INSTITUT NATIONAL POLYTECHNIQUE DE TOULOUSE

Master Informatique et Télécommunications
Parcours Réseaux & Télécoms
2010-2011

Année : 2011

Nom du Laboratoire : Télécommunications Spatiales et Aéronautiques (TéSA)

Directeur : M. Francis CASTANIÉ

Nanosatellite : état de l'art, éléments de conception et simulations

Auteur : M. Vicheka PHOR

Directeur de Recherche :

Responsable du stage : M. Ponia PECH

Nom du Projet :

Dirigé par : M. Christian FRABOUL

Résumé : Les communications par satellite qui nous permettent de communiquer à travers le monde ont été développées depuis les années 1960. Aujourd'hui, il est difficile de passer une journée sans l'aide des communications par satellite. Grâce à leurs avantages qui pourraient se résumer par la formule suivante : « Plus rapides, plus petits, meilleurs et moins chers », les nanosatellites sont récemment devenus un sujet de recherche très intéressant dans de nombreux pays développés. Ce mémoire traitera beaucoup d'aspects liés aux nanosatellites, à travers trois parties principales : une partie bibliographique, une partie théorique, et une partie réalisation et simulation. Les points les plus saillants et significatifs dans ce mémoire sont l'étude de la mécanique orbitale des nanosatellites, la détermination de constellations optimales, et le calcul des bilans de liaison pour différents types d'orbite, dont LEO (Low Earth Orbit), VEO (Very Low Earth Orbit) et MEO (Medium Earth Orbit).

ACKNOWLEDGEMENT

Study abroad requires determination, patience, hard work, and particularly encouragement from family, friends and lecturers. This thesis can be completed is thanks to them.

First of all, I would like to thank the international educational organization AUF, stand for the "Association of Universities of the Francophonie", that offered me a scholarship to continue my Master’s degree at ENSEEIHT university, in Toulouse.

I would like to thank deeply M. Fraboul CHRISTIAN, the director of department of computer science and telecommunications in French “Departement d’Informatique et Télécommunications”, who has accepted me for the master course.

I would like to say a big thank you to M. Francis CASTANIÉ, the director of TéSA (Telecommunications for Space and Aeronautics) research laboratory, who has accepted me for an internship.

I would like to express my deep gratitude to M. Ponia PECH, the research engineer at TéSA, who is my supervisor. I really appreciate all his help, his precious advices and his time.

I would like also to thank everyone in TéSA laboratory, thanks for their friendliness and kindness.

Finally, I would like to say a big thank you and love to my family, my friends and my lecturers who always support and encourage me during this year.

I wish everyone HAPPINESS always.

SUMMARY

Communications satellites which allow us to communicate throughout the world have been developed since 1960s. At the present, it is difficult to go through a day without using a communications satellite. Because of its advantages "Faster, Better, Smaller, Cheaper", Communications by nanosatellites have been recently become an interesting research topic in many developed countries. This thesis will dealt with many things about nanosatellites by going through 3 main parts: literature part, theoretical part, and the realization and simulation part. The most interested points in this thesis are the determination of the orbital mechanics, the optimal constellation, and link budget for different orbit types including LEO, VEO and MEO.

LIST OF ABBREVIATIONS

A	
ACS	Attitude Determination System
ADC	Attitude Determination and Control subsystem
AFB	Air Force Base
AFSK	Audio Frequency Shift Keying
AMBE	Advanced Multi-Band Excitation
AX.25	Amateur X.25
B	
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
C	
C&DH	Command and Data Handling subsystem
COM	Communication Subsystem
D	
DD	Digital Data
D-STAR	Digital Smart Technology for Amateur Radio
DV	Digital Voice
E	
EPS	Electrical Power Systems
F	
FSK	Frequency Shift Keying
G	
GEO	GEostationary Orbit
GMSK	Gaussian Minimum Shift Keying
GNC	Guidance and Navigation Control subsystem
GS	Ground Station
H	
HEO	High Earth Orbit
HF	High Frequency
J	
JARL	Japanese Amateur-Radio League
L	
LEO	Low Earth Orbit
Li-Po	Lithium-Polymer
M	
MCC	Mission Control Center
MECH	Mechanism Subsystem
MEO	Medium Earth Orbit
O	
OBC	On-Board Computer
OUFTI-1	Orbital Utility For Telecommunication Innovation

P	
PMAS	Passive Magnetic Attitude Stabilization
P-POD	Poly-PicoSatellite Orbital Deployer
R	
R.A.A.N	Right Ascension of the Ascending Node
S	
STK	Satellite Tool Kit
T	
TC	Telecommand
TCS	Thermal Control Subsystem
TCS	Thermal Control Subsystem
TM	Telemetry
TNC	Terminal Node Controller
TT&C	Tracking, Telemetry and Command subsystem
TTC	Tracking, Telemetry and Command
U	
UHF	Ultra High Frequency
UV	Ultra Violet
V	
VHF	Very High Frequency
VLEO	Very Low Earth Orbit
VSAT	Very Small Aperture Terminal
W	
WPM	Words Per Minutes
X	
xEPS	Experimental EPS
Tx	Tranceiver (Émetteur)
Rx	Receiver (Récepteur)
QPSK	Quadriphase Phase Shift Keying

LIST OF FIGURES

LIST OF TABLES

CONTENTS

CHAPTER IV
"Realization and simulation: realization of a simulator for orbital mechanics and communication performance analysis"

CHAPTER V
“Conclusion”

References
Annexes I
Annexes II
Annexes III

CHAPTER I

"Introduction"

This chapter will present three important points: introduction to research topic, internship objective and general theme of the Master IT-RT.

I.1 <u>Introduction to research topic</u>

Satellite communications are the outcome of research in the area of communications and space technologies whose objective is to achieve ever increasing ranges and capacities with the lowest possible costs.

The Second World War stimulated the expansion of two very distinct technologies—missiles and microwaves. The expertise eventually gained in the combined use of these two techniques opened up the era of satellite communications.

Before the 2000s, there were a lot of traditional satellites which were launched and placed on a terrestrial orbit, the minisatellites (<500 kg) and the microsatellites (<100 kg).

Since the 2000s, thanks to the progress of the microtechnologies, the aerospace industry and the research community have started directing their attention to missions involving many, small, distributed and inexpensive satellites such as the nanosatellites (<10 kg) and the picosatellites (<1 kg) because the traditional satellite missions are extremely expensive (the costs is up to billions of dollars) and requires a lot of time in the satellite development.

Hence, the nanosatellites were the objects of a huge interest that were renewed to travel throughout the world all these recent years because of its advantages as the following:

- faster duration of development;
- possibility to make satellites redundant, which increases the reliability of the system;
- reduction of the size and the cost of the earth stations;
- ideal to test new technologies;
- possibility to be launch in group or in " Piggyback " with bigger satellites;
- reduction of the manufacturing and launching costs;
- financial losses minimized in case of failure.

The nanosatellites are therefore a solution well targeted at the problems of the budget, the duration of development, and the reliability of the satellite communication system.

I.2 <u>Internship objective</u>

The technological and economic potentialities of the nanosatellites that offer some innovative perspectives for the future in the conception of the spatial system and that are susceptible to become a technological path and industrial competitor against the traditional path justifies some strategic anticipation in the research. The objective of this internship is to contribute to the study of the nanosatellites.

The internship work is divided into three parts:

1. Literature part: state of the art of the development of the nanosatellites – technologies and applications. This part will present the elements below:

- Introduction to nanosatellites: history of nanosatellite and general characteristic of nanosatellite system
  - History of nanosatellite: miniaturized satellite and birth of nanosatellite;
  - General characteristic of nanosatellite system: satellite communication system architecture, types of orbit and frequency Bands;
- Technologies of nanosatellites: characteristic of nanosatellite, nanosatellite subsystem, advantages and disadvantages of nanosatellite, and nanosatellite challenges will be presented;
- Application of nanosatellites.

2. Theoretical part: conception elements of nanosatellite systems. This part consists in study some elements well targeted at preliminary conception of the nanosatellite system, by going through a possible future demonstrator, a prior and lucid definition of the mission which is made in narrow conjunction with the TéSA laboratory. The following elements of conception will be considered:

- Definition of missions
- Space segment
- Ground segment
- Space environment
- Physical layer and data layer
- Orbital mechanic
- Satellite constellation
- Link budget (EIRP, S/No, G/T)

3. Realization and simulation: realization of a simulator for orbital mechanics and communication performance analysis. Literature and theoretical studies carried out in the previous parts will be completed in this third part, first of all, by the implementation under the simulation software program STK of the representative scenario of the nanosatellite system studied (spatial segment, terrestrial segment and architecture network) which will permit to simulate, to analyze and to validate the system design. This chapter will deal with:

- What is STK?
- Orbital mechanics for different orbit types
- Continuous whole Earth coverage constellation for different orbit types
- Constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations
- Link budget between OUFTI1 nanosatellite and Liege ground station for different orbit types

I.3 **General theme of the Master IT-RT**

The vast topic of the nanosatellites treated in this internship and proposed by TéSA, as it is new, has intervened in many fields of research and various disciplines of the sciences engineering:

- Electrical and energy systems (example: Pico-solar cells, batteries, sensors, etc.);
- Mechanical (example: nanosatellite structure, antennas, etc.);
- Automatic (example: attitude control of nanosatellite, speed control of nanosatellite, thermal control, etc.);
- Networks and telecommunications (example: communication protocols, communication performance, link budget, etc.).

Specifically, during this internship, the different elements of conception of a nanosatellite system are addressed, starting from the definition of missions until the communication performance analysis by going through the space environment, the ground segment and the space segment. A brief skimming of the various onboard subsystems is also given which offers the opportunity to stand in the situation of the preliminary conception of a complete nanosatellite system.

The following points:

- determination of the orbital mechanics with the comparison of the different types of orbit (VLEO, LEO, and MEO);
- determination of the optimal constellation;
- and the communication performance analysis (link budget);

are oriented more toward the communications and orbit aspects and will lead to the development of a simulator in STK and in MATLAB simulations.

Therefore, it is proven that the study of nanosatellite system achieved in this internship fits perfectly within the theme of the Research Master course in Department of Computer Science and Telecommunications; option Networks and Telecommunications (Master IT-RT).

CHAPTER II

“Literature part: state of the art of the development of the nanosatellites – technologies and applications”

This chapter will describe three main points:

1. Introduction to nanosatellites: history of nanosatellite and general characteristic of nanosatellite system.
2. Technologies of nanosatellites: characteristic of nanosatellite, nanosatellite subsystem, advantages and disadvantages of nanosatellite, and nanosatellite challenges will be presented.
3. Application of nanosatellites

II.1 Introduction to nanosatellites

II.1.1 History of nanosatellites

A. Miniaturized satellite

Miniaturized satellites or small satellites are artificial satellites with low weights and small sizes, usually under 500 kg. The miniaturized satellite technology has opened a new era of satellite engineering by decreasing space mission cost, without reducing the performance. Miniaturized satellite was classified into 4 groups based on their mass as the following:

- Minisatellite: a "wet mass" (including fuel) between 100 and 500 kg
- Microsatellite: a wet mass between 10 and 100 kg
- Nanosatellite: a wet mass between 1 and 10 kg
- Picosatellite: a wet mass between .1 and 1 kg

Traditional satellites refer to minisatellite or microsatellite. The CubeSat design with 1 kg maximum mass is an example of a large picosatellite or minimum nanosatellite.

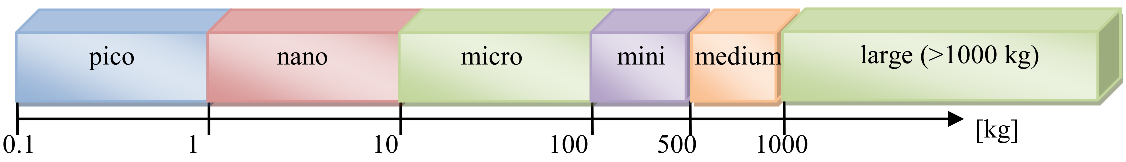


Figure II.1: Classification of miniature satellite

B. Birth of nanosatellite

Satellite communications are the outcome of research in the area of communications and space technologies whose objective is to achieve ever increasing ranges and capacities with the lowest possible costs.

The Second World War stimulated the expansion of two very distinct technologies—missiles and microwaves. The expertise eventually gained in the combined use of these two techniques opened up the era of satellite communications.

The first traditional satellite with radio transmitter for atmospheric studies, Sputnik with mass 83.6 kg, was launched into an elliptical low earth orbit (LEO: Low Earth Orbit, Apogee: 947 km, Perigee: 215 km, Inclination: 65°) by the Soviet Union on 4 October 1957. Sputnik only remained in orbit for 3 months before burning up as it re-entered the earth's atmosphere.

Traditional/Conventional satellite missions are extremely expensive (cost billions of dollars) to design, build, launch and operate. Consequently, both the aerospace industry and the research community have started directing their attention to missions involving many, small, distributed and inexpensive satellites such as nanosatellite and picosatellite.

On 12 December 1961, the first nanosatellite named Orbiting Satellite Carrying Amateur Radio (OSCAR) with mass 4.5 kg was launched into very low earth orbit (VLEO: Very Low Earth Orbit, Apogee: 431.00 km, Perigee: 245.30 km, Inclination: 81.14°) at Vandenberg AFB (Vandenberg Air Force Base, California, in United States) and only remained in orbit for 22 days.

On 27 January 2000, ASU-OSCAR37, the rebirth of nanosatellite for amateur radio, was launched from Vandenberg AFB (Vandenberg Air Force Base, California, in United States) aboard a Minotaur-1 into low earth orbit (LEO: Low Earth Orbit, Apogee: 799.00 km, Perigee: 746.30 km, Inclination: 100.19°) and weighed 6 kg. This satellite is currently non-operational.

On 30 June 2003, CubeSat-OSCAR 55, the first successful nanosatellite for amateur radio which has operated till present, was launched from Baikonur Cosmodrome aboard a Dnepr and was inserted into low earth orbit (LEO: Low Earth Orbit, Apogee: 831.00 km, Perigee: 816.30 km, Inclination: 98.72°) The satellite measured 10 x 10 x 10 cm, and weighed 1 kg. It was a project of Tokyo Institute of Technology Matunaga LSS.

The history of nanosatellites [8] which were successfully launched and operated till present is shown in Annex I, Table 1.

