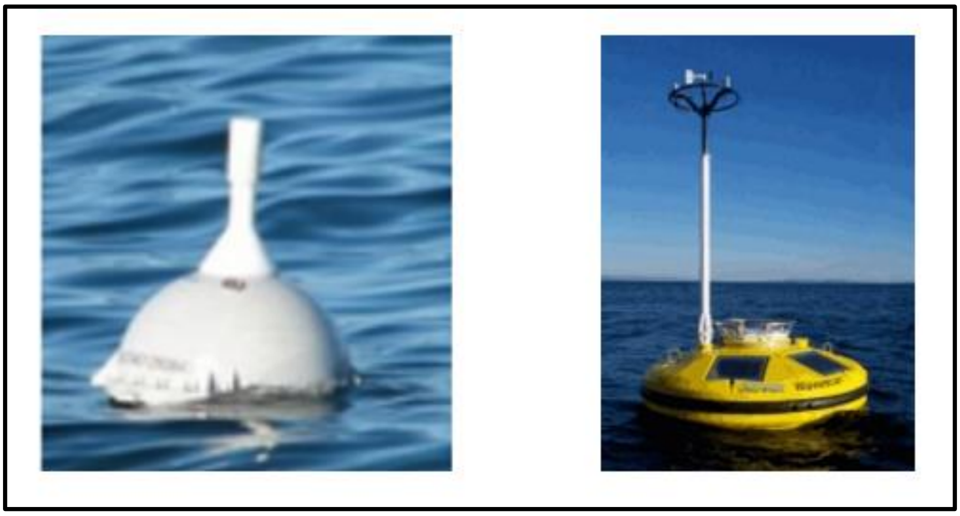

Figure 2.14: Drifting buoys for measurement of currents and wave buoys for measurement of frequency and size of wave energy to capture ocean dynamics on surface

(Adapted from Data Buoy Cooperation Panel, n.d)

Figure 2.15: Ground-based lightning sensor for detection of electromagnetic radiation from lightning

(Adapted from NASA, 2007)

2.4.6 Amateur radio ground stations

Ground stations provide telecommand, telemetry and control (TT&C) and data communications with the satellite. The ground station antennas installed at the Cape Peninsula University of Technology (CPUT) on the roof-top of the Gold Fields Electrical Engineering building are shown in Figure 2.16.

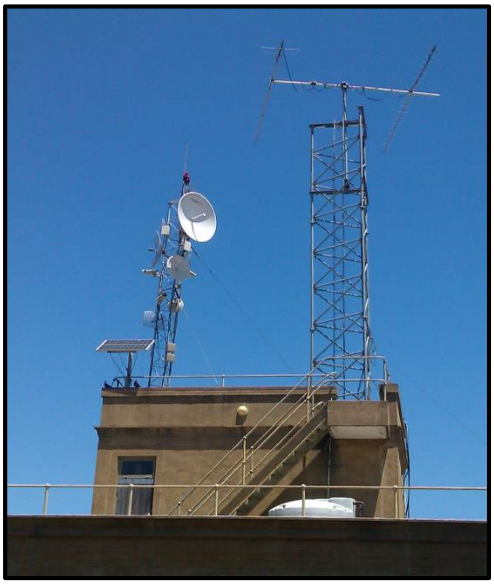

Figure 2.16: F'SATI ground station (to the right) with UHF and VHF yagi antennas to transmit/receive signals to/from satellite

The basic configuration of the ground station is depicted in Figure 2.17. It includes PCs with application software to perform interfacing, the Terminal Node Controller (TNC), which maintains management of the link (implementing the AX.25 protocol), the transmitter, receiver, and antenna system. The antenna system includes rotors for tracking.

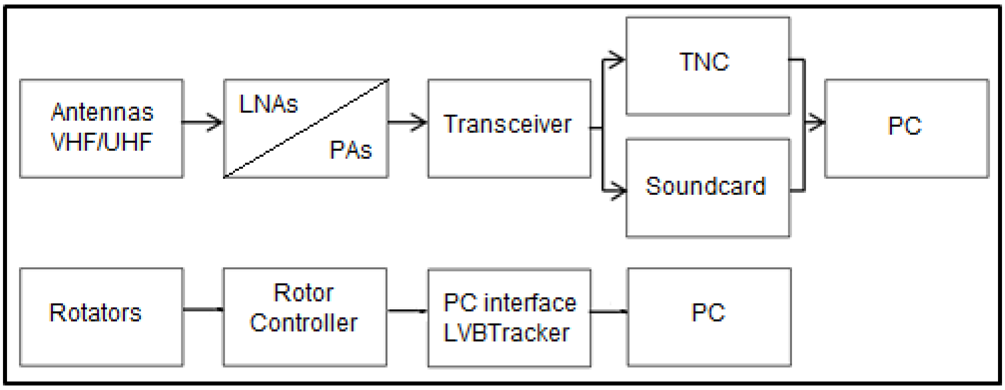

Figure 2.17: System overview of the F'SATI amateur ground station

TT&C

The function of spacecraft management is supported by the telemetry, tracking and command (TT&C) systems. These are vital for the successful overall operation of the satellite and are distinguished from communications management. The main functions of the TT&C systems are:

- Monitoring the performance of all satellite subsystems and transmitting the monitored data to the ground station;
- Supporting the determination of orbital parameters;
- Providing a source (radio beacon) to the ground stations for tracking; and
- Receiving commands from the ground station to perform various functions of the satellite.

The function of the telemetry subsystem is to monitor various spacecraft parameters, such as battery voltage and current, temperature and equipment status, and to transmit the measured values to the ground station for analysis and routine operational and failure diagnostic purposes. Typical telemetry data rates are quite low, in the range of about 100-150 bps.

The command subsystem receives commands transmitted from the ground station, verifies correct reception and executes these commands (Larson & Wertz, 2005:547).

Data

In the context of in-situ monitoring missions, the downlink operation transfers data acquired from a ground sensor network. The data is typically stored onboard the satellite until it passes over a ground station.

All data download operations take place within the time the satellite is visible to the ground station. This inevitably requires a higher bitrate communication link. The number of sensors, amount of data per sensor, and the number of satellites and ground stations impact on the required downlink bandwidth and data rate, and are therefore important design criteria. The advantages of more satellites and ground stations against cost are trade-offs.

Satellite Networked Open Ground Station:

The SatNOGS project (Satnogs, 2017) is a platform developed to create a network of ground stations for satellites, utilising free software and open source hardware. SatNOGS is optimised and built from easily accessible resources and tools. The objective of the project is the development of a stack of open technologies, which are based on open standards. This initiative will create a globally operated network via a software standard, making access to a global network of amateur ground stations possible. More access to satellites by their users would be obtained. This is similar to the older initiative of the Global Educational Network for Satellite Operations (GENSO) (European Space Agency, n.d.).

2.5 SATELLITE CONSTELLATION DESIGN

Large satellites are preferable for accommodating a larger number of instruments and when high power devices are required for a mission; yet, a constellation of small satellites with distributed functionality can perform complementary tasks with less risk.

Concepts that determine the characteristics of an Earth observation mission are often that of spatial and temporal resolution. *Spatial* resolution relates to the ability of the imager to observe small objects on the Earth’s surface. An increased *temporal* resolution is required if passing over a specific region of interest more often than is possible with a single satellite, is needed. The answer to this problem is to use constellations of satellites, where satellites are placed in a coordinated orbital framework to effectively reduce the revisit time. CubeSats are ideal for this purpose as their low-cost development allows many to be built and launched. Constellations also have redundancy inherently built into the mission, since spacecraft are flying independently. A constellation of satellites in three orbital planes is graphically illustrated in Figure 2.18.

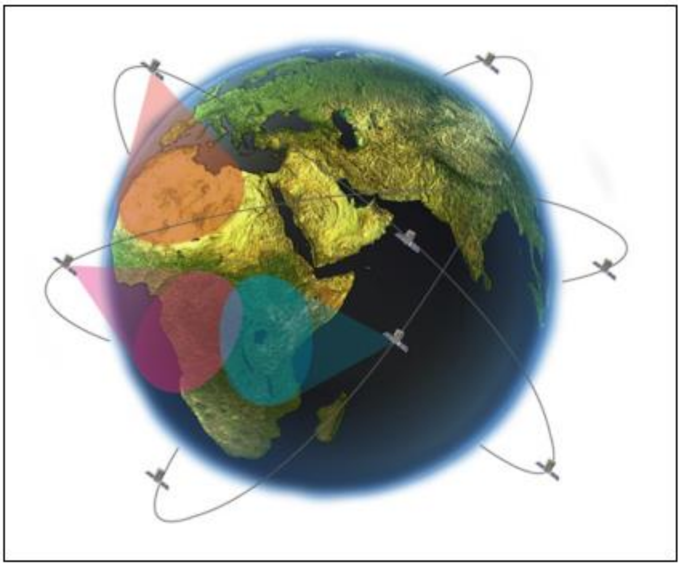

Figure 2.18: Constellation of satellites in three orbital planes

The *revisit* and *access* times are evidently important temporal parameters. Communication and navigation systems must usually be available at all times. A resource management satellite may require only weekly viewing of points within its area of interest. A surveillance satellite may require viewing certain seaports, for instance, every few hours.

Satellites operating in groups or constellations also improve the spatial coverage obtained by a single satellite. The optimisation of satellite constellations reduces mission cost through utilising as few satellites as possible to achieve the necessary coverage performance (Chobotov, 2002:411).

In designing a constellation, the following are considered: number of satellites, their relative positions, and how these positions change with time, both in the course of an orbit and over the lifetime of the constellation. A reasonable point of departure is considering constellations with all satellites in circular orbits at a common altitude and inclination. This means that the period, angular velocity, and node rotation rate will be the same for all of the satellites. A principal characteristic of any satellite constellation is the number of orbital planes in which the satellites reside. Symmetry in constellation structure requires the same number of satellites in each orbital plane (Larson & Wertz, 2005:188-190).

The *Walker delta* configuration is a satellite constellation design for similar circular orbits (Larson & Wertz, 2005:194). These orbits provide even coverage through a system of symmetrically separated satellites. Complete coverage is not guaranteed by this pattern but rather regular, repeating performance. All satellites are approximately at the same altitude and inclination and there are the same number of satellites in each plane. Usually a Walker constellation is written in the shorthand notation, *t/p/f,* to fully describe it, where *t* being the number of satellites, *p* being the number of planes, and *f* describing the relative spacing between satellites in adjacent planes. These values can then be used to calculate the nodal separation and planar phase difference as shown in Table 2.2, with PU defined as the pattern unit. Figure 2.19 illustrates a typical Walker delta pattern constellation.

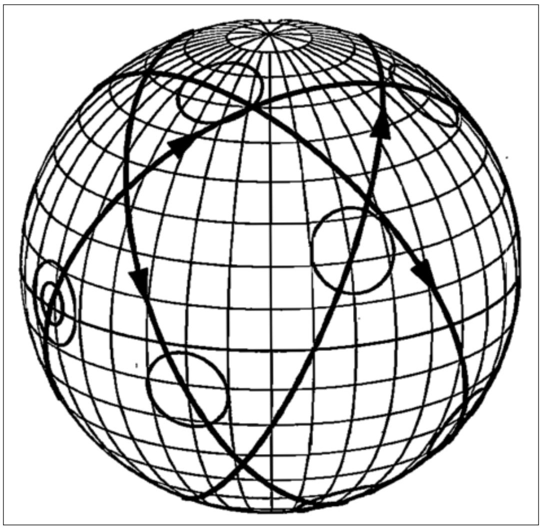

Figure 2.19: Walker delta pattern constellation

(From Larson & Wertz, 2005:195)

Table 2.2: Walker delta pattern definition

Parameter	Description
t	number of satellites
p	number of planes
f	relative spacing between planes (1 to *p* – 1)
s	*t/p* number of satellites per plane
PU	360°/*t* pattern unit
PU x s	node spacing
PU x p	in – plane spacing between satellites
PU x f	planar phase difference

(From Larson & Wertz, 2005:195)

Walker orbits attempt to provide balanced, continuous coverage of the Earth's surface given enough satellites and/or altitude. However, this may or may not meet the design goals, since constellation design is mission specific and global coverage may not be of interest to certain missions. If the main area of interest does not include the poles and is within 40° or 50° of the equator, the mission could be fulfilled with a single plane equatorial orbit with multiple satellites. If high latitudes are the regions of interest, then polar orbits would be advantageous.

Figure 2.20 shows additional constellation configurations (Larson & Wertz, 2005:194-196).

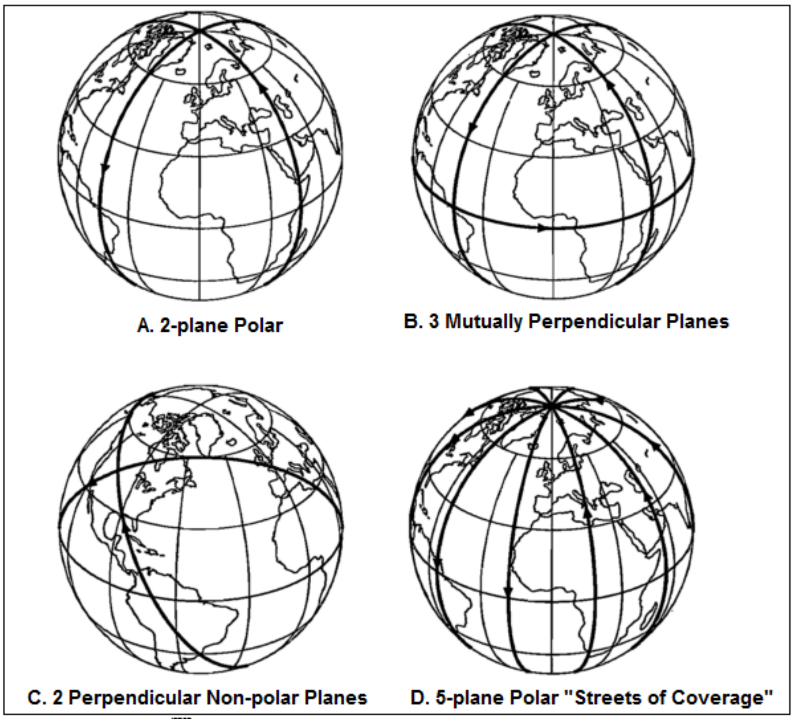

Figure 2.20: Satellite constellation configurations

(From Larson & Wertz, 2005:196)

2.6 SUMMARY

This chapter introduced nanosatellites, with a particular focus on the CubeSat standard and typical applications for this category of satellites. Steps in the SMAD process were presented, though not all are addressed in this work. This was followed by an overview of satellite communications theory and the principles governing communications between space and ground segments. Concepts that are relevant to amateur communications systems were presented. The chapter concluded with a brief overview of satellite constellation design. This is considered in more detail in the next chapter.

CHAPTER 3: CONSTELLATION ORBITAL DESIGN

3.1 INTRODUCTION

This chapter addresses the design of a CubeSat constellation by first considering a single CubeSat for in-situ monitoring missions and then gradually expanding it into a constellation of identical CubeSats. STK (Analytical Graphics Inc, n.d.), a comprehensive software application commonly used for satellite mission simulation, is utilised. The launching and orbital maintenance of the CubeSat constellation in space are beyond the scope of this project, and will not be considered.

3.2 SIMULATED ORBITAL DYNAMIC BEHAVIOUR

The approach here starts with the temporal performance analysis of one satellite with known orbital elements, followed by comparative simulated studies of two to twelve satellites in one, two and three orbital planes (maximum of 12 satellites in total). The proposed orbital design is primarily driven by the temporal behaviour of the constellation in terms of revisit and access times to geographic areas of interest across Africa where the ground sensors are located.

3.2.1 Orbital definition of single satellite

The movement of the satellite along its orbital trajectory is characterised by the six orbital parameters in Table 3.1. These are also referred to as *orbital elements*. The values of the elements are representative of typical CubeSat orbits and for coverage of the African continent. These values are motivated in the following paragraphs.

The apogee and perigee altitude is the same for circular orbits. An altitude of 500 km is selected to ensure that the satellites deorbit well within the 25 years guideline. The eccentricity of a circular orbit is 0; eccentricity being the parameter that describes the lengthening of an elliptical orbit.

The inclination angle is determined through simulating its effect on the access time for the geographic target areas and selecting an optimum value.

Table 3.1: Orbital parameters for LEO CubeSat constellation

Parameter	Description	Definition	Value
Altitude	Orbit size	Distance between the satellite and the Earth's surface	500 km
Eccentricity	Orbit shape	Measure of how circular an orbit is	0
Inclination	Orbital plane's tilt	Angle of the satellite orbit plane measured from Earth's equatorial plane	39°
RAAN	Orbital plane's rotation about the Earth	Angle, eastward, from the vernal equinox to the Earth's equatorial plane traveling northward (ascending)	45°
True anomaly	Satellite's location in its orbit	Angle from perigee to the satellite's position	0°

(Adapted from CASTOR, 2016)

The STK *Analyzer Module* (AGI, 2017) is an add-on module that integrates with the STK software to allow automated trade studies. The parametric tool enables a study to be carried out when only one parameter is varied.

In the initial study, the inclination angle of the satellite is variable. The total access time is determined for a range of 10 different inclination angles and presented in Figure 3.1. South Africa is the main target area for this exercise. The total access time over South Africa peaks at 45°, and drops with inclination angles above and below the optimum value of 45°.

Figures 3.2 to 3.4 illustrate the corresponding results for the other regions of interest; Algeria, Kenya and Nigeria.

NOTE: Considering that an inclination angle of 39°, as compared to 45°, decreases the total access time for South Africa by only 100 seconds, but increases the total daily access time to other regions by up to 1300 seconds (see Figures 3.35, 3.37 and 3.38), it has been selected as the preferred inclination angle in all subsequent simulations.

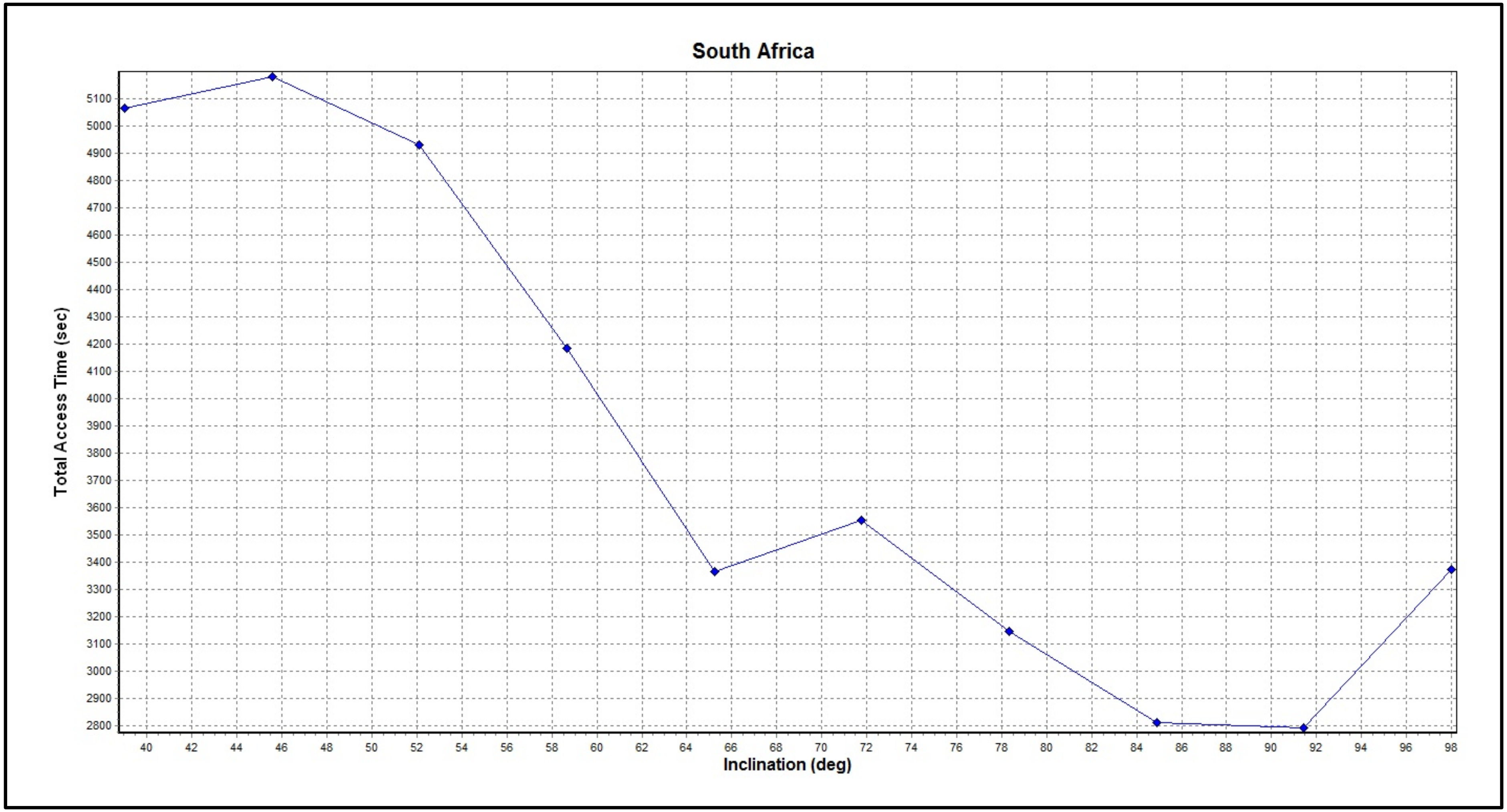

Figure 3.1: Daily simulated total access time for South Africa as a function of satellite orbit inclination angle

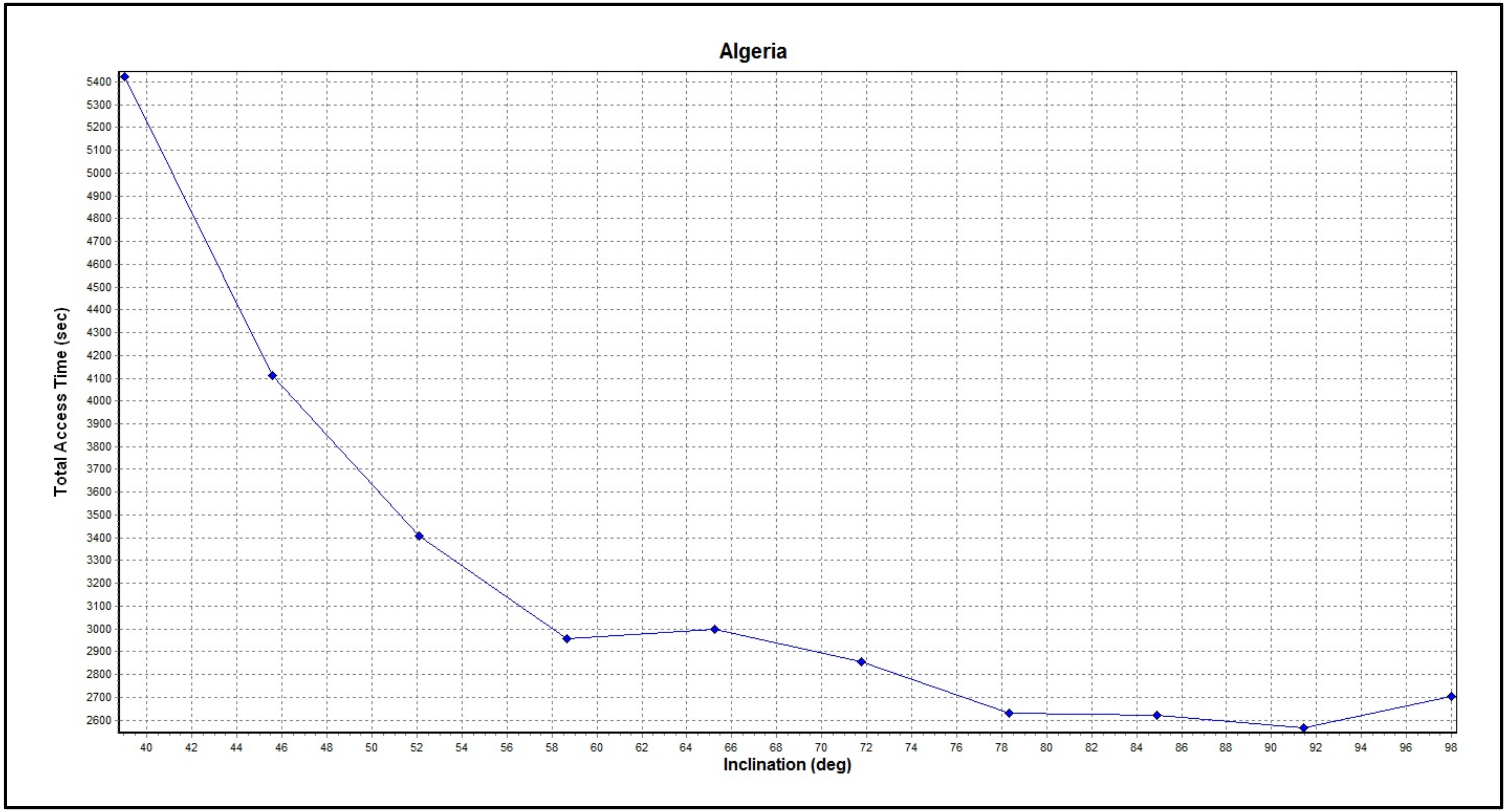

Figure 3.2: Daily simulated total access time for Algeria as a function of satellite orbit inclination angle

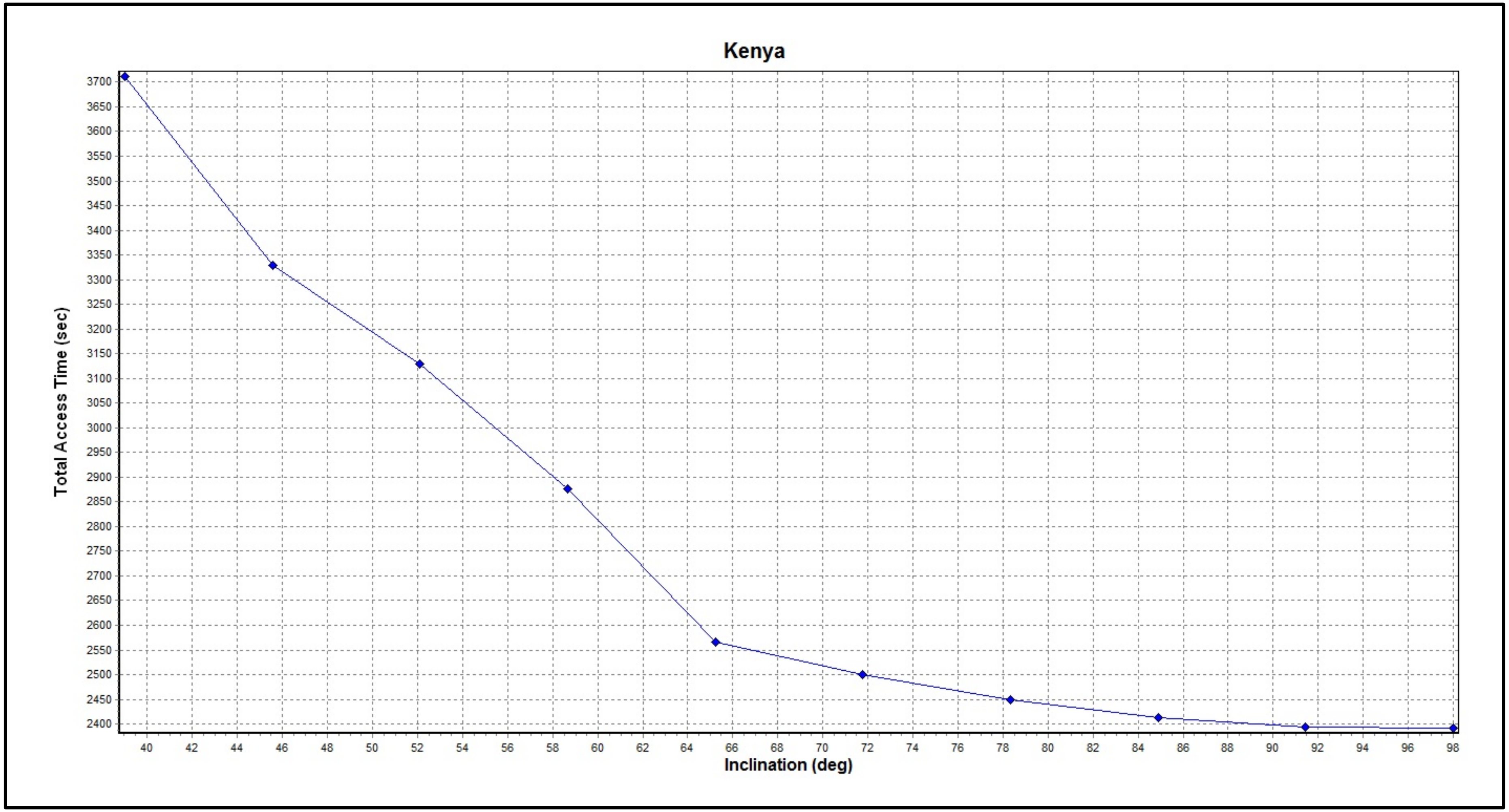

Figure 3.3: Daily simulated total access time for Kenya as a function of satellite orbit inclination angle

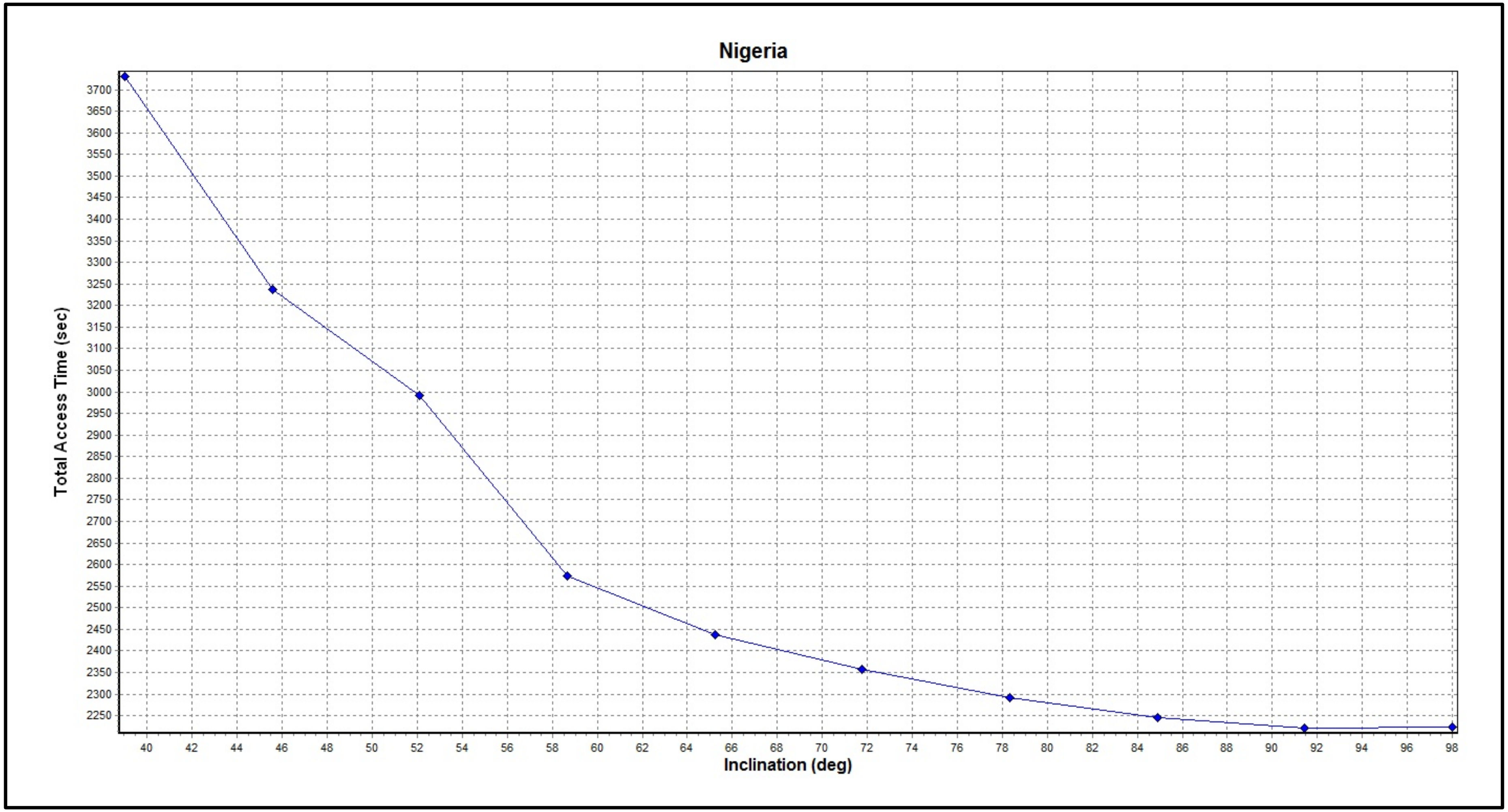

Figure 3.4: Daily simulated total access time for Nigeria as a function of satellite orbit inclination angle

3.2.2 Temporal performance of constellation

The Walker constellation of satellites is the chosen configuration, as already described in Chapter 2.

Figures 3.5 to 3.8 show typical simulated orbits. It can be seen that the footprint of the satellite has an effect on revisit and access times where the footprint size is determined by the orbital altitude.

The procedure involved in determining the optimum solution for the mission entails simulating a single satellite and then using it as benchmark for evaluating each possible constellation configuration as the number of satellites in each plane increases, while maintaining symmetry. Revisit and access times for the constellation configurations are calculated.