II.1.2 General characteristic of nanosatellite system

A. Satellite communication system architecture

The satellite system is composed of a space segment, a control segment and a ground segment. [1]

- Space segment: contains one or several active and spare satellites organized into a constellation.
- Control segment: consists of all ground facilities for the control and monitoring of the satellites, also named TTC (Tracking, Telemetry and Command) stations, and for the management of the traffic and the associated resources on-board the satellite (Network management station).
- Ground segment: consists of all the traffic earth stations.

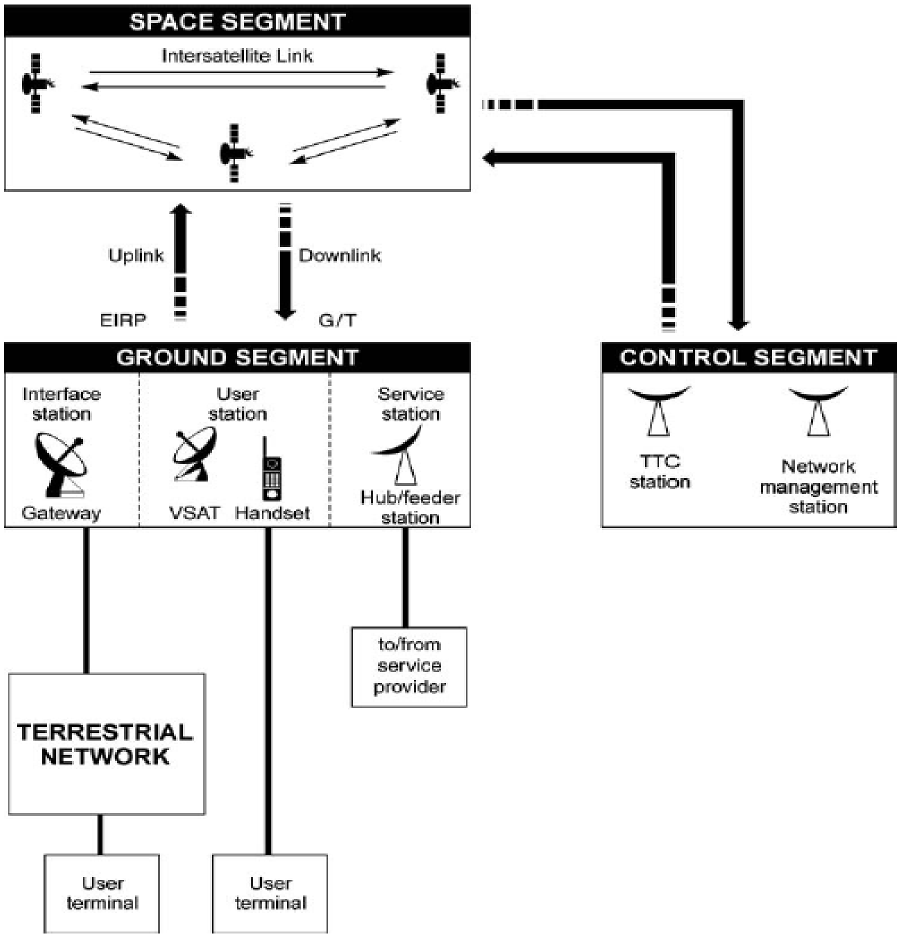


Figure II.2: Satellite communication system architecture

B. Types of orbit

The path of the satellite through space is called its orbit; the orientation of the satellite in space is called its altitude. There are 4 mains types of orbit for satellite communications [2]: LEO, MEO, GEO and HEO which is showed in Figure II.3 and in Table II.1.

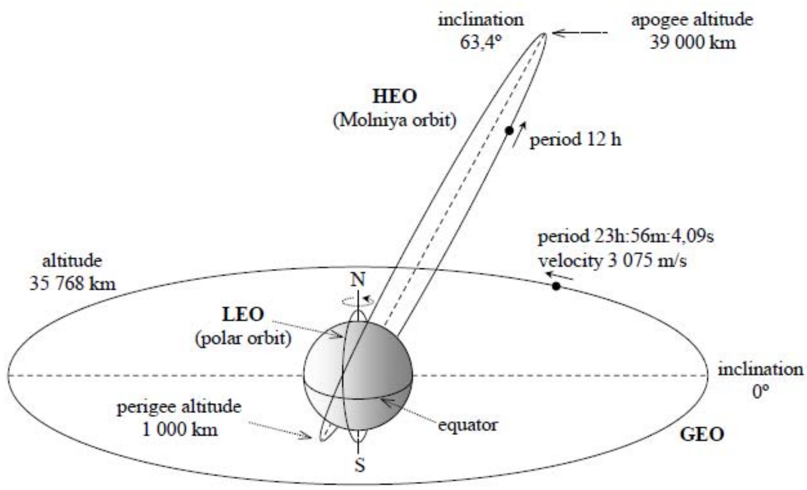


Figure II.3: Types of satellite orbits

Table II.1: Orbit comparison for satellite communications

ORBITS	LEO	MEO	HEO	GEO
Environment constraints	Currently low (space debris: growing concern)	Low/medium	Medium/high (Van Allen belts: 4 crossings/day)	Low
Orbital period	1.5-2 h	5-10 h	12 h	24 h
Altitude range	500-1 500 km	8 000-18 000 km	40 000 km apogee (perigee below 1 000 km)	40 000 km (i = 0)
Visibility duration	15-20 mn/pass	2-8 h/pass	8-11 h/pass (apogee)	Permanent
Elevation	Rapid variations; high and low angles	Slow variations; high angles	No variations (apogee); high angles	No variation; low angles at high latitudes
Propagation delay	Several milliseconds	Tens of milliseconds	Hundreds of milliseconds (apogee)	> 250 milliseconds
Link budget (distance)	Favourable; compatible with small satellites and handheld user terminals	Less favourable	Not favourable for handheld or small terminals	Not favourable for handheld or small terminals
Instantaneous ground coverage (diameter at 10° elevation)	≈ 6 000 km	≈ 12 000-15 000 km	16 000 km (apogee)	16 000 km
Examples of systems	IRIDIUM, GLOBALSTAR TELEDESIC, SKYBRIDGE, ORBCOMM…	ODYSSEY, INMARSAT P21…	MOLNYA, ARCHIMEDES…	INTELSAT, INTERSPOUTNIK, INMARSAT…
LEO : low-Earth orbits MEO : medium-Earth orbits HEO : highly-eccentric orbits GEO : geostationary orbits				

C. Frequency Bands

Frequency ba nds are allocated according t o radio-communications services t o allow compatible us e. Different f requency ba nds us ed i n s atellite c ommunications a ccording t o IEEE US are shown in Table II.2.

Table II.2: Frequency Bands of satellite communications

Band	Frequency Range
HF band (High Frequency)	3 to 30 MHz
VHF band (Very High Frequency)	30 to 300 MHz
UHF band (Ultra High Frequency)	300 to 1000 MHz
L band (Long Wave)	1 to 2 GHz
S band (Short Wave)	2 to 4 GHz
C band	4 to 8 GHz
X band	8 to 12 GHz
Ku band (Kurz-Under)	12 to 18 GHz
K band (Kurz)	18 to 27 GHz
Ka band (Kurz-Above)	27 to 40 GHz
V band	40 to 75 GHz
W band	75 to 110 GHz
mm band	110 to 300 GHz

II.2 Technologies of nanosatellites

For the last few years, the aerospace industry, the research community and many space projects in universities laboratories have focused on development of nanosatellite which is the recent and powerful technology.

This part will discuss about the characteristic of nanosatellite, advantages and disadvantages of nanosatellites over the traditional/conventional satellites, nanosatellite challenges and nanosatellite subsystems.

II.2.1 Characteristic of nanosatellite

The characteristic of nanosatellite [7] is shown in the Table II.3.

Table II.3: Characteristic of nanosatellite

Mass	1 to 10 kg
Size	1 Unit CubeSat (Length × Width × Height: about 10 × 10 × 10 cm); 1.5 Unit CubeSat (10 × 10 × 15 cm); 2 Unit CubeSat (10 × 10 × 20 cm); 3 Unit CubeSat (10 × 10 × 30 cm); 4 Unit CubeSat (10 × 10 × 40 cm); 5 Unit CubeSat (10 × 10 × 50 cm); 6 Unit CubeSat (10 × 20 × 30 cm);…
Orbit types	VLEO (Very Low Earth Orbit, altitude less than 500 km) or LEO (500 to 800 km)
Power source	3.3 V, 5 V, 6.5 V, 8.2 V, 12 V, 12.5 V or 24 V DC depends on technology design of power supply
Frequency band	VHF (130-160 MHz) or UHF (400-450 MHz)
Modulation schemes	BPSK, FSK, AFSK or GMSK
Transmit power	150 mW or 25 dBm average
Receiver sensitivity	about -100 dBm for BER 10^{-5}
Downlink data rate	1200, 2400, 4800 or 9600 bps
Uplink data rate	300 to 1200 bps
Protocol	many protocols available (AX. 25 the most usage)
Number of nanosatellite require for cover the earth	30 to 60 nanosatellites depends on altitude of orbit type Ex: a constellation of about 60 low-earth orbit (LEO) Israel's nanosats can cover the earth
Cost	less than $1 million
Life time	2 to 5 years depends on many parameters such as type of orbit, payload, battery cycling, launching, etc…

II.2.2 Nanosatellite subsystem

A satellite system comprises a number of satellite subsystems [4] as the following:

- *Attitude Determination and Control subsystem (ADC).*
  - Stabilizes and orients the vehicle in desired directions (to maintain the antenna RF beam pointed at the intended areas on Earth) during the mission despite the external disturbance torques and forces acting on it.

- *Guidance and Navigation Control subsystem (GNC).*
  - *Navigation* and *orbit determination* interchangeably to mean determining the satellite's position and velocity or, equivalently, its orbital elements as a function of time;
  - *Guidance* and *orbit control* to mean adjusting the orbit to meet some predetermined conditions.

- *Tracking, Telemetry and Command subsystem (TT&C).* It provides the interface between the spacecraft and ground systems:
  - *Tracking* to determine the position of the spacecraft and follow its travel using angle, range and velocity information;
  - *Telemetry* to collect, encode and transmit information for the other subsystems;
  - *Command* element that receives and executes remote control commands to effect changes to the platforms functions, configuration, position and velocity.

- *Command and Data Handling subsystem (C&DH).*
  - Receive, validation and decoding of the commands, and distributes the commands to the appropriate spacecraft subsystems and components;
  - Receives housekeeping data and science data from the other spacecraft subsystems and components, and packages the data for storage on a data recorder or transmission to the ground via the communications subsystem.

- *Electrical Power Subsystem (EPS).*
  - The power subsystem consists of solar panels, backup batteries and electrical power systems that generate power to supply the various satellite subsystems.

- *Thermal Control Subsystem (TCS).*
  - To maintain the equipment in and about the spacecraft structure within their required temperature limits for each mission phase
- *Structures and Mechanisms subsystem.*
  - Supports all other spacecraft subsystems, attaches the spacecraft to the launch vehicle, and provides for ordnance-activated separation.

- *Antenna subsystem.*
  - To collect and to transmit the radio waves, transmitted in a given frequency band and with a given polarization, by ground stations situated within a particular region on the surface of the earth.

- *Communication payload subsystem.*
  - Collect microwave signals from given zone on earth
  - Amplify radio frequency carrier
  - Convert carrier frequency from uplink to downlink frequency
  - Transmit microwave signals to given zone on earth

II.2.3 Advantages and disadvantages of nanosatellite

The advantages and disadvantages of nanosatellites over the traditional/conventional satellites [9] are shown in Table II.4.

Table II.4: Advantages and disadvantages of nanosatellite

Advantages "Faster, Better, Smaller, Cheaper"	**Disadvantages**
▪ Faster building times ▪ Ability for satellites redundant which increases the reliability of system ▪ Reduction of earth station size and cost ▪ Ideal test for new technologies ▪ Ability to be launched in groups or "piggyback" along with larger satellites ▪ Lower cost of manufacture and launch ▪ Minimal financial loss in case of failure	▪ More rapid orbital decay ▪ Generally shorter working life ▪ Lower transmitter output power capability ▪ Reduced hardware-carrying capacity

II.2.4 Nanosatellite challenges

Nanosatellite which is low mass, low cost and missions in VLEO or LEO have presented new challenges for research such as:

- Advances in electronic miniaturization, the progress in data manipulation, storage, power availability, imaging technology, autonomous intelligence and associated performance capability
- Appearance of new small launchers on the market (e.g., modified long-range and intercontinental military missiles, special structure for auxiliary payloads which allows simultaneous launching of several small satellites), the innovations in propulsion and other technologies as well as operations and management for broader applications in future launch systems.
- Ongoing reduction in mission complexity and costs
- A potential new market with Government, commercial, and academic customers.

II.3 Application of nanosatellites

At present, nanosatellite was used in various applications such as:

- *Telecommunications*. It involves many applications such as:
  - Voice: Telephony Trunking, Personal Telephony, Remote Pay Phones
  - Messaging: Pager, Meter Reading
  - Data: Software Distribution, Databases, E-mail, Very Small Aperture Terminal (VSAT) network, etc
  - Broadcast: Digital Audio Radio, Television Distribution, Direct Broadcast Television
  - Multimedia: Telemedicine, Tele-Education, Teleconferencing, Telecommuting, Video on Demand, Home Shopping, Satellite News Gathering
  - Internet

- *Earth Observations*. It covers activities related to data collection and to imagery for earthquake forecasts, storms early detection and predictions of volcanic activity.

- *Scientific Research*. Nanosatellites can offer a very quick turn-around and inexpensive means of exploring well-focused, small-scale science objectives (e.g.: monitoring the space radiation environment, updating the international geo-magnetic reference field, etc.) or providing an early proof-of-concept prior to the development of large-scale instrumentation.

- *Technology Demonstrations*. Nanosatellites can provide an attractive and low-cost means of testing, verifying and evaluating new technologies or services on a real orbital environment and within acceptable risks prior to a commitment to a full-scale, expensive mission.

- *Military Applications*. It is used for a military purpose, often for gathering intelligence, as a communications satellite used for military purposes, or as a military weapon.

- *Academic Training*. Nanosatellite satellites programs are a mean to enhance the industrial domain and to provide education and training of students, scientists and engineers in space related skills, by allowing them direct, hands-on, experience at all stages (technical and managerial) of a particular space mission (including design, production, test, launch and orbital operations).

Conclusion

Throughout this chapter, an introduction to nanosatellites, technologies of nanosatellite and application of nanosatellite were described. By going through an overview of nanosatellite system including history of nanosatellite, general characteristic of nanosatellite system, characteristic of nanosatellite, nanosatellite subsystem, advantages and disadvantages of nanosatellite, nanosatellite challenges and application of nanosatellites, these basic information will help us to enter the next chapter which will describes about the conception elements of nanosatellite system.

CHAPTER III

"Theoretical part: conception elements of nanosatellite systems"

From chapter II, an overview of nanosatellite system including its technologies and its application was described. This chapter III will deal with the conception elements of nanosatellite system such as:

1. Definition of missions
2. Space segment
3. Ground segment
4. Space environment
5. Physical layer and data layer
6. Orbital mechanic
7. Satellite constellation
8. Link budget (EIRP, S/No, G/T)

III.1 Definition of missions

To simplify work, we will study on the hypotheses of OUFTI-1 nanosatellite which is used for telecommunications (amateur radio or ham-radio) and developed by the University of Liege in Belgium [4]. The main hypotheses are summarized in Table III.1.

Table III.1: Characteristic of OUFTI-1 nanosatellite

Mass	1 kg
Size	1 Unit CubeSat (Length × Width × Height: about 10 × 10 × 10 cm)
Orbit types	LEO Apogee (h_a): 1447.00 km Perigee (h_p): 354.00 km
Inclination (i)	71°
Argument of perigee (ω)	230° (defined for simulation)
R.A.A.N (Ω)	10° (defined for simulation)
True anomaly	90° (defined for simulation)
Elevation angle (δ)	5°
Frequency band	- VHF band: 145 MHz for downlink - UHF band: 435 MHz for uplink
Power source	Batteries: 2.7 – 4.2 V. It consists of three converters providing currents at three different voltages of 3.3V, 5V, and 7.2V, and supplying various subsystems with the voltage required.
Protocol	- D-STAR: used in payload communication to perform ham-radio communication - AX.25: used for telemetry/telecommand (TM/TC) - Beacon: used to send 12 critical parameters in Morse code
Data rate	- D-STAR: 4800 bps - AX.25: 9600 bps - Beacon: 12 WPM (Words Per Minute)

Modulation schemes	- D-STAR: GMSK - AX.25: FSK - Beacon: GMSK or FSK (user defined)
Transmit power	- D-STAR; AX.25: about 750 mW or +28.7 dBm - Beacon: about 100 mW or +20 dBm
Receiver sensitivity	Less than -100 dBm for BER 10^{-5}
Cost	Less than $1 million
Life time	1 to 2 years (4.8 years estimated by STK)

III.2 Space segment

In this section, the main characteristics of different subsystems of OUFTI-1 nanosatellite are described [4]. The exploded view of OUFTI-1 nanosatellite was shown in Figure III.1.

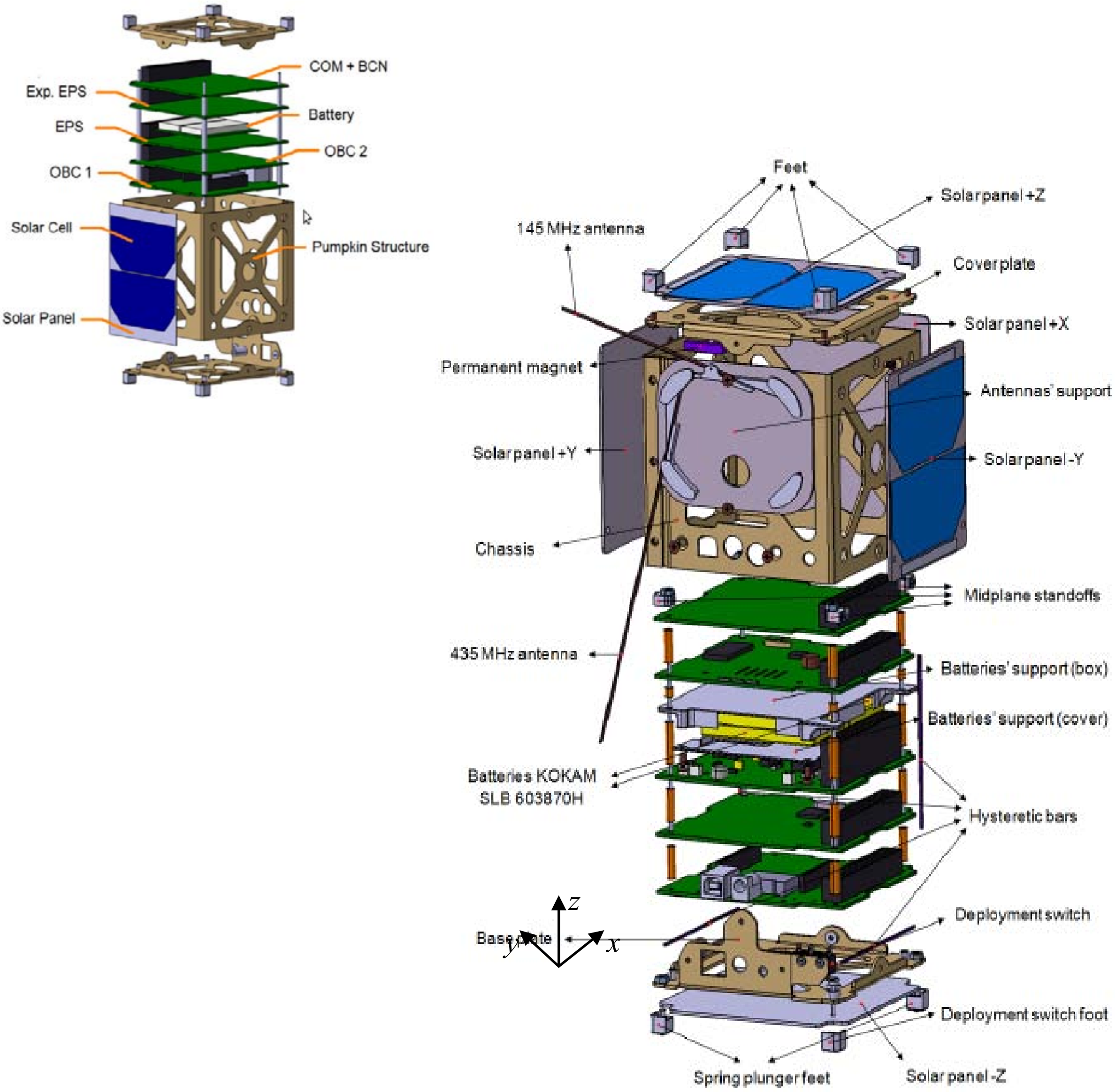


Figure III.1: Exploded view of OUFTI-1 nanosatellite

III.2.1 Attitude Determination and Control subsystem (ADC)

Attitude Determination and Control subsystem (ADC) stabilizes and orients the vehicle in desired directions (to maintain the antenna RF beam pointed at the intended areas on Earth) during the mission despite the external disturbance torques and forces acting on it. The ADC subsystem is made of two different parts: Attitude Determination System (ADS) and Attitude Control System (ACS).

- Attitude Determination System (ADS):

Attitude determination system refers to the process of measuring and determining spacecraft orientation. Spacecraft attitude can be determined by one or more of the following sensors: Earth sensors, Sun sensors, star trackers, radio frequency sensors, or gyroscopes.

For OUFTI-1, an accurate attitude determination is not necessary. In this case, OUFTI-1 has advantageous to use the existing solar panels as analogue sun sensors which allow an estimation of the attitude.

- Attitude Control System (ACS):

Attitude control system refers to the process of orienting the spacecraft in the given direction. Satellite attitude control systems are divided into two categories: passive and active control systems.

Passive attitude control: refers to the use of mechanisms which stabilize the satellite without putting a drain on the satellite's energy supplies (meaning that the satellite uses external torques that occurs due to its interaction with the environment and thus they cannot be avoided, in this case the disturbances being used for forcing the attitude of the satellite). Examples of the passive attitude control system are: spin stabilization, magnetic attitude stabilization and gravity gradient stabilization.

Active attitude control: there is no overall stabilizing torque present to resist the disturbance torques. The controller calculates corrective torques which is applied as required in response to disturbance torques. Examples of the active attitude control system are: momentum wheels, electromagnetic coils, and mass expulsion devices, such as gas jets and ion thrusters.

For OUFTI-1, it does not require high-precision orientation or specific manoeuvres during the flight. In such condition, OUFTI-1 use Passive Magnetic Attitude Stabilization (PMAS) which is the best solution because of some advantages such as robust, cheap, simple, easy to realize, light and do not require software development and on-board energy consumption.

The passive magnetic attitude stabilization system that is developed for OUFTI-1 is based on 1 permanent magnet and 4 hysteresis rods. A permanent magnet provides a restoring torque to align an oriented axis of the satellite with the Earth's magnetic field direction like a compass needle, in order to provide a favorable antenna footprint. Hysteresis rods are used to dissipate kinetic (rotational) energy by means of the magnetic hysteresis effect. The passive magnetic attitude stabilization system of OUFTI-1 nanosatellite is shown in Figure III.2.

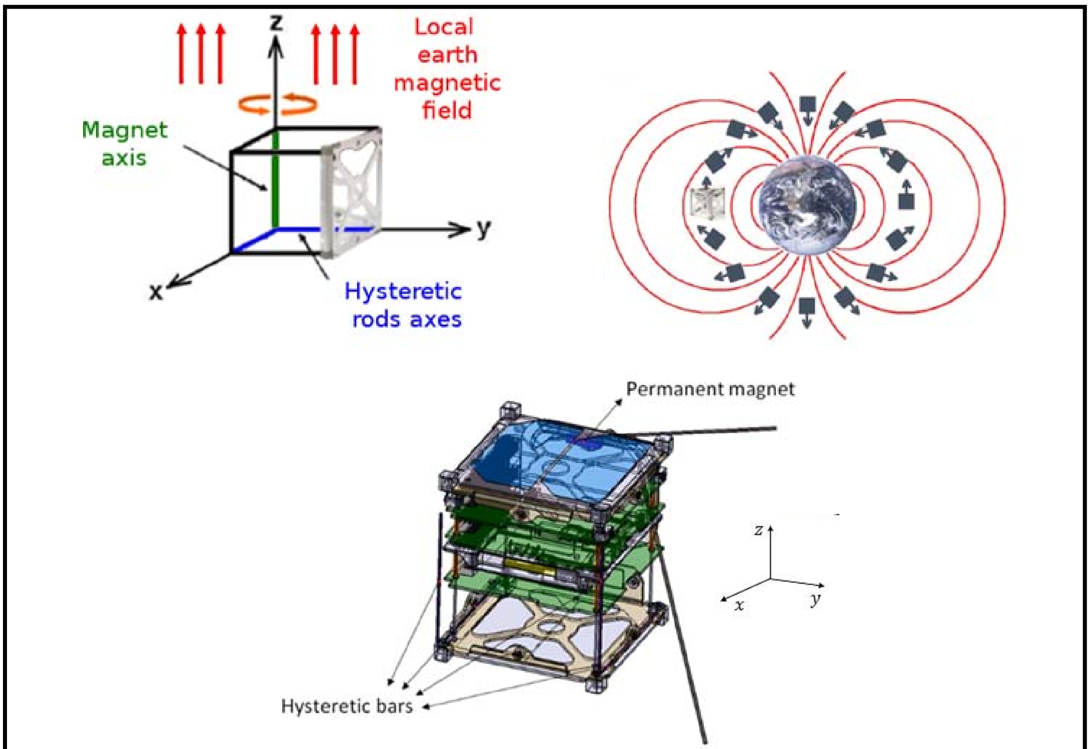


Figure III.2: Passive magnetic attitude stabilization system of OUFTI-1

III.2.2 <u>Structure and configuration subsystem</u>

The functions of structure and configuration subsystem are:

- Supporting all other spacecraft subsystems
- Attaching the spacecraft to the launch vehicle via P-POD. P-POD (Picosatellite Orbital Deployer) is the interface between launch vehicle and Cubesats
- Robustness with vibrations during the flight, the shocks during the separation, the ignition and the jettisoning of the fairing
- Protecting the main payload against the harsh space environment, including radiation, debris, and thermal variations.

▪ <u>OUFTI-1 structure</u>: it is produced by Pumpkin society. The structure of OUFTI-1 nanosatellite is in aluminum which is undergone by a chemical treatment process (Alodine, chromate conversion). The chemical treatment process, Alodine, is used to provide corrosion protection against oxidation, and to remain electrically conductive.

▪ <u>OUFTI-1 configuration</u>: Five electronic cards are stacked on top of each other and held in place by four vertical endless screws and mid-plane standoff components from Pumpkin structure. The batteries which are the heaviest elements are placed near the center of the structure in order to fulfill the Cubesat requirement for gravity center. Five of the six faces of the cube will be covered by solar cells fixed on aluminum panels. These panels will be useful to protect electronic components against radiations. The sixth face will be dedicated to external ports and antennas deployment mechanisms.

The structure and configuration subsystem of OUFTI-1 and P-POD is shown in Figure III.3.