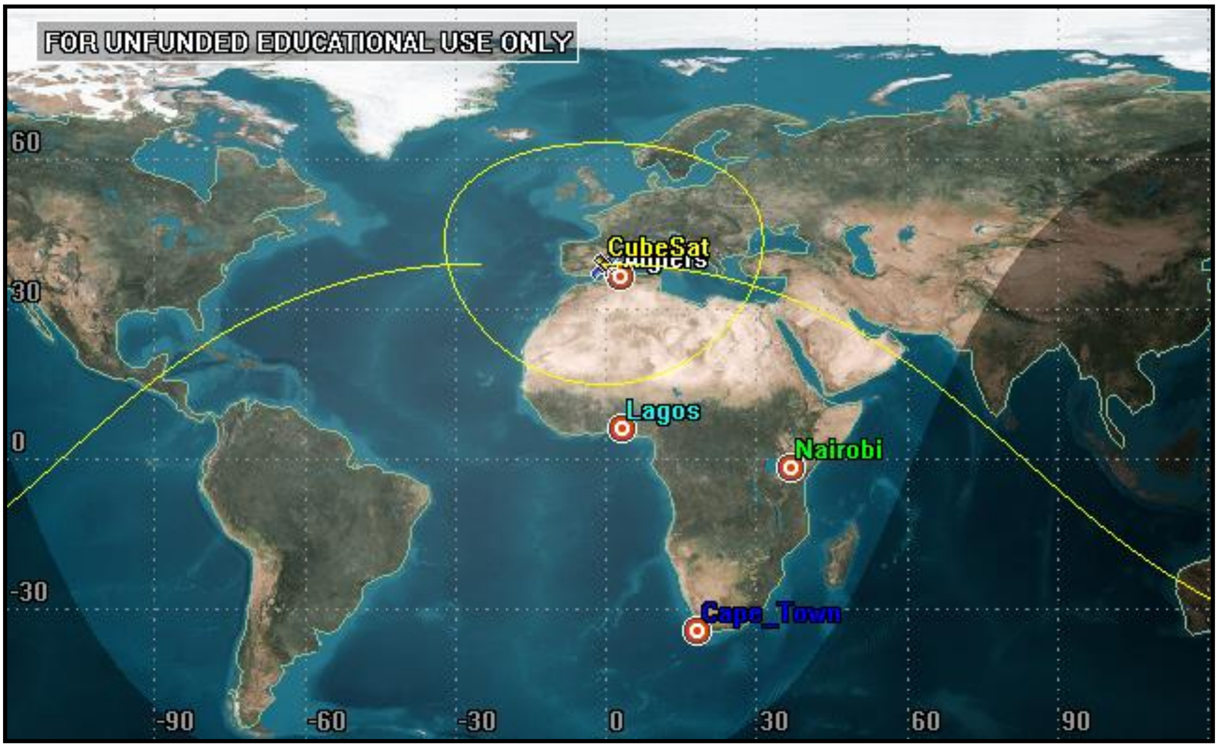

Figure 3.5: Simulated ground track and footprint of single satellite (one orbit shown)

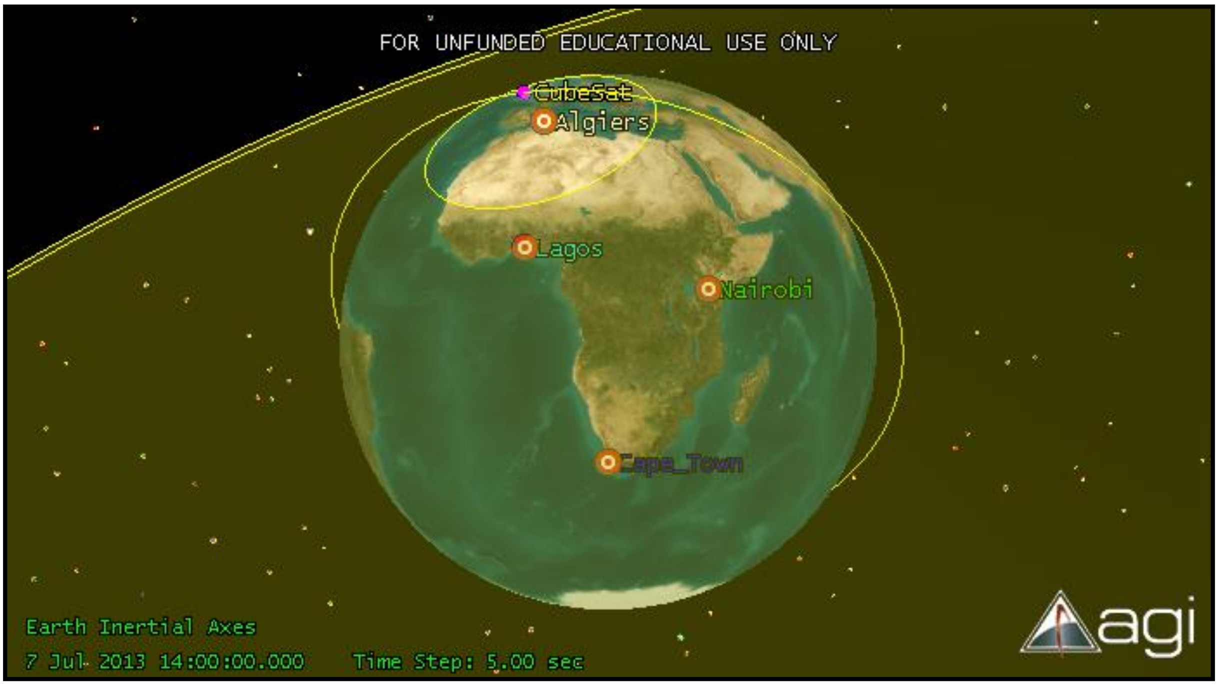

Figure 3.6: Three-dimensional view of simulated orbit in Figure 3.5

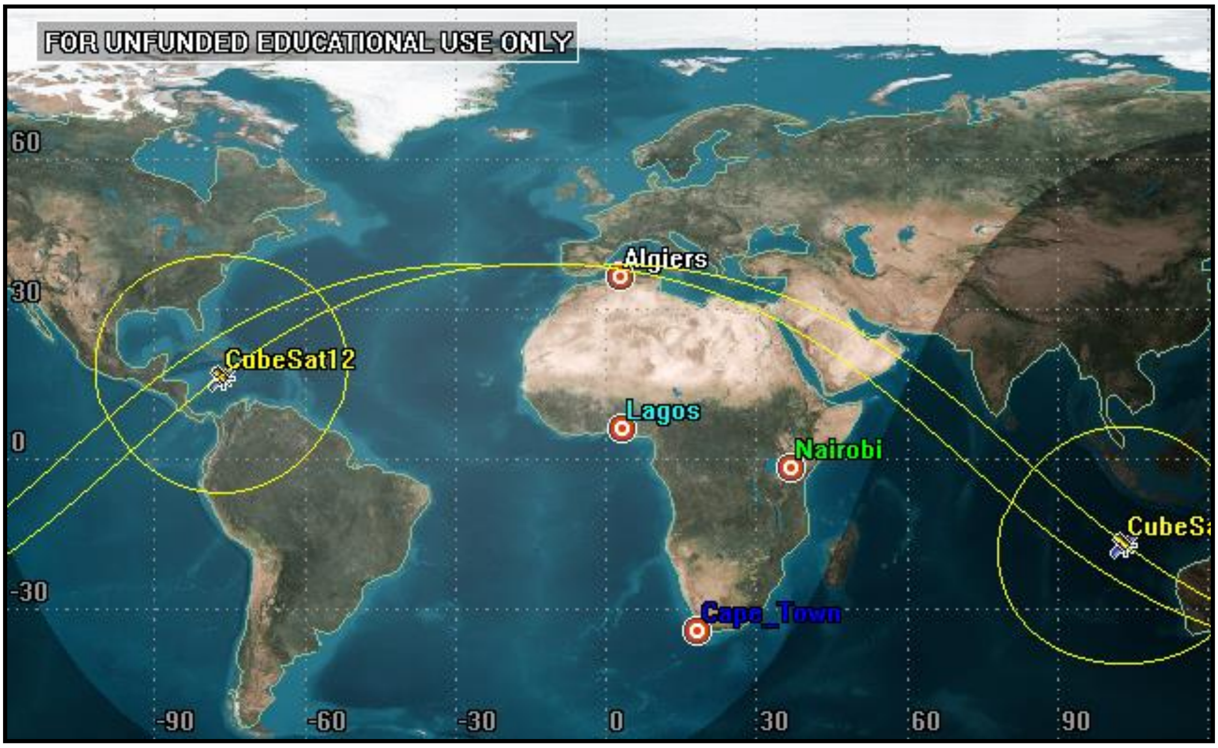

Figure 3.7: Simulated ground tracks and footprints of two satellites in one orbital plane (one orbit shown)

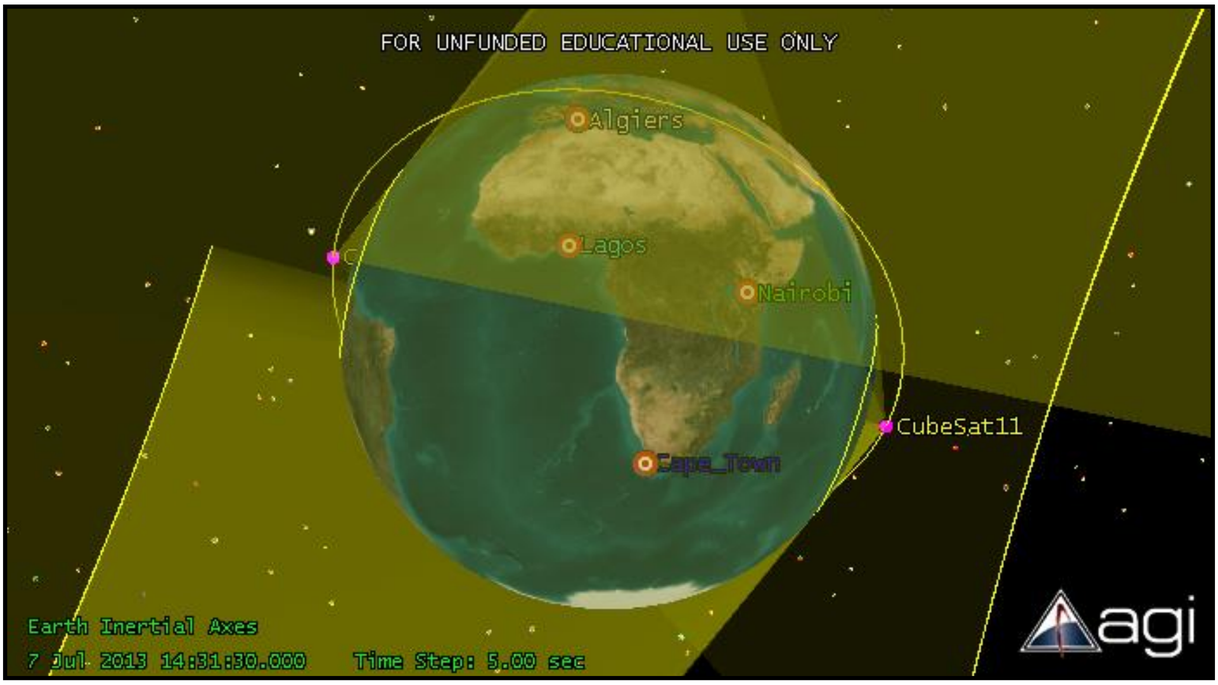

Figure 3.8: Three-dimensional view of simulated orbits in Figure 3.7

3.2.2.1 Access time

Figures 3.9 to 3.32 depict the simulated times of access between the satellite and the ground sensor networks in the different countries with their major cities Cape Town in South Africa, Nairobi in Kenya, Lagos in Nigeria, and Algiers in Algeria for all the orbital configurations during July 2013. The access intervals are symbolised by vertical segments of varying thickness, depending on the duration of each access window. It is assumed that the satellite establishes communications with the sensors when it is more than 5° above the horizon.

Simulated times of access will be presented for all combinations of the number of satellites in one, two and three orbital planes.

For clarification, the access times computed over a 24-hour period for subsequent passes over Cape Town are depicted by the horizontal lines in Figure 3.10. The vertical line annotations show the start time and stop time for the satellite access windows over the target areas. The horizontal line annotations show that there is access between the start time and stop time as shown in Figure 3.11. This represents the first window of access between the satellite and the South Africa target area for a single overpass.

- Single orbital plane

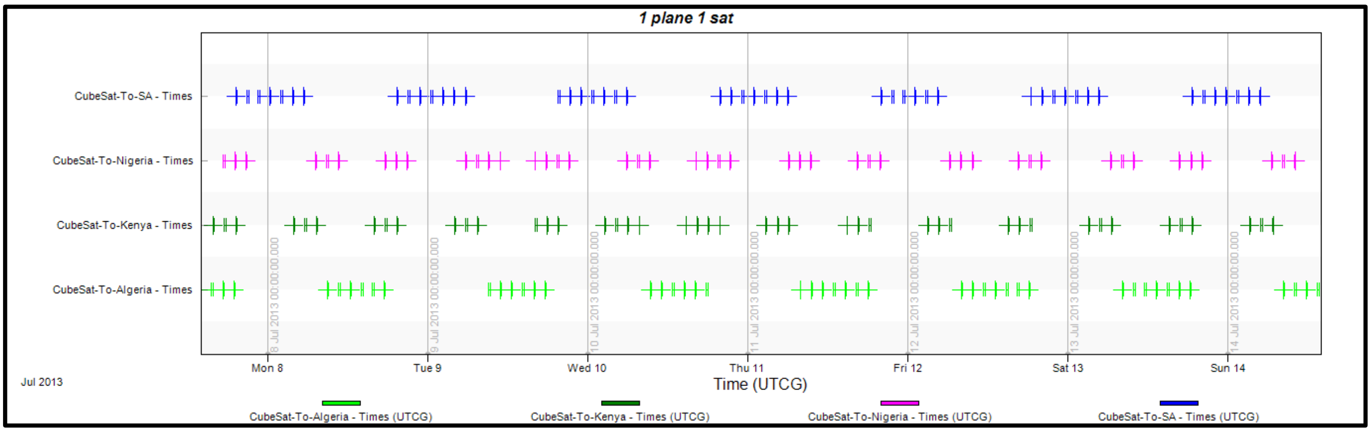

Figure 3.9: Simulated times of access between single satellite and target areas

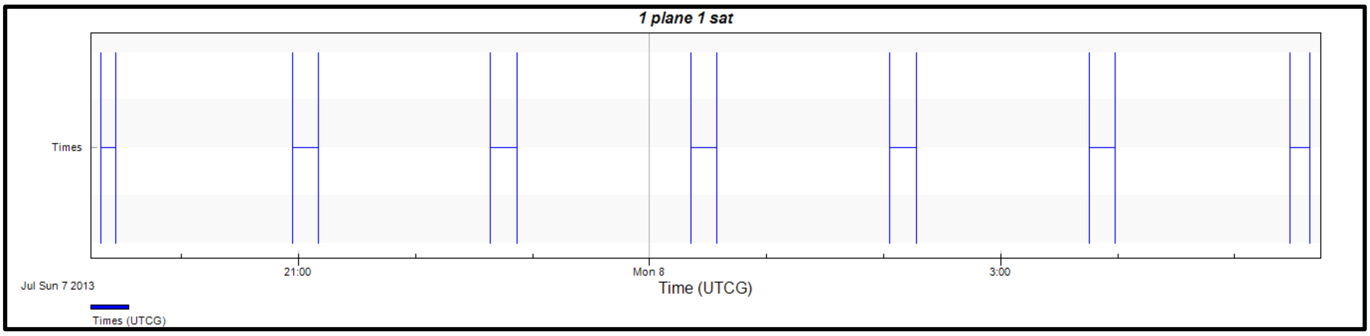

Figure 3.10: Simulated times of access between single satellite and South Africa in Figure 3.9

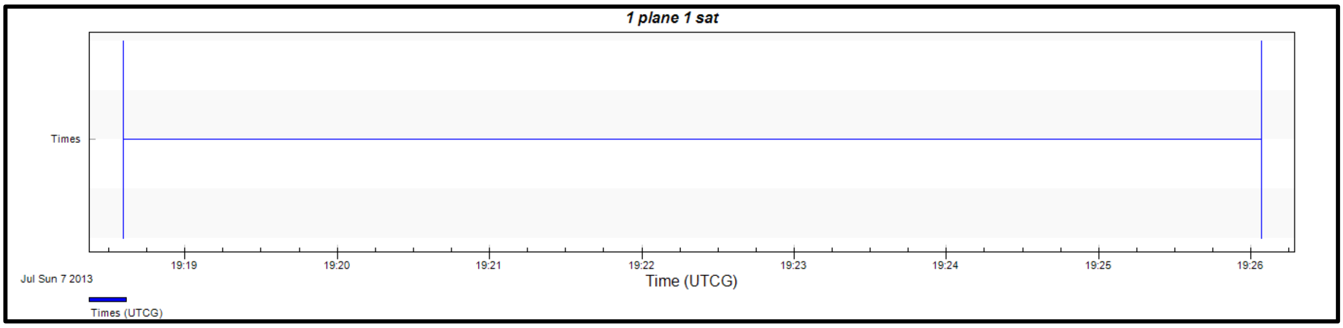

Figure 3.11: Simulated times of access between single satellite and South Africa in Figure 3.10

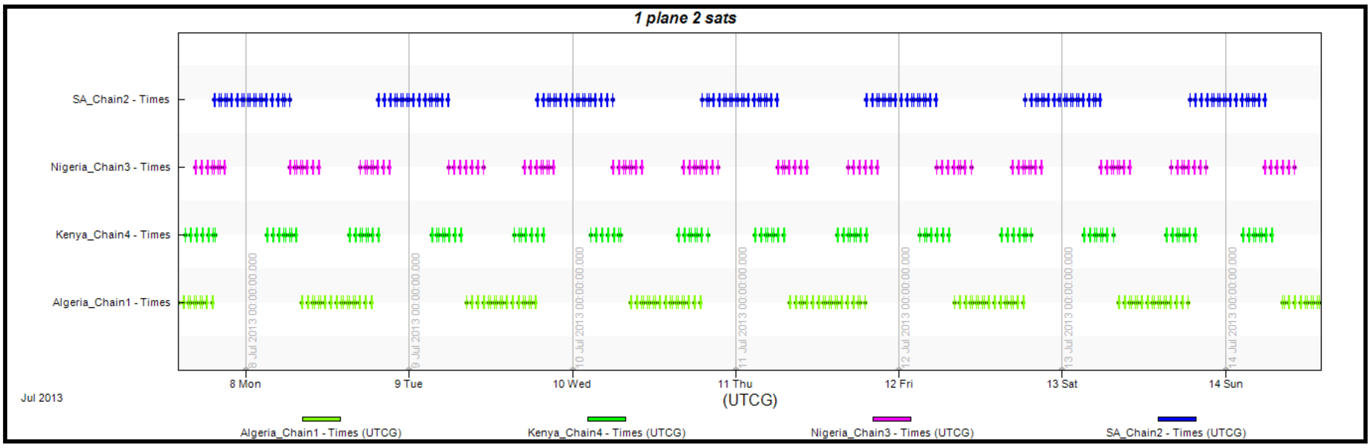

Figure 3.12: Simulated times of access between a constellation of two satellites in one orbital plane and the target areas

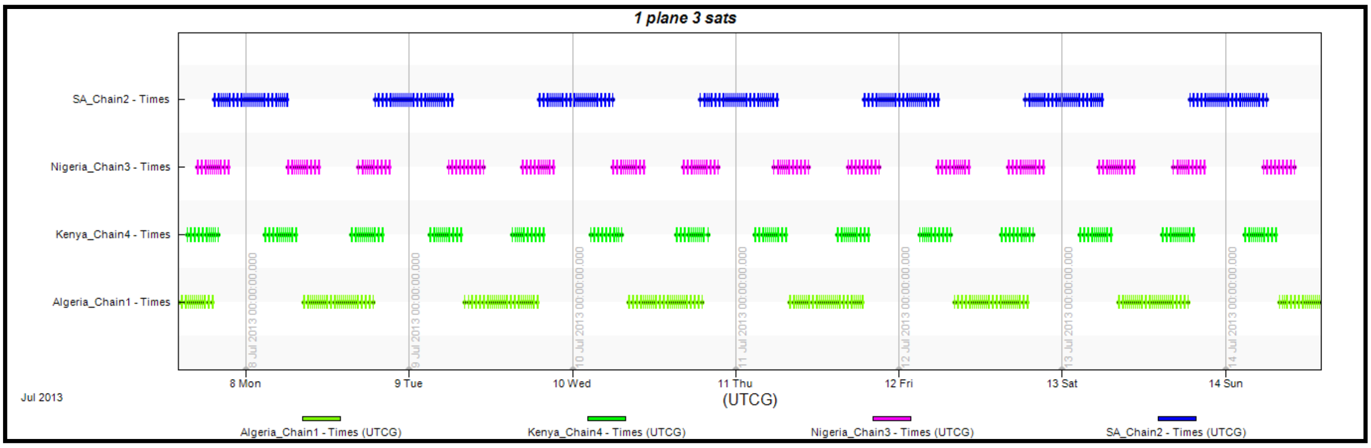

Figure 3.13: Simulated times of access between a constellation of three satellites in one orbital plane and the target areas

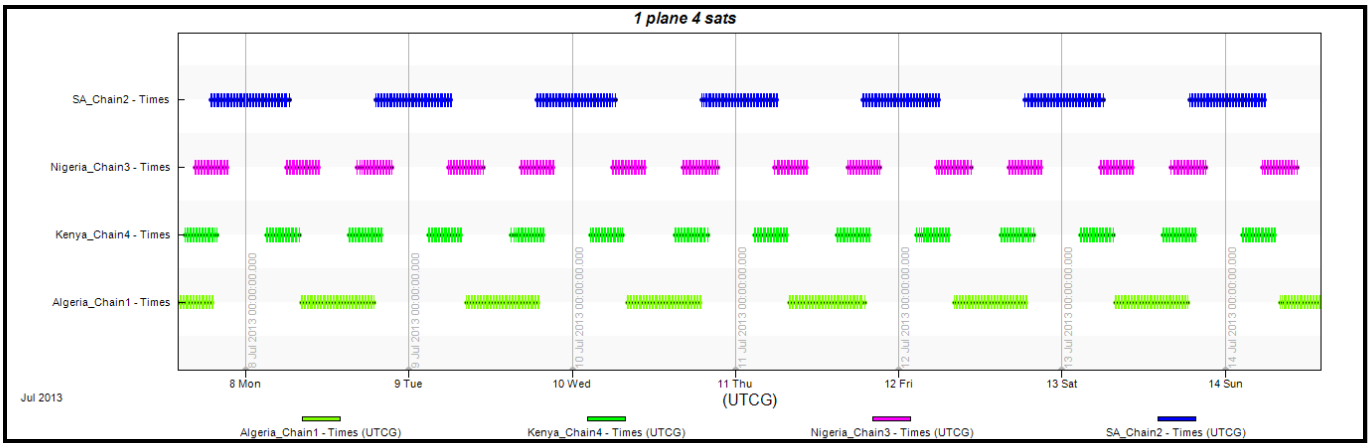

Figure 3.14: Simulated times of access between a constellation of four satellites in one orbital plane and the target areas

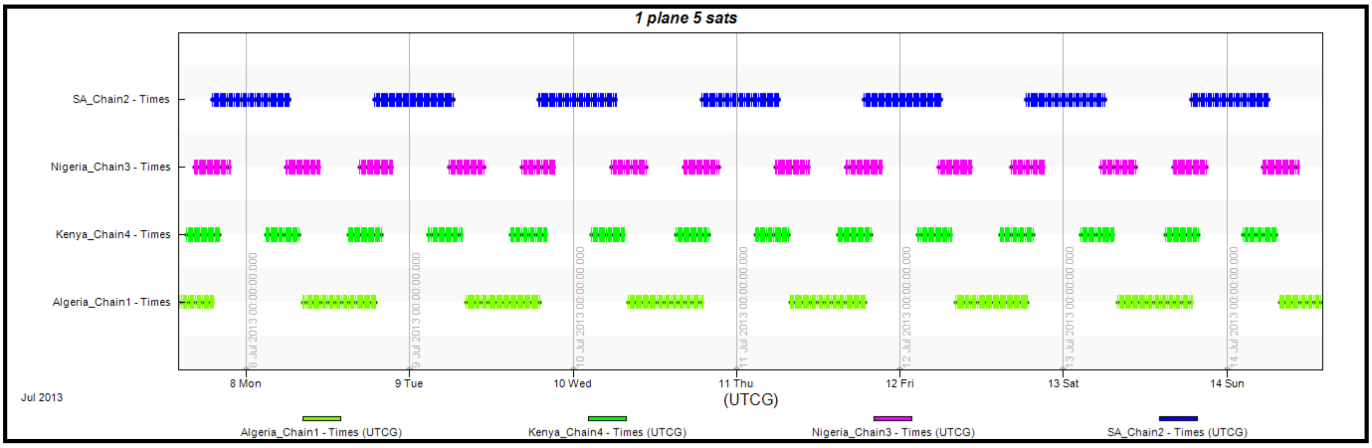

Figure 3.15: Simulated times of access between a constellation of five satellites in one orbital plane and the target areas

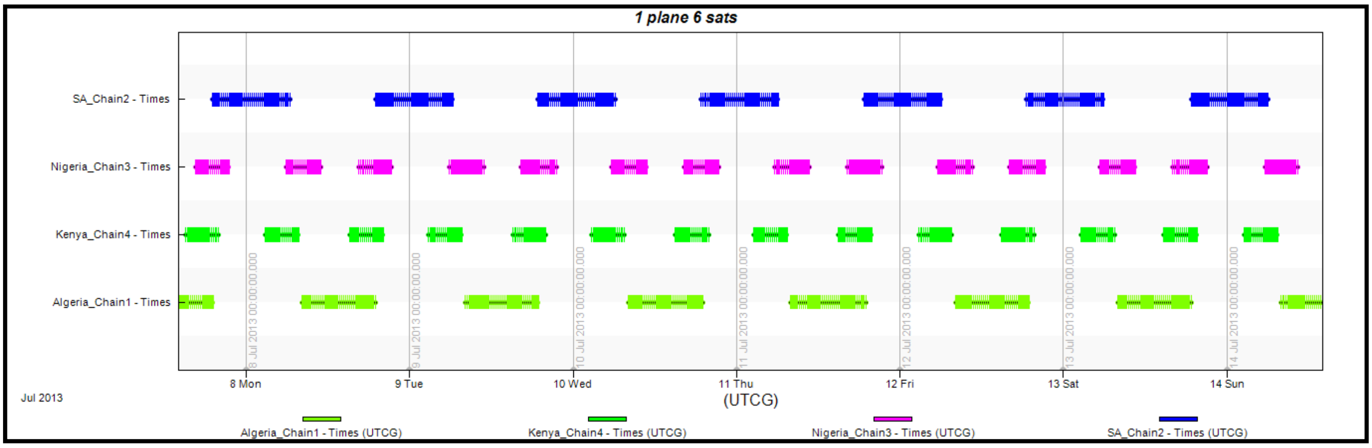

Figure 3.16: Simulated times of access between a constellation of six satellites in one orbital plane and the target areas

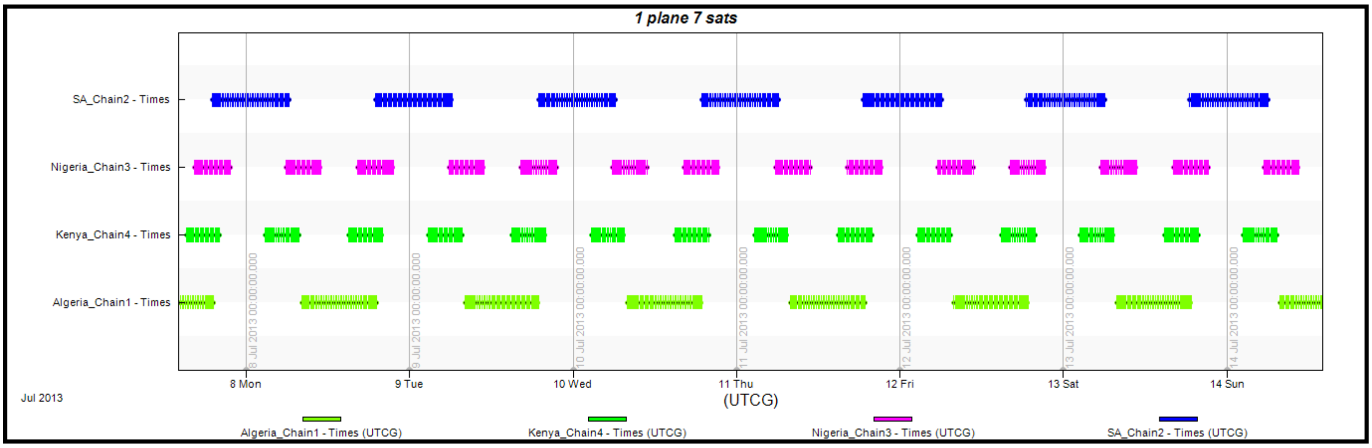

Figure 3.17: Simulated times of access between a constellation of seven satellites in one orbital plane and the target areas

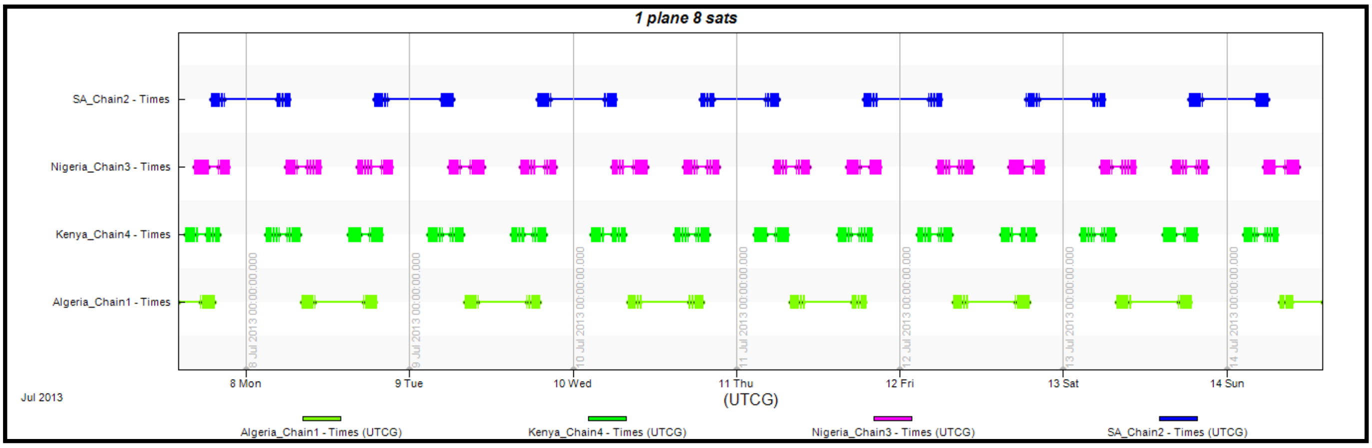

Figure 3.18: Simulated times of access between a constellation of eight satellites in one orbital plane and the target areas

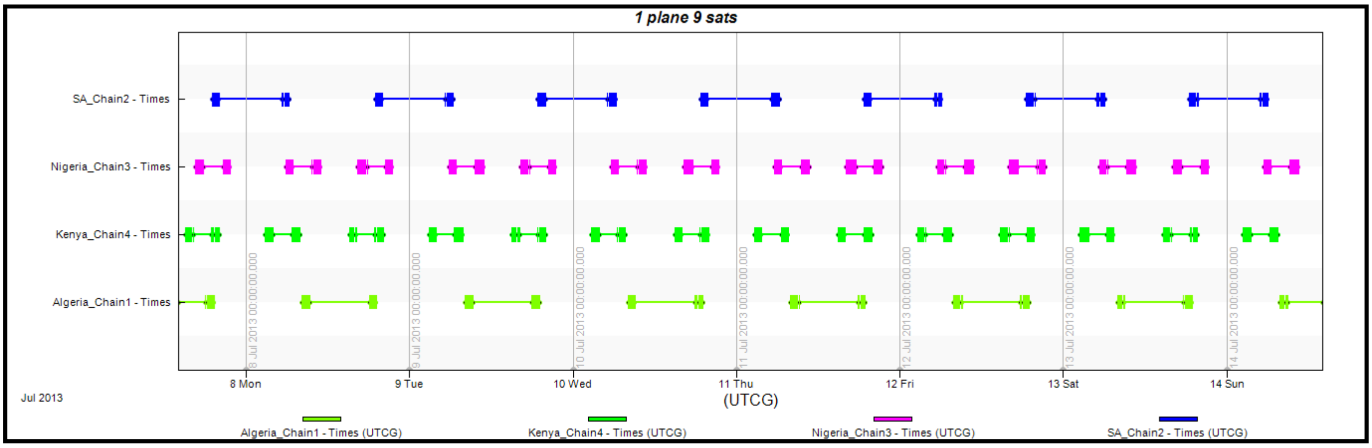

Figure 3.19: Simulated times of access between a constellation of nine satellites in one orbital plane and the target areas

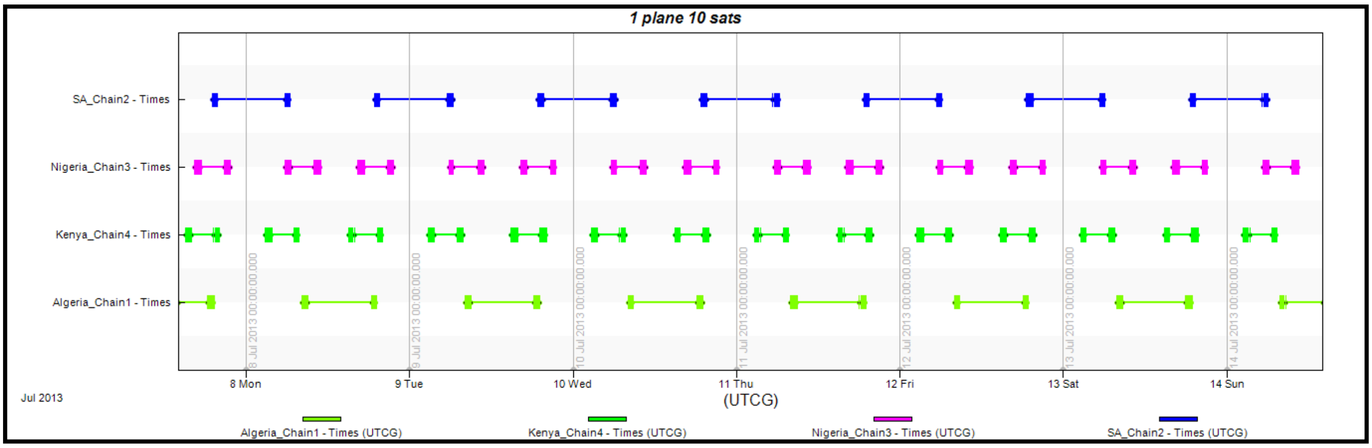

Figure 3.20: Simulated times of access between a constellation of ten satellites in one orbital plane and the target areas

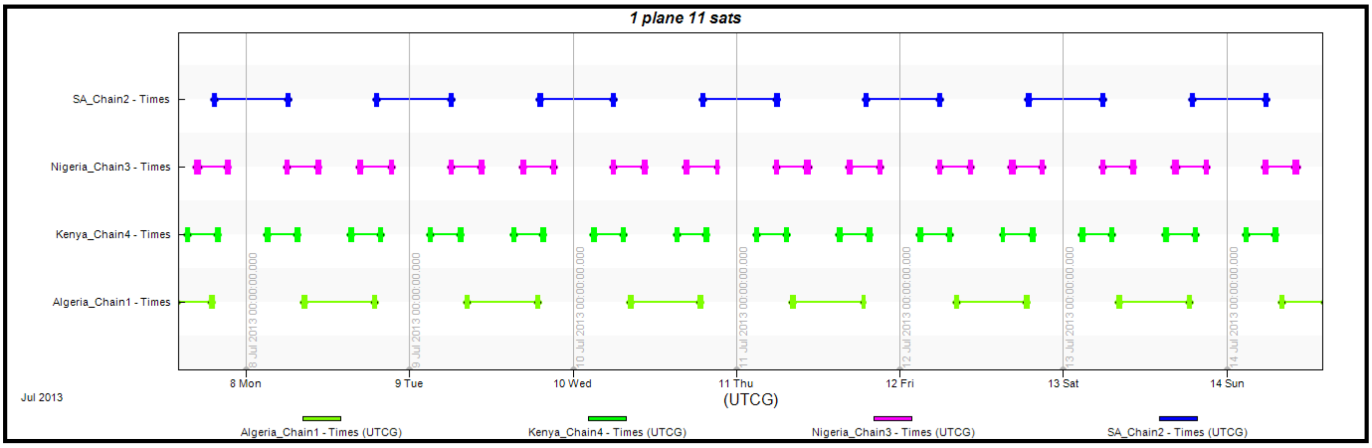

Figure 3.21: Simulated times of access between a constellation of eleven satellites in one orbital plane and the target areas

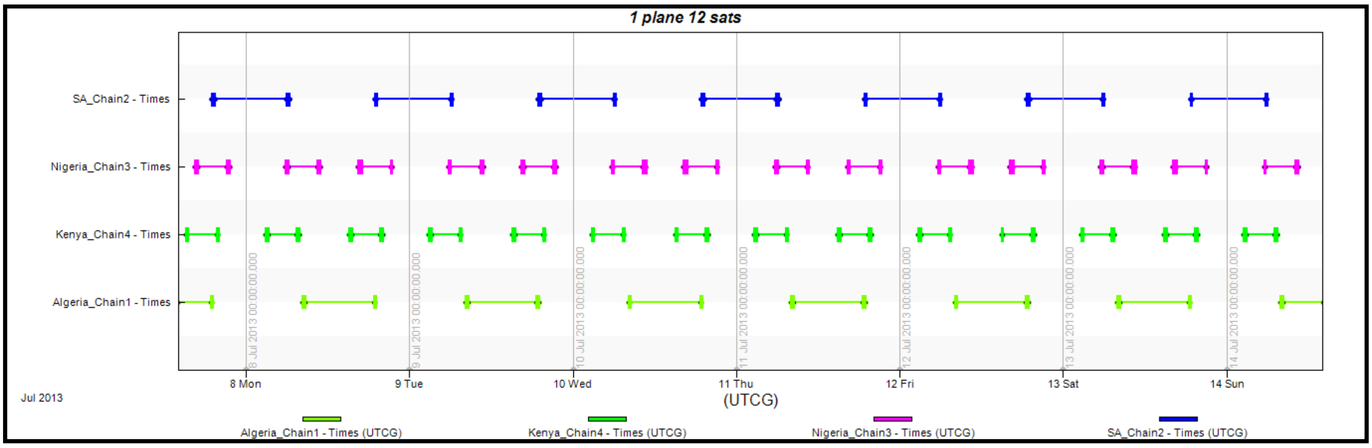

Figure 3.22: Simulated times of access between a constellation of twelve satellites in one orbital plane and the target areas

-Two orbital planes

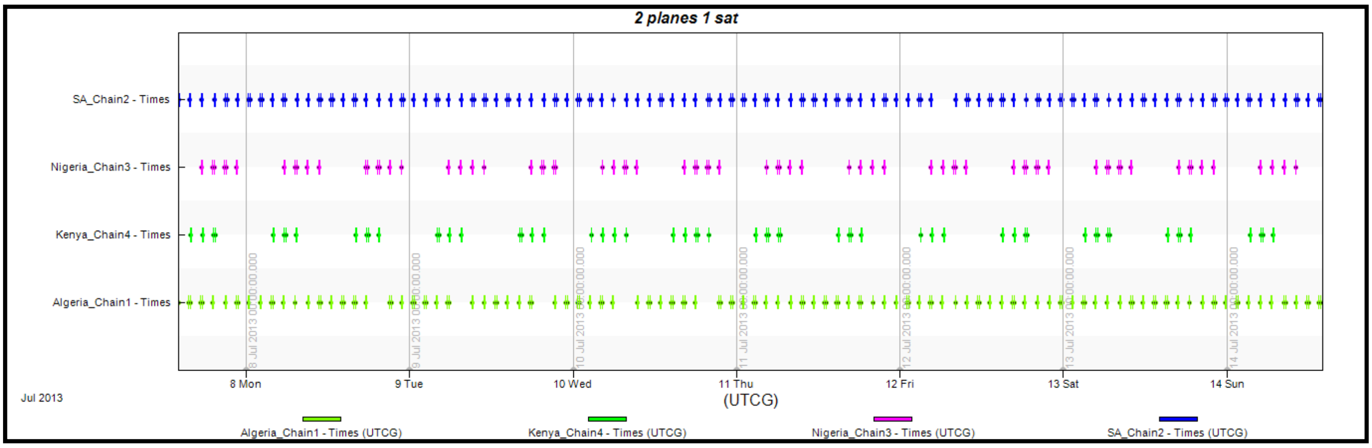

Figure 3.23: Simulated times of access between a constellation of one satellite in two orbital planes and the target areas

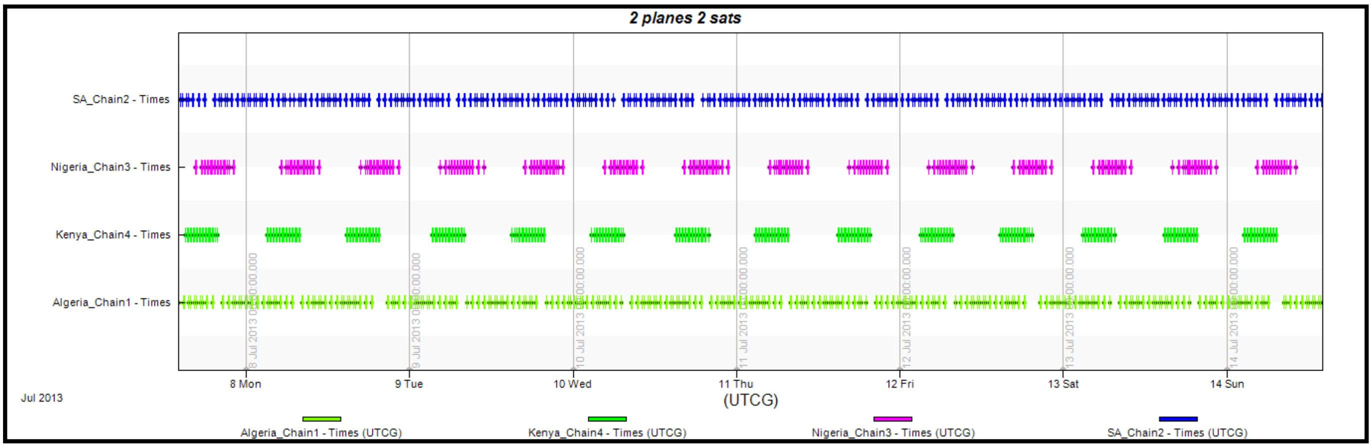

Figure 3.24: Simulated times of access between a constellation of two satellites in two orbital planes and the target areas

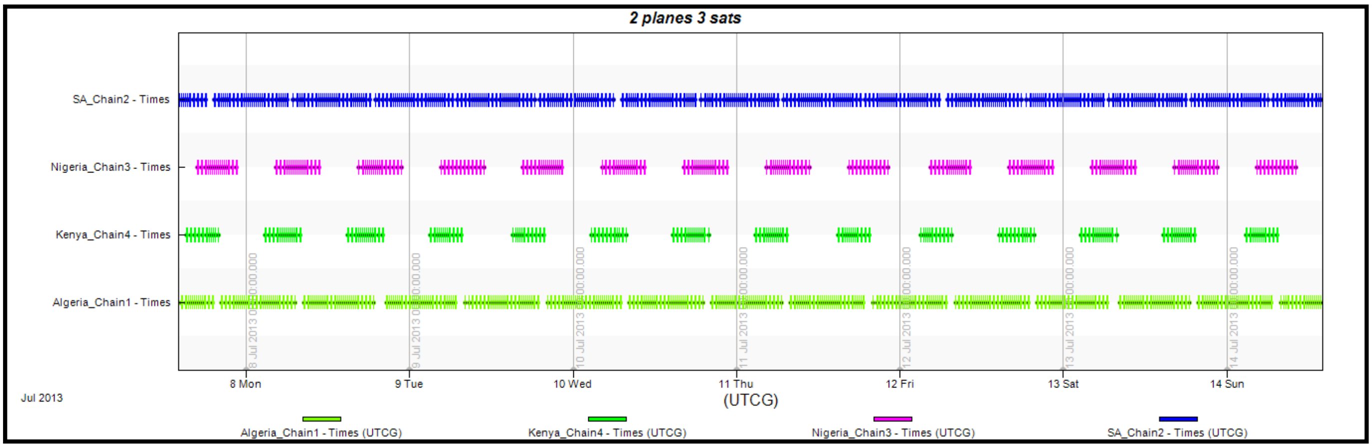

Figure 3.25: Simulated times of access between a constellation of three satellites in two orbital planes and the target areas