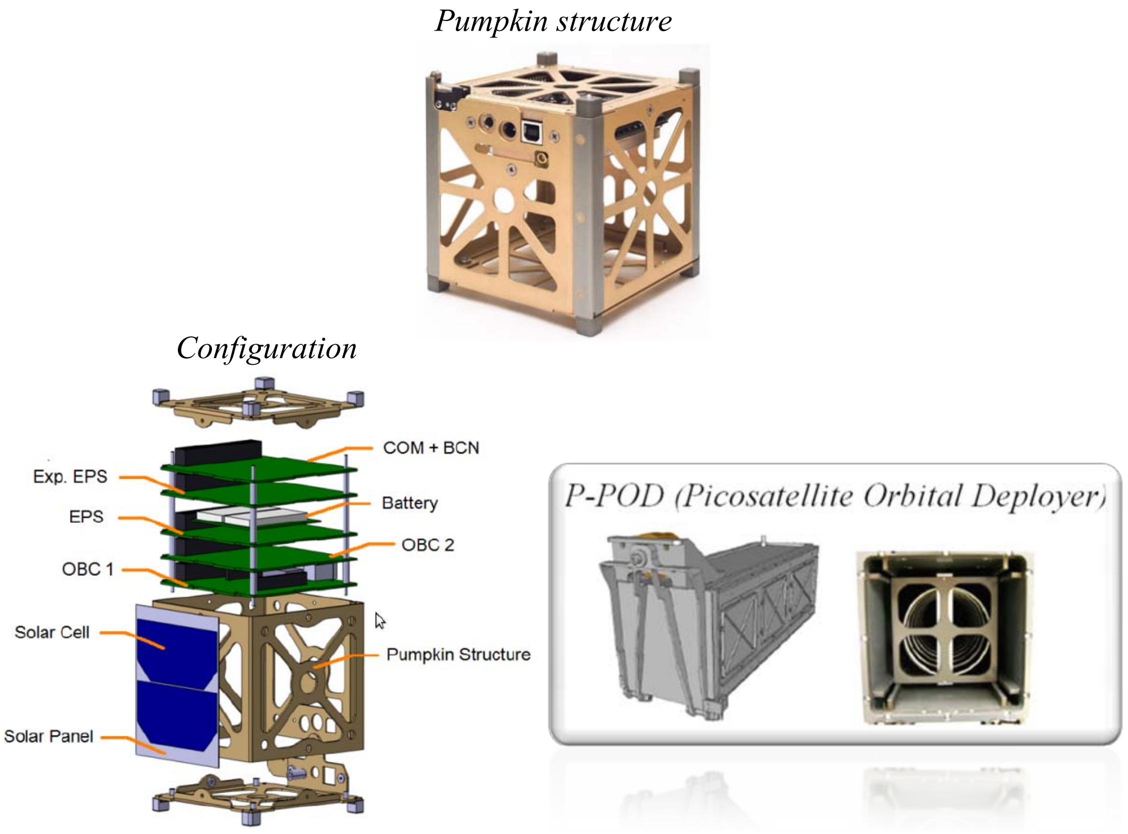


Figure III.3: Structure and configuration subsystem of OUFTI-1 and P-POD

III.2.3 Thermal Control Subsystem (TCS)

The function of thermal control subsystem is to maintain the equipment in and about the spacecraft structure within their required temperature limits for each mission phase.

Thermal control techniques are generally either passive or active. Passive techniques include good layout of equipment, careful selection of materials for the structure such as radiators, thermal blankets, coatings, reflectors, insulations, heat sinks, louvres, and so on. Active techniques include heaters, heat pipes, and pumped fluid loops with heat exchangers.

OUFTI-1 uses passive thermal control techniques because of the size and weight constraint. The thermal requirement of OUFTI-1 is summarized in Table III.2.

Table III.2: Thermal requirement of OUFTI-1

Component		T_{min}[°C]	T_{max}[°C]
Main structure		-40	+85
Solar cells		-100	+100
Electronics		-40	+85
Li-Po (Lithium-Polymer) batteries	Charge	0	+45
	Discharge	-20	+60

III.2.4 Mechanism subsystem

OUFTI-1 nanosatellite has two mechanisms, Dyneema wire and a current in a simple thermal knife, for the retention and the deployment of the two antennas (VHF and UHF). We refer to these as the "MECH" subsystem.

Each antenna is a quarter-wavelength monopole. This means that the VHF (145 MHz, wave length about 2 m) antenna and UHF (435 MHz, wave length about 70 cm) antenna will be about 17 cm and 50 cm in length respectively. Both antennas will be wound around a support and held in place by a piece of Dyneema wire. To deploy each antenna, a current in a simple thermal knife will melt the wire. The melting of the wire takes at least 15 minutes after ejection of nanosatellite from the P-POD to its final configuration.

The two mechanisms will be installed on the -X face, without obstructing communication ports as illustrated in Figure III.4.

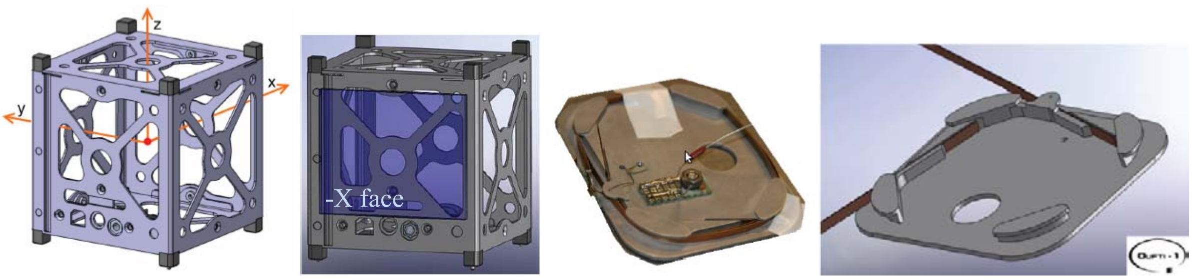


Figure III.4: "MECH" subsystem

III.2.5 Electrical power subsystem

The electrical power subsystem consists of solar panels, backup batteries and electrical power systems that generate power to supply the various satellite subsystems.

For the electrical power subsystem of OUFTI-1, there are:

- Solar cells placed on only 5 of the 6 faces of the CubeSat. OUFTI-1 use triple junction GaAs-based solar cells from AzurSpace which have an efficiency of 30% at the begin of life
- Two Li-Po (Lithium-Polymer) batteries in parallel as storing devices due to their high energy density. Li-Po batteries vary between 2.7V and 4.2V, depending on the state of charge/discharge
- Two electrical power systems (EPS), a main EPS and an Experimental EPS (xEPS). EPS consists of three converters providing currents at three different voltages of 3.3V, 5V, and 7.2V, and supplying various subsystems with the voltage required such as: OBC (OBC1 and OBC2), the COM and the beacon. xEPS is a digitally-controlled flyback converter. The input of the xEPS is connected to the batteries and the solar cells with the unregulated bus. The xEPS provides a 3.3V power output for other electrical systems.

The electrical power subsystem of OUFTI-1 is shown in the Figure III.5.

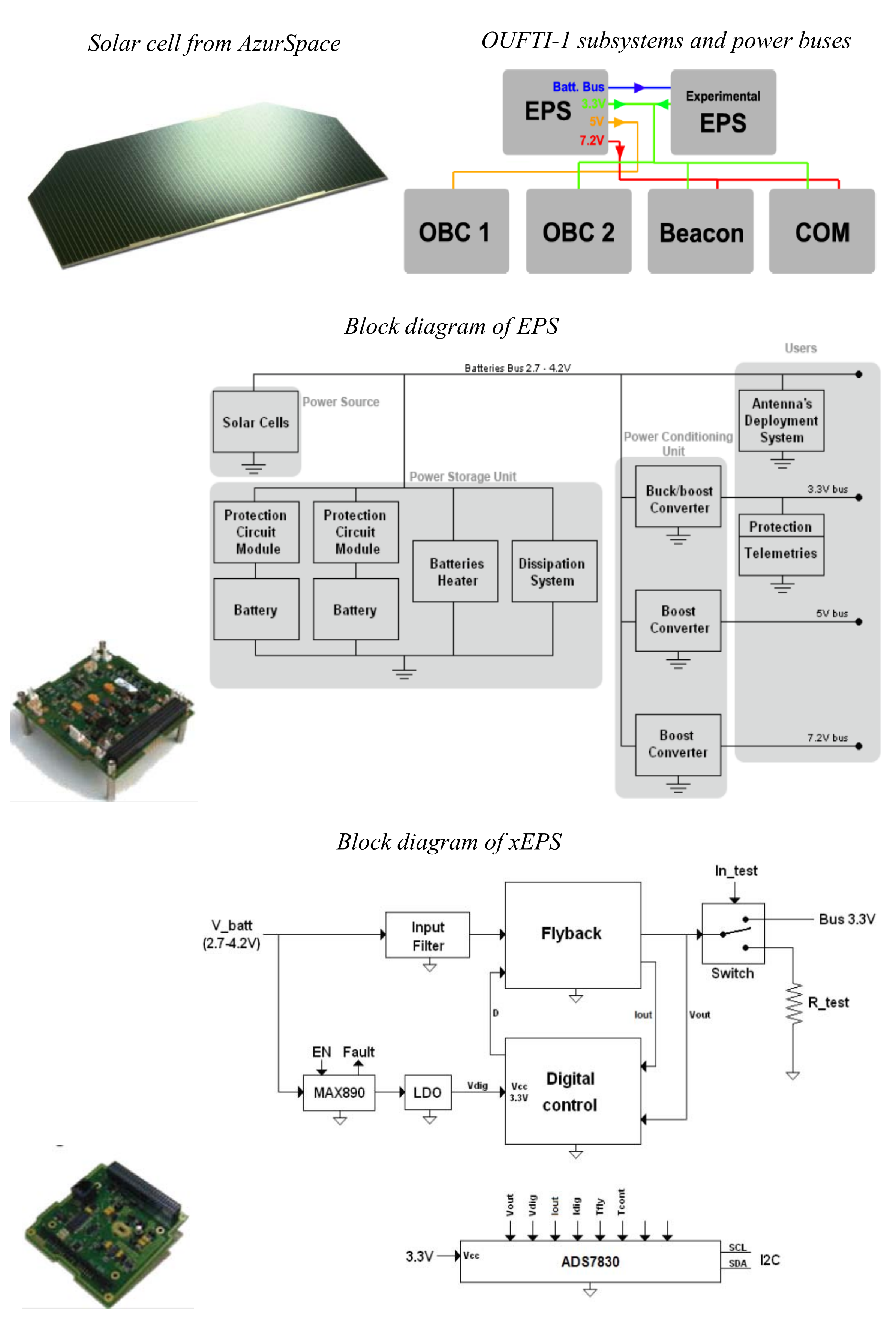


Figure III.5: Electrical power subsystem of OUFTI-1

III.2.6 On-board computer subsystem

The On-Board Computer (OBC), consisting in OBC1 and OBC2, will provide the following services on-board:

- Overall management
- Monitoring and control
- Telecommand and telemetry processing
- Data storage
- Data management
- Time keeping and synchronization.

These high level services can be converted into the following software functionalities:

1. Perform the initial satellite operations (antennas deployment, first activation of the other subsystems) according to a predefined sequence.
2. Perform AX.25 and D-STAR encoding and decoding.
3. Handle telecommands received on the uplink channel.
4. Perform measurements of housekeeping and science parameters aboard the satellite.
5. Store relevant measurements until they can be sent to the ground station.
6. Respond to telemetry requests by sending to ground present or past (stored) measurements.
7. Provide a time reference.
8. Perform power supply management, by enabling and disabling other subsystems in predefined conditions (e.g. a low battery voltage).
9. Perform power cycling in case of latch-up in a subsystem.
10. Manage the experimental electrical power supply (xEPS), by enabling and disabling it in predefined conditions.
11. Manage the D-STAR system, by configuring it (e.g. for Doppler compensation) according to data received via specific telecommands.
12. Keep a log of meaningful events happening aboard the satellite, and send to ground the log entries requested by specific telecommands.
13. Monitor, for the backup processor (OBC1), the activity of the default processor (OBC2) and detect when it stops functioning.

Figure III.6: On-board computer (OBC) subsystem of OUFTI-1

III.2.7 Antennas subsystem

OUFTI-1 uses two quarter-wavelength monopole antennas, one for the VHF band (145 MHz) and one for the UHF band (435 MHz). This means that the VHF (145 MHz, wave length about 2 m) antenna and UHF (435 MHz, wave length about 70 cm) antenna will be about 17 cm and 50 cm in length respectively.

III.2.8 Communication subsystem

OUFTI-1 uses three different communication systems (COM subsystem): the beacon, AX.25 for data exchanges of TC/TM, and D-STAR as the main payload. The functionalities of the communication subsystem are shown in Table III.3. The block diagram of the communication subsystem is illustrated in Figure III.7.

Table III.3: Functionalities of the COM subsystem

	Beacon	AX.25	D-STAR
Status	Always on	Rx always on, Tx on after TC reception	Rx and Tx on after TC reception
Data rate	12 WPM	9.6 kbps	DV mode: 4.8 kbps
Modulation type	FSK	FSK	GMSK
Function	Send 12 critical parameters in Morse code	Used for TC/TM	Payload, used to perform ham-radio communication

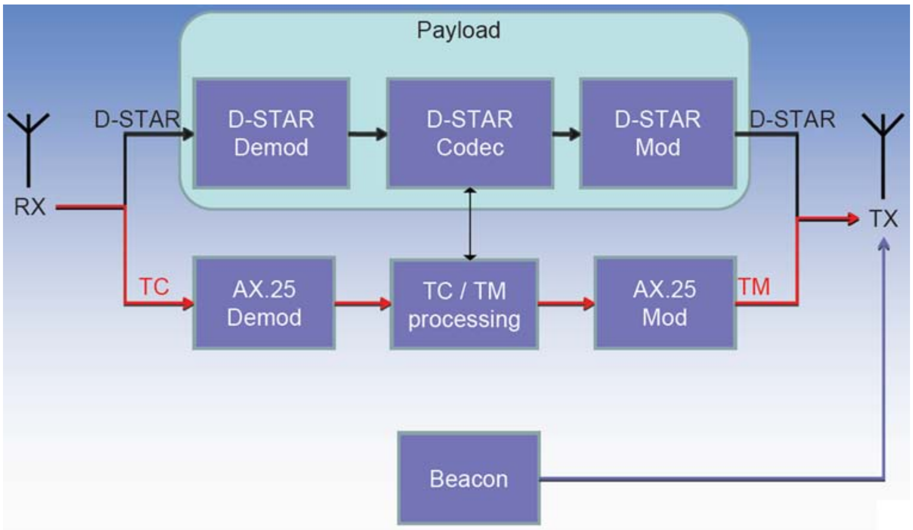


Figure III.7: Block diagram of the COM subsystem

III.3 Ground segment

There are 3 segments for satellites communications: space segment, control segment and ground segment. For OUFTI-1 nanosatellite communication, there are only 2 segments: space segment and ground segment since the control segment is included in ground segment. This section will describe about the architecture of the ground segment, the ground station, the Mission Control Center (MCC), the D-STAR repeater, and the D-STAR satellite communication module (Satellite Extension) [4].

III.3.1 Architecture of the ground segment

The ground segment architecture composes 4 elements: the Ground Station (GS), the Mission Control Center (MCC), the D-STAR Repeater, and the D-STAR satellite communication module (Satellite Extension). The architecture of the ground segment is illustrated in Figure III.8.