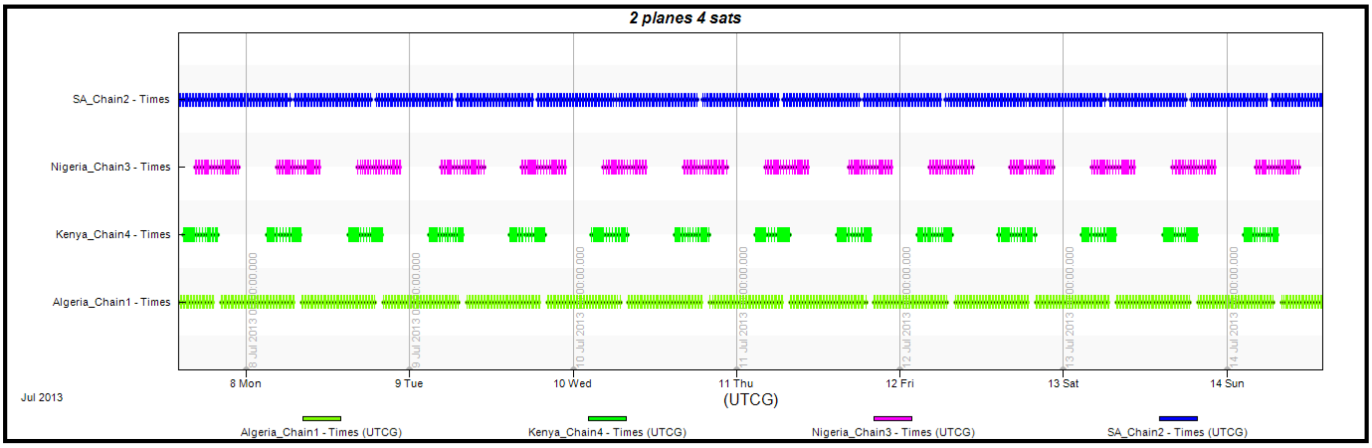

Figure 3.26: Simulated times of access between a constellation of four satellites in two orbital planes and the target areas

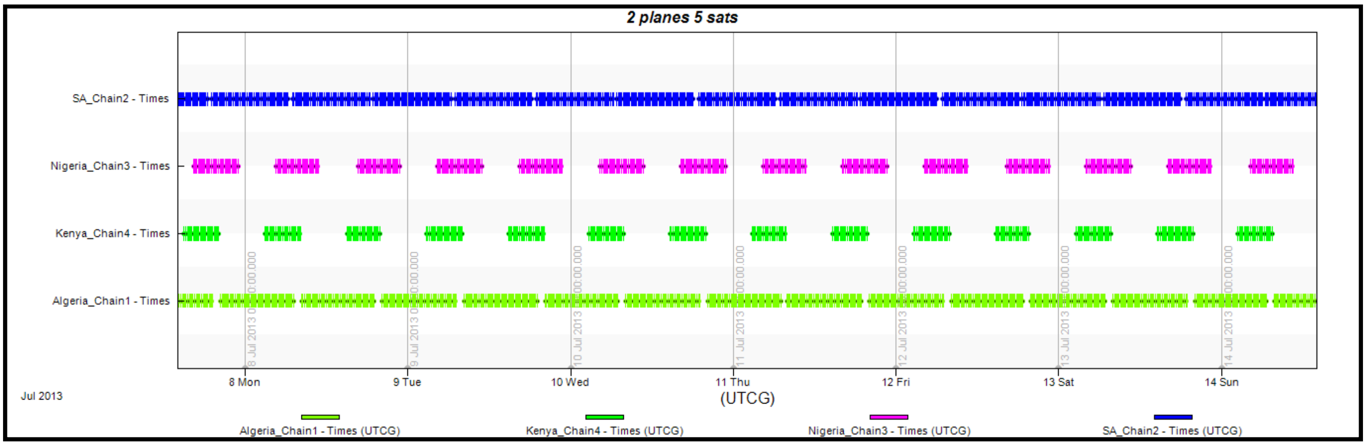

Figure 3.27: Simulated times of access between a constellation of five satellites in two orbital planes and the target areas

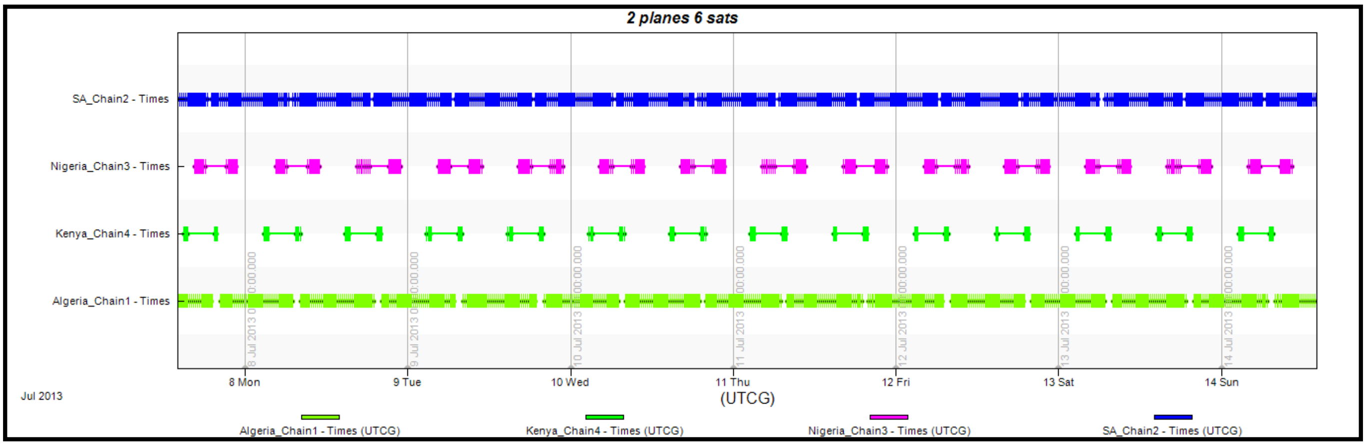

Figure 3.28: Simulated times of access between a constellation of six satellites in two orbital planes and the target areas

-Three orbital planes

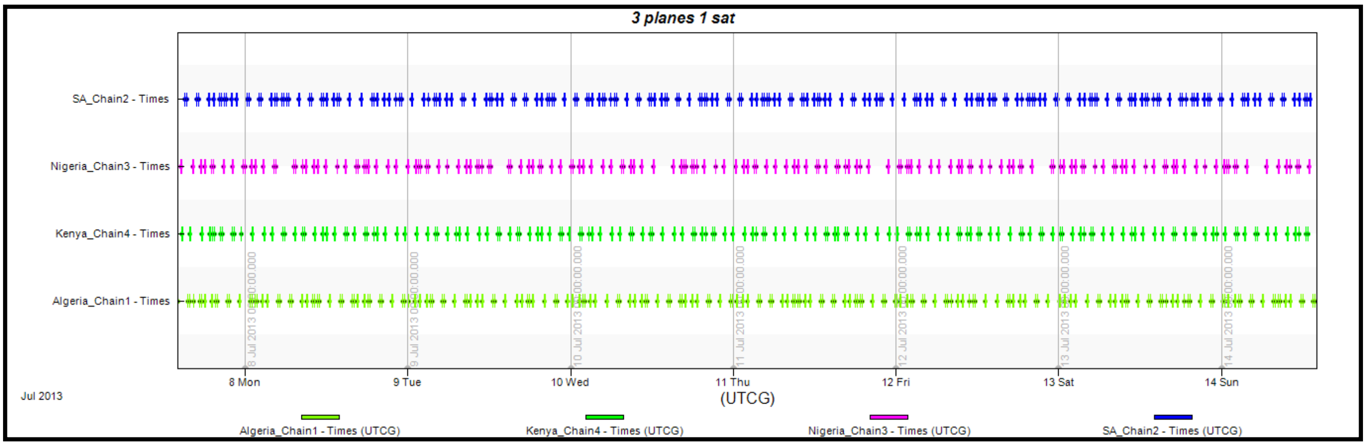

Figure 3.29: Simulated times of access between a constellation of one satellite in three orbital planes and the target areas

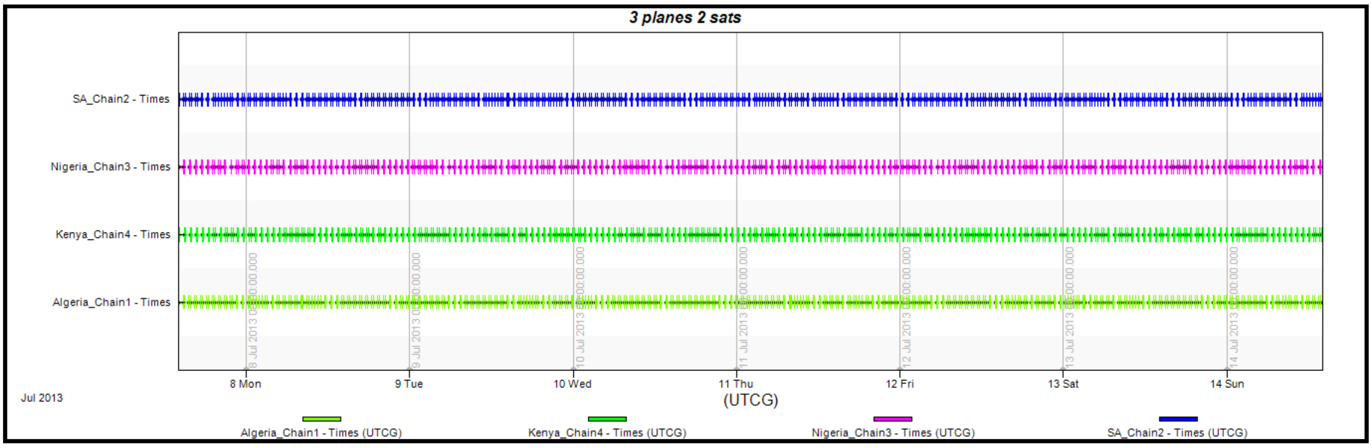

Figure 3.30: Simulated times of access between a constellation of two satellites in three orbital planes and the target areas

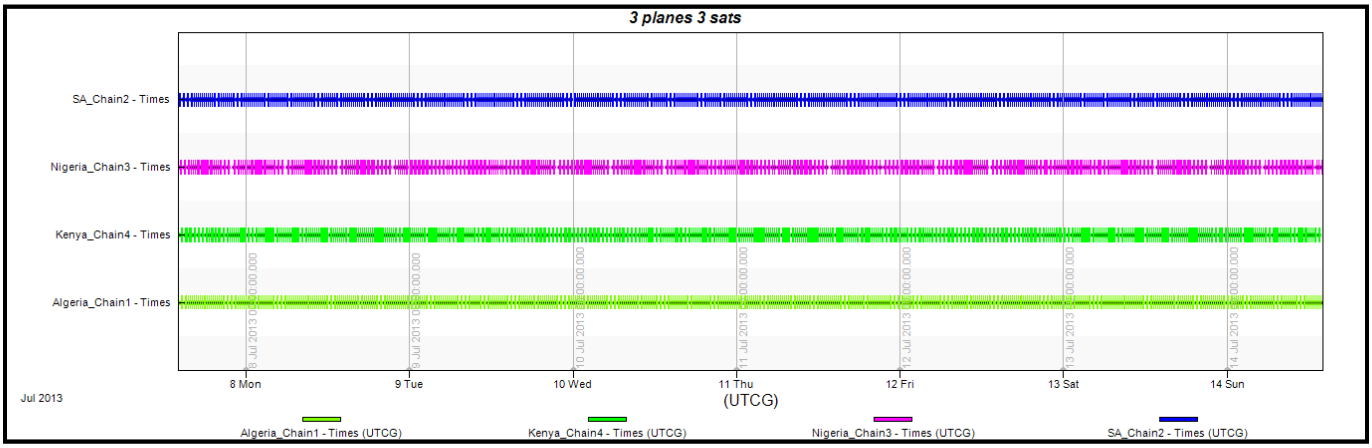

Figure 3.31: Simulated times of access between a constellation of three satellites in three orbital planes and the target areas

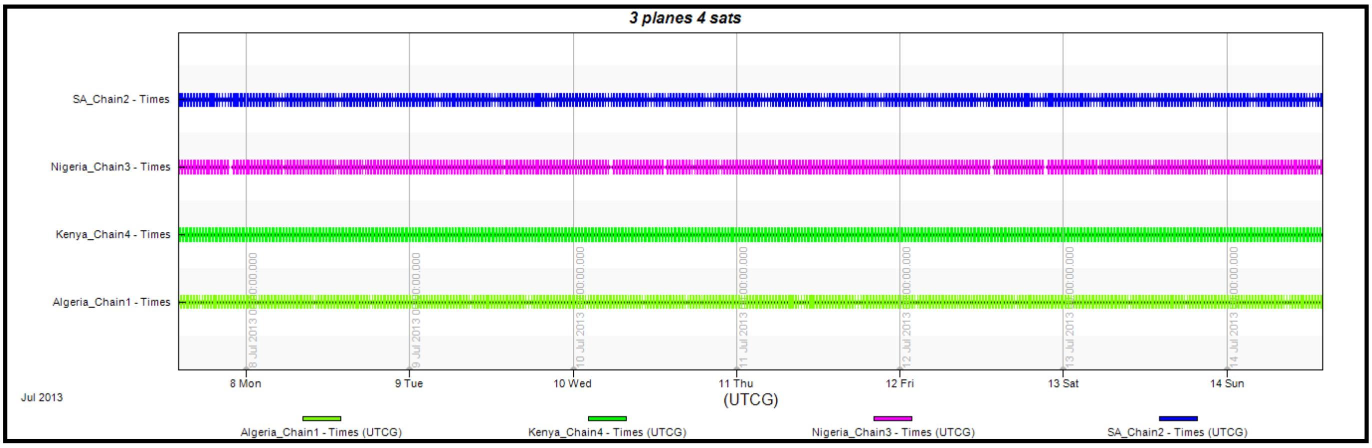

Figure 3.32: Simulated times of access between a constellation of four satellites in three orbital planes and the target areas

The observations for access time as a function of the constellation configuration is presented in Figure 3.33 for different inclination angles, using a specific tool within the STK/Analyzer module. There are many different sets of analysis tools within this module, such as those listed in Table 3.2.

Table 3.2: Types of analyses used for trade studies performed with STK/Analyser module

Tool	**Variance**	**Description**
Parametric Study	One independent variable	Vary one item over a range and study the effects on the various figures of merit defining performance.
Design of Experiments (DOE)	Table of runs	Vary multiple parameters, creating a table of runs, using various design-type algorithms, to study the effects on various parameters.
Optimisation	Minimise, maximise, or target a specific value	Systematically modify variables in a scenario until some objective is achieved.

The *Design of Experiment* tool is used here to analyse multiple variables, by creating a table of 108 runs for the examined scenario. Three different parameters, namely inclination angle (39°, 45° and 98°), number of orbital planes (1, 2 and 3) and number of satellites per plane (1 to 12) are all varied to study the resultant total daily access time depicted in Figures 3.33 and 3.34 for South Africa.

South Africa Target Area:

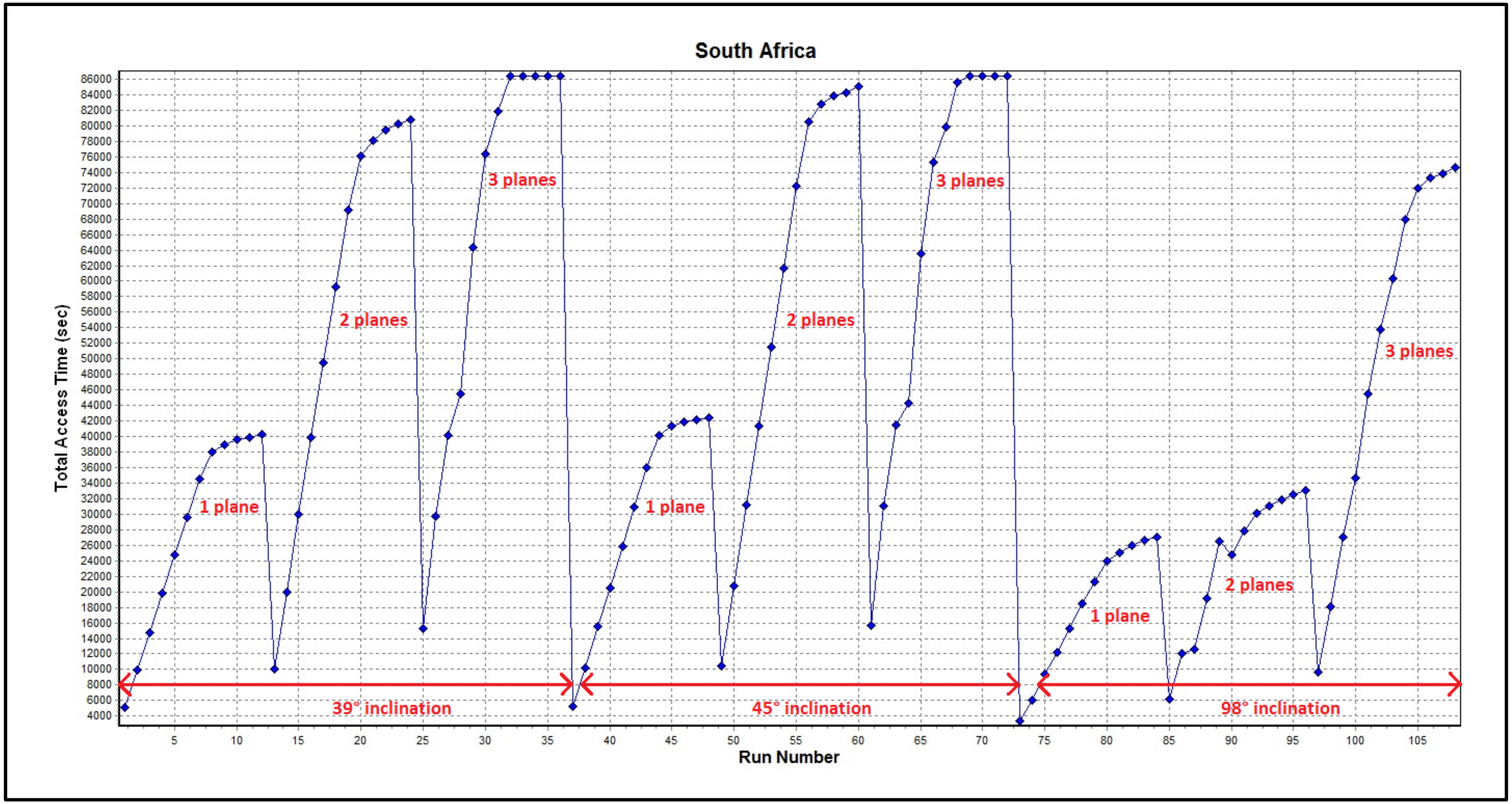

Figure 3.33: Total simulated daily access time for South Africa as a function of satellites per plane and inclination for the constellations considered

Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value	Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value	Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value
1	39	1	1	5062.46	37	45	1	1	5182.46	73	98	1	1	3373.85
2	39	1	2	9898.11	38	45	1	2	10246.30	74	98	1	2	6064.28
3	39	1	3	14761.21	39	45	1	3	15507.97	75	98	1	3	9329.06
4	39	1	4	19784.16	40	45	1	4	20488.17	76	98	1	4	12211.52
5	39	1	5	24701.35	41	45	1	5	25774.43	77	98	1	5	15300.90
6	39	1	6	29632.29	42	45	1	6	30884.02	78	98	1	6	18444.38
7	39	1	7	34462.61	43	45	1	7	35960.84	79	98	1	7	21277.15
8	39	1	8	38035.19	44	45	1	8	40186.20	80	98	1	8	23979.35
9	39	1	9	38954.26	45	45	1	9	41303.37	81	98	1	9	25081.43
10	39	1	10	39564.76	46	45	1	10	41826.01	82	98	1	10	25997.02
11	39	1	11	39926.82	47	45	1	11	42089.42	83	98	1	11	26699.33
12	39	1	12	40295.96	48	45	1	12	42455.31	84	98	1	12	27084.90
13	39	2	1	10037.87	49	45	2	1	10446.20	85	98	2	1	6148.11
14	39	2	2	20014.42	50	45	2	2	20749.40	86	98	2	2	12058.68
15	39	2	3	29949.10	51	45	2	3	31150.52	87	98	2	3	12618.72
16	39	2	4	39821.00	52	45	2	4	41314.84	88	98	2	4	19209.89
17	39	2	5	49448.95	53	45	2	5	51562.12	89	98	2	5	26490.45
18	39	2	6	59196.49	54	45	2	6	61707.57	90	98	2	6	24721.32
19	39	2	7	69123.85	55	45	2	7	72176.84	91	98	2	7	27783.43
20	39	2	8	76171.65	56	45	2	8	80508.33	92	98	2	8	30141.36
21	39	2	9	78149.75	57	45	2	9	82753.09	93	98	2	9	30993.71
22	39	2	10	79404.88	58	45	2	10	83848.86	94	98	2	10	31906.28
23	39	2	11	80183.78	59	45	2	11	84289.23	95	98	2	11	32546.66
24	39	2	12	80823.48	60	45	2	12	85030.92	96	98	2	12	33032.08
25	39	3	1	15293.08	61	45	3	1	15609.04	97	98	3	1	9707.48
26	39	3	2	29771.18	62	45	3	2	31020.45	98	98	3	2	18021.17
27	39	3	3	40100.11	63	45	3	3	41461.22	99	98	3	3	26996.85
28	39	3	4	45544.76	64	45	3	4	44237.24	100	98	3	4	34634.88
29	39	3	5	64330.50	65	45	3	5	63601.50	101	98	3	5	45514.49
30	39	3	6	76385.48	66	45	3	6	75305.75	102	98	3	6	53775.34
31	39	3	7	81838.75	67	45	3	7	79892.85	103	98	3	7	60325.19
32	39	3	8	86400.00	68	45	3	8	85641.65	104	98	3	8	68004.93
33	39	3	9	86400.00	69	45	3	9	86400.00	105	98	3	9	72026.88
34	39	3	10	86400.00	70	45	3	10	86400.00	106	98	3	10	73285.56
35	39	3	11	86400.00	71	45	3	11	86400.00	107	98	3	11	73860.42
36	39	3	12	86400.00	72	45	3	12	86400.00	108	98	3	12	74640.91

Figure 3.34: Screen shot of parameter scan and data explorer results summary in table view for trade study in Figure 3.33

To explain the structure of the graph in Figure 3.33 more clearly, the points on the graph are represented by a table of runs. With reference to the STK screen shot in Figure 3.34, runs number 1 to 36 show the total access time for constellations at 39° inclination. Runs number 37 to 72 are constellations at 45°, and runs number 73 to 108 at 98° inclination. The varied number of orbital planes and number of satellites per plane are arranged by the parameter scan of the analyses tool in such a way that runs number 1 to 12 represent 1 orbital plane; runs number 13 to 24 represent 2 orbital planes; and runs number 25 to 36 representing 3 orbital planes for a constellation at 39°. The number of satellites per plane is varied from 1 to 12. This pattern is maintained throughout for each inclination angle.

An objective of this study is to determine the total daily access time to the target areas using a constellation consisting of a *total of 12 satellites*.

The analyses show that constellations at 39° and 45° inclinations yield improved access times for these areas. Overall, the configuration with 6 satellites in 2 orbital planes yield a total daily access time of 59507 seconds (16 hours) and 61961 seconds (17 hours) for constellations at 39° and 45° inclinations, respectively, whereas 4 satellites in 3 orbital planes yield 45483 and 44183 seconds (approximately 12 hours) at these inclinations.

For a constellation at 98° inclination, the configuration with 6 satellites in 2 orbital planes performs poorer than a constellation with 4 satellites in 3 orbital planes; 6 hours compared to 9 hours of daily access time.

The *Design of Experiment* described above for the South Africa target area is now repeated for the Algeria, Kenya and Nigeria target areas.

Algeria Target Area:

The analyses represented in Figures 3.35 and 3.36 show that constellations at 39° and 45° inclinations yield superior access time for the target areas. Overall, the configurations with 6 satellites in 2 orbital planes yield a total daily access time of 61745 seconds (17 hours) and 48202 seconds (13 hours) for constellations at 39° and 45° inclinations, respectively, whereas 4 satellites in 3 orbital planes yield 48264 seconds (13 hours) and 37927 seconds (10 hours) at these inclinations. For a constellation at 98° inclination, the configuration with 6 satellites in 2 orbital planes performs poorer than a constellation with 4 satellites in 3 orbital planes; 6 hours compared to 8.5 hours of total daily access time. Hence, the optimum constellation is 6 satellites in 2 orbital planes at 39° inclination.

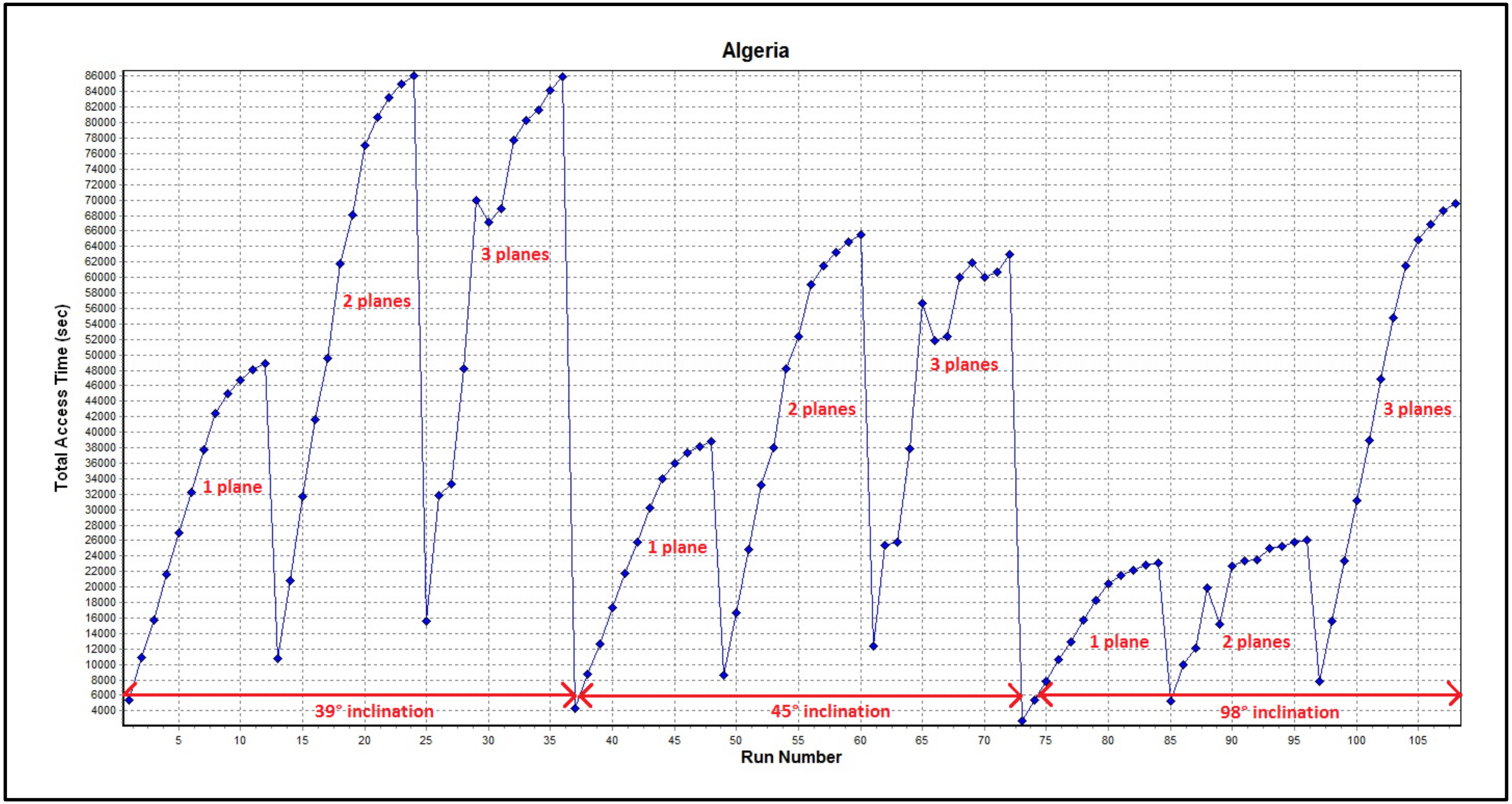

Figure 3.35: Total simulated daily access time for Algeria as a function of satellites per plane and inclination for the constellations considered

Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value	Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value	Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value
1	39	1	1	5422.57	37	45	1	1	4304.04	73	98	1	1	2702.93
2	39	1	2	10852.24	38	45	1	2	8705.01	74	98	1	2	5409.77
3	39	1	3	15788.60	39	45	1	3	12611.53	75	98	1	3	7862.70
4	39	1	4	21622.97	40	45	1	4	17291.47	76	98	1	4	10604.49
5	39	1	5	27058.22	41	45	1	5	21749.84	77	98	1	5	12962.59
6	39	1	6	32226.89	42	45	1	6	25788.31	78	98	1	6	15729.02
7	39	1	7	37716.78	43	45	1	7	30196.57	79	98	1	7	18228.54
8	39	1	8	42381.03	44	45	1	8	33948.58	80	98	1	8	20446.97
9	39	1	9	44963.80	45	45	1	9	35927.47	81	98	1	9	21550.40
10	39	1	10	46697.30	46	45	1	10	37270.33	82	98	1	10	22223.08
11	39	1	11	48012.79	47	45	1	11	38145.35	83	98	1	11	22812.40
12	39	1	12	48816.59	48	45	1	12	38800.33	84	98	1	12	23142.26
13	39	2	1	10785.42	49	45	2	1	8611.65	85	98	2	1	5242.99
14	39	2	2	20832.15	50	45	2	2	16653.97	86	98	2	2	10011.13
15	39	2	3	31650.62	51	45	2	3	24853.52	87	98	2	3	12070.03
16	39	2	4	41598.44	52	45	2	4	33174.16	88	98	2	4	19886.26
17	39	2	5	49536.88	53	45	2	5	38018.05	89	98	2	5	15213.90
18	39	2	6	61745.17	54	45	2	6	48202.77	90	98	2	6	22710.26
19	39	2	7	68045.88	55	45	2	7	52427.05	91	98	2	7	23434.07
20	39	2	8	77078.03	56	45	2	8	59033.04	92	98	2	8	23462.25
21	39	2	9	80683.67	57	45	2	9	61531.60	93	98	2	9	24999.08
22	39	2	10	83186.03	58	45	2	10	63303.34	94	98	2	10	25190.93
23	39	2	11	84935.86	59	45	2	11	64538.10	95	98	2	11	25754.95
24	39	2	12	86054.51	60	45	2	12	65501.73	96	98	2	12	26019.73
25	39	3	1	15606.33	61	45	3	1	12383.06	97	98	3	1	7739.75
26	39	3	2	31794.37	62	45	3	2	25428.64	98	98	3	2	15640.56
27	39	3	3	33291.32	63	45	3	3	25738.68	99	98	3	3	23331.25
28	39	3	4	48264.23	64	45	3	4	37927.75	100	98	3	4	31162.79
29	39	3	5	69927.04	65	45	3	5	56616.80	101	98	3	5	38992.99
30	39	3	6	67187.90	66	45	3	6	51864.17	102	98	3	6	46859.59
31	39	3	7	68820.31	67	45	3	7	52322.48	103	98	3	7	54754.94
32	39	3	8	77730.41	68	45	3	8	60040.08	104	98	3	8	61469.55
33	39	3	9	80295.52	69	45	3	9	61937.60	105	98	3	9	64789.77
34	39	3	10	81584.54	70	45	3	10	60010.31	106	98	3	10	66881.13
35	39	3	11	84200.99	71	45	3	11	60629.94	107	98	3	11	68580.92
36	39	3	12	85879.81	72	45	3	12	62933.45	108	98	3	12	69587.46

Figure 3.36: Screen shot of parameter scan and data explorer results summary in table view for trade study in Figure 3.35

Kenya Target Area:

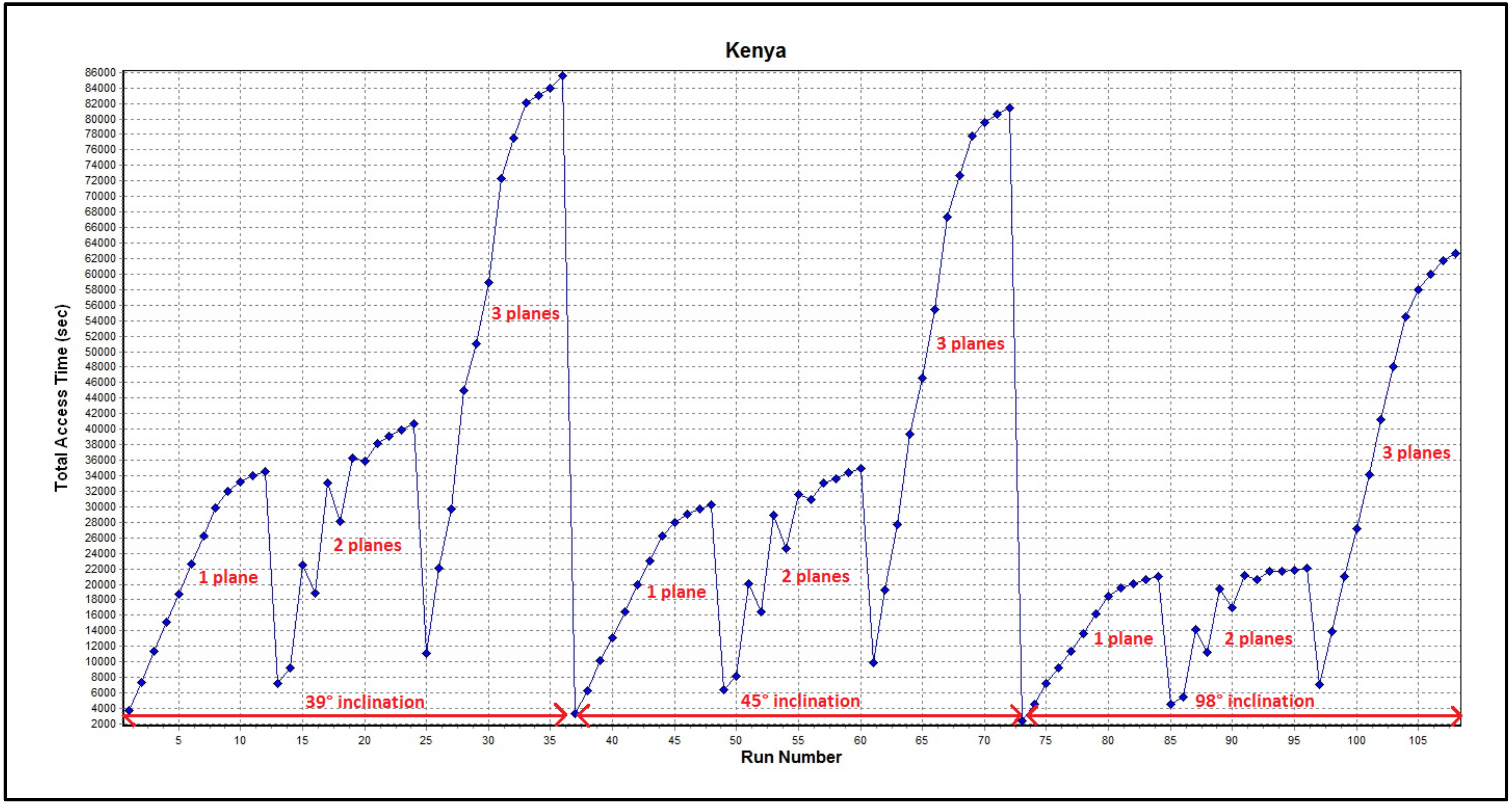

Figure 3.37: Total simulated daily access time for Kenya as a function of satellites per plane and inclination for the constellations considered

The analyses represented in Figure 3.37 show that constellations at 39° and 45° inclinations yield superior access time for the target areas.

The configurations with 6 satellites in 2 orbital planes yield a total daily access time of 28173 seconds (7.8 hours) and 24580 seconds (6.8 hours), respectively, whereas 4 satellites in 3 orbital planes yield 44981 seconds (12.5 hours) and 39349 seconds (10.9 hours) at these inclinations.

A constellation at 98° inclination configured with 6 satellites in 2 planes yields a total daily access time of 17034 seconds (4.7 hours), and 4 satellites in 3 orbital planes 27173 seconds (7.5 hours).

The optimum constellation is, therefore, 4 satellites in 3 orbital planes at 39° inclination.

Nigeria Target Area:

The analyses represented in Figure 3.38 show that constellations at 39° and 45° inclinations yield superior access time for the target areas. The configurations with 6 satellites in 2 orbital planes yield a total daily access time of 28891 seconds (8 hours) and 25129 seconds (6.9 hours), respectively, whereas 4 satellites in 3 orbital planes yield 45032 seconds (12.5 hours) and 39058 seconds (10.8 hours) at these inclinations.

A constellation at 98° inclination configured with 6 satellites in 2 planes yields a total daily access time of 17258 seconds (4.8 hours), and 4 satellites in 3 orbital planes 27353 seconds (7.6 hours).

The optimum constellation configuration is, therefore, 4 satellites in 3 orbital planes at 39° inclination.

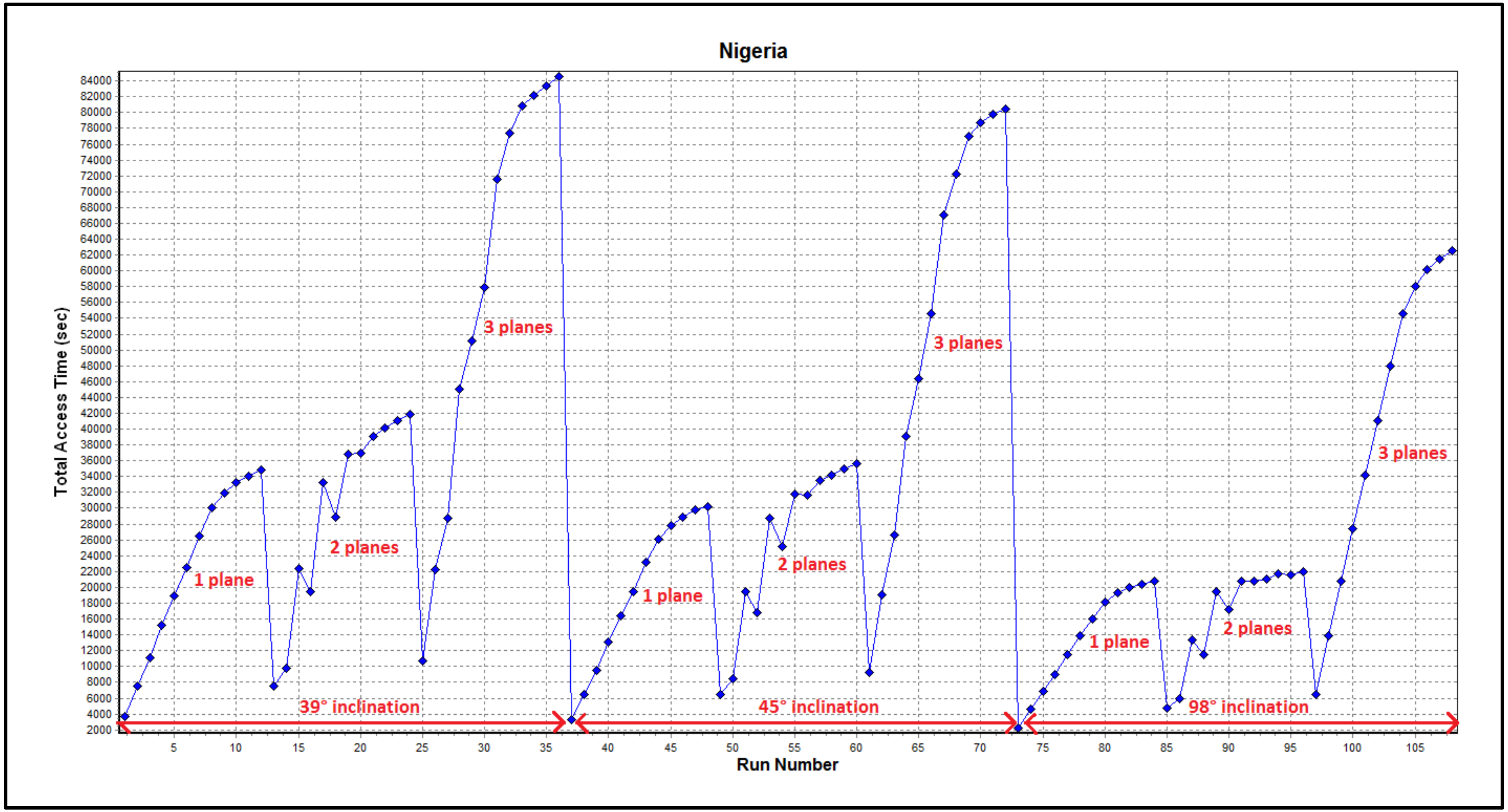

Figure 3.38: Total simulated access time for Nigeria as a function of satellites per plane and inclination for the constellations considered

Summary:

The optimum constellation configurations for the various target areas is summarised as follows:

- For the South Africa target area, the optimum constellation configuration is 6 satellites in 2 orbital planes at 45° inclination, yielding a total daily access time of 61961 seconds (17 hours);
- For the Algeria target area, the optimum constellation configuration is also 6 satellites in 2 orbital planes, but at 39° inclination, yielding a total daily access time of 61745 seconds (17 hours); and
- For the Kenya and Nigeria target areas, the optimum constellation configuration is 4 satellites in 3 orbital planes at 39° inclination, both yielding a total daily access time of around 12.5 hours.

Considering the above, and noting the remark in Section 3.2.1, the constellation configuration with 6 satellites in 2 orbital planes at 39° inclination yields the best performance when considering all target areas.

3.2.2.2 Revisit time

Typically, satellite constellations are designed to improve revisit times of geographic target areas and to optimise coverage of these areas. Figures 3.39 to 3.60 illustrate the simulated revisit times of the satellite(s) over the ground station in *Cape Town*, for each constellation configuration and to a maximum of 12 satellites. The simulated revisit times are for constellations at 39° inclination, as motivated earlier.

The y-axis represents time in seconds. This is the time of no access to the satellite. *Zero* represents access to the satellite.

-Single orbital plane

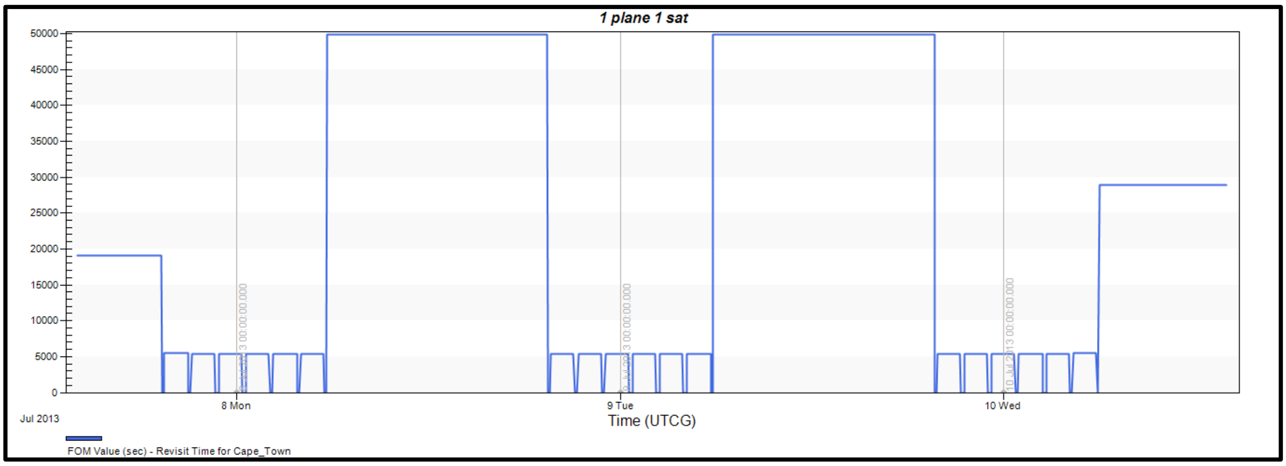

Figure 3.39: Simulated revisit times of a constellation of a single satellite in one orbital plane for the Cape Town target area

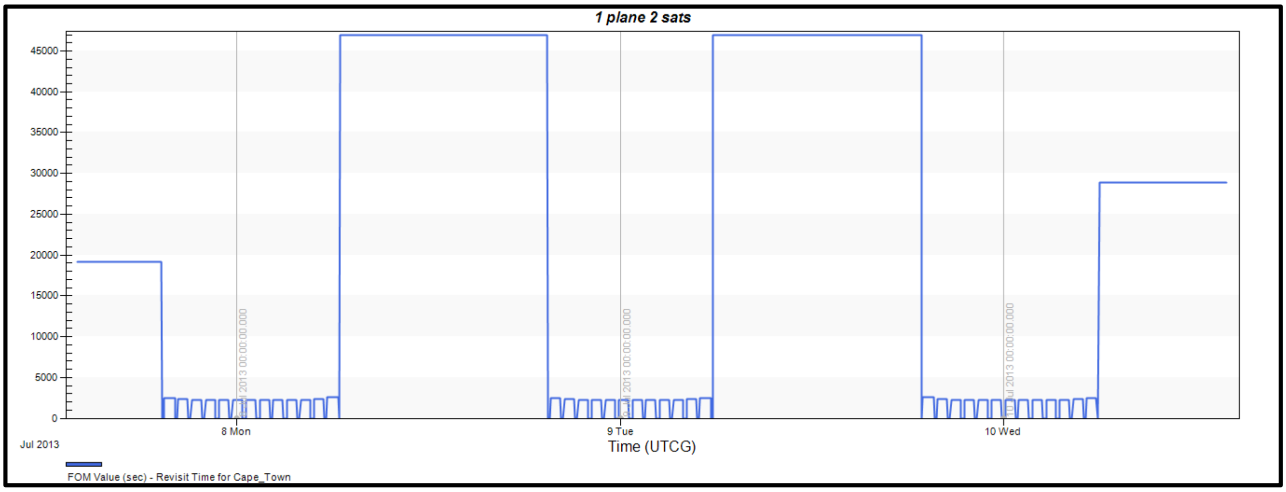

Figure 3.40: Simulated revisit times of a constellation of two satellites in one orbital plane for the Cape Town target area

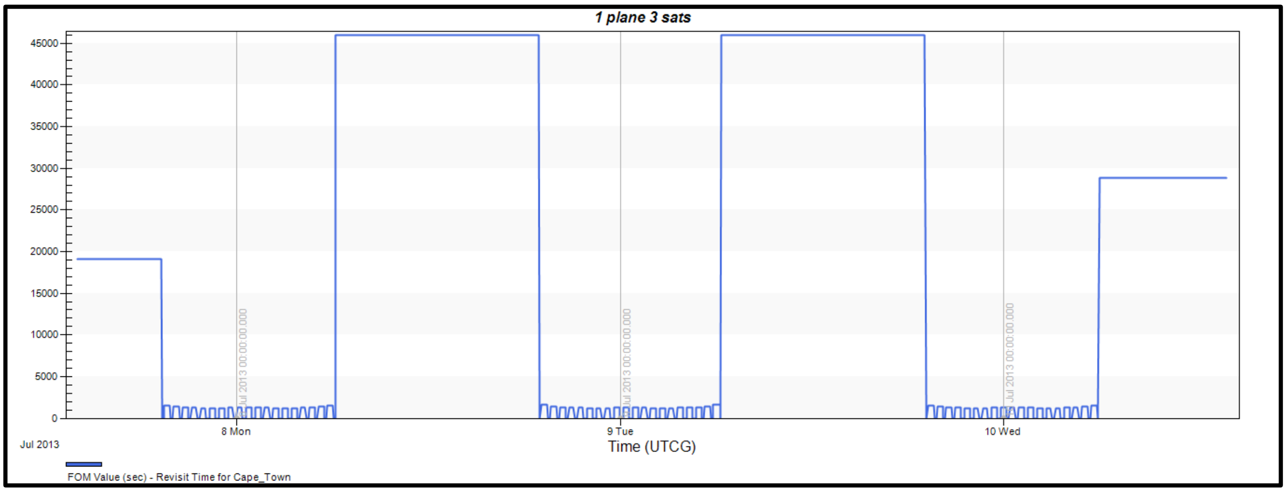

Figure 3.41: Simulated revisit times of a constellation of three satellites in one orbital plane for the Cape Town target area

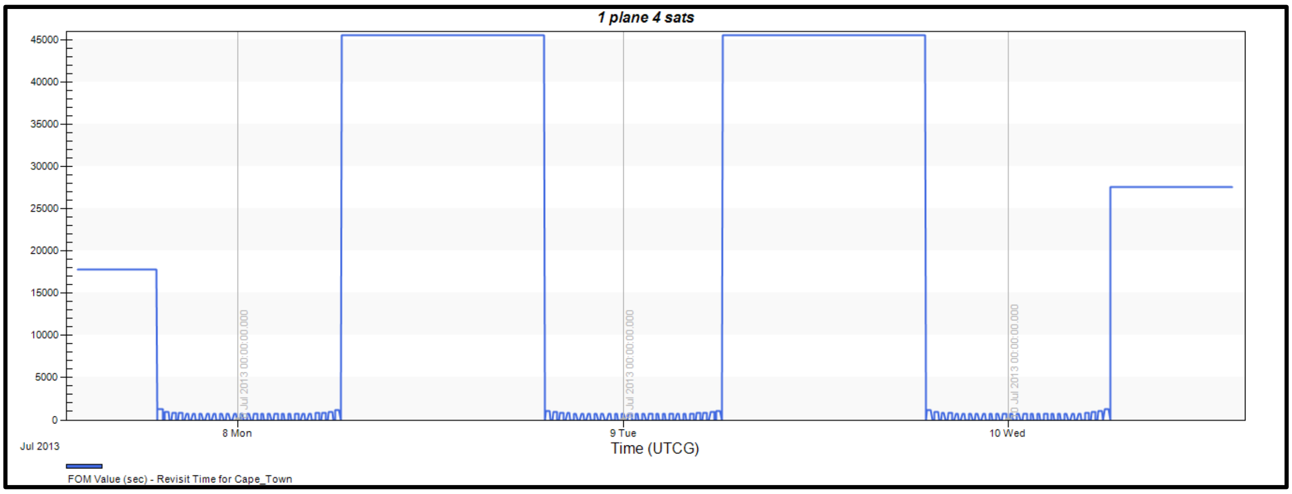

Figure 3.42: Simulated revisit times of a constellation of four satellites in one orbital plane for the Cape Town target area

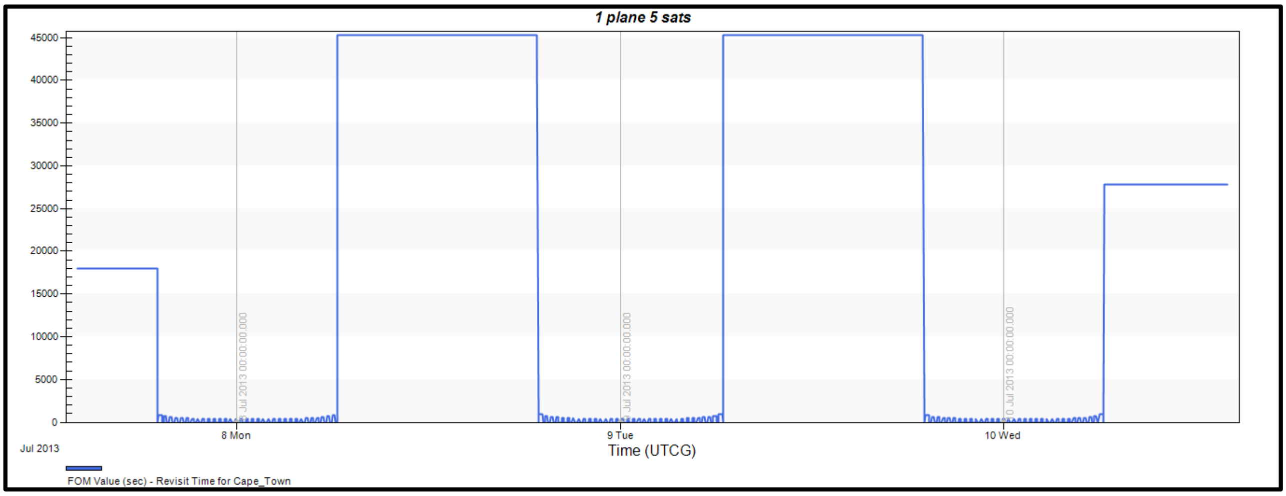

Figure 3.43: Simulated revisit times of a constellation of five satellites in one orbital plane for the Cape Town target area

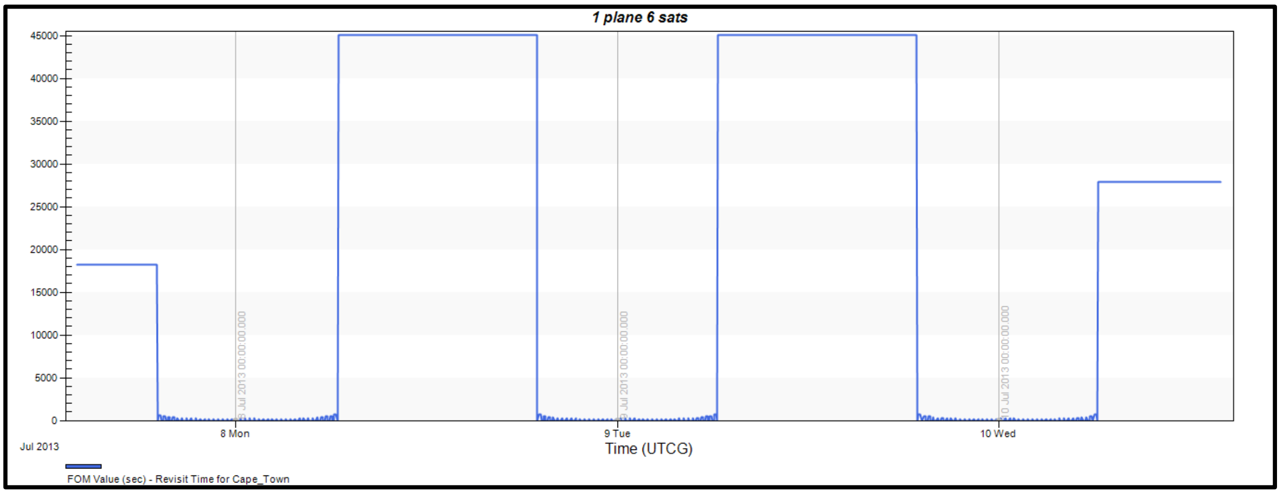

Figure 3.44: Simulated revisit times of a constellation of six satellites in one orbital plane for the Cape Town target area

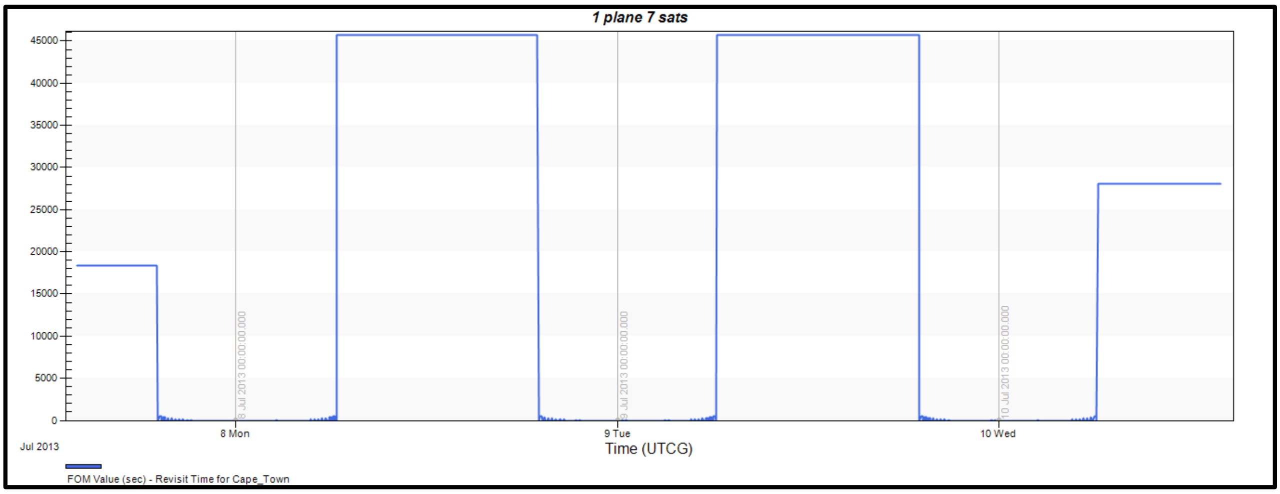

Figure 3.45: Simulated revisit times of a constellation of seven satellites in one orbital plane for the Cape Town target area

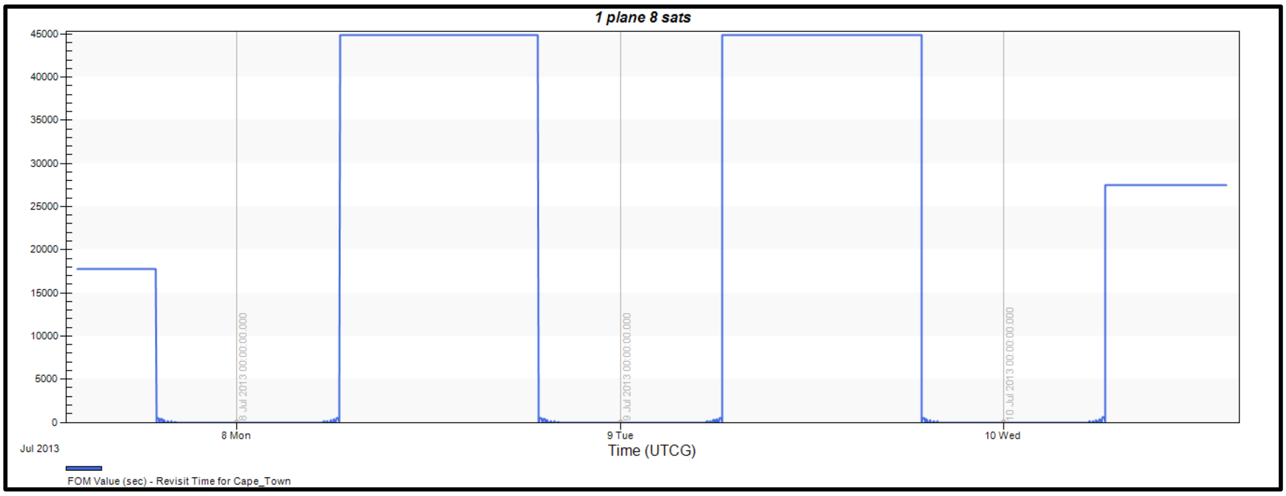

Figure 3.46: Simulated revisit times of a constellation of eight satellites in one orbital plane for the Cape Town target area

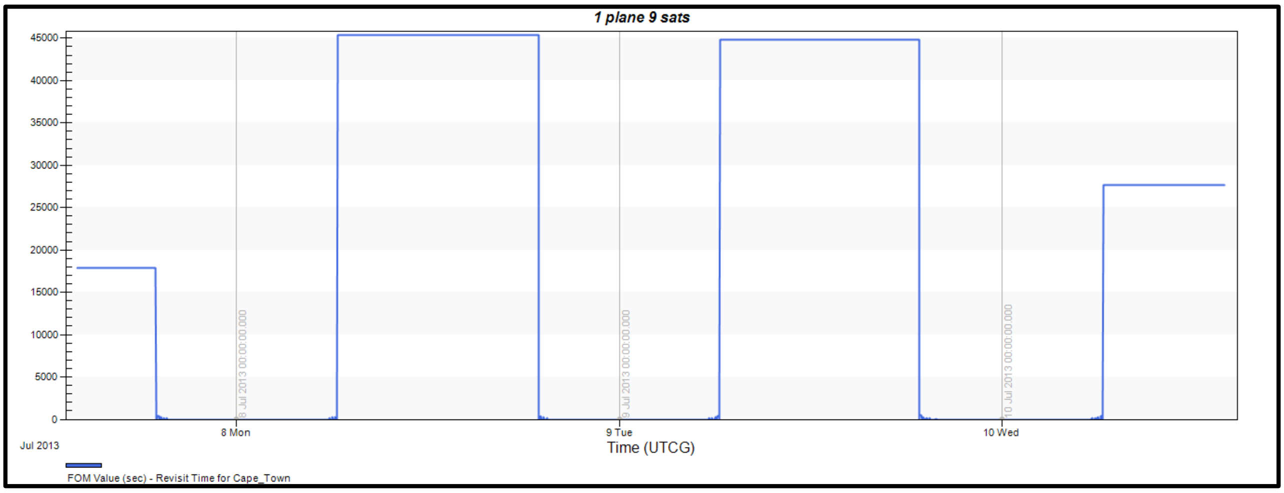

Figure 3.47: Simulated revisit times of a constellation of nine satellites in one orbital plane for the Cape Town target area

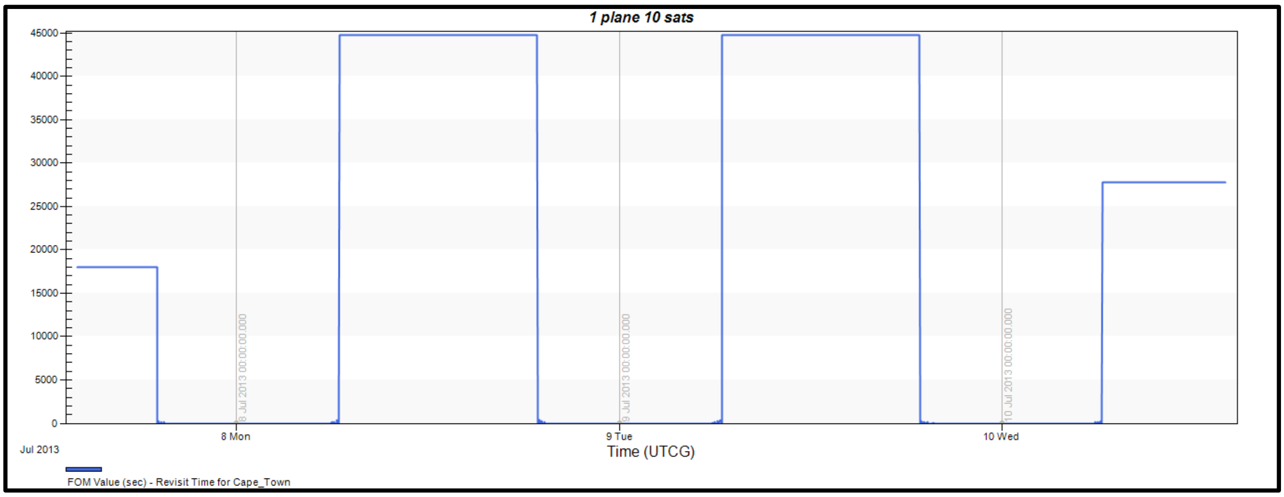

Figure 3.48: Simulated revisit times of a constellation of ten satellites in one orbital plane for the Cape Town target area

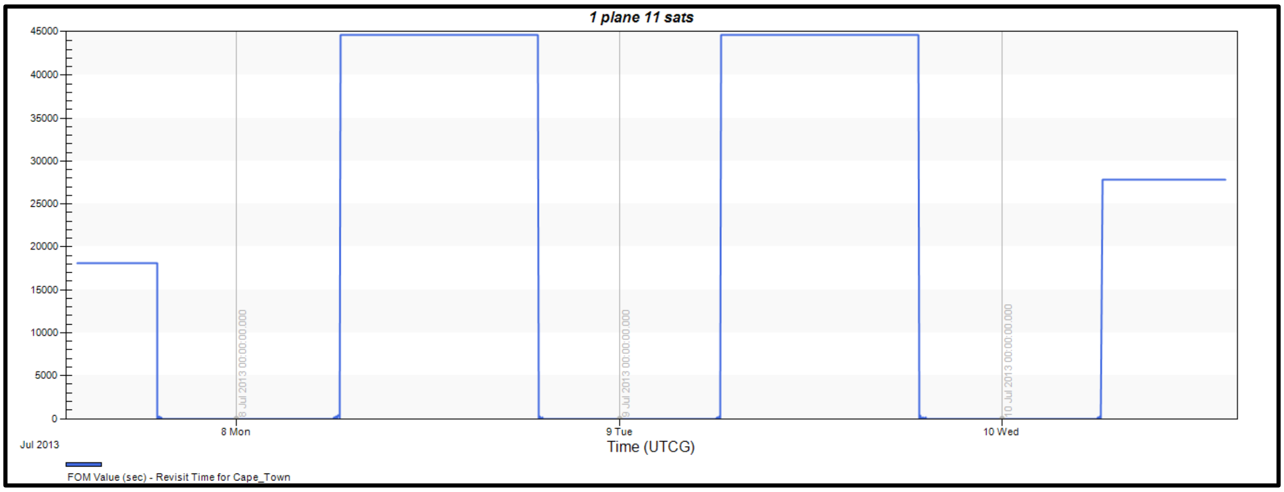

Figure 3.49: Simulated revisit times of a constellation of eleven satellites in one orbital plane for the Cape Town target area

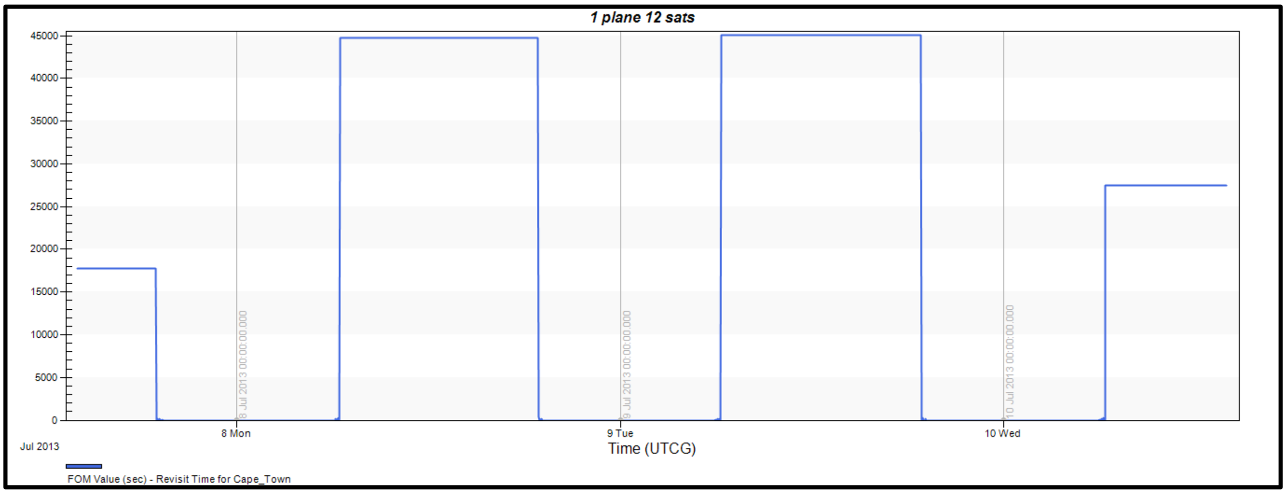

Figure 3.50: Simulated revisit times of a constellation of twelve satellites in one orbital plane for the Cape Town target area

-Two orbital planes

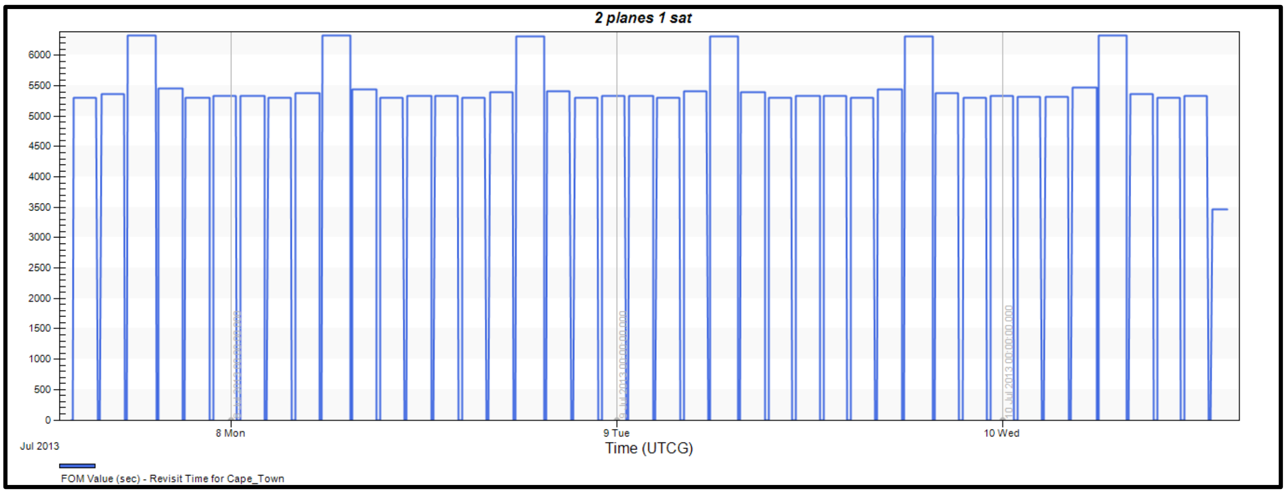

Figure 3.51: Simulated revisit times of a constellation of one satellite in two orbital planes for the Cape Town target area

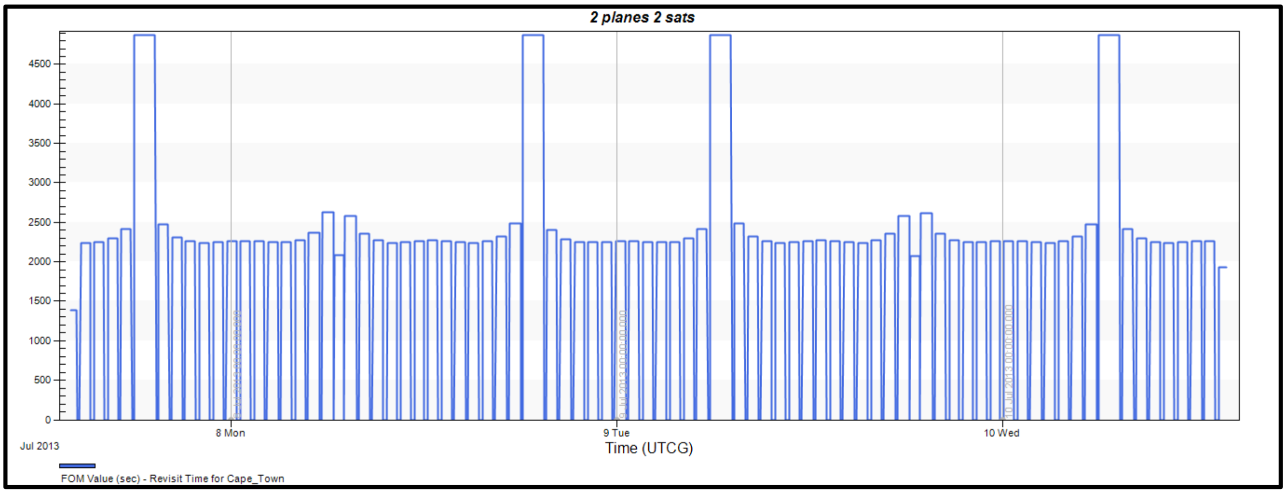

Figure 3.52: Simulated revisit times of a constellation of two satellites in two orbital planes for the Cape Town target area

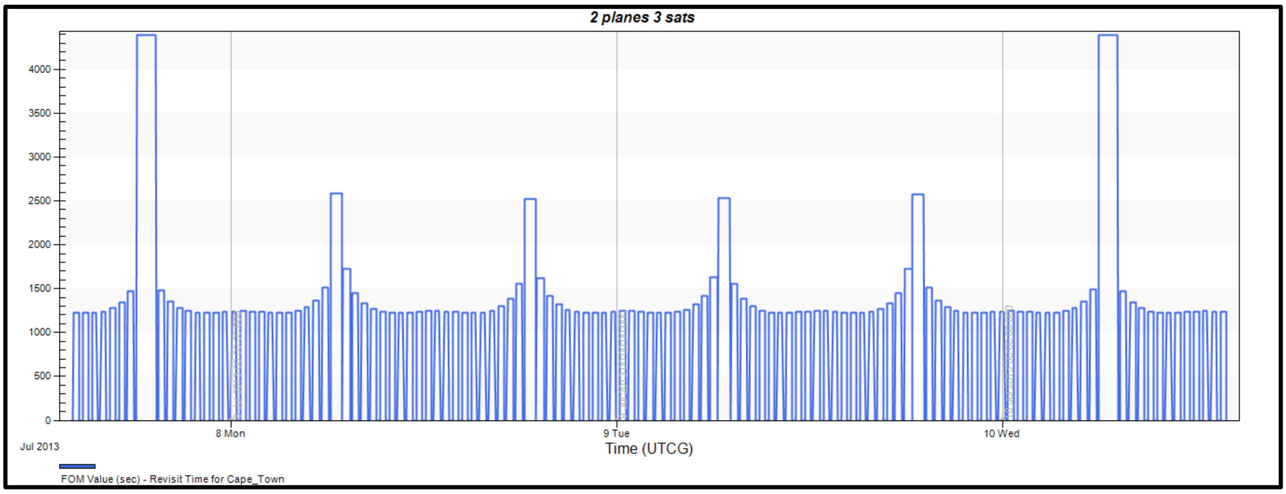

Figure 3.53: Simulated revisit times of a constellation of three satellites in two orbital planes for the Cape Town target area

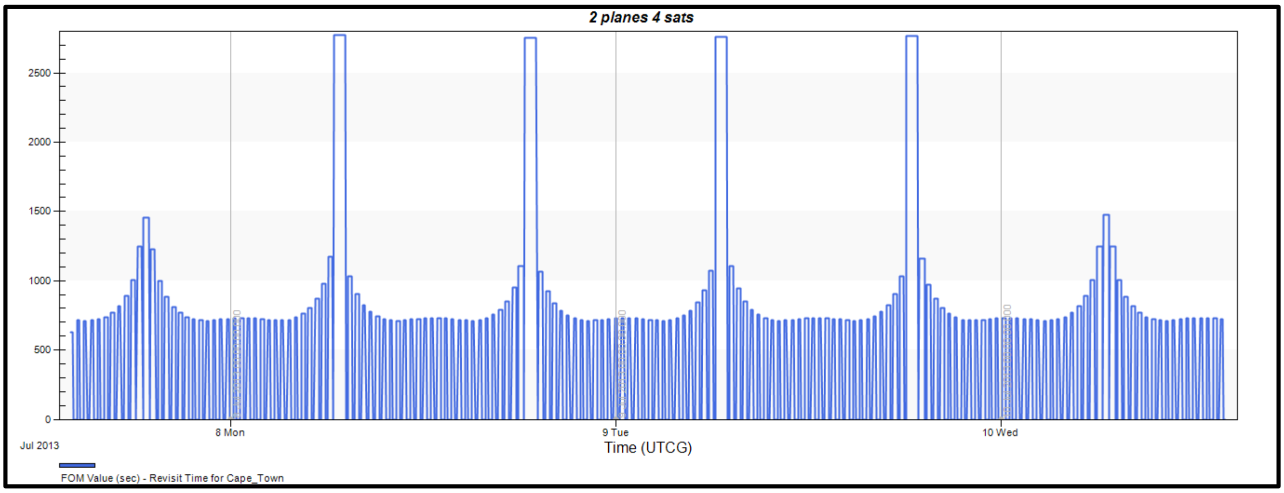

Figure 3.54: Simulated revisit times of a constellation of four satellites in two orbital planes for the Cape Town target area

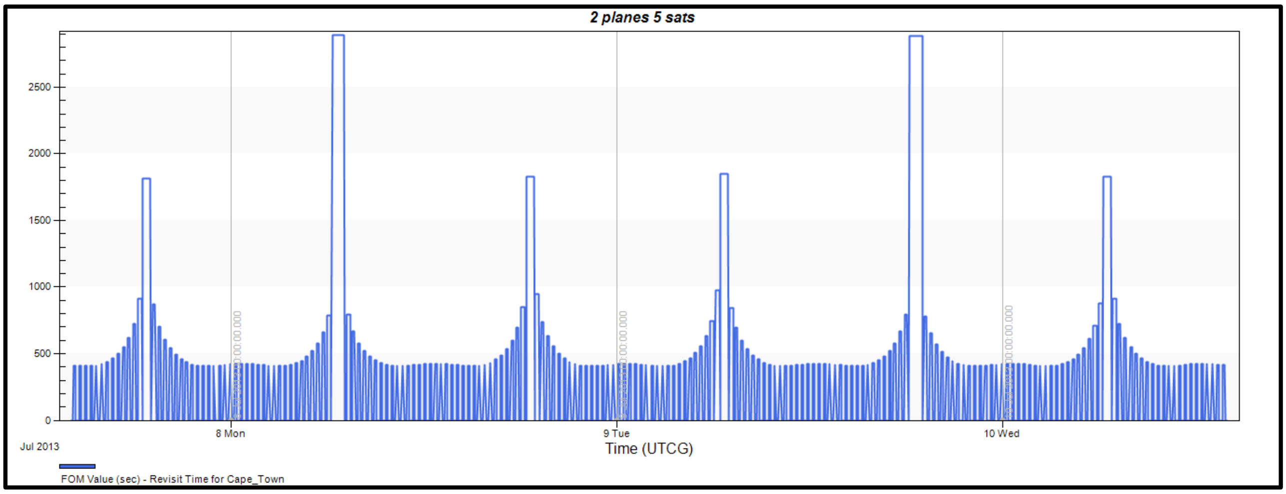

Figure 3.55: Simulated revisit times of a constellation of five satellites in two orbital planes for the Cape Town target area