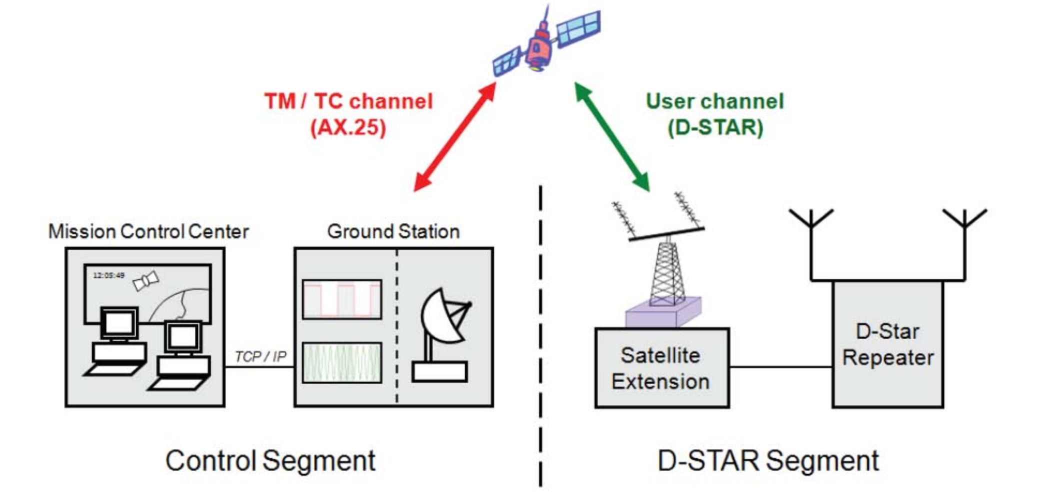


Figure III.8: Architecture of the ground segment

III.3.2 <u>Ground station</u>

The ground station is responsible for:

- The RF links between the satellites and the ground system. It controls the antenna rotors, the Terminal Node Controller (TNC), and the transceivers used
- The link between MCC and any ground station or any ground station network.

The architecture of the ground station is shown in Figure III.9.

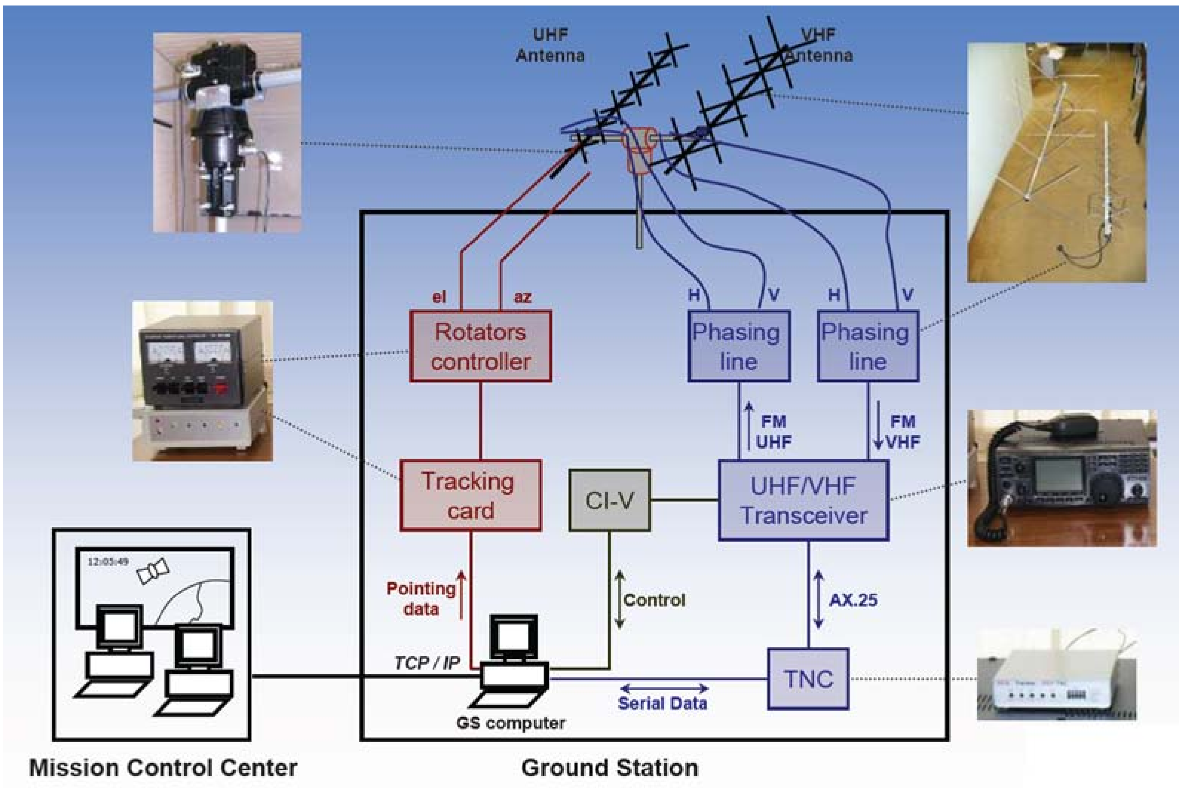


Figure III.9: Architecture of the ground station

III.3.3 Mission control center

OUFTI-1's Mission Control Center (MCC) allows operators to command and control the satellite from terminals via the operation server. It is designed to perform the following functions:

- Preparation and transmission of telecommands, both manually and automatically
- Reception and processing of telemetry, both manually and automatically
- Archiving and retrieval of data
- Displays of data
- Real-time updates.

III.3.4 D-STAR repeater

D-STAR, Digital Smart Technologies for Amateur-Radio, is a digital telecommunication system developed by the Japanese Amateur-Radio League (JARL) in 2003. It is the main payload of OUFTI-1 nanosatellite communication system, which is used to perform ham-radio communication.

▪ The features of D-STAR

The main features of D-STAR are the following:

- Offer two modes of communication, Digital Data (DD) mode and Digital Voice (DV) mode. The DD mode transmits and receives data only, at a rate of 128 kbps, while the DV mode simultaneously transmits voice and data, at a rate of 4.8 kbps (Data: 1.2 kbps and Voice: 3.6 kbps with AMBE encoding, GMSK modulation). The DV mode can operate in the 144 MHz (VHF), 440 MHz (UHF), and 1.2 GHz (L-band) bands, while the DD mode requires the 1.2 GHz (L) band. The DV mode, which is of interest to OUFTI-1, provides a limited bandwidth of about 6 kHz.
- D-STAR uses Gaussian Minimum Shift Keying (GMSK), with a bandwidth-duration product of 0.5, denoted by 0.5-GMSK which offers high bandwidth efficient.
- Ham-radio operators can afford buying D-STAR equipment and are able to use it on the ground (independently of any satellite).

▪ The architecture of D-STAR system

The architecture of D-STAR system is illustrated in Figure III.10. It consists of a bi-band antenna (145.625 MHz, and 439.525 MHz) mounted on a 12 m mast. The antenna is connected to the VHF and UHF modules of the D-STAR repeater through bandpass filter and duplexer. The controller manages the D-STAR repeater and the gateway links the repeater D-STAR to the worldwide D-STAR network. Note that the D-STAR repeater is an independent part of the OUFTI-1 system. It is also a service offered to the ham-radio community.

▪ The D-STAR communications

The communications between two users can be accomplished either by direct communication or indirect communication through a D-STAR repeater. There are several possibilities for establishing an indirect communication between two users through D-STAR repeater, which is shown in Figure III.11.

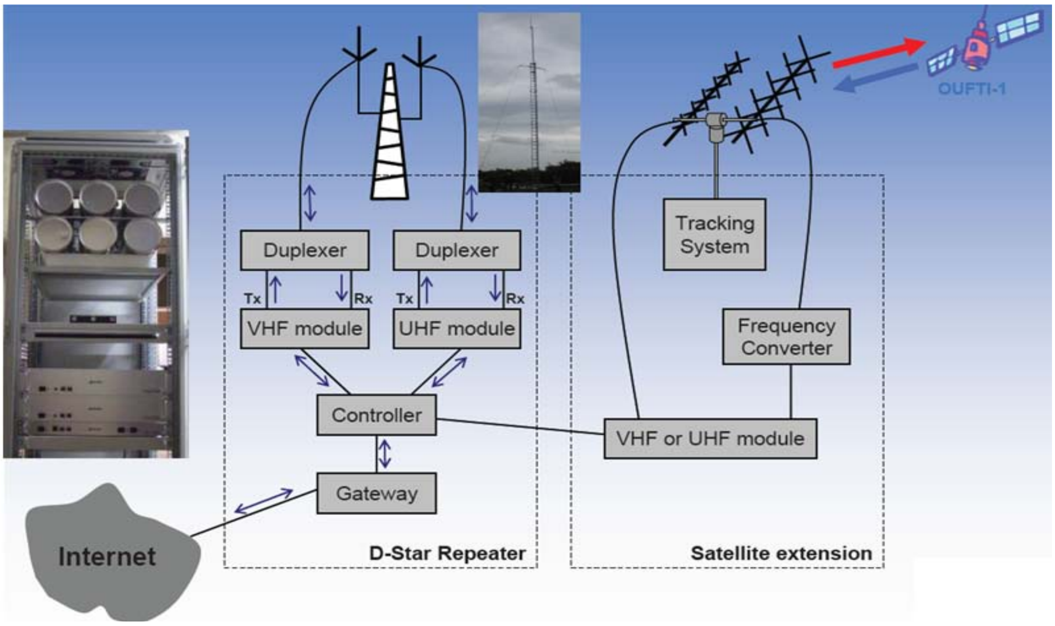


Figure III.10: Architecture of D-STAR

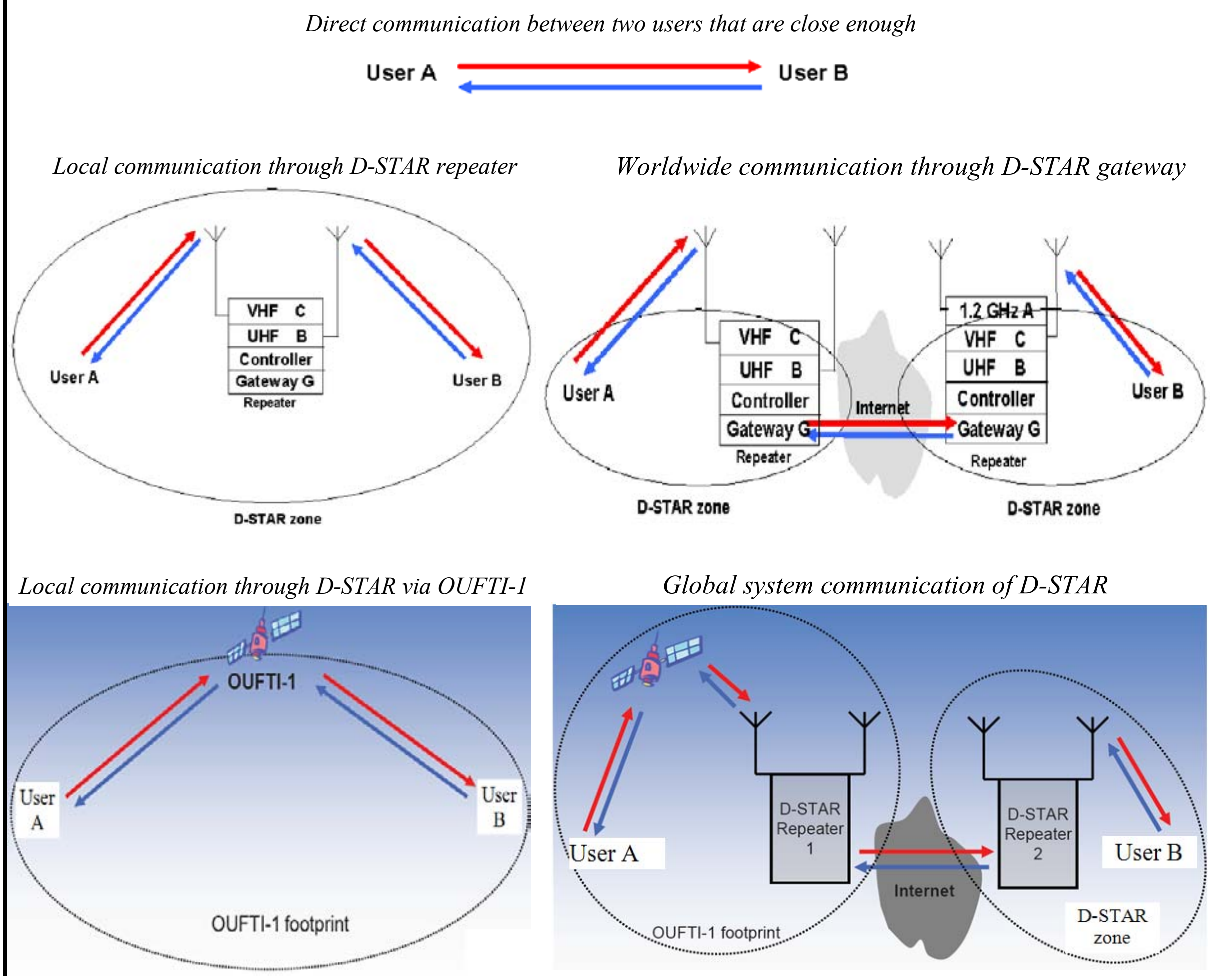


Figure III.11: D-STAR communications

III.3.5 D-STAR satellite communication module

D-STAR satellite communication module or satellite extension has to be added between the D-STAR repeater and the satellite OUFTI-1 in order to make the communication system able to be fully compliant with the D-STAR network (e.g. the OUFTI-1 shall be entirely compatible with the existing D-STAR network). This module performs the RF link between the repeater's controller and the satellite's D-STAR payload. It consists in a tracking system with its proper antennas and rotors, and in a VHF or UHF module linked to the rest of the D-STAR repeater. The architecture of this module (Satellite Extension) is shown in Figure III.10.

III.4 Space environment

This section will present about the earth's atmosphere and the space environment effects on satellites.

IV.4.1 Earth's atmosphere

The Earth's atmosphere ([6], [10]) is divided into 5 regions: troposphere, stratosphere, mesosphere, thermosphere and exosphere. The boundaries between these regions are called the tropopause, stratopause, mesopause, and exobase. The earth's atmosphere is illustrated in Table III.4 and in Figure III.12.

Table III.4: Earth's atmosphere

	Troposhpere	Stratosphere	Mesosphere	Thermosphere	Exosphere
Altitude	Between about 0 to 10 km	Between about 10 to 50 km	Between about 50 to 80 km	Between about 80 to 500 km	Between about > 500 km
Temperature	Decrease with altitude 20 to -60 °C	Increase with altitude -60 to -15 °C	Decrease with altitude -15 to -100 °C	Increase with altitude -100 to 2 000 °C	Increase with altitude > 2 000 °C

- *Ozone layer* (Ozonosphere): is in the stratosphere region which is vitally important to life because it absorbs biologically harmful UV radiation from the Sun.