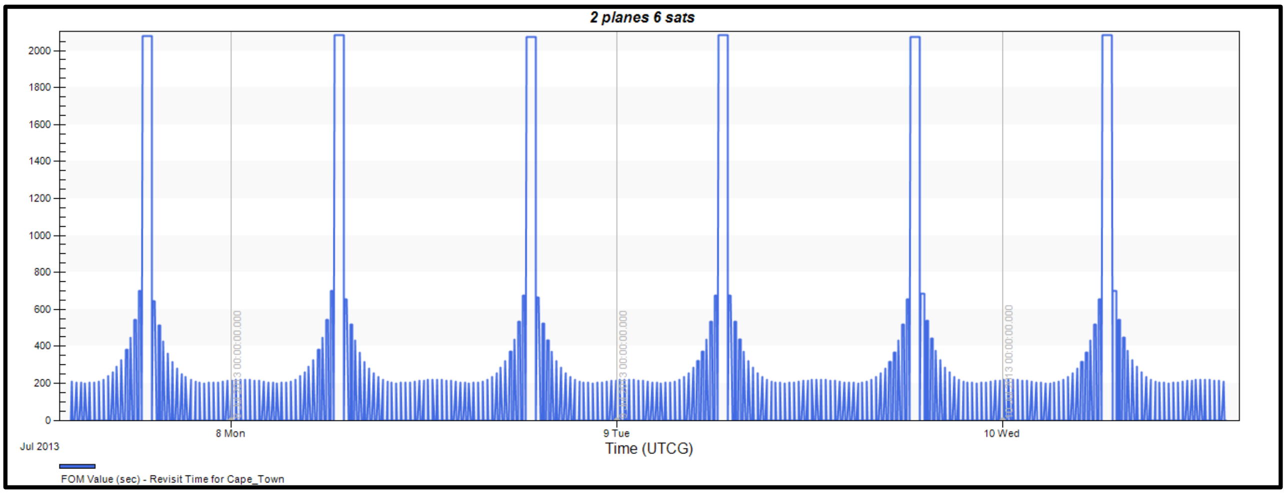

Figure 3.56: Simulated revisit times of a constellation of six satellites in two orbital planes for the Cape Town target area

-Three orbital planes

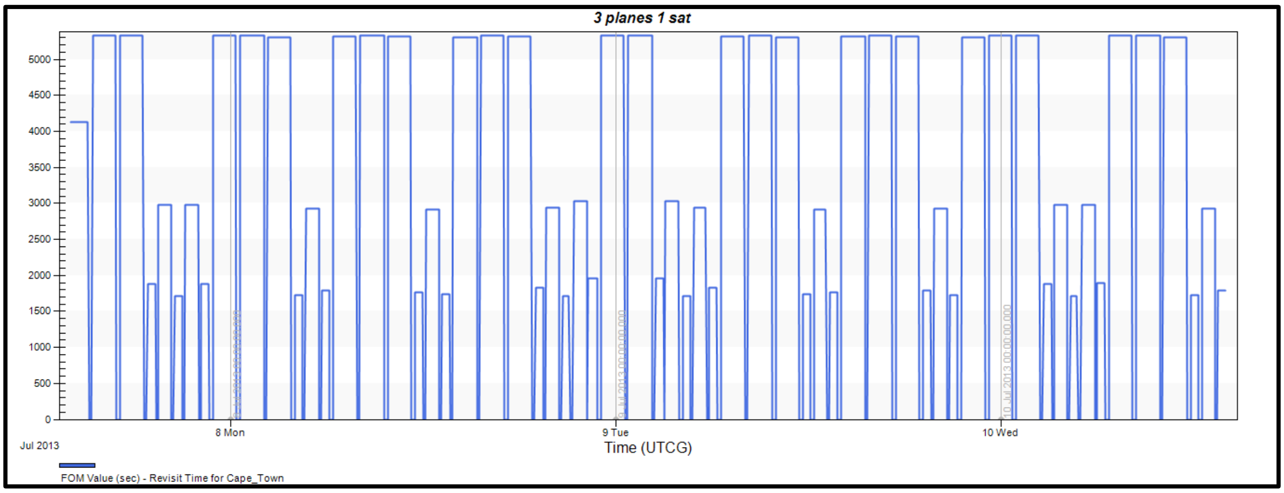

Figure 3.57: Simulated revisit times of a constellation of one satellite in three orbital planes for the Cape Town target area

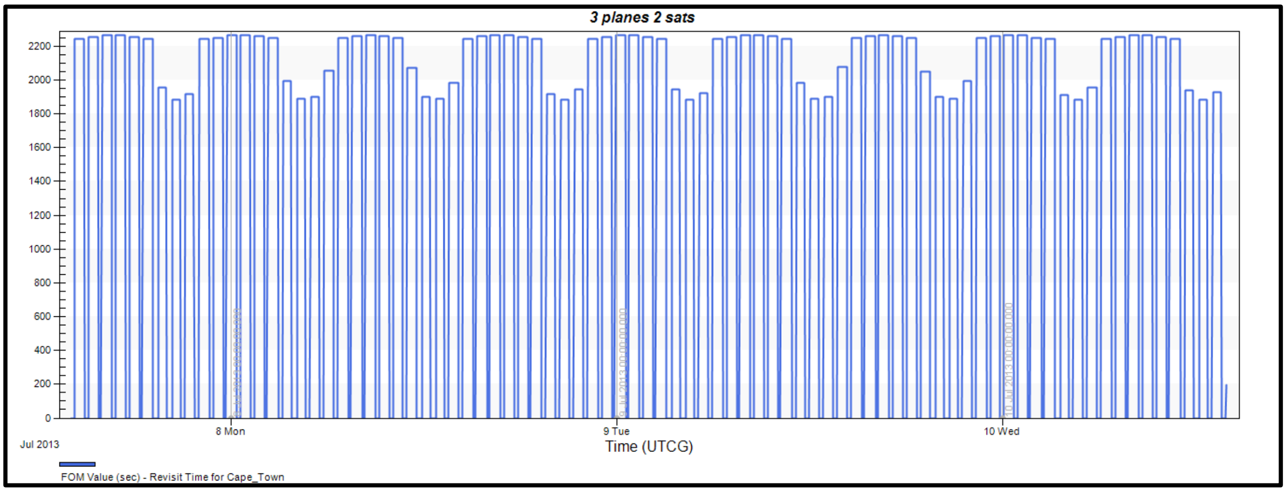

Figure 3.58: Simulated revisit times of a constellation of two satellites in three orbital planes for the Cape Town target area

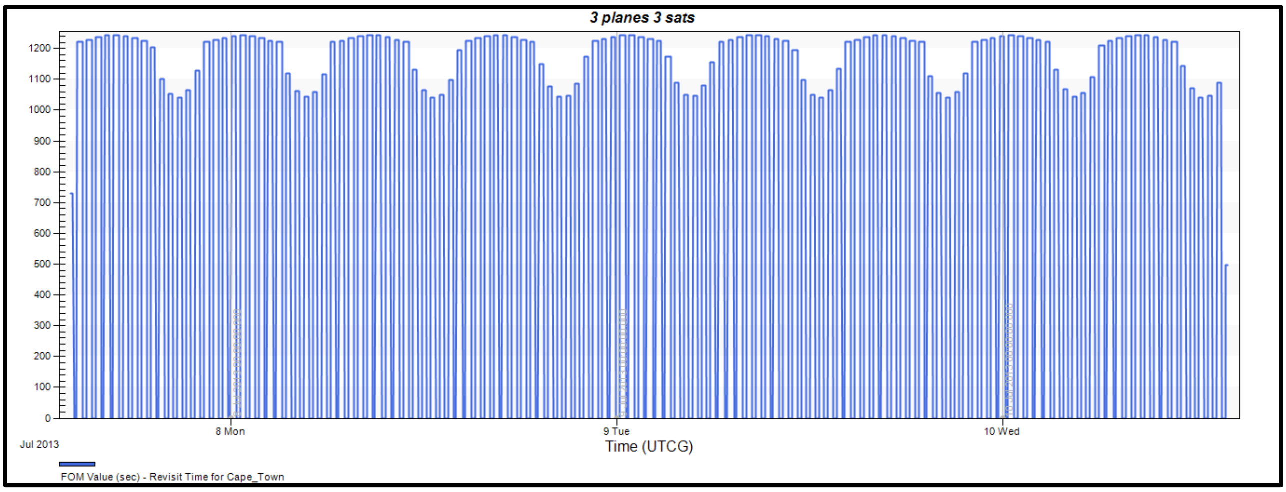

Figure 3.59: Simulated revisit times of a constellation of three satellites in three orbital planes for the Cape Town target area

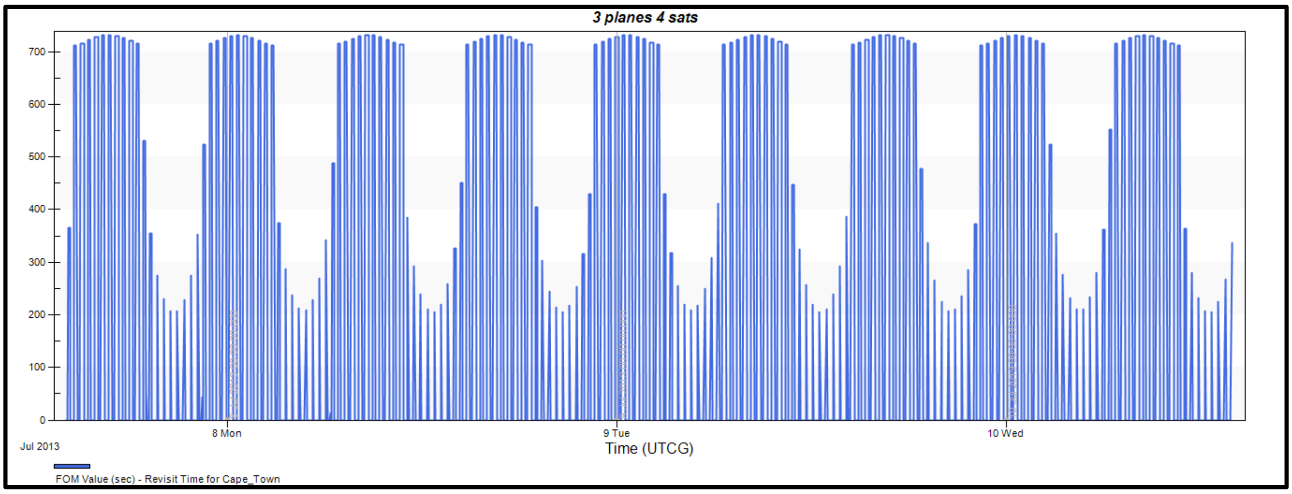

Figure 3.60: Simulated revisit times of a constellation of four satellites in three orbital planes for the Cape Town target area

The *Design of Experiment* tool in STK is again used to analyse the average revisit time as a function of inclination, number of satellites and orbital planes. This is done by creating a table of 108 runs for the examined scenarios. The optimum configuration of the constellation to meet the required revisit time can then be determined.

Analyses of the average revisit time have been carried out for South Africa, Algeria, Kenya and Nigeria. These results are summarised in Figures 3.61 to 3.65.

South Africa Target Area:

The observations for the revisit times presented in Figure 3.39 to 3.60 are summarised in Figure 3.61. Figure 3.62 shows a screen shot of the parameter scan and data explorer results in table view for the trade study in Figure 3.61.

The analysis shows that constellations at lower inclinations of 39° and 45° improve the revisit time as compared for higher inclinations at 98°. The configuration with 6 satellites in 2 orbital planes yields an average revisit time of 327 and 287 seconds (approximately 5 minutes), respectively, at the lower two inclinations, while 4 satellites in 3 orbital planes gives yields 717 and 740 seconds (about 12 minutes) at these inclinations.

A constellation at 98° inclination with 6 satellites in 2 orbital planes (with a revisit time of 27 minutes) performs worse than a constellation with 4 satellites in 3 orbital planes with a revisit time of 15 minutes.

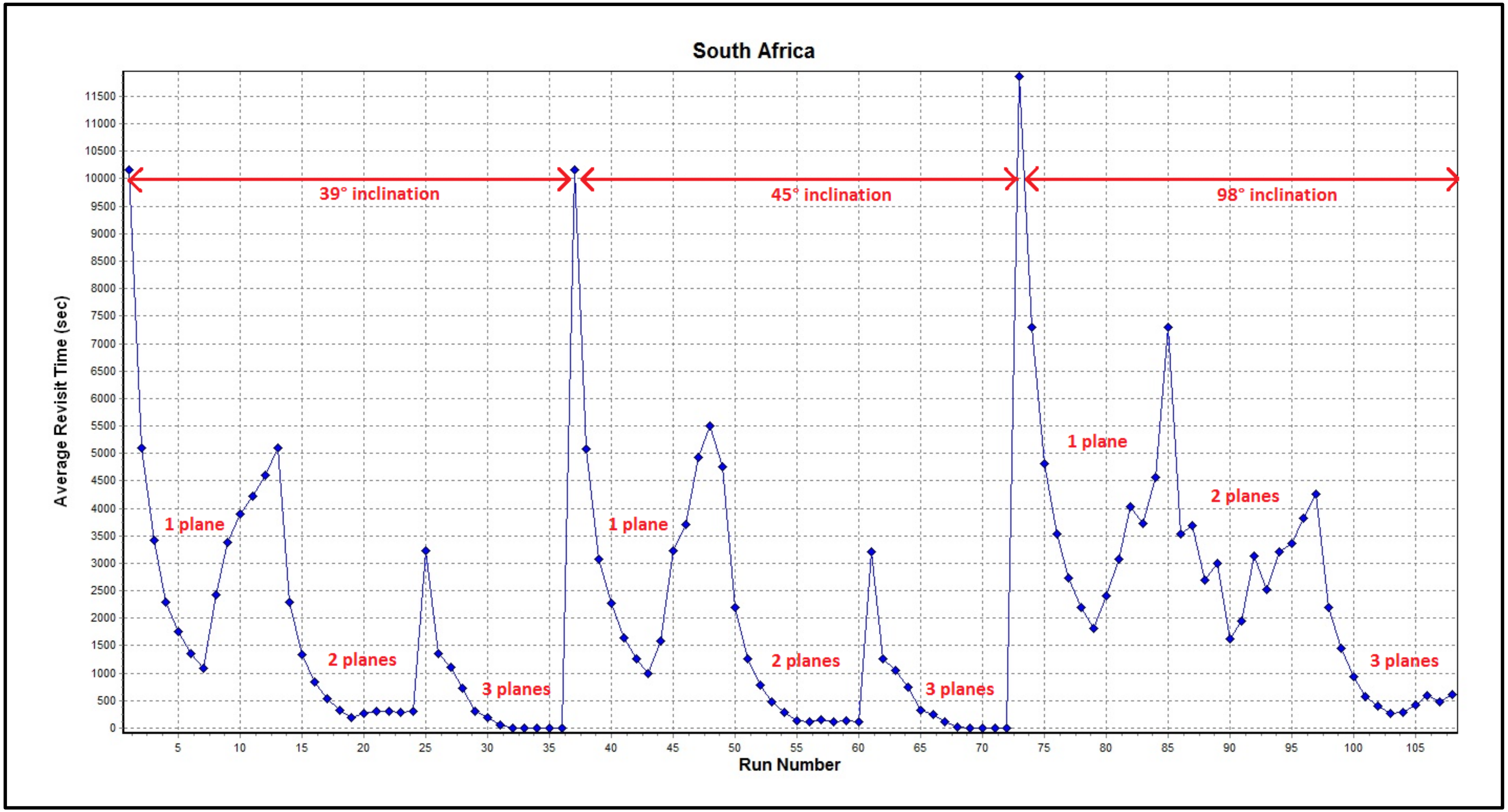

Figure 3.61: Average simulated revisit time for South Africa as a function of satellites per plane and inclination for the constellations considered

Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value	Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value	Num.	Incl.	numPlanes	numSatPerPlane	FOM_Value
1	39	1	1	10167.19	37	45	1	1	10152.19	73	98	1	1	11860.88
2	39	1	2	5100.13	38	45	1	2	5076.91	74	98	1	2	7303.25
3	39	1	3	3411.37	39	45	1	3	3082.26	75	98	1	3	4816.93
4	39	1	4	2297.10	40	45	1	4	2272.82	76	98	1	4	3532.78
5	39	1	5	1762.82	41	45	1	5	1638.53	77	98	1	5	2734.58
6	39	1	6	1351.61	42	45	1	6	1261.73	78	98	1	6	2192.12
7	39	1	7	1082.03	43	45	1	7	989.00	79	98	1	7	1808.97
8	39	1	8	2418.24	44	45	1	8	1593.58	80	98	1	8	2400.79
9	39	1	9	3388.98	45	45	1	9	3221.19	81	98	1	9	3065.93
10	39	1	10	3902.94	46	45	1	10	3714.50	82	98	1	10	4026.87
11	39	1	11	4224.83	47	45	1	11	4923.40	83	98	1	11	3731.29
12	39	1	12	4610.40	48	45	1	12	5493.09	84	98	1	12	4562.70
13	39	2	1	5090.81	49	45	2	1	4747.11	85	98	2	1	7295.63
14	39	2	2	2289.16	50	45	2	2	2188.35	86	98	2	2	3540.06
15	39	2	3	1344.07	51	45	2	3	1255.67	87	98	2	3	3689.06
16	39	2	4	831.77	52	45	2	4	777.33	88	98	2	4	2687.60
17	39	2	5	535.52	53	45	2	5	477.23	89	98	2	5	2995.48
18	39	2	6	327.75	54	45	2	6	287.12	90	98	2	6	1623.12
19	39	2	7	181.85	55	45	2	7	140.82	91	98	2	7	1953.89
20	39	2	8	269.17	56	45	2	8	105.21	92	98	2	8	3125.48
21	39	2	9	305.56	57	45	2	9	158.56	93	98	2	9	2518.47
22	39	2	10	304.14	58	45	2	10	121.48	94	98	2	10	3205.51
23	39	2	11	296.01	59	45	2	11	140.72	95	98	2	11	3365.83
24	39	2	12	309.81	60	45	2	12	105.31	96	98	2	12	3811.99
25	39	3	1	3232.13	61	45	3	1	3217.77	97	98	3	1	4260.70
26	39	3	2	1348.31	62	45	3	2	1258.63	98	98	3	2	2205.77
27	39	3	3	1102.38	63	45	3	3	1045.09	99	98	3	3	1448.86
28	39	3	4	716.76	64	45	3	4	739.70	100	98	3	4	941.18
29	39	3	5	310.84	65	45	3	5	321.11	101	98	3	5	575.85
30	39	3	6	196.36	66	45	3	6	252.14	102	98	3	6	402.77
31	39	3	7	57.74	67	45	3	7	106.67	103	98	3	7	274.47
32	39	3	8	0.00	68	45	3	8	19.96	104	98	3	8	287.42
33	39	3	9	0.00	69	45	3	9	0.00	105	98	3	9	422.74
34	39	3	10	0.00	70	45	3	10	0.00	106	98	3	10	596.11
35	39	3	11	0.00	71	45	3	11	0.00	107	98	3	11	482.29
36	39	3	12	0.00	72	45	3	12	0.00	108	98	3	12	618.90

Figure 3.62: Screen shot of parameter scan and data explorer results summary in table view for trade study in Figure 3.

Algeria Target Area:

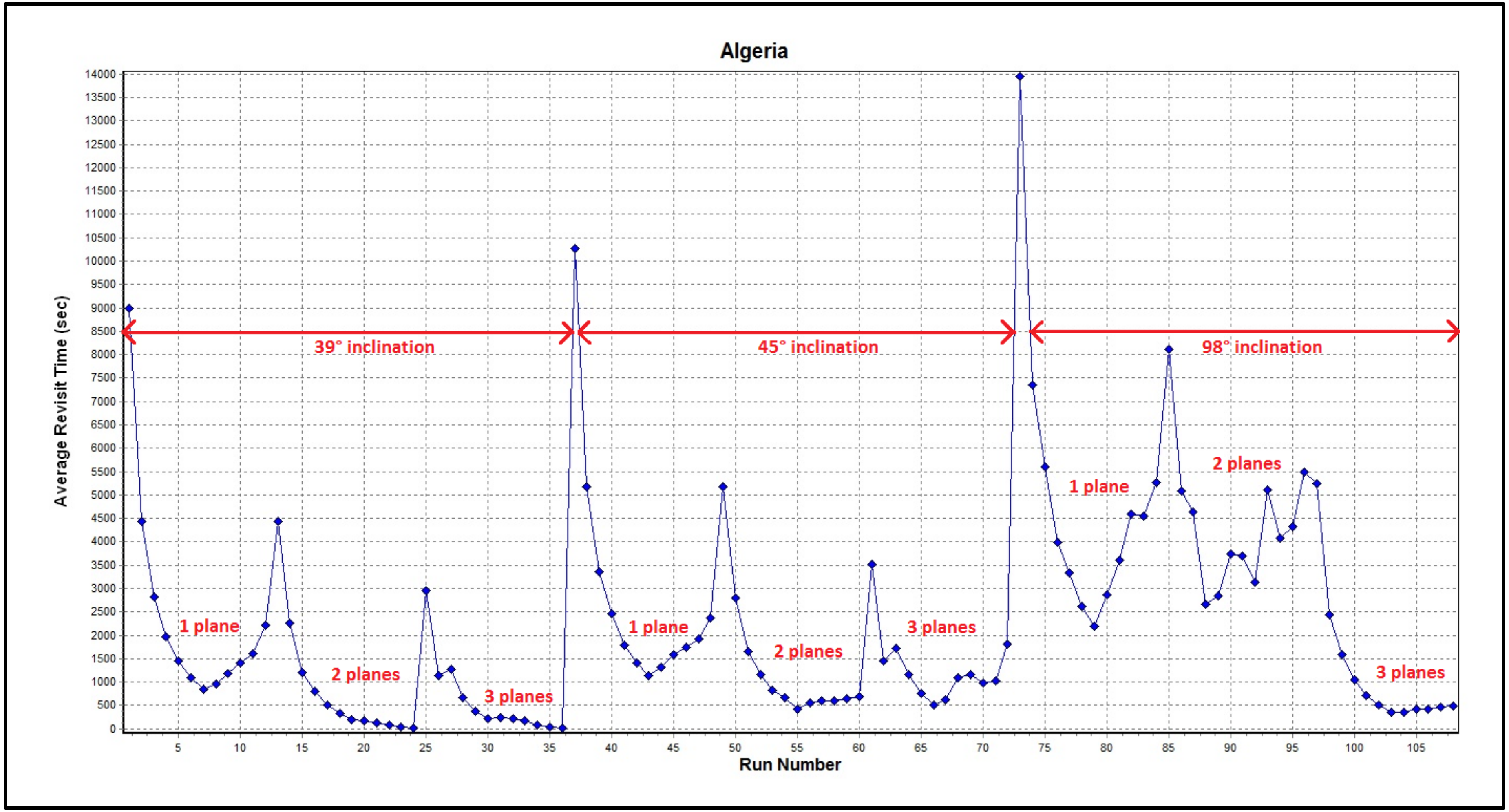

Figure 3.63: Average simulated revisit time for Algeria as a function of satellites per plane and inclination for the constellations considered

Kenya Target Area:

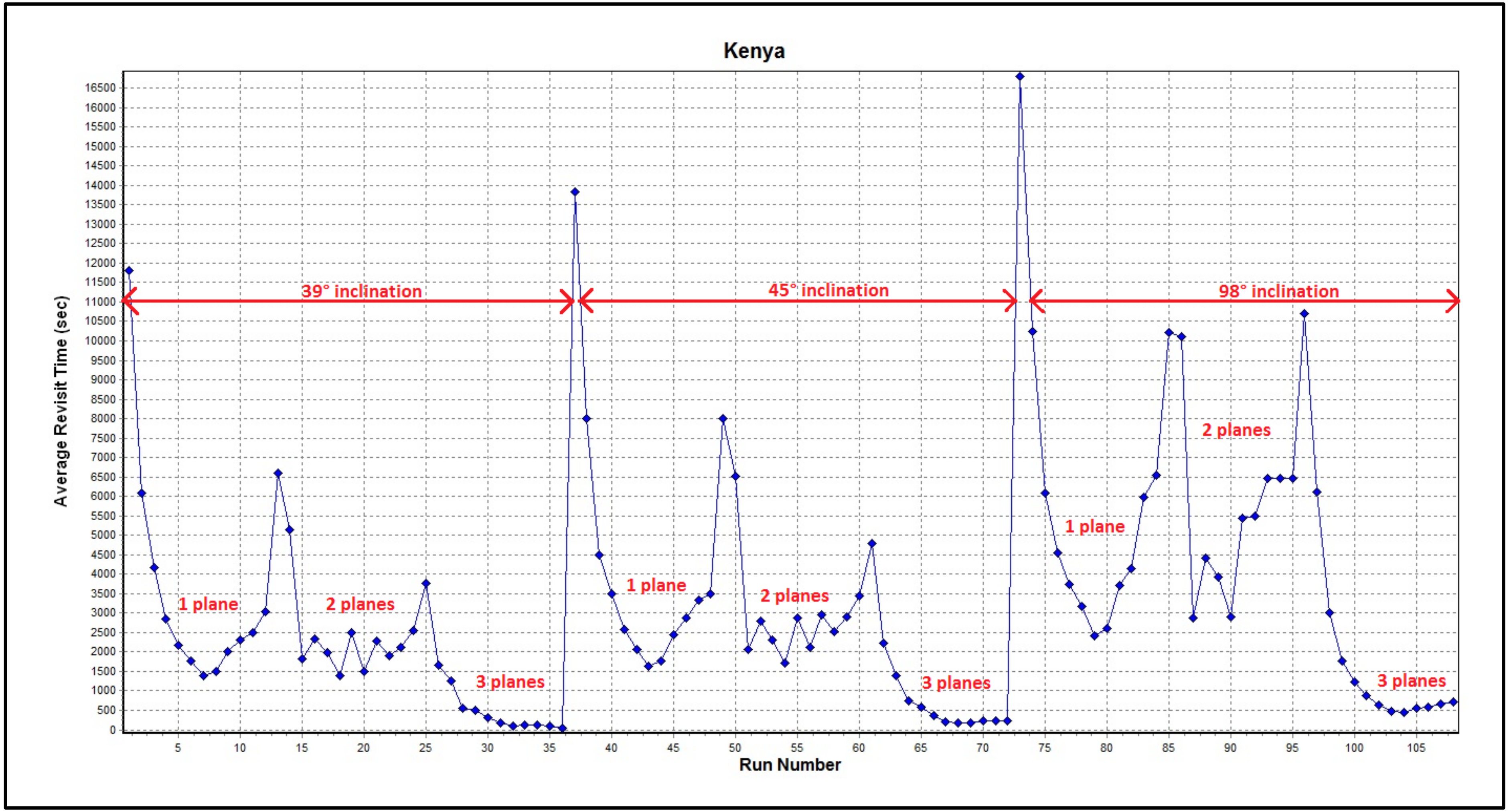

Figure 3.64: Average simulated revisit time for Kenya as a function of satellites per plane and inclination for the constellations considered

Nigeria Target Area:

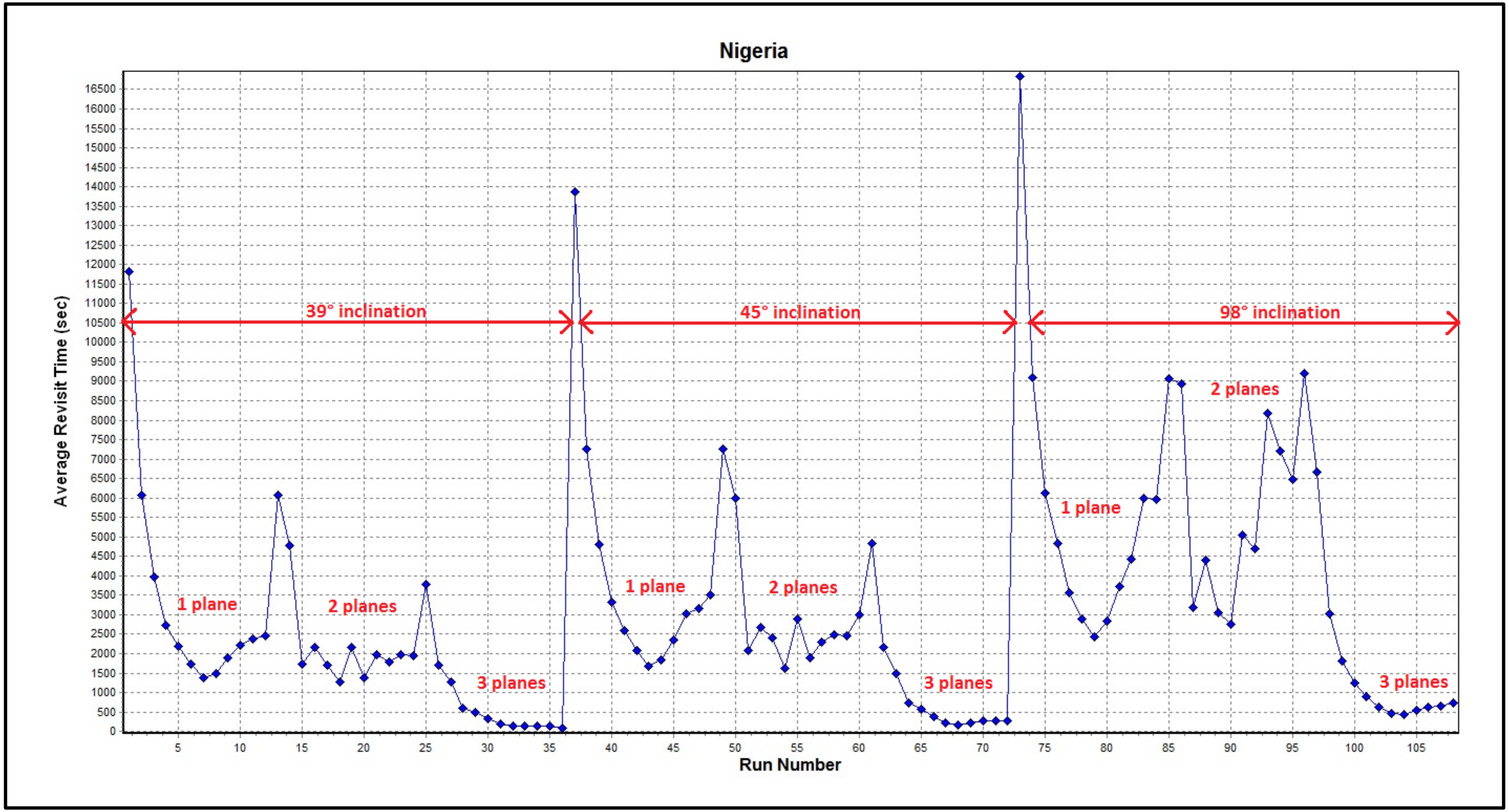

Figure 3.65: Average simulated revisit time for Nigeria as a function of satellites per plane and inclination for the constellations considered

Summary:

From the analyses presented in the aforegoing sections, the pertinent findings for the various geographic target are summarised in Table 3.3.

Table 3.3: Simulated average revisit times for geographic areas of interest

Geographic area	Constellation configuration (number of satellites x orbital planes)	Average revisit time (minutes)		
		39^0	45^0	98^0
South Africa	7 x 1	17	17	30
	6 x 2	5	5	27
	4 x 3	12	12	15
Algeria	12 x 1	15	18	35
	6 x 2	5	10	60
	4 x 3	11	19	17
Kenya	12 x 1	23	27	41
	6 x 2	23	28	60
	4 x 3	9	12	17
Nigeria	7 x 1	23	27	41
	6 x 2	21	9	46
	4 x 3	26	12	20

From Table 3.3 and the analysis results represented in Figure 3.61 to 3.65, the following findings can be made:

- For South African and Algeria
  - The 6x2 constellation configuration outperforms the 4x3 configuration for all inclinations;
  - At 39^o and 45^o inclinations, similar performance is achieved;
  - At 98^o inclination, the performance is comparatively poor; and
  - Revisit times of between 5 and 12 minutes are possible with 12 satellites in 6x2 or 4x3 constellation configurations for 39^o and 45^o inclinations; and
  - All configurations meet the required revisit time of 45 minutes.
- For Kenya
  - The 4x3 constellation configuration outperforms the 6x2 configuration for all inclinations with revisit times ranging from 9 to 17 minutes for all inclinations; and
  - The 6x2 configuration at an inclination of 98^o does not meet the required revisit time of 45 minutes.
- For Nigeria
  - The constellations at 45^o inclination yield improved revisit times compared to the other configurations;

  - All constellation configurations, except the 6x2 configuration at 98º inclination meet the required revisit time of 45 minutes.
- For all geographic areas considered
  - The revisit time for a single oribital plane constellation improves for up to 7 satellites per plane, whereafter there is no decrease. This is due to overlap of satellite footprints over the target areas, providing periods of continuous access rather than improving revisit time.

The observations reported in Section 3.2 lead us to Section 3.3 where an optimal design for the South African target area will be further evaluated.

3.3 OPTIMAL ORBIT DESIGN FOR SOUTH AFRICA

From the work above, the optimal constellation configuration for the South Africa target area is presented here. The ground station is assumed to be situated in Cape Town.

3.3.1 Primary selection criteria

The main criteria for selecting the optimal design are revisit time and total access time.

3.3.1.1 Total access time

Figure 3.66 shows the impact on total access time as a function of the number of satellites and orbital planes over a period of a day. The orbits have an inclination angle of 39°. As expected, the duration of access to a region of interest improves with an increase in both the number of satellites and orbital planes.

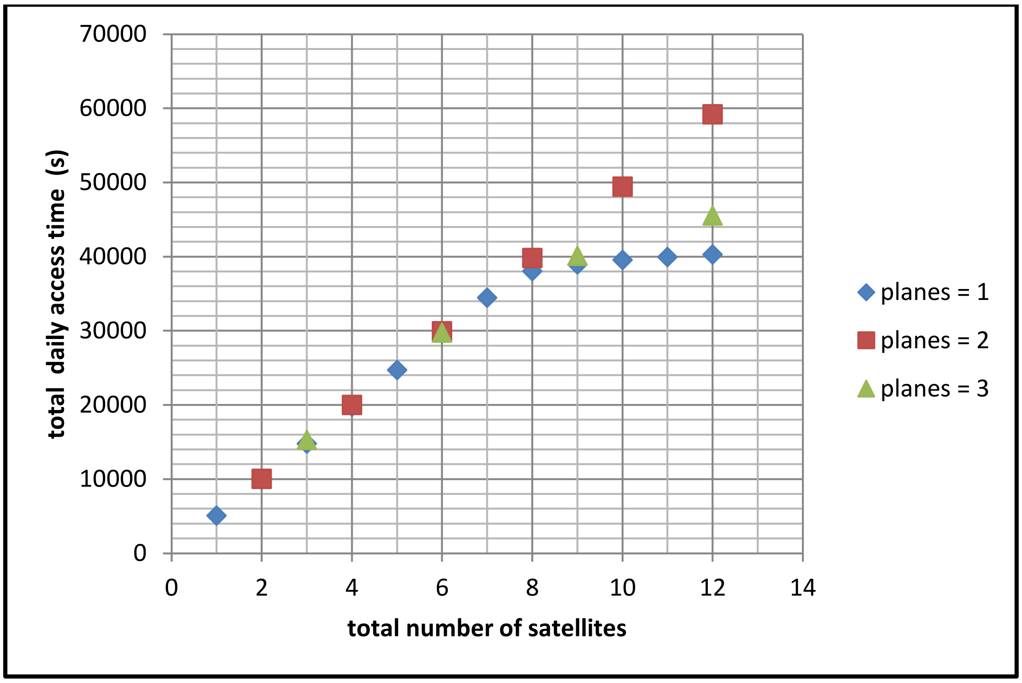

Figure 3.66: Total simulated daily access time for the Cape Town ground station as a function of satellites per plane for the constellations considered

3.3.1.2 Revisit time

The impact of the number of satellites and orbital planes on the average revisit time over a period of a day is depicted in Figure 3.67. The orbits have an inclination angle of 39°. The revisit time decreases with an increase in number of satellites and planes within a constellation.

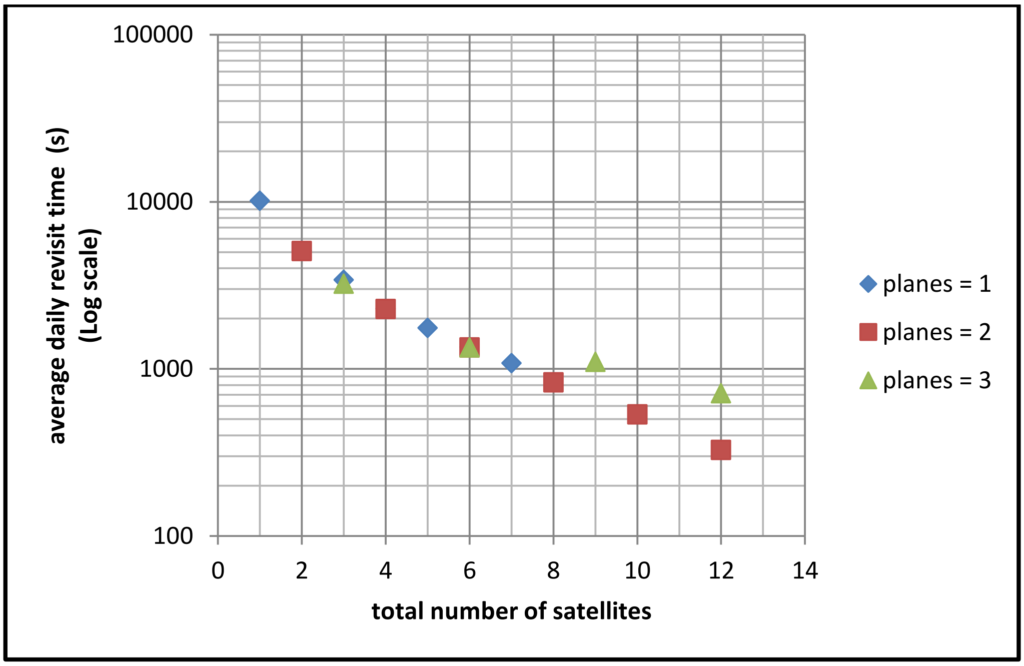

Figure 3.67: Average simulated daily revisit time for the Cape Town ground station as a function of satellites per plane for the constellations considered

As mentioned in the previous section, a constellation with a single orbital plane shows that up to 7 satellites per plane improve the average revisit time, whereas 8 or more satellites per plane do not reduce revisit time. This is caused by the overlap of satellite footprints to the target area when more satellites are added to a particular plane; thus, providing moments of continuous access rather than improving revisit time. (The performance of 8 or more satellites distributed over a single orbital plane is not presented in Figure 3.67.) The graphs show that using a higher number of satellites has the best temporal performance and distributing them over more planes optimises the performance.