- *Ionosphere*: This is the region of the atmosphere that contains ions (that form a "plasma"), created by the interaction of solar radiation with gas particles. The ionosphere overlaps with the mesosphere and thermosphere, going up to an altitude of 550 km.

- *Homosphere* (or *Turbosphere*) and *Heterosphere*: The region below the turbopause (that is, below an altitude of about 100 km) is known as the *homosphere* or *turbosphere*, where the chemical constituents are well mixed and the composition of the atmosphere remains fairly uniform. The region above the turbopause is called the *heterosphere*, where, in the absence of mixing, the chemical composition of the atmosphere varies.

- *Van Allen radiation belts*: These are regions where charged particles (forming a plasma) from the solar wind are trapped by the Earth's magnetic field. Qualitatively, there are two belts: an inner belt, consisting mostly of protons, and an outer belt, consisting mostly of electrons. The Van Allen radiation belts are shown in Figure III.13.

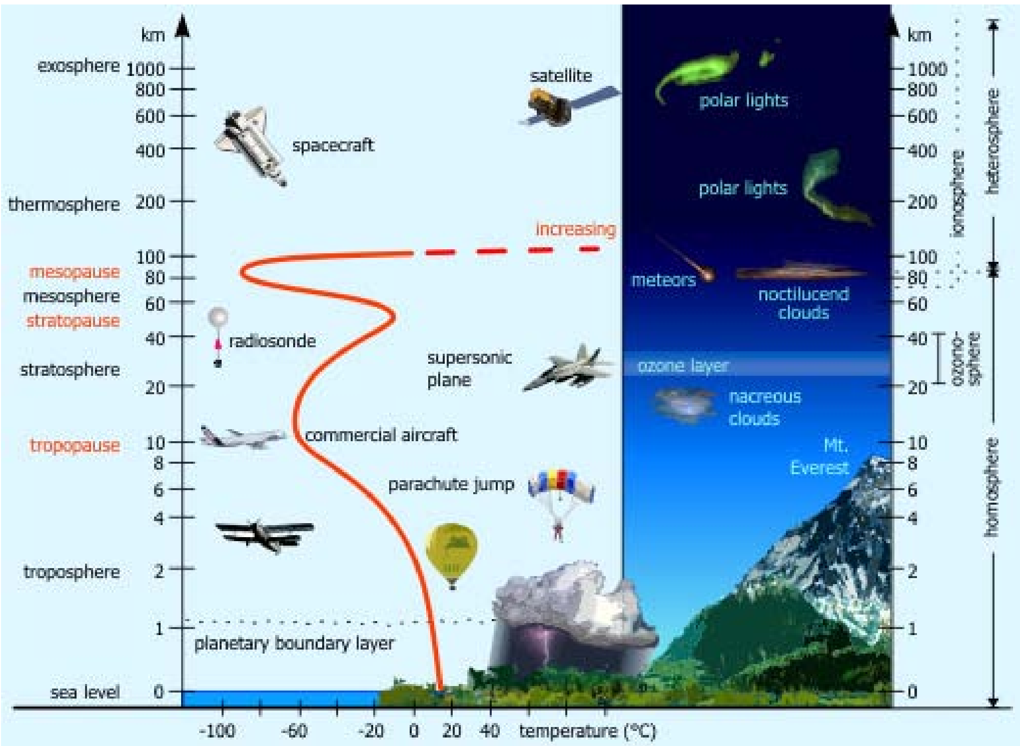
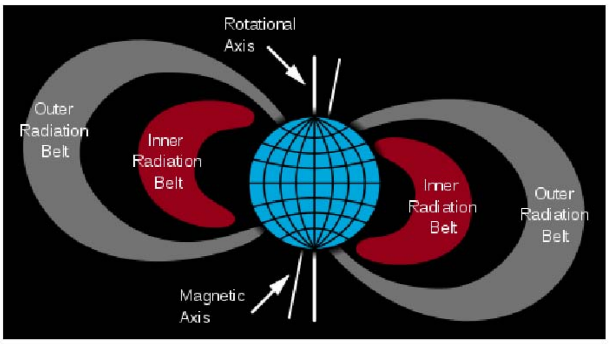


Figure III.12: Earth's atmosphere

Van Allen radiation belts



Space debris

Figure III.13: Van Allen radiation belts and space debris

IV.4.2 Space environment effects on satellites

The space environment has significant effects on satellites. The discussion below highlights the principal effects experienced by satellites orbiting the Earth.

- Atomic oxygen

The atomic oxygen atoms impact the satellite materials with their high chemical reactivity. To provide corrosion protection against atomic oxygen, the satellite faces are covered with a protective layer through the chemical treatment process, Alodine.

- Plasma

Particles in plasma around the spacecraft are not neutral, therefore possibly leading to charging of the spacecraft, and hence to subsequent electric discharges. This can occur in the proximity of the Van Allen radiation belts.

- Charging from plasma bombardment usually results in a negative charge on the surface of the satellite.
- The photoelectric effect results from solar radiation which liberates electrons on a satellite's surface, resulting in a positive charge on the satellite's sunlit side. A satellite will usually have a negative potential on shaded areas (due to plasma charging) and a positive potential on sunlit areas (due to the photoelectric effect). If the surface of the satellite is conductive, a current will develop to cancel these potentials. For a non-conducting surface, the charge separation will be maintained until voltage exceeds the resistive threshold of the material. This leads to a sudden electrostatic discharge.

These discharges can cause:
- Hardware damage: structural damage, deterioration of the thermal shielding, blown fuses or exploded transistors, capacitors and other electronic components.
- Electrical or electronic problems: false commands, on/off circuit switching, memory changes, degradation of solar cell and optical sensors.

Therefore, to prevent these problems, the outer surfaces of the satellite will be electrically connected and will be recovered by a conducting layer.

- High energy solar flare effect

The high energy solar flare can cause electronic problems and direct damage to satellite's hardware. In order to protect the satellite from this high energy solar flare effect, we need to harden the sensible parts and carefully select of materials.

- Out-gassing

Above 100 miles altitude, there is almost no atmospheric pressure, similar to a complete vacuum. In a vacuum, some materials experience out-gassing. Out-gassing is a phenomenon where molecules of material evaporate into space. Out-gassing can result in changes to the physical properties of a material, affecting their performance (decrease of their efficiency). For OUFTI-1, the major contamination problem from out-gassing is the deposit on solar cell surfaces. This phenomenon can be minimized by the proper selection of materials.

- Thermal environment

Thermal environment changes depend on solar activity. Typically, the outer surfaces of the CubeSat, e.g. the solar cells, may experience temperatures ranging from -30°C to +60°C, whereas the inner parts, e.g. the electronic components, may experience temperatures ranging from -10 °C to +40°C. The thermal cycles create structural constraints leading to the degradation of the structure. These constraints can be reduced by using materials having the same expansion coefficients.

- Space debris

Space debris is defined as any non-operational man-made object of any size in space generated by spacecraft explosions and by collisions between satellites. The satellites can be damage due to the collision with the space debris (speed 7-8 km/s). In order to reduce collision risks between satellite and space debris, the removal of enough large debris objects need to be taken place by either return it to Earth, or alter its orbit to burn up sooner than normal. For OUFTI-1, shielding, energy absorbing panels and other design considerations can make a satellite more resistant to damage from impacts with small space debris.

III.5 Physical layer and data layer

OUFTI-1 uses an AX.25 protocol with 2-FSK modulation for TC/TM, and a D-STAR protocol with 0.5-GMSK to perform ham-radio communication. This section will talk about the digital communications techniques, the AX.25 protocols, D-STAR protocols and the beacon ([7], [8]).

III.5.1 Digital communications techniques

The block diagram of digital communications system of OUFTI-1 is illustrated in the Figure III.14.

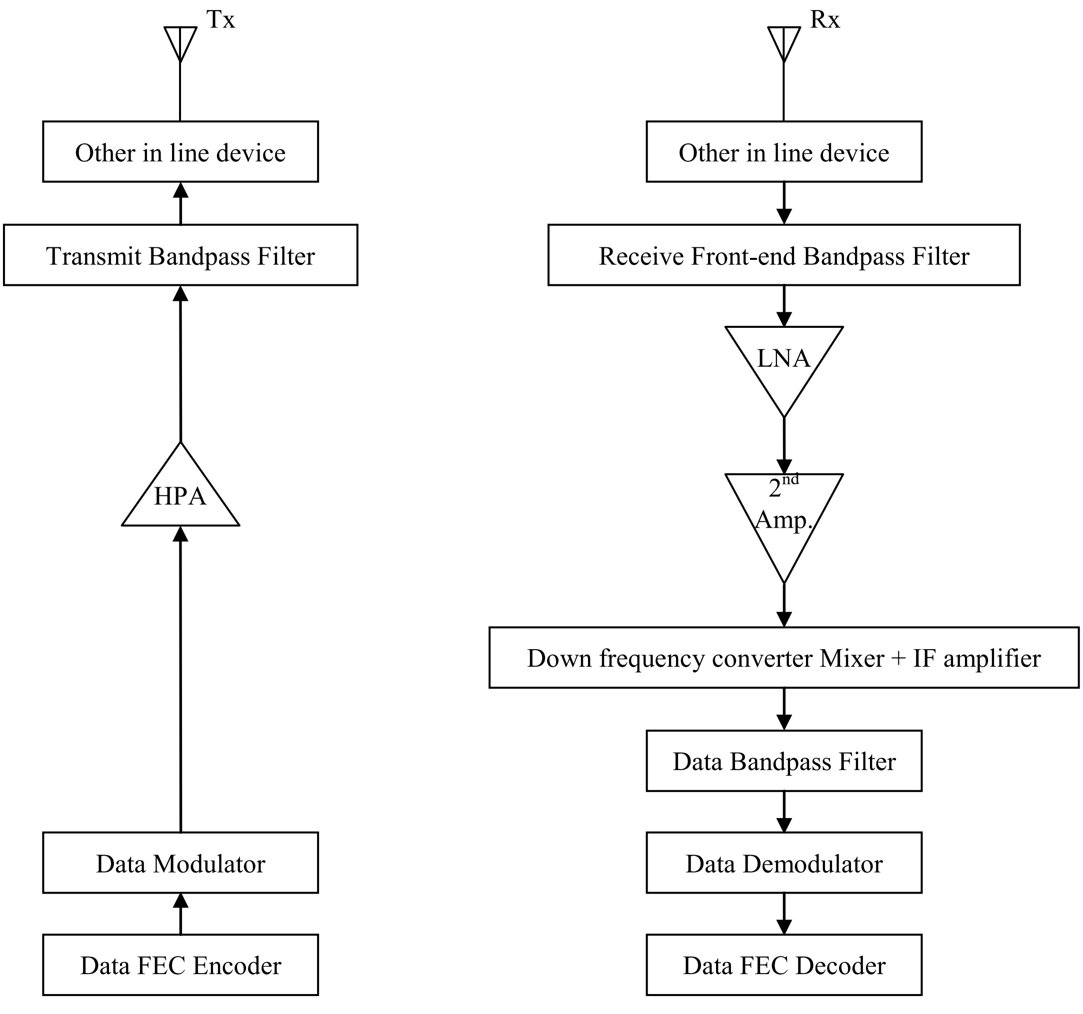


Figure III.14: Elements of a digital transmission system of OUFTI-1

The elements of a digital transmission system of OUFTI-1 are described in the following:

- *High Power Amplifier* (HPA): is a device for increasing the power of a signal. The efficient of the HPA of OUFTI-1 is around 40%.

- *Band-Pass Filter* (BPF): is a device that passes frequencies within a certain range and rejects (attenuates) frequencies outside that range.

- *Other in line devices*: other devices used in-line between the transmitter and the antenna such as directional coupler, hybrids coupler, etc.

- *Low Noise Amplifier* (LNA): is a key component which is placed at the front-end of the antenna, used to amplify very weak signals. Using an LNA, the effect of noise from subsequent stages of the receive chain is reduced by the gain of the LNA, while the noise of the LNA itself is injected directly into the received signal. Thus, it is necessary for an LNA to boost the desired signal power while adding as little noise and distortion as possible, so that the retrieval of this signal is possible in the later stages in the system. The gain of the LNA of OUFTI-1 is around 18 dB.

- *Down frequency converter Mixer + IF amplifier*: Intermediate Frequency (IF) is a frequency to which a carrier frequency is shifted as an intermediate step in transmission or reception. The intermediate frequency is created by mixing the carrier signal with a local oscillator signal in a process called heterodyning, resulting in a signal at the difference frequency. Then, IF amplifier amplifies the IF signal, raising the level of signal.

- *Modulation and demodulation*
  - Modulation is the process of varying one or more properties of a high-frequency periodic waveform, called the carrier signal, with respect to a modulating signal (which typically contains information to be transmitted).
  - Demodulation is the reverse process to modulation to extract a modulating signal (which typically contains information to be transmitted) from a modulated carrier wave.

OUFTI-1 uses two type of modulation: 2-FSK with AX.25 protocol for TC/TM and 0.5-GMSK with D-STAR protocol for ham-radio communication.

- *Binary Frequency Shift Keying* (2-FSK or BFSK): is a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier wave by using a pair of discrete frequencies to transmit binary (0s and 1s) information. FSK is either coherent or non-coherent. For coherent FSK, there is discontinuity in the phase when frequency changes, where as the non-coherent FSK, there is no discontinuity in the phase when frequency changes (continuous-phase).
- *Gaussian Minimum Shift Keying* (GMSK): is a continuous-phase FSK modulation scheme. The digital data stream is first shaped with a Gaussian filter in order to reduce the bandwidth (or sideband power) before being applied to a FSK modulator. 0.5-GMSK means that GMSK with a bandwidth-duration product of 0.5 which offers high bandwidth efficient. The reduction in bandwidth comes at the expense of intersymbol interference (ISI). This is why GMSK requires a higher E_b/N_0 to achieve the same BER.

The required value of E_b/N_0 in accordance with the modulations, coding and BER is shown in Table III.5. The modulations are listed from the simplest (and poorest performing) type to the most complex (and best performing type). The options selectable are: Audio Frequency Shift Keying on an FM Carrier, a special form of Frequency Shift Keying developed by Mr. James Miller - G3RUH, Non-Coherently Demodulated Frequency Shift Keying, Gaussian Minimum Shift Keying, Binary Phase Shift Keying and Quadriphase Phase Shift Keying.

Table III.5: E_b/N_0 required in accordance with the modulation, coding and BER

Modulation type	Coding	BER	E_b/N_0 required [dB]
AFSK/FM	None	1.00E-04	21.0
AFSK/FM	None	1.00E-05	23.2
G3RUH FSK	None	1.00E-04	16.7
G3RUH FSK	None	1.00E-05	18.0
Non-Coherent FSK	None	1.00E-04	13.4
Non-Coherent FSK	None	1.00E-05	13.8
Coherent FSK	None	1.00E-04	10.5
Coherent FSK	None	1.00E-05	11.9
GMSK	None	1.00E-04	8.4
GMSK	None	1.00E-05	9.6
BPSK	None	1.00E-05	9.6
BPSK	None	1.00E-06	10.5
QPSK	None	1.00E-05	9.6
QPSK	None	1.00E-06	10.5
BPSK	Convolutional R=1/2, K=7	1.00E-06	4.8
BPSK	Conv. R=1/2,K=7 & R.S. (255,223)	1.00E-06	2.5
BPSK	Conv. R=1/6,K=15 & R.S. (255,223)	1.00E-07	0.8
AFSK/FM	None	1.00E-04	21.0
AFSK/FM	None	1.00E-05	23.2
G3RUH FSK	None	1.00E-04	16.7
G3RUH FSK	None	1.00E-05	18.0

- *Data Forward Error Correction (FEC) encoder and decoder*
  - A FEC encoder inserts redundancy for purposes of error control/detection and error correction.
  - A FEC decoder uses the redundant bits introduced by the FEC encoder to detect and correct errors.

There are two main categories of FEC codes are block codes and convolutional codes. Both convolutional and block codes reduce the E_b/N_0 required to achive a particular bit error rate.

- <u>Convolutional</u>

  Convolutional coding operates at the byte level and additional bits are added to each word. Errors are corrected, however, on a (bit-by-bit) sequential basis. The most popular of these methods is kown as a Viterbi convolutional encoder/decoder system, named for Andrew Viterbi, the inventor. There are two parameters select the degree of coding: the code rate R and the constraint length K. The code rate R defines how many symbols are transmitted per bit of information (e.g., 1/2, 1/3, 1/6). A rate 1/2 code contains two symbols of information for every bit. The constraint length K, is the number of output symbols that are affected by a given input symbol. For example, Convolutional code (R=1/2, K=7).

- <u>Block coding</u>

  The decoder operates on an entire block of data. Extra coding bits are added to the end of the block. The most popular of the block codes is known as Reed-Solomon, although there are many other forms of block coding. In RS coding, two parameters are again used: a block of n data information symbols and a block of k codeword symbols. The encoder codes a block of n data information symbols (bits) into a block of k codeword symbols. Thus, errors are corrected at the block (or frame) level. For example, Reed-Solomon code (k: 255 bytes, n: 223 bytes).

For OUFTI-1, FEC encoder and decoder are used or not depend on the BER and the E_b/N_0 Required which enable reliable transmission of digital data over unreliable communication channels subject to channel noise. However, pairing an efficient modulation method such as BPSK with an FEC decoder provides huge advantages in terms of link performance.

III.5.2 AX.25 protocols

The name AX25 originates from the recommendation X.25 of CCITT, adding letter A that stands for Amateur. Therefore, l'AX25 is an Amateur packet radio link layer protocol. For OUFTI-1, AX.25 is used for TM/TC with 2-FSK modulation, and 9.6 kbps data rate. There are three general types of AX.25 frames:

1. Information frame (I frame)
2. Supervisory frame (S frame)
3. Unnumbered frame (U frame)

Each frame is made up of several smaller groups, called fields. The AX.25's frame structure is shown in Figure III.15. Note that the first bit to be transmitted is on the left side.

U and S frame construction

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

Information frame construction

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

Figure III.15: AX.25's frame structure

- *Flag field*: is a frame delimiter for synchronization, one octet long "01111110", and occurs at both the beginning and the end of each frame.
- *Address field*: identifies both the source of the frame and its destination in order to route the packet. It can contain 2 to 10 ham calls.
- *Control field*: contains some control information such as the kind of packet, the number of the packet, and much more.
- *Protocol ID (PID) field*: appears in the information frames I (Information) and UI (Unnumbered information) only for identifying which kind of layer 3 protocol used.
- *Information field*: contains data to be sent (up to 256 bytes)
- *Frame Check Sequence (FCS) field*: is a code (16 bits) inserted after data to detect possible transmission errors.

III.5.3 D-STAR protocol

The D-STAR protocol offers two modes of communication: DV mode and DD mode. The DV mode can operate in the 144 MHz (VHF), 440 MHz (UHF), and 1.2 GHz (L-band) bands, while the DD mode requires the 1.2 GHz (L) band.

The OUFTI-1 uses DV mode (4.8 kbps) of D-STAR with GMSK modulation to perform ham-radio communication. The DV mode's frame structure of D-STAR is shown in Figure III.16.

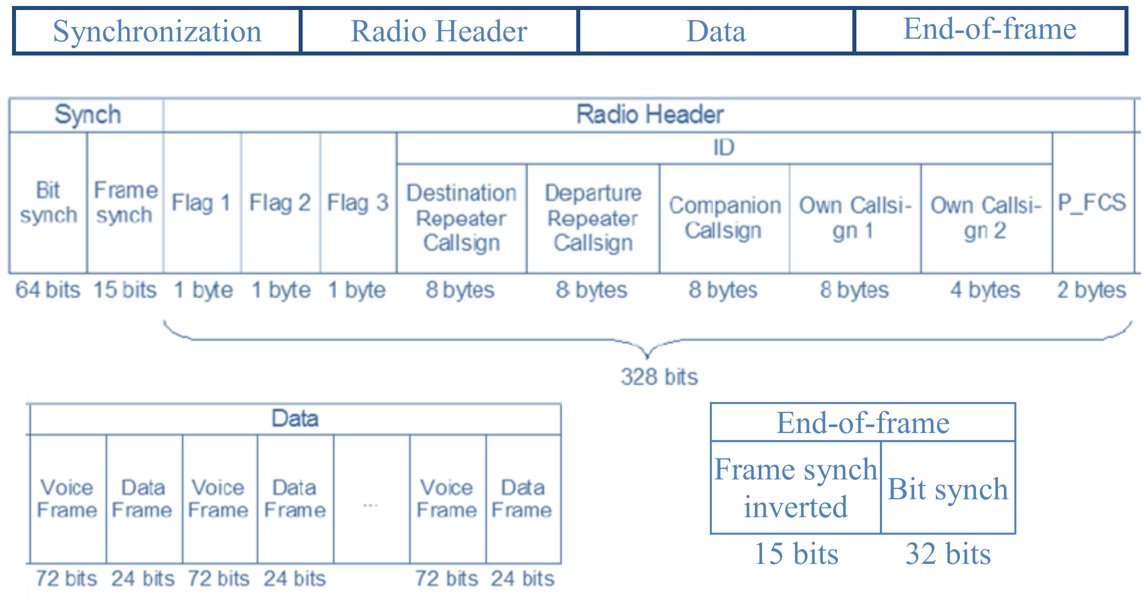


Figure III.16: D-STAR's frame structure in DV mode

- *Synchronization*

There are 2 kinds of synchronization fields (or patterns) at the beginning of the frame:

- The bit synchronization pattern (64-bit long in the protocol). For GMSK modulation, this pattern consists in 16 repetitions of the four bits 1010 placed at the beginning of the frame. For QPSK modulation, these four bits are 1001.
- The frame synchronization pattern (15-bit long in the protocol, 111011001010000).

- *Radio header*

The radio header, or simply called header, is 328 bits long (before coding) and contains some information about the frame. The successive fields are:

- Three 1-byte flags that give some information about the kind of communication (flag 1) or are left available for further development of the protocol (flags 2 and 3)
- The ID field (36 bytes) which is used to identify of the sender and destination. It consists of a series of the destination repeater call sign, the departure repeater call sign, the companion call sign, the own call sign 1, and the own call sign 2 used for additional information about the transmitter.
- P_FCS (Frame Check Sequence) which is an error-detection code (2 bytes). It permits one to detect the presence of some type of errors but not to correct them.

- *Data*

The data part of the D-STAR frame consists in an alternance of voice frame (72 bits) and data frame (24 bits), always starting with a voice frame.

- *End-of-frame pattern*

The end-of-frame pattern is composed of 32 synchronization bits 1010 followed by the beginning-of-frame pattern inverted: 000100110101111.

III.5.4 Beacon

Beacon, with 12 WPM data rate and with 2-FSK modulation, is used to send 12 critical parameters in Morse code for OUFTI-1. The Beacon's frame structure is illustrated in the Figure III.17.

HI HI DE	OUFTI1	SW	AA BB … PP	YY	ZZ

Figure III.17: Beacon's frame structure

HI HI DE and ZZ: Synchronization

OUFTI1: Identification

SW (Status Word): 8 bits of status

AA BB … PP: 16 value of 8 bits

YY: Checksum

III.6 Orbital Mechanics

III.6.1 Classical orbital elements

The Keplerian or classical orbital elements [5] are useful for space operations and tell us four parameters about orbits, namely: orbit size, orbit shape, orientation (orbit plane in space and orbit within plane) and location of the satellite.

The classical orbital elements are shown in the Table III.6 and in the Figure III.18.

The definitions of some words related to orbital mechanics are:

- *Perigee*: The point where the satellite is closest to the earth.
- *Apogee*: The point where the satellite is farthest from earth.
- *Equatorial orbit*: $i = 0°$ or 180°, the orbital plane is contained within the equatorial plane.
- *Prograde orbit*: $0° \leq i < 90°$, the satellite orbits in the same general direction as the Earth (orbiting eastward around the Earth).

- *Polar orbit*: i = 90°, the satellite orbits over the poles.
- *Retrograde orbit*: 90° < i≤ 180°, the satellite orbits in the opposite direction of the Earth's rotation (orbiting westward about the Earth).
- *Vernal Equinox axe*: an axe which is picked the principle direction from the Sun's center through the Earth's center on the first day of spring.

Table III.6: The classical orbital elements

Element	Name	Description	Definition	Remarks
a	Semi-major axis	Orbit size	Half of the distance between apogee and perigee on the ellipse	Orbital period and energy depend on orbit size.
e	Eccentricity	Orbit shape	Ratio of half the foci separation (c) to the semi-major axis	- Circle : e = 0 - Ellipse : e < 1 - Parabola : e = 1 - Hyperbola : e > 1
i	Inclination	Orbital plane's tilt	Angle between the orbital plane and equatorial plane, measured counterclockwise at the ascending node	- Equatorial: i = 0° or 180° - Prograde: 0° ≤ i < 90° - Polar: i = 90° - Retrograde: 90° < i ≤ 180°
Ω	R.A.A.N : Right Ascension of the Ascending Node	Orbital plane's rotation about the Earth	Angle, measured eastward, from the vernal equinox to the ascending node	0° ≤ Ω < 360°
ω	Argument of perigee	Orbit's orientation in the orbital plane	Angle, measured in the direction of satellite motion, from the ascending node to perigee	0° ≤ ω < 360°
ν	True anomaly	Satellite's location in its orbit	Angle, measured in the direction of satellite motion, from perigee to the satellite's location	0° ≤ ν < 360°

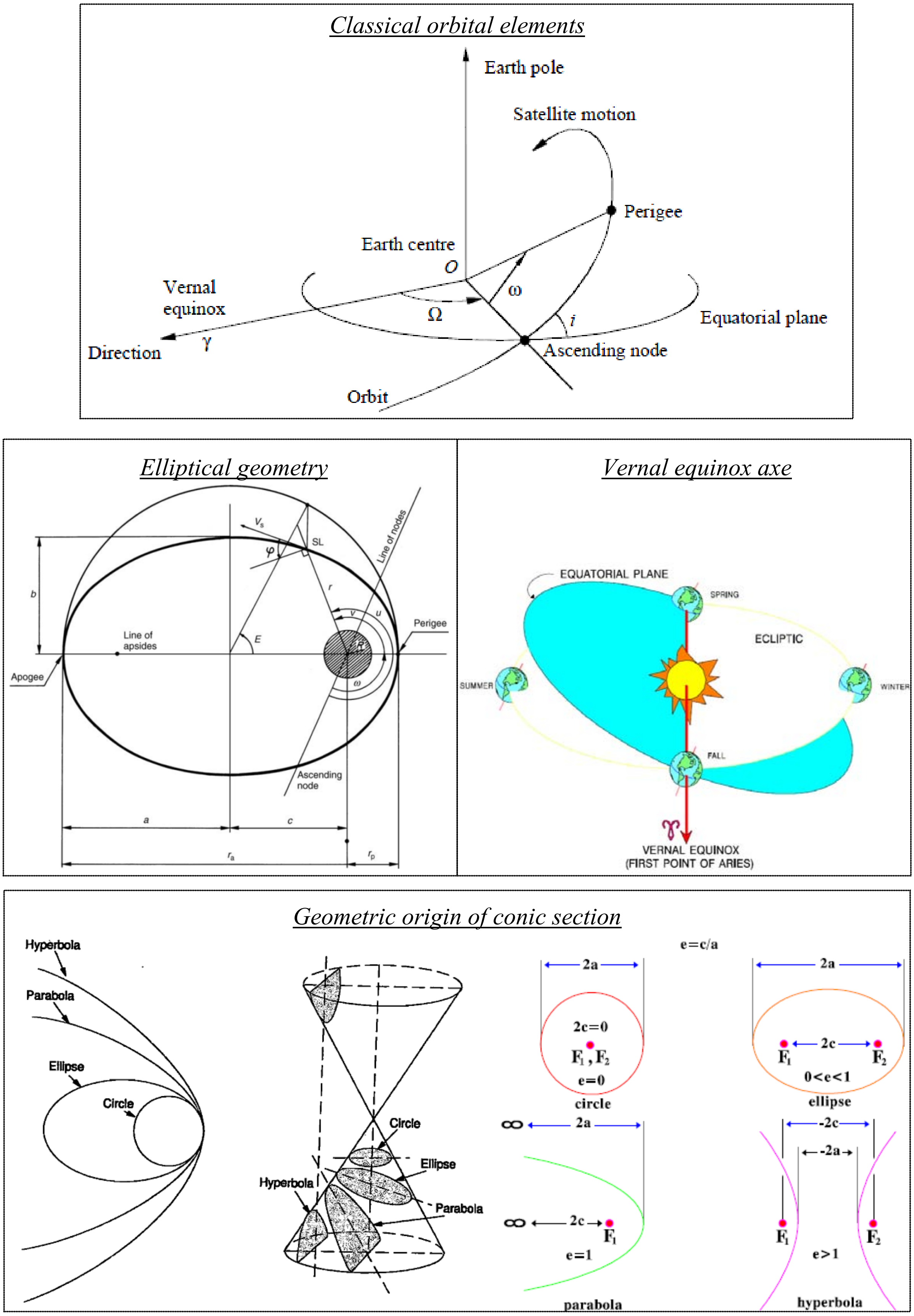


Figure III.18: Classical orbital elements

III.6.2 Orbits comparison

This section will study about the impacts of the different types of orbits, which are shown in Table III.7, on orbital parameters, slant range, free space path losses, zone coverage, duration of visibility, and time of flight [5].