3.3.2 Selection of optimum design and motivation

With reference to the graphs of access time and revisit time, the constellation configuration of two orbital planes with six satellites in each plane is best suitable for the mission objective. This configuration offers an improved average daily revisit time of approximately 300 seconds, while four satellites in three orbital planes is above 500 seconds. This makes the configuration with two planes the favourable one for the mission.

Figure 3.28 shows the simulated times of access between a constellation of six satellites in two orbital planes and the target areas, Algeria, Kenya, Nigeria, and South Africa. Each access has a mean duration of approximately 7 to 8 minutes. It can also be seen in Figure 3.66 that, on average, the satellite constellation with a total of twelve satellites in two orbital planes is visible for more than 16 hours/day, far exceeding that of the 4x3 constellation configuration.

The ground tracks of the 6x2 constellation configuration are presented in Figure 3.68.

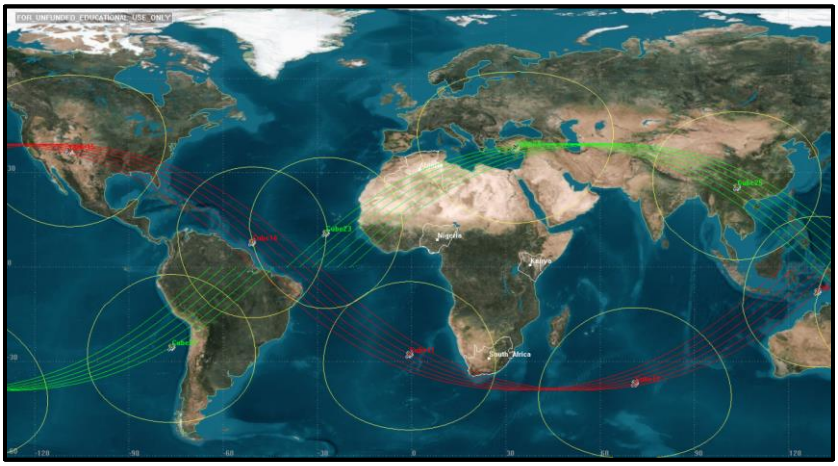

Figure 3.68: Ground tracks of a constellation of twelve satellites distributed over two orbital planes

Table 3.4 lists the satellite orbital elements for the Walker constellation of satellites.

Table 3.4: Satellite orbital elements for optimised constellation

Orbital planes	**Plane 1**	**Plane 2**
Altitude (km)	500	500
Inclination (°)	39	39
RAAN (°)	45	225
True Anomaly (°)	Satellites 1-6:	Satellites 7-12:
	0, 60, 120, 180, 240, 300	30, 90, 150, 210, 270, 330

3.4 SUMMARY

The temporal performance of various constellation configurations in terms of revisit and access times were investigated through simulation for all the geographic target areas. From the analyses of the simulations, a Walker configuration of 12 satellites distributed over 2 orbital planes at a 39^{o} inclination was selected as an optimum constellation configuration.

This configuration yields *average revisit times* of less than 45 minutes (2700 seconds) for all target areas, which is within the range specified in the objectives of the research. The South Africa and Algeria target areas experience *average daily access times* of more than 16 hours per day; the corresponding access times for the Kenya and Nigeria target areas are in excess of 7 hours per day.

These temporal characteristics of the optimum constellation configuration will be used in the design of the communications systems presented in the following chapter.

CHAPTER 4: COMMUNICATIONS SYSTEM DESIGN

4.1 INTRODUCTION

This chapter covers the communications system design for low bitrate sensor networks operating in the amateur frequency bands, specifically for the South African region. The frequencies investigated are VHF (145 MHz) and UHF (437 MHz) for sensor data uplink at both 1200 bps and 9600 bps bitrates using a Gaussian Minimum Shift Keying (GMSK) modulation scheme. For the data downlink from the satellite, a 9600 bps UHF link with GMSK modulation and 2 Mbps S-band link with QPSK modulation are considered. The chapter concludes with a data budget analyses for several sensor deployment scenarios.

4.2 SYSTEM REQUIREMENTS

Link budget calculations are performed in the following section to determine the feasibility of communications between sensors and satellites. This is followed by a data budget calculation in Section 4.2.2 for the maximum number of nodes in the satellites' footprints.

4.2.1 Amateur VHF/UHF band in-situ monitoring network link budget

This section covers the link budget calculations for the ground sensor uplink to the CubeSats and downlink to the ground station located in the Cape Town region. Two calculators for determining link budgets have been used; the AMSAT-IARU link model spreadsheet calculator[1] used by almost all CubeSat missions, and STK's built-in calculator. The link model spreadsheet calculator determines the link budget for the uplink and downlink designs for the worst-case scenario.

The satellite-based system collects data from ground sensors and relays it to the ground station. Transmitters are attached to sensors from which data is collected by the satellites in the constellation. Low power consumption of the sensors is obtainable due to the satellites' low Earth orbit and the relatively high sensitivity of receivers. Ground sensors communicate with a CubeSat at an orbital height of about 500 km. On receiving the packet data from the ground sensor, the telecommand and sensor packets are treated separately at all times. The satellite that is visible to the ground station downlinks the data to the ground station.

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[1] Link model spreadsheet calculator was developed by Jan A. King for the Radio Amateur Satellite Corporation (AMSAT) and the International Amateur Radio Union (IARU).

Tables 4.1, 4.2 and 4.3 list the performance specifications, respectively, of the VHF/UHF receiver, VHF/UHF transmitter and S-band transmitter that have been developed at CPUT (Clyde Space, n.d.). The link calculations are based on these specifications.

Table 4.1: VHF/UHF receiver specifications

DC Power	< 250 mW
Sensitivity	130 – 150 MHz / 420 – 450 MHz, -120 dBm for 12 dB SINAD
Noise Figure	< 1.5 dB
Channel Spacing	25 kHz
Spurious Response	<-65 dBc
Dynamic Range	-120 dBm to -70 dBm
Frequency Stability	± 50 ppm
Modulation (1200 baud)	AFSK
Modulation (9600 baud)	GMSK

Table 4.2: VHF/UHF transmitter specifications

DC Power	4 – 10 W (27 – 33 dBm)
Frequency	130 – 150 MHz / 420 – 450 MHz
RF Power	27 – 33 dBm (3 dBm steps)
Channel Spacing	25 kHz
Spurious Response	<-65 dBc
Frequency Deviation	3 kHz (FM)
Frequency Stability	± 50 ppm
Modulation (1200 baud)	AFSK
Modulation (9600 baud)	GMSK
Protocol	AX.25

Table 4.3: S-band transmitter characteristics

DC Power	< 5 W (30 dBm)
Frequency	2.4 - 2.483 GHz
RF Power	24 – 30 dBm
Channel spacing	500 kHz
Transmission data rate	Up to 1 Mbps
Spurious Response	<-60 dBc
SNR	> 20 dB
Frequency Stability	± 2.5 ppm
Output return loss	7 dB
Modulation	QPSK

4.2.1.1 Sensor data uplink communication

The link budget is calculated to ensure that communication is obtainable, with the satellite considered at 5° above the horizon (the lowest elevation to satisfy the link budget). The ground sensor antenna system does not include tracking capabilities, and are assumed to be dipole antennas.

(1) *VHF uplink at 9600 bps:*

Link budget: AMSAT-IARU Link Model

The orbital parameters for the worst-case link margin, where the satellite is at 5º elevation, is shown in Figure 4.1 The maximum range between the sensors and the satellite where the link budget must still be satisfied, is given by the slant range (2078 km).

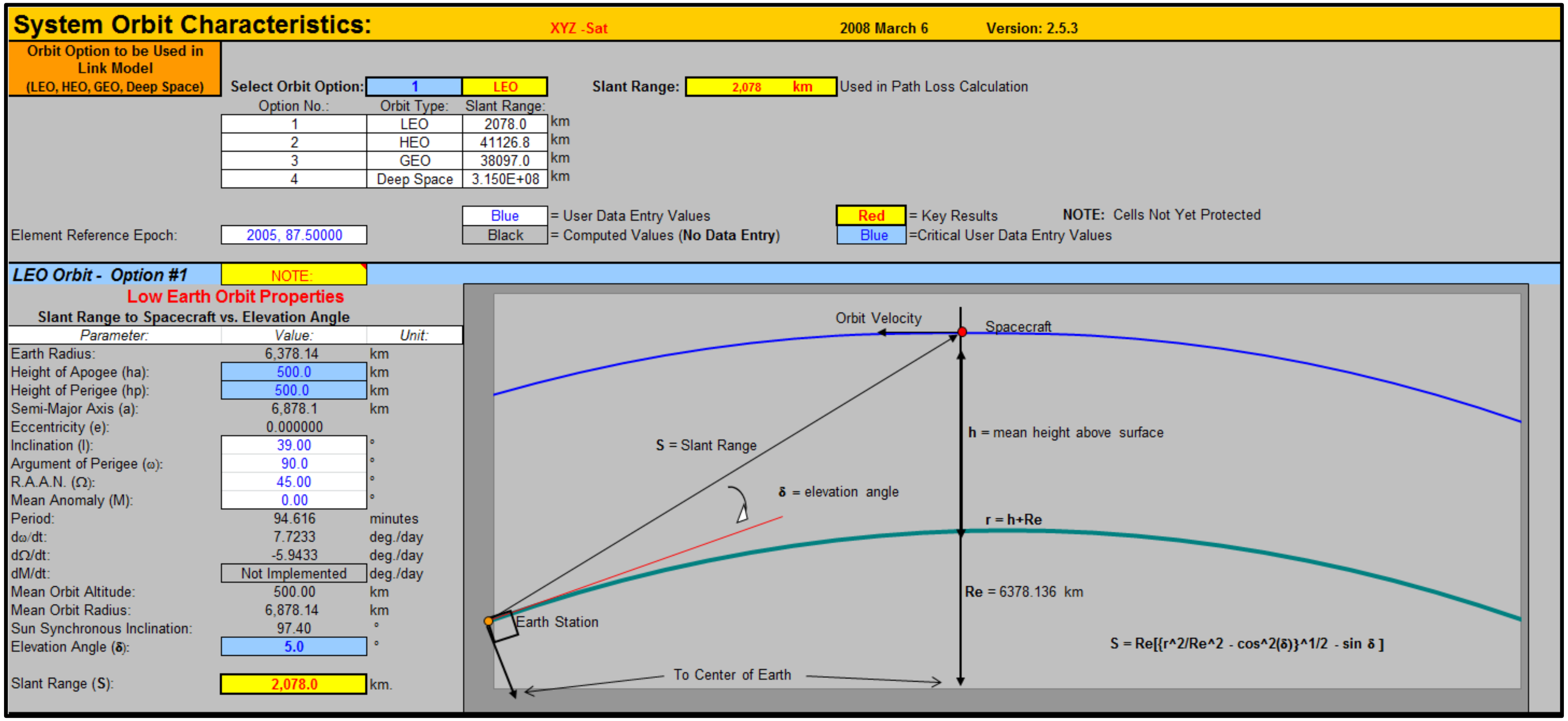

Figure 4.1: E_b/N_o result for VHF at 9600 bps for the satellite passing over a ground sensor located in South African

Table 4.4 summarises the ground sensor link budget calculations.

Table 4.4: Link budget for ground sensor VHF uplink at 9600 bps (AMSAT-IARU Link Model)

Parameter:	Value:	Units:
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	1.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	9	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	1	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	9600	bps
In dBHz:	39.8	dBHz
Command System Eb/No:	12.1	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	3.6	dB

The Link Model spreadsheet calculator considers various link losses, including ground-to-satellite antenna polarisation, atmospheric, ionospheric and rain. The GMSK modulation option is selected. The corresponding E_b/N_o threshold is 8.5 dB for a bit error rate of 1×10^{-4} (refer to Figure 2.6).

A link margin of 3.6 dB is expected, which is acceptable and implies that communications will be reliable for the VHF 9600 bps uplink.

Link budget: STK

In order for the STK calculator to compute a link budget, several input parameters as listed in Table 4.5 are required to simulate the link performance.

Table 4.5: STK link budget calculator input parameters

Model Type	
Transmitter/Receiver Model	Complex Transmitter Model
Model Specification	
Frequency	145/437 MHz
Power	6 W
Antenna Gain	3 dB
Data Rate	1k2/9k6 bps
Modulator	
Name	GMSK
Signal Bandwidth	25 kHz
Filter Type	Butterworth
Additional Gains and Losses	
Total Extra Losses	1.8 dB
Model Type	
Transmitter/Receiver Model	Receiver
Model Specification	
Frequency	145/437 MHz
Antenna to LNA Line Loss	1 dB
LNA Gain	18 dB
LNA to Receiver Line Loss	1 dB
Link Margin	
Type	E_b/N_o
Threshold	8.5 dB
System Noise Temperature	
LNA Noise Figure	2 dB
Temperature	382 K

The ground sensor and CubeSat antennas, transmitters and receivers have been modeled using the communications module in STK. The module also computes antenna noise temperature, which has an effect on link performance, and antenna gains based on the tumbling CubeSat's attitude. The energy per bit to noise spectral density (E_b/N_o) ratio is computed, given transmitter power, data rates, and receiver noise temperature.

The link performance is affected by the slant range between the satellite and sensors, which varies as a function of satellite elevation angle. The STK link budget computations take into consideration this variation. Figure 4.2 shows the calculated E_b/N_o for the uplink as the CubeSat moves from horizon to horizon for a single overpass (as a function of time). For clarity, Figure 4.3 illustrates the main simulated results as a function of elevation angle.

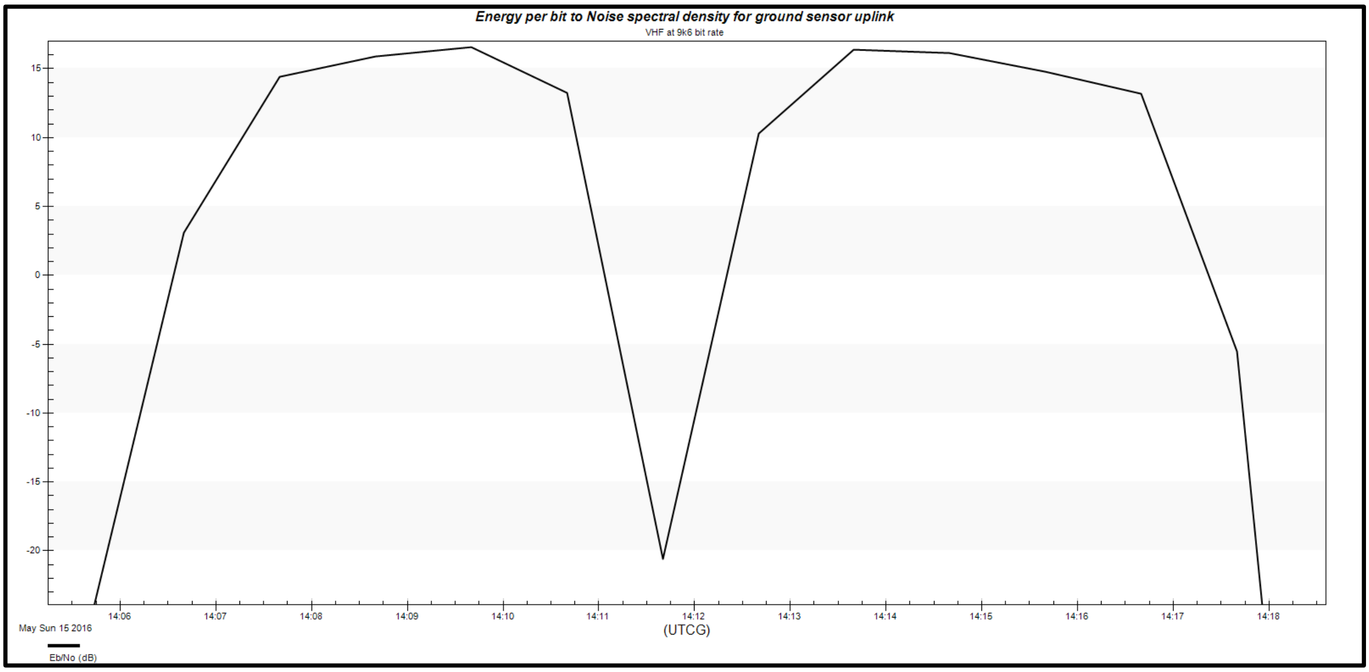

Figure 4.2: Simulated *Eb/No* for VHF 9600 bps uplink for the satellite passing over a ground sensor located in South Africa

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Facility-Ground_Sensor_SA-Transmitter-TransmitterGS_SA-To-Satellite-ZACube1_-Receiver-Receiver_CubeSat

Elevation (deg)	Xmtr Power (dBW)	Xmtr Gain (dB)	EIRP (dBW)	Rcvd. Frequency (MHz)	Eb/No (dB)	Link Margin (dB)	BER
-0.111	7.782	3.0055	10.787	145.003	-25.7813	-34.1813	4.710281e-001
3.831	7.782	2.9546	10.736	145.003	3.1082	-5.2918	2.155322e-002
8.730	7.782	2.7414	10.523	145.003	14.4362	6.0362	4.564306e-014
15.383	7.782	2.1873	9.969	145.003	15.8986	7.4986	5.746468e-019
25.705	7.782	0.7333	8.515	145.003	16.6200	8.2200	4.702077e-022
44.940	7.782	-3.8398	3.942	145.002	13.3615	4.9615	2.266093e-011
83.362	7.782	-24.3001	-16.519	145.000	-20.3290	-28.7290	4.458453e-001
52.620	7.782	-6.3343	1.447	144.998	10.4407	2.0407	1.270102e-006
29.512	7.782	0.0181	7.800	144.997	16.4143	8.0143	4.024516e-021
17.663	7.782	1.9279	9.709	144.997	16.1741	7.7741	4.365620e-020
10.341	7.782	2.6351	10.417	144.997	14.8122	6.4122	3.553298e-015
5.103	7.782	2.9152	10.697	144.997	13.1860	4.7860	5.453548e-011
0.966	7.782	3.0023	10.784	144.997	-5.4876	-13.8876	2.260675e-001
-0.111	7.782	3.0055	10.787	144.997	-25.8539	-34.2539	4.712687e-001

Figure 4.3: Screen shot of link budget report for the communications link in Figure 4.2

From Figure 4.3 it is evident that a link margin of greater than 3 dB is satisfied for elevation angles around 5^{o}, which is in agreement with the AMSAT-IARU Link Model.

(2) *VHF uplink at 1200 bps:*

Link budget: AMSAT-IARU Link Model

Table 4.6 summarises the ground sensor link budget calculations.

Table 4.6: Link budget for ground sensor VHF uplink at 1200 bps (AMSAT-IARU Link Model)

Parameter:	Value:	Units:
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	1.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	9	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	1	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	1200	bps
In dBHz:	30.8	dBHz
Command System Eb/No:	21.1	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	12.6	dB

A link margin of 12.6 dB is expected, which is considerably better than for the 9600 bps uplink, and implies that communications will be reliable for the VHF 1200 bps uplink.

Link budget: STK

Figures 4.4 and 4.5 illustrate the simulated E_b/N_o for the uplink as the CubeSat moves from horizon to horizon over a single overpass (as a function of time and elevation angle, respectively).

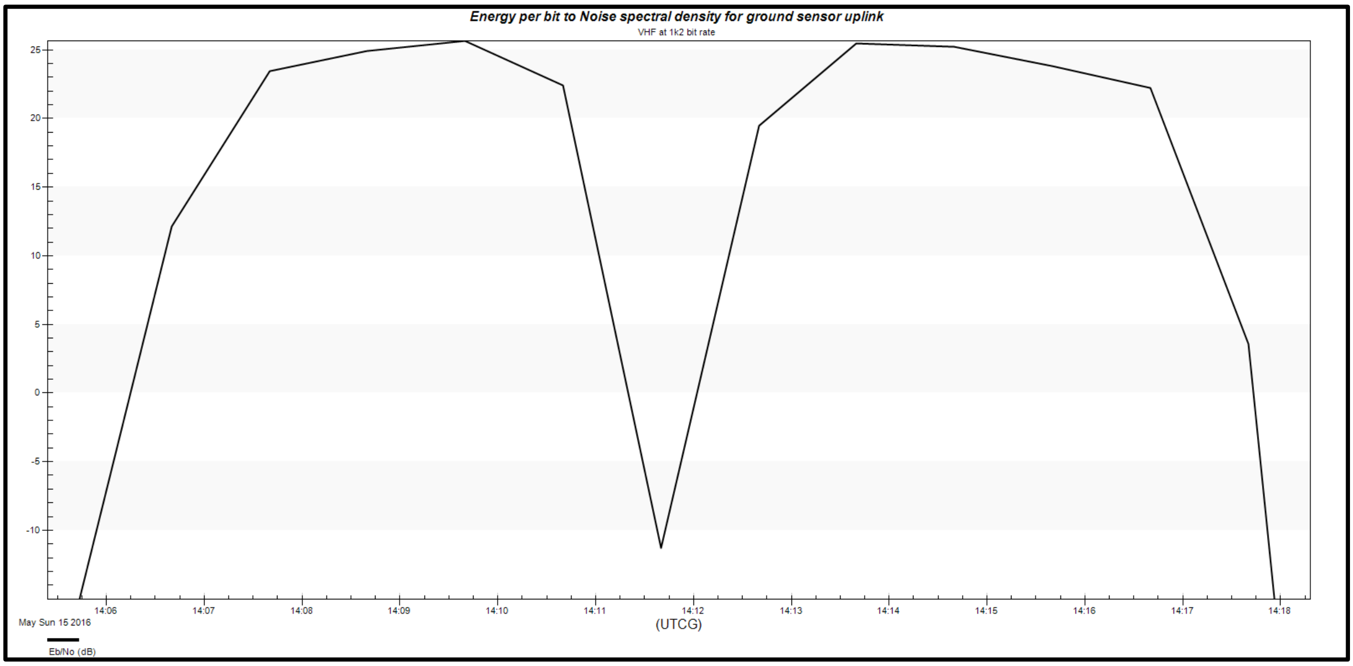

Figure 4.4: Simulated E_b/N_o for VHF 1200 bps uplink for the satellite passing over a ground sensor located in South Africa

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Facility-Ground_Sensor_SA-Transmitter-TransmitterGS_SA-To-Satellite-ZACube1_-Receiver-Receiver_CubeSat

Elevation (deg)	Xmtr Power (dBW)	Xmtr Gain (dB)	EIRP (dBW)	Rcvd. Frequency (MHz)	Eb/No (dB)	Link Margin (dB)	BER
-0.111	7.782	3.0055	10.787	145.003	-17.7504	-26.1504	4.273091e-001
3.831	7.782	2.9546	10.736	145.003	11.1391	2.7391	1.708686e-007
8.730	7.782	2.7414	10.523	145.003	22.4671	14.0671	1.000000e-030
15.383	7.782	2.1873	9.969	145.003	23.9295	15.5295	1.000000e-030
25.705	7.782	0.7333	8.515	145.003	24.6509	16.2509	1.000000e-030
44.940	7.782	-3.8398	3.942	145.002	21.3924	12.9924	1.000000e-030
83.362	7.782	-24.3001	-16.519	145.000	-12.2981	-20.6981	3.657050e-001
52.620	7.782	-6.3343	1.447	144.998	18.4716	10.0716	1.000000e-030
29.512	7.782	0.0181	7.800	144.997	24.4452	16.0452	1.000000e-030
17.663	7.782	1.9279	9.709	144.997	24.2050	15.8050	1.000000e-030
10.341	7.782	2.6351	10.417	144.997	22.8431	14.4431	1.000000e-030
5.103	7.782	2.9152	10.697	144.997	21.2169	12.8169	1.000000e-030
0.966	7.782	3.0023	10.784	144.997	2.5433	-5.8567	2.902509e-002
-0.111	7.782	3.0055	10.787	144.997	-17.8230	-26.2230	4.279073e-001

Figure 4.5: Screen shot of link budget report for the communications link in Figure 4.4

Comparing the simulated E_b/N_o values presented in Figure 4.2 and 4.4, it is evident that the 1200 bps link has a link margin of about 8 dB more than that of the 9600 bps link. This is also in agreement with the AMSAT-IARU Link Model where an improvement in link margin of 9 dB was calculated.

(3) *UHF uplink at 9600 bps:*

Link budget: AMSAT-IARU Link Model

Table 4.7 summarises the ground sensor link budget calculations.

Table 4.7: Link budget for ground sensor UHF uplink at 9600 bps (AMSAT-IARU Link Model)

Parameter:	*Value:*	*Units:*
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	1.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	9	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	151.6	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.4	dB
Rain Losses:	1	dB
Isotropic Signal Level at Spacecraft:	-146.4	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	42.7	dBHz
System Desired Data Rate:	9600	bps
In dBHz:	39.8	dBHz
Command System Eb/No:	2.8	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	-5.7	dB

From Table 4.7 it is evident that the link budget for the UHF 9600 bps uplink does not give a satisfactory E_b/N_o result, with a -5.7 dB link margin at 5° elevation.

Link budget: STK

Figures 4.6 and 4.7 illustrate the simulated E_b/N_o for the uplink.

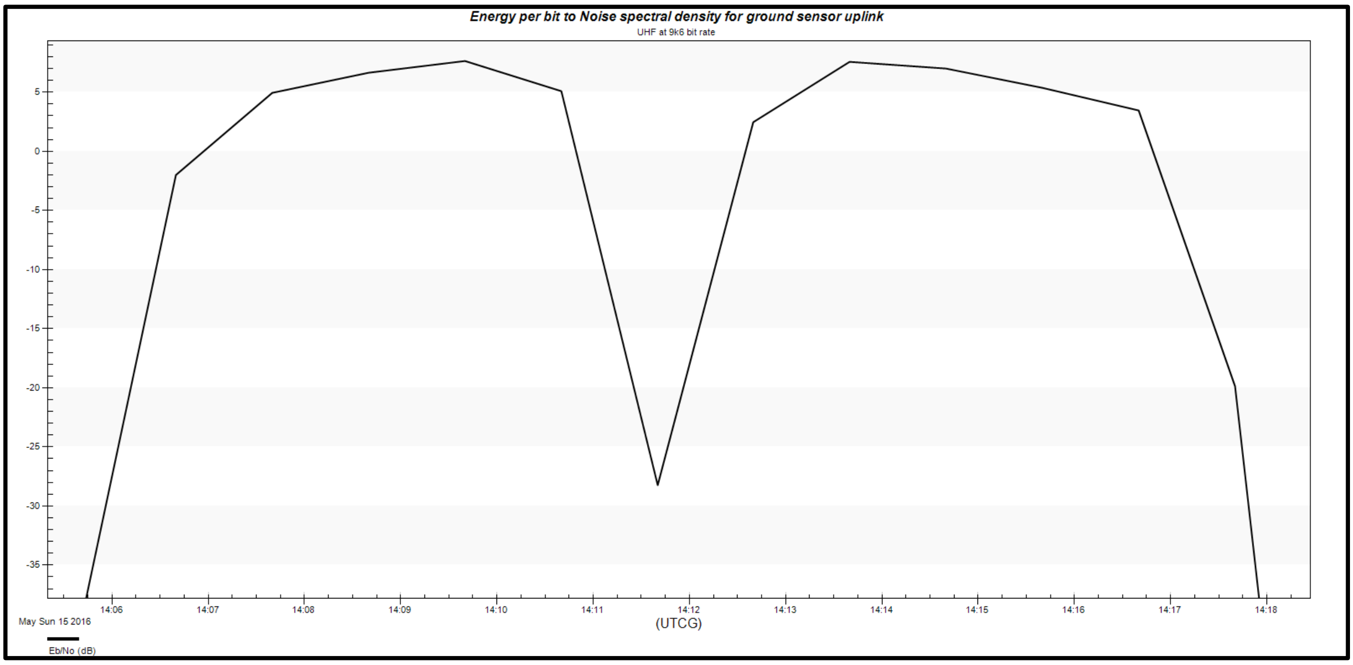

Figure 4.6: Simulated E_b/N_o for UHF 9600 bps uplink for the satellite passing over a ground sensor located in South Africa

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Facility-Ground_Sensor_SA-Transmitter-TransmitterGS_SA-To-Satellite-ZACube1_-Receiver-Receiver_CubeSat

Elevation (deg)	Xmtr Power (dBW)	Xmtr Gain (dB)	EIRP (dBW)	Rcvd. Frequency (MHz)	Eb/No (dB)	Link Margin (dB)	BER
-0.111	7.782	3.0272	10.809	437.010	-40.4186	-48.8186	4.946237e-001
3.831	7.782	2.9757	10.757	437.010	-1.9910	-10.3910	1.303973e-001
8.730	7.782	2.7600	10.541	437.010	4.9592	-3.4408	6.155962e-003
15.383	7.782	2.1990	9.981	437.009	6.6339	-1.7661	1.201303e-003
25.705	7.782	0.7269	8.508	437.009	7.6499	-0.7501	3.224386e-004
44.940	7.782	-3.9043	3.877	437.007	5.0616	-3.3384	5.658109e-003
83.362	7.782	-24.5131	-16.732	437.001	-28.2540	-36.6540	4.781975e-001
52.620	7.782	-6.4300	1.351	436.994	2.4317	-5.9683	3.066528e-002
29.512	7.782	0.0027	7.784	436.992	7.5607	-0.8393	3.662289e-004
17.663	7.782	1.9364	9.718	436.991	6.9703	-1.4297	8.018556e-004
10.341	7.782	2.6523	10.434	436.990	5.3955	-3.0045	4.243898e-003
5.103	7.782	2.9359	10.717	436.990	3.4813	-4.9187	1.736682e-002
0.966	7.782	3.0240	10.806	436.990	-19.8909	-28.2909	4.430624e-001
-0.111	7.782	3.0272	10.809	436.990	-40.5334	-48.9334	4.946943e-001

Figure 4.7: Screen shot of link budget report for the communications link in Figure 4.6

From Figure 4.6 and 4.7 it is clear that a satisfactory link margin is not achieved *at any elevation*; hence, the UHF 9600 bps uplink is not viable for uplinking sensor data from the South African geographic area.

(4) *UHF uplink at 1200 bps:*

Link budget: AMSAT-IARU Link Model

Table 4.8 summarises the ground sensor link budget calculations.

Table 4.8: Link budget for ground sensor UHF uplink at 1200 bps (AMSAT-IARU Link Model)

Parameter:	*Value:*	*Units:*
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	1.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	9	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	151.6	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.4	dB
Rain Losses:	1	dB
Isotropic Signal Level at Spacecraft:	-146.4	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	42.7	dBHz
System Desired Data Rate:	1200	bps
In dBHz:	30.8	dBHz
Command System Eb/No:	11.9	dB
Demodulation Method Seleted:	**GMSK**	
Forward Error Correction Coding Used:	**None**	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**3.4**	dB

A link margin of 3.4 dB is expected, which is acceptable and implies that communications will be reliable for the UHF 1200 bps uplink.

Link budget: STK

Figures 4.8 and 4.9 illustrate the simulated E_b/N_o for the uplink.

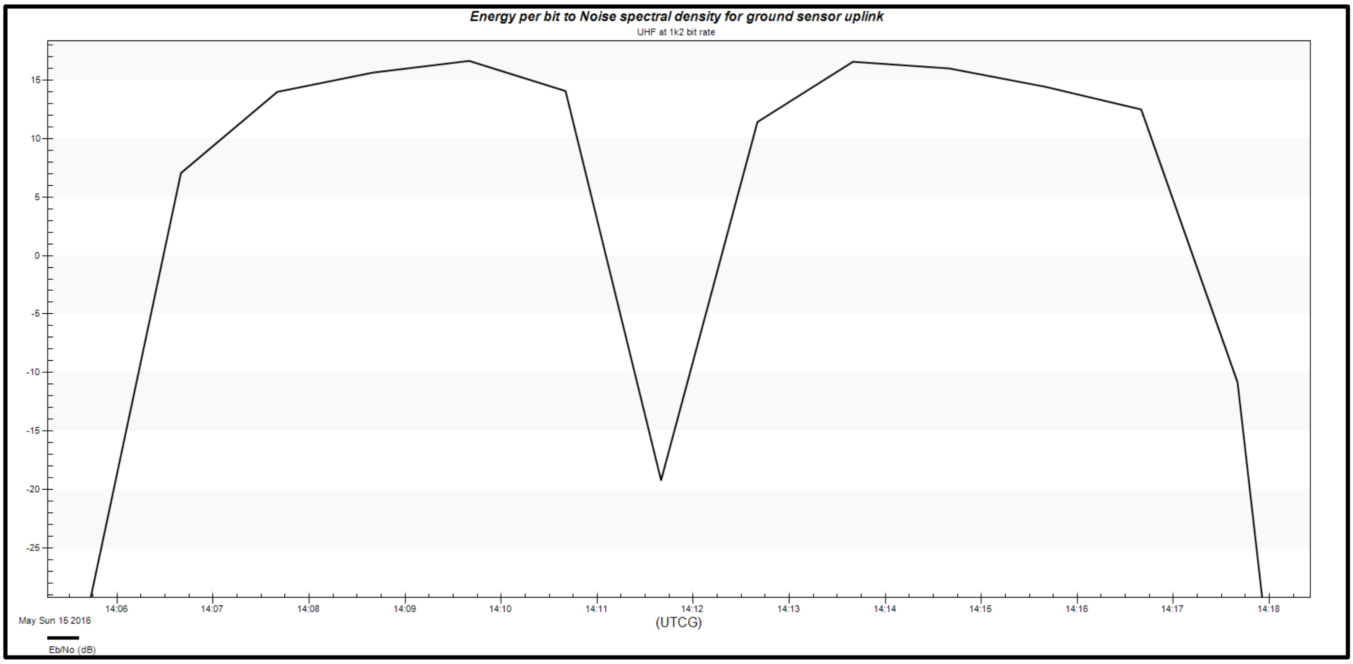

Figure 4.8: Simulated E_b/N_o for UHF 1200 bps for the satellite passing over a ground sensor located in South Africa

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Facility-Ground_Sensor_SA-Transmitter-TransmitterGS_SA-To-Satellite-ZACube1_-Receiver-Receiver_CubeSat

Elevation (deg)	Xmtr Power (dBW)	Xmtr Gain (dB)	EIRP (dBW)	Rcvd. Frequency (MHz)	Eb/No (dB)	Link Margin (dB)	BER
-0.111	7.782	3.0272	10.809	437.010	-31.3877	-39.7877	4.847967e-001
3.831	7.782	2.9757	10.757	437.010	7.0399	-1.3601	7.348312e-004
8.730	7.782	2.7600	10.541	437.010	13.9901	5.5901	7.219860e-013
15.383	7.782	2.1990	9.981	437.009	15.6648	7.2648	4.531855e-018
25.705	7.782	0.7269	8.508	437.009	16.6808	8.2808	2.443495e-022
44.940	7.782	-3.9043	3.877	437.007	14.0925	5.6925	3.924072e-013
83.362	7.782	-24.5131	-16.732	437.001	-19.2231	-27.6231	4.385475e-001
52.620	7.782	-6.4300	1.351	436.994	11.4626	3.0626	6.039926e-008
29.512	7.782	0.0027	7.784	436.992	16.5916	8.1916	6.362478e-022
17.663	7.782	1.9364	9.718	436.991	16.0012	7.6012	2.241809e-019
10.341	7.782	2.6523	10.434	436.990	14.4264	6.0264	4.866094e-014
5.103	7.782	2.9359	10.717	436.990	12.5122	4.1122	1.171216e-009
0.966	7.782	3.0240	10.806	436.990	-10.8600	-19.2600	3.427176e-001
-0.111	7.782	3.0272	10.809	436.990	-31.5025	-39.9025	4.849963e-001

Figure 4.9: Screen shot of link budget report for the communications link in Figure 4.8

From Figures 4.8 and 4.9 it can be seen that a satifactory link margin is achievable for elevation angles around 5^{o}, which is in agreement with AMSAT-IARU Link Model.

(5) *Data uplink performance summary:*

The performance of the four cases of data uplinks described above is summarised in Table 4.9.

Table 4.9: Data uplink performance summary

		Theoretical Result		AMSAT- IARU Link Model		Satellite Tool Kit	
Band	**Data rate [bps]**	E_b/N_o **[dB]**	**Link margin [dB]**	E_b/N_o **[dB]**	**Link margin [dB]**	E_b/N_o **[dB]**	**Link margin [dB]**
VHF	9600	15.9	7.4	12.1	3.6	14.4	6.0
	1200	24.9	16.4	21.1	12.6	12.4	14.1
UHF	9600	6.7	-1.8	2.8	-5.7	5.0	-3.4
	1200	15.7	7.3	11.9	3.4	14.0	5.6

Also shown are the performance results based on the theoretical link model presented in Chapter 2. Generally, all models are in agreement, showing that the UHF 9600 bps data uplink is not feasible for low data rate in-situ monitoring applications with sensors in the South African geographical region. Improved link performance is obtained at VHF than at UHF.

The theoretical model consistently predicts improved link margins than for the other two models (between 1.4 dB to 3.9 dB improvement). This is primarily ascribed to additional link losses being incorporated into the AMSAT-IARU and STK models.

The simulations presented in this section considered the VHF and UHF communications links for sensors in South Africa and a single satellite in oribit. Appendix A presents a performance summary of a VHF 9600 bps uplink from sensors across the other geographic areas to a constellation of a total number of 12 satellites in 2 planes. The link, based on the VHF communications systems developed at CPUT, is found to be feasible for all regions.

4.2.1.2 Data downlink communication

The data collected by the satellites is sent down to the ground station. This section analyses the performance of a 9600 bps UHF and 2 Mbps S-band downlink that will be used to download the accumulated data. The link margin is again determined for the worst case scenario where the satellite is at 5° elevation, which translates into a 2100 km slant range as previously calculated (see Figure 4.1).

The calculations are again based on the technology developed at CPUT (see Tables 4.2 and 4.3). For the ground station, a UHF antenna with gain 18.9 dBi and an S-band dish with gain 33 dBi are assumed, which are typical for commercial off-the-shelf antennas used in university ground stations. An S-band patch antenna with 7 dBi gain is used at the transmit side on the satellite. For the downlink, a BER of 10^{-5} is required, which translates into a threshold E_b/N_o of 9.6 dB (see Figure 2.6).

(1) *UHF downlink at 9600 bps:*

Link budget: AMSAT-IARU Link Model

Table 4.10 summarises the link budget calculations for the data downlink.

Table 4.10: Link budget for ground sensor UHF uplink at 9600 bps (AMSAT-IARU Link Model)

Parameter:	*Value:*	*Units:*
Spacecraft:		
Spacecraft Transmitter Power Output:	2	watts
In dBW:	3	dBW
In dBm:	33	dBm
Spacecraft Total Transmission Line Losses:	2.6	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft EIRP:	-9.6	dBW
Downlink Path:		
Spacecraft Antenna Pointing Loss:	0.5	dB
S/C-to-Ground Antenna Polarization Loss:	3	dB
Path Loss:	151.6	dB
Atmospheric Loss:	2.1	dB
Ionospheric Loss:	0.4	dB
Rain Loss:	0	dB
Isotropic Signal Level at Ground Station:	-167.2	dBW
Ground Station (EbNo Method):		
------- Eb/No Method -------		
Ground Station Antenna Pointing Loss:	0.3	dB
Ground Station Antenna Gain:	18.9	dBi
Ground Station Total Transmission Line Losses:	1.7	dB
Ground Station Effective Noise Temperature:	175	K
Ground Station Figure of Merrit (G/T):	-5.3	dB/K
G.S. Signal-to-Noise Power Density (S/No):	55.8	dBHz
System Desired Data Rate:	9600	bps
In dBHz:	39.8	dBHz
Telemetry System Eb/No for the Downlink:	16	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-05	
Demodulator Implementation Loss:	0	dB
Telemetry System Required Eb/No:	9.6	dB
Eb/No Threshold:	9.6	dB
System Link Margin:	**6.4**	dB

A link margin of 6.4 dB is expected, which is acceptable and implies that communications will be reliable for the UHF 9600 bps downlink.

Link budget: STK

In order for the STK calculator to compute a link budget, several input parameters as listed in Table 4.11 are required to simulate the link performance.

Table 4.11: STK input parameters

Model Type	
Transmitter/Receiver Model	Medium Transmitter Model
Model Specification	
Frequency	427 MHz / 2.4 GHz
Power	2 W / 1 W
Antenna gain	-10 dB / 7 dB
Data Rate	9600 / 2x10^6 bps
Modulator	
Name	MSK / QPSK
Signal Bandwidth	25 / 500 kHz
Additional Gains and Losses	
Total Extra Losses	2.8 dB
Model Type	
Transmitter/Receiver Model	Transmitter
Model Specification	
Frequency	427 MHz / 2.4 GHz
Antenna to LNA Line Loss	1.48 dB
LNA Gain	15 dB
LNA to Receiver Line Loss	5.0 dB
Link Margin	
Type	E_b/N_o
Threshold	9.6 dB
System Noise Temperature	
LNA Noise Figure	1.2 dB
Temperature	175 K

Figures 4.10 and 4.11 illustrate the simulated E_b/N_o for the UHF data downlink as the satellite passes over the ground station in South Africa.

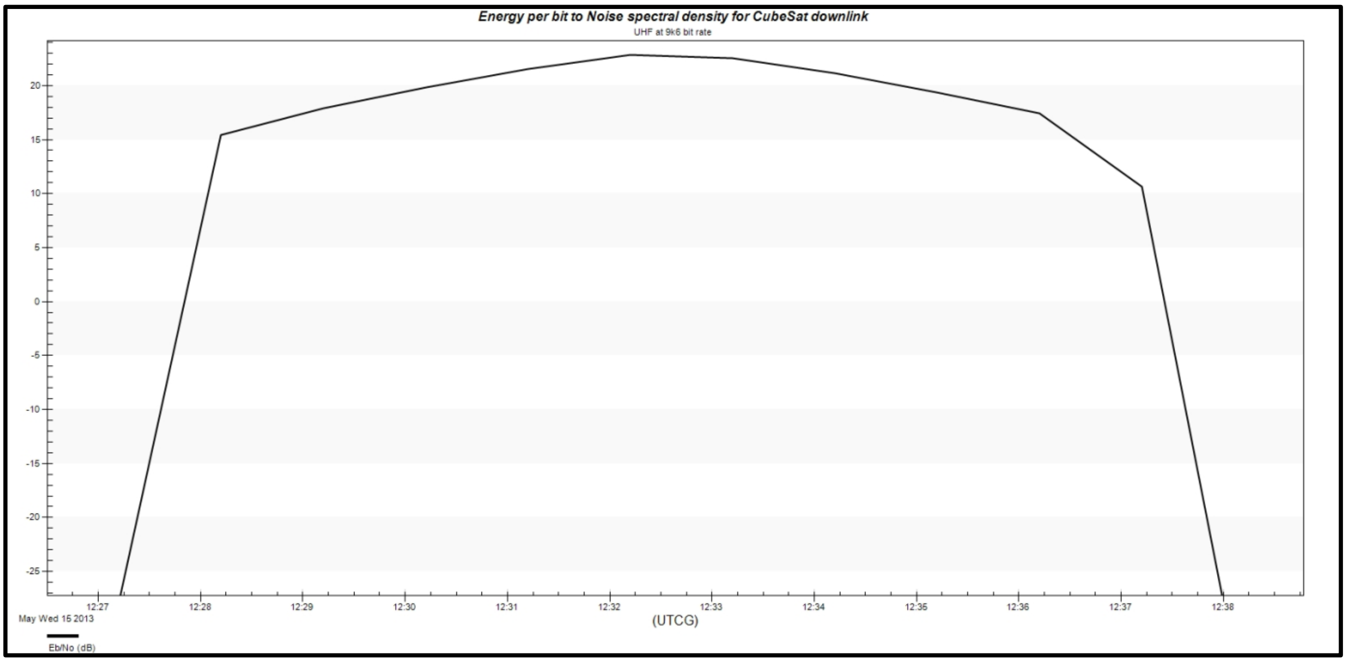

Figure 4.10: Simulated E_b/N_o for UHF 9600 bps downlink for the satellite passing over the ground station located in Cape Town

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Satellite-ZACube1_500-Transmitter-Transmitter_500-To-Facility-Ground_StationES_CT-Receiver-ReceiverES

Time (UTCG)	EIRP (dBW)	Free Space Loss (dB)	g/T (dB/K)	C/No (dB*Hz)	Eb/No (dB)	C/N (dB)	Link Margin (dB)	BER
15 May 2013 12:27:12.670	-9.590	153.3064	-8.813755	13.432314	-27.3904	-30.5471	-37.8904	4.759208e-001
15 May 2013 12:28:12.000	-9.590	152.0798	-7.233409	56.274014	15.4513	12.2946	4.9513	2.718449e-017
15 May 2013 12:29:12.000	-9.590	150.7468	-6.950216	58.751356	17.9286	14.7720	7.4286	3.935047e-029
15 May 2013 12:30:12.000	-9.590	149.3928	-6.834626	60.667686	19.8450	16.6883	9.3450	1.000000e-030
15 May 2013 12:31:12.000	-9.590	148.2037	-6.805249	62.380484	21.5578	18.4011	11.0578	1.000000e-030
15 May 2013 12:32:12.000	-9.590	147.5112	-6.796390	63.644886	22.8222	19.6655	12.3222	1.000000e-030
15 May 2013 12:33:12.000	-9.590	147.6162	-6.800980	63.392151	22.5694	19.4128	12.0694	1.000000e-030
15 May 2013 12:34:12.000	-9.590	148.4675	-6.818403	61.971267	21.1486	17.9919	10.6486	1.000000e-030
15 May 2013 12:35:12.000	-9.590	149.7247	-6.900629	60.157678	19.3350	16.1783	8.8350	1.000000e-030
15 May 2013 12:36:12.000	-9.590	151.0871	-6.987369	58.254916	17.4322	14.2755	6.9322	3.396711e-026
15 May 2013 12:37:12.000	-9.590	152.4028	-8.126143	51.422988	10.6003	7.4436	0.1003	8.250898e-007
15 May 2013 12:37:59.695	-9.590	153.3776	-8.833204	13.273503	-27.5492	-30.7059	-38.0492	4.763566e-001

Figure 4.11: Screen shot of link budget report for the communications link in Figure 4.10

From Figures 4.10 and 4.11 it can be seen that the minimum link margin is satisfied immediately after the satellite appears over the horizon. It has been determined that a link margin of 6.9 dB is achieved at 5° elevation, which is in close agreement with the AMSAT-IARU Link Model.

(2) *S-band downlink at 2 Mbps:*

Link budget: AMSAT-IARU Link Model

Table 4.12 summarises the link budget calculations of the data downlink *for an elevation of 17^o*.

Table 4.12: Link budget for S-band 2 Mbps data downlink at 17º elevation (AMSAT-IARU Link Model)

Parameter:		*Value:*	*Units:*
Spacecraft:			
Spacecraft Transmitter Power Output:		1	watts
	In dBW:	0	dBW
	In dBm:	30	dBm
Spacecraft Total Transmission Line Losses:		1.3	dB
Spacecraft Antenna Gain:		7	dBi
Spacecraft EIRP:		5.7	dBW
Downlink Path:			
Spacecraft Antenna Pointing Loss:		0	dB
S/C-to-Ground Antenna Polarization Loss:		0.2	dB
Path Loss:		162.5	dB
Atmospheric Loss:		1.1	dB
Ionospheric Loss:		0.1	dB
Rain Loss:		0	dB
Isotropic Signal Level at Ground Station:		-158.2	dBW
Ground Station (EbNo Method):			
------- Eb/No Method -------			
Ground Station Antenna Pointing Loss:		0.9	dB
Ground Station Antenna Gain:		33	dBi
Ground Station Total Transmission Line Losses:		1.9	dB
Ground Station Effective Noise Temperature:		269	K
Ground Station Figure of Merrit (G/T):		6.8	dB/K
G.S. Signal-to-Noise Power Density (S/No):		76.3	dBHz
System Desired Data Rate:		2000000	bps
	In dBHz:	63	dBHz
Telemetry System Eb/No for the Downlink:		13.3	dB
Demodulation Method Seleted:		**QPSK**	
Forward Error Correction Coding Used:		**None**	
System Allowed or Specified Bit-Error-Rate:		1.00E-05	
Demodulator Implementation Loss:		0	dB
Telemetry System Required Eb/No:		9.6	dB
Eb/No Threshold:		9.6	dB
System Link Margin:		**3.7**	dB

A link margin of 3.7 dB is expected at an elevation of 17º. The link margin at 5º has been found to be below the required 3 dB threshold. This implies that a satisfactory data downlink at S-band can only be achieved for elevations above around 17º, which is still very useful considering that the link provides data download speeds of about 200 times that of the UHF link.

Link budget: STK

Figure 4.12 illustrates the simulated E_b/N_o for the S-band data downlink as the satellite passes over the ground station in South Africa.

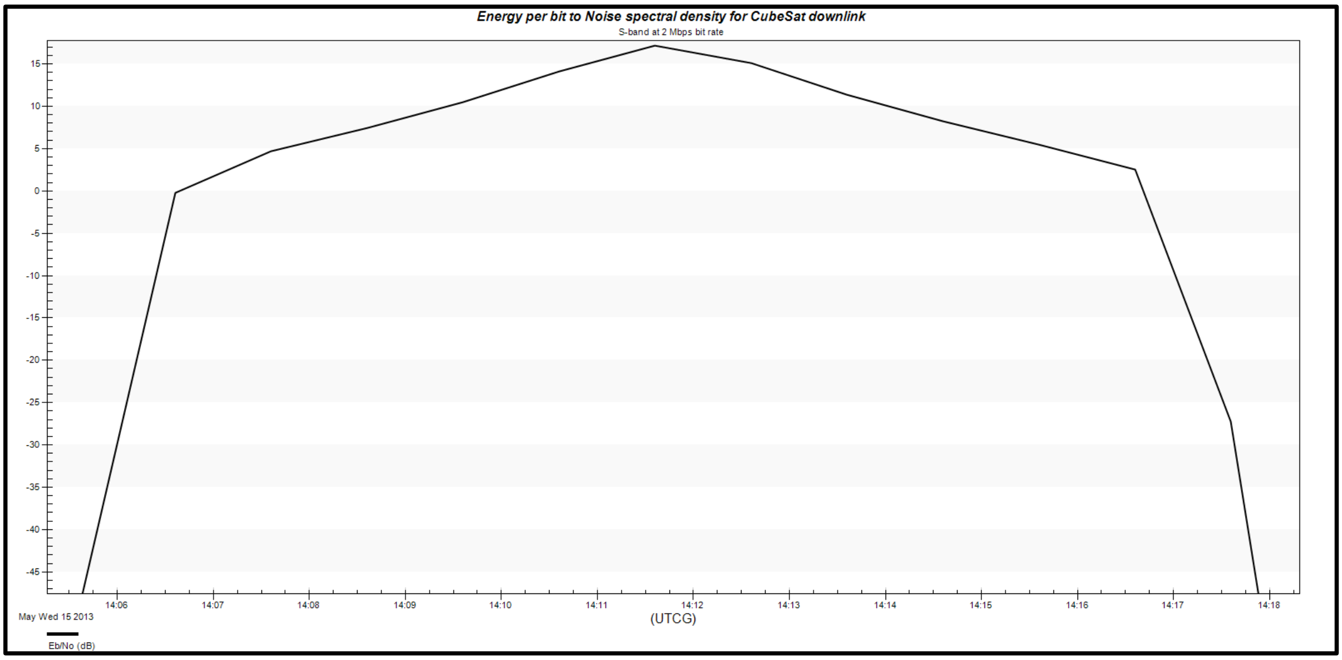

Figure 4.12: Simulated E_b/N_o for S-band 2 Mbps data downlink for the satellite passing over the ground station located in Cape Town

It is observed that the minimum link margin of 3 dB is satisfied for some portion of the overpass (approximately 3 minutes out of a 12 minute overpass), but not from low elevation angles. This finding has also been borne out by the AMSAT-IARU Link Model.

(3) *Data downlink performance summary:*

The performance of the data downlinks described above, are summarised in Table 4.13.

Table 4.13: Satellite downlink performance summary

		Theoretical Result		**AMSAT- IARU Link Model**		**Satellite Tool Kit**	
Band	**Data rate [bps]**	**E_b/N_o [dB]**	**Link margin [dB]**	**E_b/N_o [dB]**	**Link margin [dB]**	**E_b/N_o [dB]**	**Link margin [dB]**
UHF	9600	18	8.4	16	6.4	15.4	5.8
S	$2x10^6$	14.3	4.7	13.3 *(1)*	3.7	11.4(1)	1.8

Note 1: At 17^o elevation

Also shown are the performance results based on the theoretical link model presented in Chapter 2. Generally, there is agreement among the three models; the UHF 9600 bps downlink is found to provide a feasible channel for most of the satellite overpass (from 5^o elevation), but the S-band downlink performs satisfactorily only for higher elevations (exceeding around 17^o).

As with the modeling of the data uplink, the theoretical model consistently predicts improved link margins than for the other two models. This can again be attributed to additional link losses being incorporated into the AMSAT-IARU and STK models.

4.2.2 Data budget

Data budget calculations are necessary to determine the amount of data that is possible to transmit between the ground sensors and the satellite. As an example, the South African region is again investigated for the calculation of the data budgets.

Types of data that needs to be considered when calculating the data budget include:

- **Overheads**
  This is data mainly for obtaining reliable transmission.
- **Telemetry**
  This information includes the status of all subsystems, including temperature, battery charge, position and altitude of the satellite.
- **Payload data**
  This refers to the data generated from sensors onboard the satellite sensors, or from remotely sensed measurements.

Access time for satellites to the ground sensors is a fundamental parameter in this calculation. For the purpose of illustrating the calculation of data budgets, a maximum daily access time of 84 000 seconds (1400 minutes) is assumed. This can be achieved with a 10x2 constellation configuration at 45^o inclination. For other constellations, the number of sensors can be scaled to satisfy the data budget.

4.2.2.1 Sensor uplink data communication

Data Collection:

As pointed out in Chapter 1, a constellation of nanosatellites is to relay in-situ data from around 1250 sensors in each of the four geographical areas of interest across Africa.

Several in-situ monitoring applications have been considered. The types of applications and their associated data packet sizes (in brackets) are (Silva & Vuran, 2010:3; Vasilescu *et al.*, 2005:2):

- Emergency and control (37 bytes); and
- Environmental and atmospheric monitoring (2 to 4 bytes).

It is assumed that for each service different sampling rates of data are applied, depending on operational requirements and urgency of updating information.

Data Budget Calculations:

The total amount of data that can be uploaded over a daily cycle depends on various parameters, namely, total access time, number and types of sensors, rate at which sensors are sampled, and the uplink speed. Consider, for example, the scenario where each ground sensor node is sampled (polled) at 10 second intervals and each data package comprises 4 bytes. This translates into 24 bytes of data collected every minute, or 34.5 kbyte per day, from each sensor. For 100 sensors, the total amount of data accumulated is then 3.456 Mbytes per day. The time required to upload the data to the constellation on a 9600 bps link is 48 minutes (well within the capability of the constellation).

To facilitate the investigation of different scenarios of sensor node configurations and services, spreadsheets such as presented in Tables 4.14 and 4.15 can be deployed. Four node configurations are investigated for each data uplink. The parameters stated earlier are adjusted to determine feasible scenarios for varying number of sensors of the different types of services. The link budgets calculated for the various types of sensors and nodes are summarised in Appendix B. Generally, the number of nodes and the sampling rate of collecting data from the sensors are trade off to meet the overall data budget.

All scenarios presented are technically feasible for a daily access time of 1400 minutes. However, the 1200 bps uplink limit the number of sensors that can be accessed by such constellations.

Table 4.14: Scenario planning tool for in-situ monitoring data budget on VHF 9600 bps uplink assuming total daily access time of 1400 minutes

	Service	Emergency	Border Control	Environmental / Atmospheric Monitoring	Environmental / Atmospheric Monitoring
Node Configuration 1	Focus Area	Land & Sea	Land & Sea Security	Land	Sea
	Node Type	Buoy / Data Collection Platform / Coast guard boat / Lifevest	Buoy / Data Collection Platform / Coast guard boat	Ground sensor	Buoy
	Sample Times (sec)	30	10	60	120
	Number of Nodes	373	194	162	504
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	38815313	60564375	455625	1417500
	Data Rate (bps)	3680	5742	43	134
	Upload Times (min)	539.10	841.17	6.33	19.69
	VHF Simplex Rate (bps)	9600	9600	9600	9600
Node Configuration 2	Sample Times (sec)	600	60	60	2700
	Number of Nodes	1450	1600	3697	500
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	7544531	83250000	10397813	62500
	Data Rate (bps)	715	7893	986	6
	Upload Times (min)	104.79	1156.25	144.41	0.87
	VHF Simplex Rate (bps)	9600	9600	9600	9600
Node Configuration 3	Sample Times (sec)	60	360	2700	3600
	Number of Nodes	1425	3122	300	110
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	74144531	27073594	18750	10313
	Data Rate (bps)	7030	2567	2	1
	Upload Times (min)	1029.79	376.02	0.26	0.14
	VHF Simplex Rate (bps)	9600	9600	9600	9600
Node Configuration 4	Sample Times (sec)	30	45	350	600
	Number of Nodes	616	535	25	30
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	64102500	37115625	12054	16875
	Data Rate (bps)	6078	3519	1	2
	Upload Times (min)	890.31	515.49	0.17	0.23
	VHF Simplex Rate (bps)	9600	9600	9600	9600

Table 4.15: Scenario planning tool for in-situ monitoring data budget on VHF 1200 bps uplink assuming total daily access time of 1400 minutes

	Service	*Emergency*	*Border Control*	*Environmental / Atmospheric Monitoring*	*Environmental / Atmospheric Monitoring*
Node Configuration 1	***Focus Area***	Land & Sea	Land & Sea Security	Land	Sea
	Node Type	Buoy / Data Collection Platform / Coast guard boat / Lifevest	Buoy / Data Collection Platform / Coast guard boat	Ground sensor	Buoy
	Sample Times (sec)	30	10	60	120
	Number of Nodes	46	24	56	77
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	4786875	7492500	157500	216563
	Data Rate (bps)	454	710	15	21
	Upload Times (min)	531.88	832.50	17.50	24.06
	VHF Simplex Rate (bps)	1200	1200	1200	1200
Node Configuration 2	***Sample Times (sec)***	600	60	60	2700
	Number of Nodes	100	215	318	450
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	520313	11186719	894375	56250
	Data Rate (bps)	49	1061	85	5
	Upload Times (min)	57.81	1242.97	99.38	6.25
	VHF Simplex Rate (bps)	1200	1200	1200	1200
Node Configuration 3	***Sample Times (sec)***	60	360	2700	3600
	Number of Nodes	223	118	290	180
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	11602969	1023281	18125	16875
	Data Rate (bps)	1100	97	2	2
	Upload Times (min)	1289.22	113.70	2.01	1.88
	VHF Simplex Rate (bps)	1200	1200	1200	1200
Node Configuration 4	***Sample Times (sec)***	30	45	350	600
	Number of Nodes	78	57	585	530
	Data Packet Size (bytes)	37	37	2	4
	Network Capacity (bytes)	8116875	3954375	282054	298125
	Data Rate (bps)	770	375	27	28
	Upload Times (min)	901.88	439.38	31.34	33.13
	VHF Simplex Rate (bps)	1200	1200	1200	1200

4.2.2.2 Downlink data communication

For data collection in geographic areas where there is a ground station, the uplink data can generally be downloaded immediately to the ground station. The data budget scenario planning tool discussed in the previous section can therefore also be applied here. In these cases, the 9600 bps VHF transmitter developed at CPUT provides a feasible solution.

If data is collected by satellites that are not in view of the ground station, the data will be stored onboard the satellites and forwarded when the satellites are visible to the ground station. In such instances, the 2 Mbps S-band transmitter will have to be used in order to download all onboard data in a single overpass lasting around 6 minutes. This is feasible for the sensor deployment scenarios considered in Table 4.14. The total data uploaded from all sensors in Table 4.14 is 101.8 MByte per day, which for a 20-satellite constellation means that each satellite receives around 101.8 / 20 = 5.1 MByte per day for a 20-satellite constellation. To download this data in a single 6-minute overpass requires a bit rate of 113 kbps, which is far less than the capability of the S-band transmitter developed at CPUT.

4.3 SUMMARY

The simulation and analysis of satellite communication links, in terms of link and data budgets, were conducted.

VHF and UHF sensor data uplinks for both 1200 bps and 9600 bps bitrates using GMSK modulation were considered. A 9600 bps UHF and a 2 Mbps S-band payload data downlink were investigated using, respectively, GMSK and QPSK modulation.

The link budget and margin for each link were calculated using the AMSAT-IARU Link Model and the STK Communications tools. The simulations provided an analytical comparison for ground sensor uplink and satellite downlink link budgets at differing elevation angles and bitrates.

In the next chapter, a case study of in-situ monitoring in the maritime domain for ship tracking will be investigated.

CHAPTER 5: MDASAT CASE STUDY

5.1 INTRODUCTION

This chapter reports on a case study into utilising a constellation of nanosatellites (MDASAT) to provide Automatic Identification System (AIS) in-situ monitoring services for vessel tracking. The target area is assumed to be the Southern African continental shelf. AIS services facilitate maritime domain awareness (MDA), which is especially relevant to Operation Phakisa.

5.2 TECHNOLOGY

5.2.1 Automatic Identification System

AIS is an automatic tracking system used for maritime navigation. This system has been adopted by the International Maritime Organisation (IMO, 2016). Vessel information that is provided, includes the vessel's identification, type, speed, position, course, navigational status and other information relating to safety. Maritime organisations are interested in detecting and tracking ships to assist them in maritime border control operations, law enforcement, fisheries control, maritime safety and security, and issues involving marine pollution response, antipiracy, search and rescue (Cervera *et al.*, 2011:131). ZACUBE-2 will demonstrate the South African capability in vessel detection through satellite-based AIS.

Packets of AIS data are transferred over a VHF data link, enabling vessels and shorebased stations equipped with AIS to send and receive identification information. This information assists in collision avoidance and enhance situational awareness of nearby ships, buoys and light houses. AIS messages are transmitted at intervals between 2 seconds and 3 minutes, depending on a vessel's speed and course change.

The channels that have been allocated for AIS use are *AIS 1* (channel 2087) at 161.975 MHz and *AIS 2* (channel 2088) at 162.025 MHz. Two other channels used for long-range AIS are channel 75 at 156.775 MHz and channel 76 at 156.825 MHz (ITU, 2010).

AIS is based on Time Division Multiple Access (TDMA). This is a dynamic slot reservation selection method used to avoid data collision, which may occur from multiple users in dynamic monitoring of ships (Liping & Shexiang, 2012:661-669).

5.2.2 Time Division Multiple Access

Time Division Multiple Access (TDMA) is a digital technique that allows multiple users to share the same transmission channel (Yoon, 2015:14). The different users transmit in different time slots (Uniroma, 2007) of a single band or channel.

The satellite receives AIS messages and data from the AIS transmitters, or beacons, on ships in separate time slots whereby communication is performed by means of non-overlapping bursts of signals. Transmission timing of the bursts is synchronised accurately so that reception occurs one burst at a time. A frame consists of a number of bursts, which originate from the sensor network (Yu & Qian, 2011:11).

The time plan of the burst is fixed for each TDMA frame to ensure allocation of each sensor node a particular portion of the total TDMA frame.

Self-Organised Time Division Multiple Access (SOTDMA) is a channel access method used in AIS. It is a technique applied in navigation and traffic management applications that are based on TDMA. This method allocates 2250 time slots over a 1-minute period for one frame of AIS information. One slot equals 26.67 millisecond (Liping & Shexiang, 2012:661-669). The typical self-organised cell area is approximately 74 km^2 (Cervera *et al.*, 2011:121).

5.2.3 AIS message collision issue

The SOTDMA protocol is used in AIS to autonomously resolve the data conflict problem within individual TDMA regions or cells. As shown in Figure 5.1, the coverage radius of a self-organised cell is approximately 30 – 40 nautical miles. The transmission error rates over these distances are negligible in general marine conditions. However, if there are more ships within a self-organising cell, more information needs to be transmitted through the AIS data link. An overlapping of slot reservations can then occur with more than one ship selecting the same time slot. This results in slot collisions, which compromise the safety and navigation of ships (Liping & Shexiang, 2012:661-669).

Slot collision is exacerbated in space-based AIS. As shown in Figure 5.1 the satellite footprint can cover more than one AIS TDMA region or cell. Messages can be received by the satellite from ships in different TDMA regions, but that are within the satellite field of view.

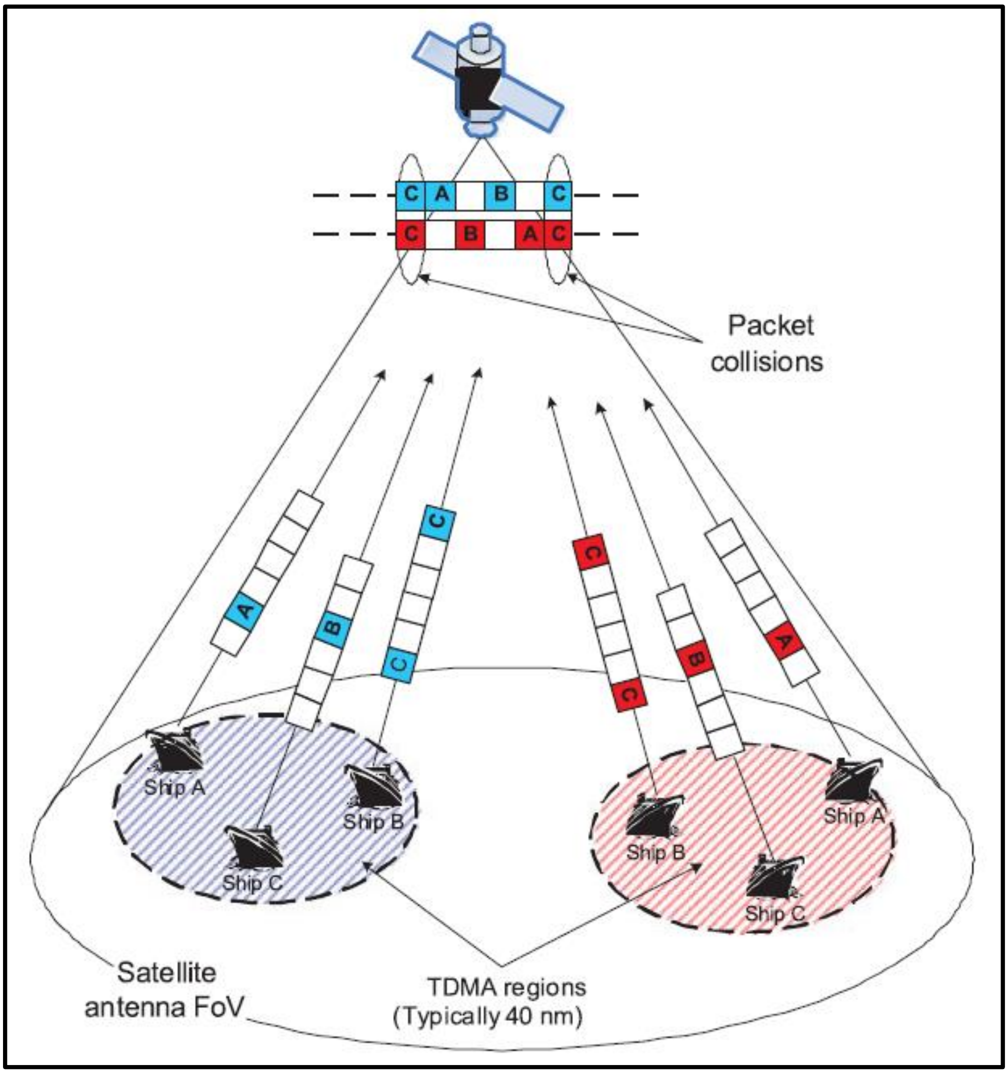

Figure 5.1: Message collision problem for satellite-based AIS

(Adapted from Cervera *et al.*, 2011:121)

5.3 MDASAT MISSION CONCEPT

For this case study, the 'MDASAT' constellation will provide maritime domain awareness services, primarily within the South African Economic Exclusive Zone (EEZ). The objective of the "MDASAT" mission is to relay AIS signals from ships through a constellation of satellites to the ground station during an overpass. It is envisioned that future MDASAT missions will have *global* coverage.

The ground station is assumed to be in Cape Town. The constellation is required to have a revisit time that will allow vessels in the South African continental shelf to be tracked every 45 minutes.

5.3.1 Orbital design

An orbital inclination of 98° (sun-synchronous) is assumed, although it was shown in Chapter 3 that lower inclinations provide better temporal perfomance for the geographic areas of interest. The reasons for selecting a sun-synchronous orbit for this case study are, first, that global coverage can be achieved with this orbit, and second, that realistically there are more CubeSat launch opportunities for this inclination. Global coverage is not possible with 39° or 45° inclinations. Furthermore, it was shown in Chapter 3 that a temporal revisit time of 45 minutes is indeed achievable with a sun-synchronous orbit. An altitude of 500 km is again assumed.

For clarity, the South African EEZ is shown in Figure 5.2.

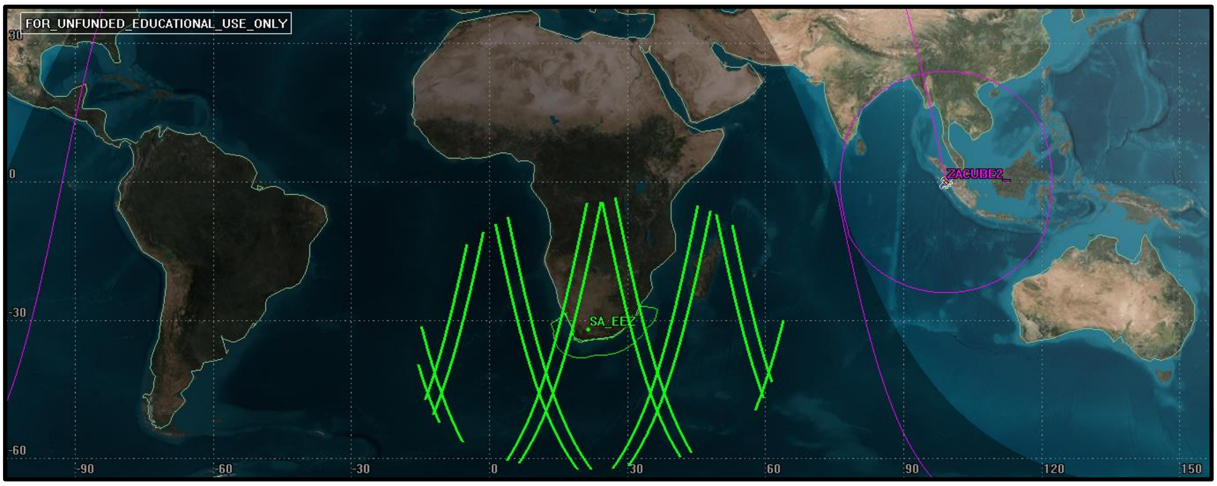

Figure 5.2: Simulated ground track and footprint of single satellite (one orbit shown) passing over the South African Exclusive Economic Zone

5.3.1.1 Access time

The total access times for Cape Town and the South African Exclusive Economic Zone (EEZ) are presented in Figures 5.3 and 5.4 for the constellation configurations considered in Chapter 3.

The access time to the EEZ is generally higher than for Cape Town, as the EEZ is geographically spread around the coast of South Africa.

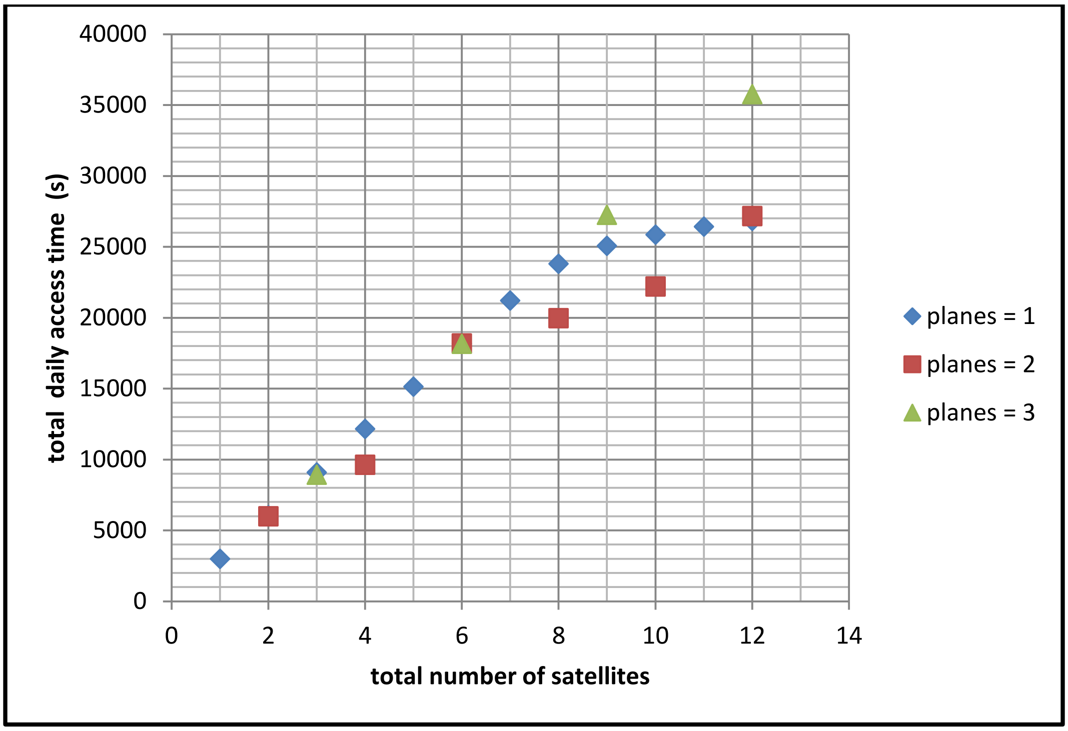

Figure 5.3: Simulated total daily access time for the Cape Town ground station as a function of total number of satellites for the constellations considered

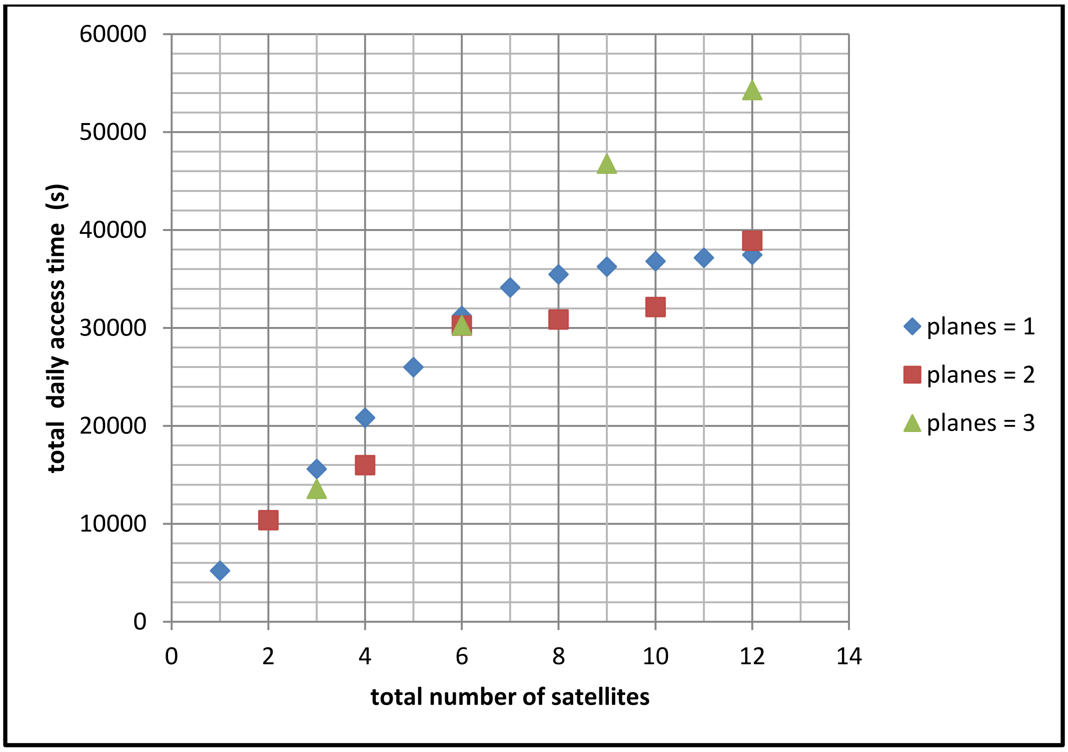

Figure 5.4: Simulated total daily access time for the South African Exclusive Economic Zone as a function of total number of satellites for the constellations considered

5.3.1.2 Revisit time

The simulated average daily revisit time for the ground station based in Cape Town is shown in Figure 5.5 for the constellation configurations considered in Chapter 3.

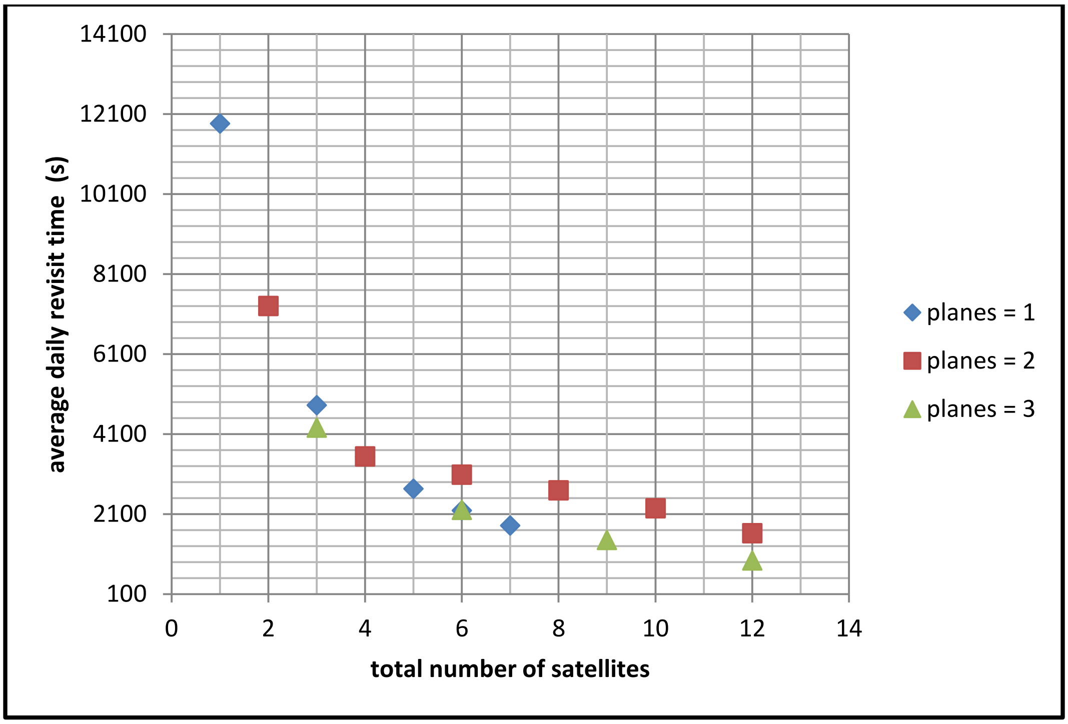

Figure 5.5: Simulated average daily revisit time for the Cape Town ground station as a function of satellites per plane

5.3.1.3 Selection of constellation configuration

From Figure 5.5, the primary requirement of a 45 minute (2700 second) revisit time is achieved with 1 x 6, 2 x 4 and 3 x 2 constellation configurations. These configurations also give similar access times as shown in Figure 5.4. Considering the cost of launching satellites in multiple plane constellations, the 1 x 6 constellation configuration has been selected. The average overpass time for the Cape Town ground station is of the order 12 minutes.

5.3.2 Payload communications link

The nanosatellites receive the AIS messages on the VHF uplink and the information is forwarded to the ground station using either the UHF or S-band downlinks considered in Chapter 4. The footprints of the individual satellites enable quasi-real-time relaying of data from the ships in the EEZ to the ground station.

5.3.2.1 Link budget

An uplink budget is determined for validating that the nanosatellites can reliably receive AIS signals. The transmit power for AIS from a Class A transponder is maximum 12.5 W. Table 5.1 summarises the link budget calculations for the 9600 bps VHF uplink (orbital altitude 500 km; slant range 2077 km; minimum elevation 5°).

Table 5.1: VHF uplink performance

Parameter	Value	Unit	Comment
Frequency (AIS 1)	161.975	MHz	Default channel 1 (2087)
Frequency (AIS 2)	162.025	MHz	Default channel 2 (2088)
Transmitter power (Class A) 12.5 W	10.97	dB	Performance requirements for physical layer (defined in Recommendation ITU-R M.1371)
Data rate	9600	bps	Defined in Recommendation ITU-R M.1371
Transmit antenna gain	5	dBi	Vertical dipole antenna (defined in Rec. ITU-R M.2092)
Minimum elevation	5	deg	Ship e.i.r.p. vs. elevation angle (from ITU-R M.2092)
Transmitter line loss	-1.0	dB	
Effective isotropic radiated power	14.97	dB	
Propagation path length	2077	km	Distance from satellite to Earth's horizon
Space path loss	142.9	dB	
Satellite receive antenna gain	-10.0	dBi	Satellite tumbling; assume null in radiation pattern pointing to Earth
Receiver noise figure	3.0	dB	
Receiver noise temperature	288.63	K	
Receiver IF bandwidth	25	kHz	Channel spacing (from Recommendation ITU-R M.1371)
Minimum required receiver SNR	15	dB	GMSK/FM (defined in Recommendation ITU-R M.1371)
Other losses	6	dB	
Received signal power	-107.93	dBm	
Received signal to noise ratio	19.8	dB	
Link margin	**4.8**	**dB**	Minimum of 3 dB acceptable.

A worst case study has also been conducted to determine if the link budget performance for AIS is satisfactory for *tumbling* satellites. Satellites without ADCS are less complex and the development cost is reduced, compared to satellites with pointing capabilities.

Figure 5.6 gives the probability that the link margin is above 3 dB for a tumbling satellite that is equally likely to be in any orientation. It is evident that there is a probability of at least 95% that the uplink will be satisfied from 5° to 80° elevations. Communication does not occur when the satellite is directly overhead, since the ships' AIS antennas do not radiate vertically up.

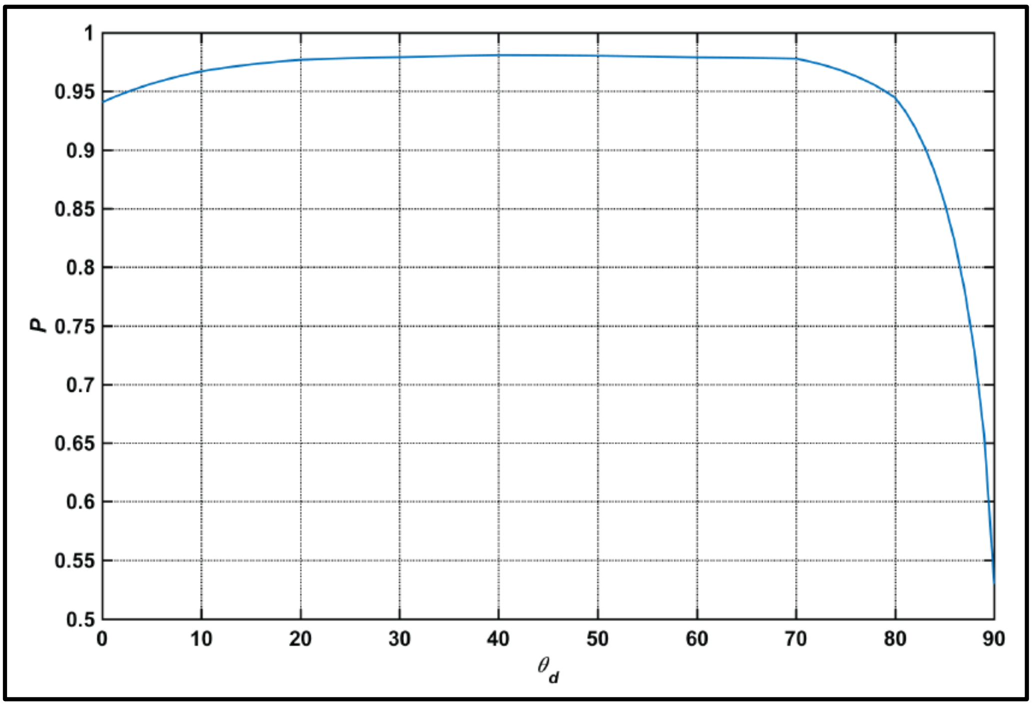

Figure 5.6: Simulated probability that the uplink VHF link margin is satisfied as a funciton of elevation angle.

It is clear that the VHF uplink performs satisfactorily.

5.3.2.2 Data budget

Link requirements for two cases are examined. A scenario is first investigated whereby an AIS message is transmitted every 20 seconds, followed by a scenario where AIS messages are transmitted every 2 seconds. Each AIS message comprises 21 bytes. At any given time, there are about 10 000 vessels off the coast of Africa. Conservatively, for the purpose of this case study, it is assumed that 5000 ships will transmit AIS signals in the South Africa EEZ.

- Scenario 1:

For this scenario, the steps in determining the data budget are summarised as follows:

- Each ship transmits 21 bytes every 20 seconds at 9600 bps;

- The total daily data upload to the constellation is therefore 21 x 5000 x 24 x 3600 / 20 = 453.6 Mbyte;
- To download this data to the ground station, the collective average data rate required is 453.6×10^6 / 18159 (daily access time to ground station) = 25 kByte per second, or 200 kbps.
- Averaged over 6 satellites, each satellite is requied to transmit at 200 000 / 9600 = 33 kbps.

UHF/VHF downlink:

From the above, it is evident that a single channel 9600 bps VHF or UHF transmitter is not sufficient, and that a 4-channel transmitter has to be developed. Alternatively, UHF or VHF transmitters with a 38 400 bps transmission rate can be developed.

S-band downlink:

The existing CPUT S-band transmitter that transmits at 2 Mbps can be used. It has been shown in Chapter 4 that the link budget for the S-band downlink is satisfied.

- Scenario 2:

For the case where AIS messages are transmitted every 2 seconds, the calculations for the previous scenario scales 10-fold. Hence, for a single channel transmitter, a 384 kbps transmission rate is required. This can be achieved with the S-band transmitter only.

5.4 SUMMARY

A case study for providing AIS vessel-tracking services in the South African EEZ has been presented. It was found that a constellation configuration of 6 satellites evenly spaced in a single orbital plane could provide a revisit time of less than 45 minutes. The RF link budget was calculated and found to provide a feasible communications link between the ships' AIS beacons and the satellite for elevations between 5^o and 80^o. The RF link performance calculations were followed by a data budget. Two scenarios were assessed; AIS signals being transmitted every 20 seconds and 2 seconds, respectively. It was found that transmission rates of 38 400 bps and 384 kbps are required for these two scenarios, respectively. The former is achievable with UHF radio technologies, and the latter with an S-band radio based on the radios developed at CPUT. The MDASAT constellation can provide a great improvement in the monitoring of maritime activity in South Africa and in turn enhance the country's development and management of its maritime resources.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

This work presents the mission design of a CubeSat constellation for in-situ monitoring applications. The research proposes a systems framework for a constellation of CubeSats and the supporting ground segment that can provide near real-time low bit rate connectivity to a network of remote sensors distributed across the primary target areas, which are South Africa, Algeria, Kenya, and Nigeria and with the ground station located in Cape Town, South Africa. Revisit times of less than 45 minutes are required. The research addresses the constellation design and the communications systems on the satellite and on the ground as these are critical criteria that impact in-situ monitoring missions. The SMAD process has broadly been followed. Notable elements of the SMAD process have not been considered comprehensively. The work performed in this thesis within the SMAD framework is summarised in Table 6.1.

Table 6.1: SMAD process and work performed

Step		**Implementation in this work**
Define Objectives	1. Define broad objectives and constraints	1: Development of quasi-real-time monitoring CubeSat constellation and ground segment for in-situ monitoring.
	2. Estimate quantitative mission needs and requirements	2: Optimisation of the constellation configuration to maintain revisit times of less than 45 minute and optimum access time to geographic areas of interest (South Africa, Keyna, Nigeria, Algeria). Low data rate in-situ monitoring services are considered.
Characterise the Mission	3. Define alternative mission concepts	3, 4: A comparative study done, investigating 1 to 12 satellites in 1, 2 and 3 planes.
	4. Define alternative mission architectures	
	5. Identify system drivers for each	5: Optimal orbital design in terms of average total access and revisit time of geographic areas of interest.
	6. Characterise mission concepts and architecture	6: Simulations and calculations done for ground sensor uplink communications in both VHF and UHF bands at 1200/9600 bps data rates.
Evaluate the Mission	7. Identify critical requirements	7, 8, 9: A case study of AIS vessel-tracking services in the South African EEZ has been performed. An optimal constellation configuration has been proposed and the communications links investigated for feasibility.
	8. Evaluate mission utility	
	9. Define mission concept (baseline)	

Define Requirements	10. Define system requirements	10: Communications system and optimal constellation configuration defined for AIS vessel-tracking services in the South African EEZ.
	11. Allocate requirements to system elements	11. Communications link parameters determined and verified through simulation.

6.2 ADDRESSING THE RESEARCH QUESTIONS

The research questions posed in Chapter 1 are addressed in summary below.

- *What types of services can be provided with in-situ monitoring missions?*

  Low bit rate in-situ monitoring services have been investigated with bit rates up to 9600 bps on UHF/VHF for the data uplink, and 9600 bps and 2 Mbps on UHF and S-band, respectively, for the data downlink. A specific application of AIS vessel-tracking services in the South African EEZ has been assessed as a case study and found to be feasible with existing technology developed at CPUT. This case study is particulalry relevant to Operation Phakisa.

- *What is the minimum number of satellites required to maintain a frequent revisit time over South Africa, Algeria, Kenya and Nigeria?*

  From Figures 3.61, 3.63, 3.64 and 3.65 the minimum number of satellites for a 45 minute (2700 second) revisit time for each constellation configuration is summarised in Table 6.2.

Table 6.2: Minimum number of satellites to achieve 45 minute revisit time

Region	**Constellation for minimum number of satellites for each orbital inclination**		
	39^o	**45^o**	**98^o**
South Africa	4 x 1 (4)	4 x 1 (4)	5 x 1 (5)
	2 x 2 (4)	3 x 2 (6)	4 x 2 (8)
	2 x 3 (6)	2 x 3 (6)	2 x 3 (6)
Algeria	3 x 1 (3)	4 x 1 (4)	5 x 1 (5)
	2 x 2 (4)	2 x 2 (4)	2 x 2 (4)
	2 x 3 (6)	2 x 3 (6)	2 x 3 (6)
Kenya	4 x 1 (4)	5 x 1 (5)	7 x 1 (7)
	3 x 2 (6)	3 x 2 (6)	3 x 2 (6)
	2 x 3 (6)	2 x 3 (6)	3 x 3 (9)
Nigeria	4 x 1 (4)	5 x 1 (5)	7 x 1 (7)
	3 x 2 (6)	3 x 2 (6)	5 x 2 (10)
	2 x 3 (6)	2 x 3 (6)	4 x 3 (12)

From Table 6.2 and the analysis results represented in Figures 3.61 to 3.65, the following findings can be made regarding the *minimum revisit* times that can be achieved:

- For South Africa
  - Revisit times of between 5 and 12 minutes are possible with 12 satellites in 6x2 or 4x3 constellation configurations at 39^o and 45^o inclinations;
- For Algeria
  - Revisit times between 5 and 10 minutes are possible with 12 satellites in a 6x2 constellation configuration at 39^o and 45^o inclinations;
- For Kenya
  - The 4x3 constellation configuration achieves a minimum revisit time of 9 minutes at 39^o and 45^o inclinations;
- For Nigeria
  - The constellations at 45^o inclination yield improved revisit times compared to the other configurations and revisit times between 9 and 12 minutes can be achieved with 6x2 and 4x3 constellation configurations;
- For all geographic areas considered
  - The sun-synchrounous orbital configurations at 98^o generally performs poorly in terms of revisit time; and
  - The revisit time for a single oribital plane constellation improves for up to 7 satellites per plane, whereafter there is no decrease. This is due to overlap of satellite footprints to the target areas, providing periods of continuous access rather than improving revisit time.

- *What are the trade-offs between revisit time, access time and number of satellites?*
  - An increased number of satellites generally increase access time and decrease revisit times for the same orbital inclinations;
  - The lower inclinations of 39^o and 45^o improve the temporal performance of the constellations, compared to an inclination of 98^o; and
  - For South Africa and Algeria, the optimimum constellation configurations in terms of access time are those that have two orbital planes, whereas for Kenya and Nigeria, 3-plane orbital configurations improve access time (refer to Figures 3.33 to 3.38).

- *Which communications links are feasible for supporting low data rate in-situ monitoring?*

  Chapter 4 covered the communications system design for low bitrate sensor networks operating in the amateur frequency bands. The frequencies investigated were VHF

(145 MHz) and UHF (437 MHz) for sensor data uplink at both 1200 bps and 9600 bps bitrates using a Gaussian Minimum Shift Keying (GMSK) modulation scheme. For the data downlink from the satellite, a 9600 bps UHF link with GMSK modulation and a 2 Mbps S-band link with QPSK modulation were considered. The communications links were investigated for sensors and ground stations in the South African region.

From Table 4.9, it is evident that the UHF 9600 bps uplink is not feasible, and that the data rate has to be limited to 1200 bps on UHF. The VHF uplink is feasible for both 1200 bps and 9600 bps data rates.

From Table 4.13, data downlinks on UHF and S-band provide acceptable link performance at 9600 bps and 2 Mbps, respectively. (For the S-band link, an acceptable link margin was achieved at higher elevations exceeding around 17°.)

- *How does the number of in-situ sensors, type of data and geographical distribution of sensors impact the communications system design?*

  To facilitate the investigation of different scenarios of sensor node configurations and services, spreadsheets such as presented in Tables 4.14 and 4.15 have been deployed. The 1200 bps uplink limits the number of sensors that can be accessed by the constellation.

  A case study for the delivery of AIS vessel tracking services to the South African EEZ with 5000 vessels at any given time was presented in Chapter 5. The main findings of the case study were:

  - A constellation configuration of 6 satellites evenly spaced in a single orbital plane achieves a revisit time of less than 45 minutes;
  - The RF link budget provides for a feasible communications link between the ships' AIS beacons and the satellite for elevations between 5° and 80°;
  - In terms of the data budget requirements, transmission rates of 38 400 bps and 384 kbps are required, respectively, for the two scenarios where the ships' beacons transmit at 20 second and 2 second intervals; and
  - The MDASAT constellation can provide a significant improvement in the monitoring capability of maritime activity in South Africa, which in turn enhances the country's development and management of its maritime resources.

6.3 CONCLUSIONS

Typical low data rate services that can be provided with in-situ monitoring missions include emergency services, border control, environmental and atmospheric monitoring.

It has been shown that it is possible to achieve acceptable revisit and access times with 12-satellite constellations. A single plane constellation configuration has some advantages over multiple plane constellations. Placement of satellites on different orbital planes is done through multiple launches, which in turn increases launch cost and the launch sequence becomes complex. Analyses of the simulations showed that a Walker orbit configuration of 12 satellites distributed over 2 orbital planes provides an optimal solution for the South African geographic area. This configuration ensures revisit times of less than 2700 seconds for all target areas. Total daily access times of around 16 hours per day for the South African and Algerian regions are obtainable, and more than 7 hours per day of access time for Kenya and Nigeria.

A case study found that AIS services for tracking 5000 ships in the South African EEZ can be achieved with existing communications technologies developed at CPUT and that the temporal performance can be achieved with a 6-satellite constellation in one plane. These are very relevant findings in terms of the South African Government's Operation Phakisa

6.4 FUTURE WORK AND RECOMMENDATIONS

The aspects revolving around maintenance of both the ground sensor segments and the space segment for CubeSat constellation architectures are beyond the scope of this thesis, but would be necessary to investigate to assess the financial feasibility of in-situ monitoring services in Africa.

Inter-satellite network communications amongst the CubeSats and processing capacity of 'big data' remain major technological concerns relating to CubeSat constellations that have to be accomplished in future.

In this research only Walker constellations have been evaluated. Alternative constellation configurations can also be evaluated in future work.

Another issue to be addressed is the possibility of mission reconfiguration, while the system is in space, to achieve secondary mission objectives once the primary ones have been met.

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APPENDICES

Appendix A: STK link budget results for VHF 9600 bps data uplink

The presentation of results obtained from STK simulations is illustrated in report format. Parts of the link budget for the ground sensor uplink to the constellation for the different primary target countries are presented.

South Africa:

13 Jul 2017 12:22:09

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Chain-ChainSA

Strand 1

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
15 May 2016 14:05:40.024	10.787	145.003	-29.518808	25.000	-25.7813	-36.2813	4.710280e-001
15 May 2016 14:06:40.000	10.736	145.003	-29.359952	25.000	3.1082	-7.3918	2.155321e-002
15 May 2016 14:07:40.000	10.523	145.003	-28.282686	25.000	14.4362	3.9362	4.564287e-014
15 May 2016 14:08:40.000	9.969	145.003	-28.480193	25.000	15.8986	5.3986	5.746447e-019
15 May 2016 14:09:40.000	8.515	145.003	-29.062137	25.000	16.6200	6.1200	4.702088e-022
15 May 2016 14:10:40.000	3.942	145.002	-31.160309	25.000	13.3615	2.8615	2.266118e-011
15 May 2016 14:11:40.000	-16.519	145.000	-47.049874	25.000	-20.3290	-30.8290	4.458454e-001
15 May 2016 14:12:40.000	1.447	144.998	-32.471253	25.000	10.4407	-0.0593	1.270113e-006
15 May 2016 14:13:40.000	7.800	144.997	-29.356247	25.000	16.4143	5.9143	4.024538e-021
15 May 2016 14:14:40.000	9.709	144.997	-28.580505	25.000	16.1741	5.6741	4.365607e-020
15 May 2016 14:15:40.000	10.417	144.997	-28.322088	25.000	14.8122	4.3122	3.553283e-015
15 May 2016 14:16:40.000	10.697	144.997	-28.259967	25.000	13.1860	2.6860	5.453529e-011
15 May 2016 14:17:40.000	10.784	144.997	-29.492664	25.000	-5.4876	-15.9876	2.260675e-001
15 May 2016 14:17:57.597	10.787	144.997	-29.530453	25.000	-25.8539	-36.3539	4.712687e-001

Strand 2

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
15 May 2016 13:49:07.183	10.787	145.003	-29.517500	25.000	-25.7731	-36.2731	4.710009e-001
15 May 2016 13:50:07.000	10.737	145.003	-29.354754	25.000	3.2222	-7.2778	2.021223e-002
15 May 2016 13:51:07.000	10.526	145.003	-28.280920	25.000	14.4320	3.9320	4.692477e-014
15 May 2016 13:52:07.000	9.981	145.003	-28.475426	25.000	15.8889	5.3889	6.277708e-019
15 May 2016 13:53:07.000	8.576	145.003	-29.037795	25.000	16.6316	6.1316	4.149092e-022
15 May 2016 13:54:07.000	4.435	145.002	-30.919777	25.000	13.8761	3.3761	1.399199e-012
15 May 2016 13:55:07.000	-5.285	145.000	-36.999425	25.000	0.4476	-10.0524	6.824268e-002
15 May 2016 13:56:07.000	2.768	144.998	-31.758281	25.000	12.0488	1.5488	7.488249e-009
15 May 2016 13:57:07.000	8.026	144.997	-29.262151	25.000	16.4969	5.9969	1.720149e-021
15 May 2016 13:58:07.000	9.772	144.997	-28.556782	25.000	16.1129	5.6129	7.846820e-020
15 May 2016 13:59:07.000	10.438	144.997	-28.315019	25.000	14.7364	4.2364	6.051049e-015
15 May 2016 14:00:07.000	10.704	144.997	-28.261077	25.000	13.1045	2.6045	8.105681e-011
15 May 2016 14:01:07.000	10.785	144.997	-29.506366	25.000	-8.1023	-18.6023	2.889622e-001
15 May 2016 14:01:21.942	10.787	144.997	-29.530571	25.000	-25.8527	-36.3527	4.712647e-001

Strand 6

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
15 May 2016 14:22:15.259	10.787	145.003	-29.520155	25.000	-25.7894	-36.2894	4.710549e-001
15 May 2016 14:23:15.000	10.737	145.003	-29.355002	25.000	3.2518	-7.2482	1.987278e-002
15 May 2016 14:24:15.000	10.526	145.003	-28.282665	25.000	14.4117	3.9117	5.352954e-014
15 May 2016 14:25:15.000	9.982	145.003	-28.475551	25.000	15.8707	5.3707	7.395278e-019

Algeria:

13 Jul 2017 15:40:45

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Strand 8

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
15 May 2016 16:07:06.900	10.787	145.003	-29.515335	25.000	-25.7934	-36.2934	4.710683e-001
15 May 2016 16:08:06.000	10.738	145.003	-29.338322	25.000	3.5243	-6.9757	1.692205e-002
15 May 2016 16:09:06.000	10.531	145.003	-28.274378	25.000	14.3774	3.8774	6.676066e-014
15 May 2016 16:10:06.000	9.996	145.003	-28.463107	25.000	15.8358	5.3358	1.011246e-018
15 May 2016 16:11:06.000	8.619	145.003	-29.010576	25.000	16.6073	6.1073	5.382727e-022
15 May 2016 16:12:06.000	4.502	145.002	-30.864214	25.000	13.9303	3.4303	1.023697e-012
15 May 2016 16:13:06.000	-7.099	145.000	-38.289146	25.000	-2.5223	-13.0223	1.450760e-001
15 May 2016 16:14:06.000	1.843	144.998	-32.238356	25.000	10.9270	0.4270	3.248743e-007
15 May 2016 16:15:06.000	7.791	144.997	-29.356751	25.000	16.3967	5.8967	4.815350e-021
15 May 2016 16:16:06.000	9.692	144.997	-28.585610	25.000	16.1792	5.6792	4.155230e-020
15 May 2016 16:17:06.000	10.407	144.997	-28.324693	25.000	14.8372	4.3372	2.974157e-015
15 May 2016 16:18:06.000	10.693	144.997	-28.259813	25.000	13.2255	2.7255	4.489637e-011
15 May 2016 16:19:06.000	10.783	144.997	-29.481594	25.000	-3.9820	-14.4820	1.856186e-001
15 May 2016 16:19:25.272	10.787	144.997	-29.530928	25.000	-25.8473	-36.3473	4.712471e-001

Strand 9

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
15 May 2016 15:50:31.077	10.787	145.003	-29.514051	25.000	-25.7859	-36.2859	4.710433e-001
15 May 2016 15:51:31.000	10.736	145.003	-29.352915	25.000	3.1501	-7.3499	2.105406e-002
15 May 2016 15:52:31.000	10.524	145.003	-28.275132	25.000	14.4173	3.9173	5.162617e-014
15 May 2016 15:53:31.000	9.975	145.003	-28.470496	25.000	15.8765	5.3765	7.020552e-019
15 May 2016 15:54:31.000	8.538	145.003	-29.044092	25.000	16.6085	6.1085	5.312966e-022
15 May 2016 15:55:31.000	4.060	145.002	-31.088904	25.000	13.4769	2.9769	1.248041e-011
15 May 2016 15:56:31.000	-14.306	145.000	-44.703669	25.000	-15.8247	-26.3247	4.095482e-001
15 May 2016 15:57:31.000	1.308	144.998	-32.543381	25.000	10.2523	-0.2477	2.072823e-006
15 May 2016 15:58:31.000	7.748	144.997	-29.375195	25.000	16.3824	5.8824	5.565243e-021
15 May 2016 15:59:31.000	9.690	144.997	-28.585964	25.000	16.1846	5.6846	3.942009e-020
15 May 2016 16:00:31.000	10.408	144.997	-28.323425	25.000	14.8346	4.3346	3.030354e-015
15 May 2016 16:01:31.000	10.694	144.997	-28.259174	25.000	13.2154	2.7154	4.719275e-011
15 May 2016 16:02:31.000	10.783	144.997	-29.485253	25.000	-4.4460	-14.9460	1.983182e-001
15 May 2016 16:02:49.719	10.787	144.997	-29.530593	25.000	-25.8477	-36.3477	4.712484e-001

Strand 10

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
15 May 2016 15:33:56.715	10.787	145.003	-29.512851	25.000	-25.7782	-36.2782	4.710178e-001
15 May 2016 15:34:56.000	10.738	145.003	-29.342664	25.000	3.3857	-7.1143	1.838386e-002
15 May 2016 15:35:56.000	10.527	145.003	-28.273102	25.000	14.4107	3.9107	5.387375e-014
15 May 2016 15:36:56.000	9.982	145.003	-28.467106	25.000	15.8731	5.3731	7.236359e-019

Kenya:

13 Jul 2017 16:38:08

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Strand 6

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
19 May 2016 07:49:24.201	10.787	145.003	-29.506322	25.000	-25.7409	-36.2409	4.708931e-001
19 May 2016 07:50:24.000	10.737	145.003	-29.339064	25.000	3.2989	-7.2011	1.933991e-002
19 May 2016 07:51:24.000	10.526	145.003	-28.260653	25.000	14.4953	3.9953	3.100418e-014
19 May 2016 07:52:24.000	9.976	145.003	-28.452046	25.000	15.9801	5.4801	2.726169e-019
19 May 2016 07:53:24.000	8.533	145.003	-29.024471	25.000	16.7359	6.2359	1.339261e-022
19 May 2016 07:54:24.000	4.024	145.002	-31.080808	25.000	13.5864	3.0864	6.981730e-012
19 May 2016 07:55:24.000	-10.824	145.000	-41.520328	25.000	-9.1275	-19.6275	3.104871e-001
19 May 2016 07:56:24.000	2.190	144.998	-32.040140	25.000	11.4992	0.9992	5.343300e-008
19 May 2016 07:57:24.000	8.002	144.997	-29.245004	25.000	16.6268	6.1268	4.370913e-022
19 May 2016 07:58:24.000	9.788	144.997	-28.522780	25.000	16.2284	5.7284	2.575750e-020
19 May 2016 07:59:24.000	10.451	144.997	-28.282413	25.000	14.8152	4.3152	3.478689e-015
19 May 2016 08:00:24.000	10.710	144.997	-28.233601	25.000	13.1485	2.6485	6.551684e-011
19 May 2016 08:01:24.000	10.786	144.997	-29.490837	25.000	-10.9293	-21.4293	3.439017e-001
19 May 2016 08:01:36.145	10.787	144.997	-29.505661	25.000	-25.7450	-36.2450	4.709071e-001

Strand 9

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
19 May 2016 07:40:44.746	10.787	145.003	-29.512368	25.000	-25.7514	-36.2514	4.709284e-001
19 May 2016 07:41:44.000	10.738	145.003	-29.334586	25.000	3.5318	-6.9682	1.684491e-002
19 May 2016 07:42:44.000	10.530	145.003	-28.265500	25.000	14.4653	3.9653	3.776793e-014
19 May 2016 07:43:44.000	9.989	145.003	-28.451750	25.000	15.9516	5.4516	3.544656e-019
19 May 2016 07:44:44.000	8.583	145.003	-29.007011	25.000	16.7339	6.2339	1.369631e-022
19 May 2016 07:45:44.000	4.307	145.002	-30.940395	25.000	13.8788	3.3788	1.378127e-012
19 May 2016 07:46:44.000	-7.243	145.000	-38.451052	25.000	-2.6800	-13.1800	1.494580e-001
19 May 2016 07:47:44.000	2.527	144.998	-31.859044	25.000	11.9042	1.4042	1.285841e-008
19 May 2016 07:48:44.000	8.043	144.997	-29.226051	25.000	16.6439	6.1439	3.638043e-022
19 May 2016 07:49:44.000	9.796	144.997	-28.515405	25.000	16.2266	5.7266	2.620189e-020
19 May 2016 07:50:44.000	10.453	144.997	-28.275467	25.000	14.8164	4.3164	3.448461e-015
19 May 2016 07:51:44.000	10.711	144.997	-28.225732	25.000	13.1524	2.6524	6.426176e-011
19 May 2016 07:52:44.000	10.786	144.997	-29.484060	25.000	-11.1999	-21.6999	3.484489e-001
19 May 2016 07:52:55.895	10.787	144.997	-29.498006	25.000	-25.7322	-36.2322	4.708641e-001

Strand 10

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
19 May 2016 07:24:11.377	10.787	145.003	-29.513477	25.000	-25.7529	-36.2529	4.709335e-001
19 May 2016 07:25:11.000	10.737	145.003	-29.340429	25.000	3.4190	-7.0810	1.802554e-002
19 May 2016 07:26:11.000	10.529	145.003	-28.267409	25.000	14.4687	3.9687	3.693107e-014
19 May 2016 07:27:11.000	9.988	145.003	-28.453802	25.000	15.9515	5.4515	3.547641e-019

Nigeria:

13 Jul 2017 17:45:07

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Strand 1

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
21 May 2016 08:17:23.882	10.787	145.003	-29.515445	25.000	-25.7669	-36.2669	4.709800e-001
21 May 2016 08:18:23.000	10.738	145.003	-29.333771	25.000	3.6143	-6.8857	1.601520e-002
21 May 2016 08:19:23.000	10.532	145.003	-28.269715	25.000	14.4384	3.9384	4.501210e-014
21 May 2016 08:20:23.000	9.996	145.003	-28.454365	25.000	15.9239	5.4239	4.567694e-019
21 May 2016 08:21:23.000	8.606	145.003	-29.002780	25.000	16.7191	6.2191	1.609632e-022
21 May 2016 08:22:23.000	4.388	145.002	-30.903526	25.000	13.9494	3.4494	9.159519e-013
21 May 2016 08:23:23.000	-7.297	145.000	-38.482559	25.000	-2.7671	-13.2671	1.518821e-001
21 May 2016 08:24:23.000	2.352	144.998	-31.964443	25.000	11.6809	1.1809	2.865674e-008
21 May 2016 08:25:23.000	7.994	144.997	-29.258428	25.000	16.6163	6.1163	4.889098e-022
21 May 2016 08:26:23.000	9.780	144.997	-28.533729	25.000	16.2343	5.7343	2.430307e-020
21 May 2016 08:27:23.000	10.447	144.997	-28.289782	25.000	14.8302	4.3302	3.126601e-015
21 May 2016 08:28:23.000	10.709	144.997	-28.237816	25.000	13.1689	2.6689	5.931537e-011
21 May 2016 08:29:23.000	10.786	144.997	-29.491740	25.000	-10.4073	-20.9073	3.347897e-001
21 May 2016 08:29:35.587	10.787	144.997	-29.507444	25.000	-25.7351	-36.2351	4.708740e-001

Strand 11

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
21 May 2016 09:34:26.476	10.787	145.003	-29.512297	25.000	-25.7401	-36.2401	4.708904e-001
21 May 2016 09:35:26.000	10.737	145.003	-29.340814	25.000	3.4035	-7.0965	1.819194e-002
21 May 2016 09:36:26.000	10.527	145.003	-28.267184	25.000	14.4843	3.9843	3.332151e-014
21 May 2016 09:37:26.000	9.982	145.003	-28.456165	25.000	15.9676	5.4676	3.058032e-019
21 May 2016 09:38:26.000	8.559	145.003	-29.019320	25.000	16.7326	6.2326	1.389094e-022
21 May 2016 09:39:26.000	4.218	145.002	-30.988094	25.000	13.7824	3.2824	2.381417e-012
21 May 2016 09:40:26.000	-7.456	145.000	-38.612498	25.000	-3.0440	-13.5440	1.595939e-001
21 May 2016 09:41:26.000	2.588	144.998	-31.818417	25.000	11.9752	1.4752	9.884819e-009
21 May 2016 09:42:26.000	8.059	144.997	-29.216584	25.000	16.6386	6.1386	3.852416e-022
21 May 2016 09:43:26.000	9.799	144.997	-28.512872	25.000	16.2088	5.7088	3.116264e-020
21 May 2016 09:44:26.000	10.453	144.997	-28.274999	25.000	14.7988	4.2988	3.904957e-015
21 May 2016 09:45:26.000	10.711	144.997	-28.226027	25.000	13.1374	2.6374	6.912615e-011
21 May 2016 09:46:26.000	10.786	144.997	-29.484506	25.000	-11.0159	-21.5159	3.453703e-001
21 May 2016 09:46:38.096	10.787	144.997	-29.499028	25.000	-25.7505	-36.2505	4.709254e-001

Strand 12

Time (UTCG)	EIRP1 (dBW)	Rcvd. Frequency1 (MHz)	g/T1 (dB/K)	Bandwidth1 (kHz)	Eb/No1 (dB)	Link Margin1 (dB)	BER1
21 May 2016 09:17:53.312	10.787	145.003	-29.513338	25.000	-25.7395	-36.2395	4.708886e-001
21 May 2016 09:18:53.000	10.737	145.003	-29.343885	25.000	3.3586	-7.1414	1.867919e-002
21 May 2016 09:19:53.000	10.527	145.003	-28.269007	25.000	14.4864	3.9864	3.286832e-014
21 May 2016 09:20:53.000	9.982	145.003	-28.458055	25.000	15.9679	5.4679	3.051916e-019

Appendix B: Link budget results for individual nodes and network of nodes for each service

Table B.1: Uplink budget for an individual emergency sensor (on land or sea) transmitting on VHF at 10 bps

Parameter:	Value:	Units:
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	10	bps
In dBHz:	10	dBHz
Command System Eb/No:	41.9	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**33.4**	dB

Table B.2: Uplink budget for a network of 373 ground sensors for emergency transmitting on VHF at 3680 bps

Parameter:	*Value:*	*Units:*
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	3680	bps
In dBHz:	35.7	dBHz
Command System Eb/No:	16.2	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	7.7	dB

Table B.3: Uplink budget for an individual border control sensor (on land or sea) transmitting on VHF at 29 bps

Parameter:	Value:	Units:
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	29	bps
In dBHz:	14.6	dBHz
Command System Eb/No:	37.3	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**28.8**	dB

Table B.4: Uplink budget for a network of 194 ground sensors for border control transmitting on VHF at 5742 bps

Parameter:	*Value:*	*Units:*
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	5742	bps
In dBHz:	37.6	dBHz
Command System Eb/No:	14.3	dB
Demodulation Method Seleted:	**GMSK**	
Forward Error Correction Coding Used:	**None**	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**5.8**	dB

Table B.5: Uplink budget for an individual environmental / atmospheric sensor (on land) transmitting on VHF at 1 bps

Parameter:	Value:	Units:
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	1	bps
In dBHz:	0	dBHz
Command System Eb/No:	51.9	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**43.4**	dB

Table B.6: Uplink budget for a network of 162 ground sensors for environmental / atmospheric sensors (on land) transmitting on VHF at 43 bps

Parameter:	Value:	Units:
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	43	bps
In dBHz:	16.3	dBHz
Command System Eb/No:	35.5	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**27**	dB

Table B.7: Uplink budget for an individual sensor transmitting from a buoy on VHF at 1 bps

Parameter:	*Value:*	*Units:*
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	1	bps
In dBHz:	0	dBHz
Command System Eb/No:	51.9	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**43.4**	dB

Table B.8: Uplink budget for a network of 504 sensors transmitting from buoys on VHF at 134 bps

Parameter:	*Value:*	*Units:*
Ground Sensor:		
Ground Sensor Transmitter Power Output:	6	watts
In dBW:	7.8	dBW
In dBm:	37.8	dBm
Ground Snr. Total Transmission Line Losses:	2.8	dB
Antenna Gain:	3	dBi
Ground Sensor EIRP:	8	dBW
Uplink Path:		
Ground Sensor Antenna Pointing Loss:	0	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	142.1	dB
Atmospheric Losses:	2.1	dB
Ionospheric Losses:	0.7	dB
Rain Losses:	0	dB
Isotropic Signal Level at Spacecraft:	-137.1	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	0	dB
Spacecraft Antenna Gain:	-10	dBi
Spacecraft Total Transmission Line Losses:	2	dB
Spacecraft Effective Noise Temperature:	578	K
Spacecraft Figure of Merit (G/T):	-39.6	dB/K
S/C Signal-to-Noise Power Density (S/No):	51.9	dBHz
System Desired Data Rate:	134	bps
In dBHz:	21.3	dBHz
Command System Eb/No:	30.6	dB
Demodulation Method Seleted:	GMSK	
Forward Error Correction Coding Used:	None	
System Allowed or Specified Bit-Error-Rate:	1.00E-04	
Demodulator Implementation Loss:	0.1	dB
Telemetry System Required Eb/No:	8.4	dB
Eb/No Threshold:	8.5	dB
System Link Margin:	**22.1**	dB