Table III.7: Different types of orbits used for orbits comparison

Orbital parameters \ Orbit types		Elliptical				Circular
		LEO	VLEO	MEO "Molniya"	MEO "Tundra"	LEO
Apogee altitude (ha)	[km]	1447.00	370.00	39105.00	46340.00	650.00
Perigee altitude (hp)	[km]	354.00	368.00	1250.00	25231.00	650.00
Inclination (i)	[degrees]	71.00°	40.02°	63.4°	63.4°	72°
R.A.A.N (Ω)	[degrees]	45.00	45.00	45.00	45.00	45.00
Argument of perigee (ω)	[degrees]	30.00	30.00	30.00	30.00	0.00
True anomaly (v)	[degrees]	15.00	15.00	15.00	15.00	45.00

For more detailed of the following results, please run the MATLAB code in Annex II.

A. Orbital parameters

The results of orbital parameters of the different orbits in Table III.8 are obtained by applying the formulas in Annex II and computing in MATLAB.

Table III.8: Orbital parameters of different orbits

Orbit types		Elliptical				Circular
Orbital parameters	Unit	LEO	VLEO	MEO "Molnya"	MEO "Tundra"	LEO
Earth radius (Re)	[km]	6378.14	6378.14	6378.14	6378.14	6378.14
Height of apogee (ha)	[km]	1447.00	370.00	39105.00	46340.00	650.00
Height of perigee (hp)	[km]	354.00	368.00	1250.00	25231.00	650.00
Inclination (i)	[degrees]	71.00	40.02	63.4	63.4	72
R.A.A.N (Ω)	[degrees]	45.00	45.00	45.00	45.00	45.00
Argument of perigee (ω)	[degrees]	30.00	30.00	30.00	30.00	0.00
True anomaly (v)	[degrees]	15.00	15.00	15.00	15.00	45.00
Semi-major axis (a)	[km]	**7278.64**	**6747.14**	**26555.64**	**42163.64**	**7028.14**
Eccentricity (e)	[unit less]	**0.08**	**0.00015**	**0.71**	**0.25**	**0.00**
Orbital period (T)	[minutes]	**103.00**	**91.93**	**717.79**	**1436.04**	**97.73**
Mean anomaly (M)	[degrees]	**12.89**	**15.00**	**1.78**	**8.75**	**45.00**
Time rate of change of ω ($d\omega$)	[degrees/day]	**-1.49**	**7.91**	**0.00**	**0.00**	**-1.85**
Time variation of R.A.A.N ($d\Omega$)	[degrees/day]	**-2.07**	**-6.27**	**-0.13**	**-0.01**	**-2.19**
Sun-synchronous inclination	[degrees]	**98.93**	**96.92**	**None**	**None**	**97.99**

According to the results of orbital parameters of different orbits in Table III.8, we can notice that:

- Height of apogee (ha) or Height of perigee (hp) ↑ (↑: increase) ⇒ Semi-major axis (a) ↑ ⇒ Orbital period (T) ↑ (the bigger size of orbit is, the slower of velocity of satellite, and hence the longer orbital period). Also, the bigger size of orbit result in the smaller of time rate of change of ω ($d\omega$) and time variation of R.A.A.N ($d\Omega$).
- [Height of apogee (ha) – Height of perigee (hp)] ↑ ⇒ Eccentricity (e) ↑ (= 0: circular orbit, < 1: elliptical orbit, = 1: parabolic orbit, > 1: Hyperbolic orbit)
- If $0° < i < 90°$, then $d\Omega < 0$. That is, for prograde orbits, the node line drifts westward. Therefore, since the right ascension of the node continuously decreases, this phenomenon is called regression of the nodes. If $90° < i < 180°$, we see that $d\Omega > 0$. The node line of retrograde orbits therefore advances eastward. For polar orbits ($i = 90°$), the node line is stationary. (See Figure III.19)
- This expression shows that if $0° < i < 63.4°$ or $116.6° < i < 180°$ then $d\omega$ is positive, which means ***the perigee advances*** in the direction of the motion of the satellite. If $63.4° < i < 116.6°$, ***the perigee regresses***, moving opposite to the direction of motion. $i = 63.4°$ and $i = 116.6°$ are the critical inclinations at which the apse line does not move. (See Figure III.19)

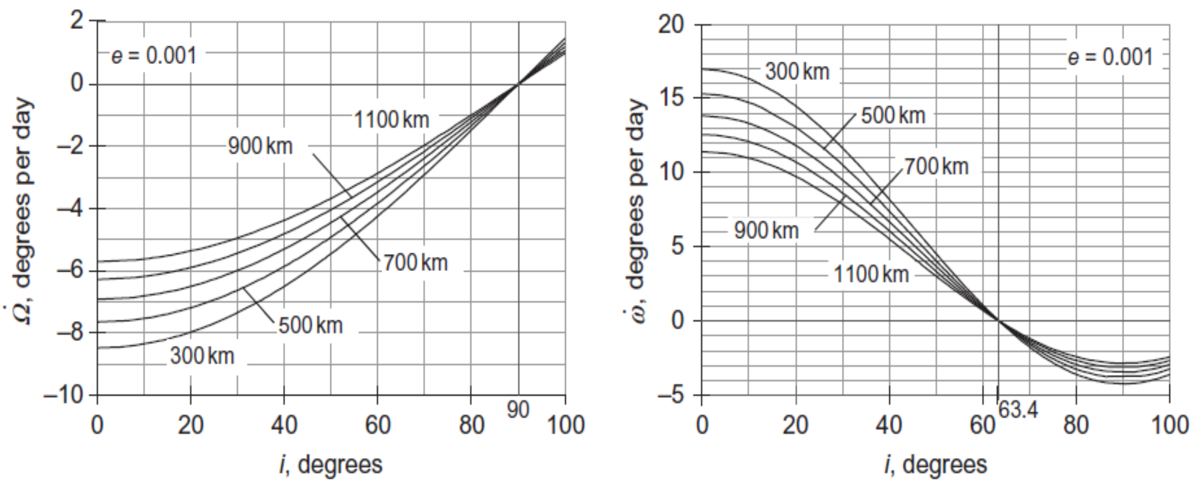


Figure III.19: Regression of the node and advance of perigee for nearly circular orbits of altitudes 300 to 1100 km.

B. <u>Slant range and free space path losses</u>

This section will study the impact of orbit types (orbit altitude), elevation angle and frequency band on slant range and free space path losses. The slant range depends on the orbit altitude and elevation angle, and the free space path losses depend on the slant range and frequency.

As shown in Table III.9, III.10 and III.11, we can observe that
- If the orbit altitude ↑ (↑: increase) ⇒ the slant range ↑ ⇒ free space path losses ↑
- If the elevation angle ↓ (↓: decrease) ⇒ the slant range ↑ ⇒ free space path losses ↑
- If the frequency ↑ (↑: increase) ⇒ free space path losses ↑

Table III.9: Slant range and free space path losses for different orbit types (orbit altitude) at minimum satellite altitude and with elevation angle 5°

Note: Minimum altitude of satellite = Altitude of perigee (hp)					
Elevation Angle	[Degrees]	5			
		Uplink		*Downlink*	
Frequency	[MHz]	435.00		145.00	
Wavelength	[m]	0.69		2.07	
		Slant Range [km]	Free Space (FS) path losses [dB]		
			Uplink	downlink	
Elliptical LEO Apogee (h_a): 1447.00 km, Perigee (h_p): 354.00 km		1668.98	149.68	140.14	
Elliptical VLEO Apogee (h_a): 370.00 km, Perigee (h_p): 368.00 km		1710.99	149.90	140.36	
Elliptical MEO "Molnya" Apogee (h_a): 39105.00 km, Perigee (h_p): 1250.00 km		3665.11	156.51	146.97	
Elliptical MEO "Tundra" Apogee (h_a): 46340.00 km, Perigee (h_p): 25231.00 km		30408.05	174.89	165.35	
Circular LEO Apogee (h_a): 650.00 km, Perigee (h_p): 650.00 km		2447.95	153.01	143.47	

Table III.10: Slant range and free space path losses for different elevation angles at minimum satellite altitude of elliptical LEO orbit

Elliptical LEO				
		Uplink	*Downlink*	
Frequency	[MHz]	435.00	145.00	
Wavelength	[m]	0.69	2.07	
Elevation Angle [Degrees]		Slant Range [km]	Free Space (FS) path loss [dB]	
			Uplink	downlink
5		1668.98	149.68	140.14
10		1314.78	147.61	138.07
15		1063.28	145.77	136.22
20		884.45	144.17	134.62
25		755.11	142.79	133.25

Table III.11: Slant range and free space path losses for different frequency bands at minimum satellite altitude of elliptical LEO orbit and with elevation angle 5°

Elliptical LEO				
Elevation Angle [Degrees]	5			
	Uplink		*Downlink*	
Frequency [MHz]	435.00		145.00	
Wavelength [m]	0.69		2.07	
Frequency bands	Slant Range [km]	Free Space (FS) path loss [dB]		
		Uplink	downlink	
UHF/VHF Uplink frequency (UHF): 435.00 MHz Downlink frequency (VHF): 145.00 MHz	1668.98	149.68	140.14	
Ku Uplink frequency (UHF): 14000 MHz Downlink frequency (VHF): 12000 MHz	1668.98	179.83	178.50	
Ka Uplink frequency (UHF): 30000 MHz Downlink frequency (VHF): 20000 MHz	1668.98	186.45	182.93	

C. Zone coverage, duration of visibility, and number of satellite required for continuous coverage under the orbit trace

The zone coverage and the duration of visibility depend on two parameters: orbit altitude and elevation angle.

The results of zone coverage, duration of visibility and number of satellites required for continuous coverage under the orbit trace shown (number of satellite required per plane, N) in Table III.12 are estimated for different orbit types at minimum, maximum and mean satellite altitude (for elliptical orbit) or at a constant satellite altitude (for circular orbit), and with an elevation angle 5 degrees. And the result shown in Table III.13, are the estimated results of zone coverage, duration of visibility, and number of satellites required for continuous coverage under the orbit trace for different elevation angles at minimum satellite altitude of elliptical LEO. These results are obtained by applying the formulas in Annex II and computing in MATLAB.

Note that value of duration of visibility is estimated for a constant velocity of satellite (calculated at an instance when the satellite is at minimum, maximum, mean or constant satellite altitude and by assuming the elevation angle is equal to 5 degrees at that instance) throughout the orbit.

As shown in Table III.12 and III.13, we can observe that:

- If the orbit altitude ↑ ⇒ the zone coverage ↑ and velocity of the satellite ↓ ⇒ the duration of visibility↑ ⇒ Number of satellite required for continuous coverage under the orbit trace, N ↓.
- If the elevation angle ↓ ⇒ the zone coverage ↑ ⇒ the duration of visibility↑ ⇒ Number of satellite required for continuous coverage under the orbit trace, N ↓.

Table III.12: Zone coverage, duration of visibility, and number of satellites required for continuous coverage under the orbit trace for different orbit types at minimum, maximum and mean satellite altitude or at a constant satellite altitude, and with an elevation angle 5°

Orbit type		Elliptical LEO, orbital period (T) = 103.00 minutes		
		Minimum Altitude	Maximum Altitude	Mean Altitude
Orbit altitude	[km]	354.00	1447.00	900.50
Orbit radius	[km]	6732.14	7825.14	7278.64
Nadir angle	[Degrees]	54.29	70.70	60.80
Central angle	[Degrees]	14.30	30.71	24.20
Footprint length	[km]	3183.34	6837.25	5387.20
Footprint area	[km^2]	7917743.81	35845129.46	22457032.18
Velocity of the satellite	[m/s]	6863.96	7978.36	7400.21
Duration of visibility	[minutes]	6.65	16.60	12.13
Number of satellite required for continuous coverage, N		**7**	**16**	**9**

Orbit type		Elliptical VLEO, orbital period (T) = 91.93 minutes		
		Minimum Altitude	Maximum Altitude	Mean Altitude
Orbit altitude	[km]	368.00	370.00	369.00
Orbit radius	[km]	6746.14	6748.14	6747.14
Nadir angle	[Degrees]	70.32	70.37	70.34
Central angle	[Degrees]	14.63	14.68	14.66
Footprint length	[km]	3258.31	3268.90	3263.61
Footprint area	[km^2]	8293032.38	8346703.93	8319866.43
Velocity of the satellite	[m/s]	7685.02	7687.30	7686.16
Duration of visibility	[minutes]	7.06	7.09	7.08
Number of satellite required for continuous coverage, N		**13**	**14**	**13**

Orbit type		Elliptical MEO "Molnya", orbital period (T) = 717.79 minutes		
		Minimum Altitude	Maximum Altitude	Mean Altitude
Orbit Altitude	[km]	1250.00	39105.00	20177.50
Orbit Radius	[km]	7628.14	45483.14	26555.64
Nadir angle	[Degrees]	8.03	56.40	13.84
Central angle	[Degrees]	28.60	76.97	71.16
Footprint length	[km]	6366.78	17136.45	15842.27
Footprint area	[km^2]	31181392.57	197973707.52	173048953.63
Velocity of the satellite	[m/s]	1586.63	9460.34	3874.28
Duration of Visibility	[minutes]	11.22	180.01	68.15
Number of satellite required for continuous coverage, N		**4**	**64**	**11**

Orbit type		Elliptical MEO "Tundra", orbital period (T) = 1436.04 minutes		
		Minimum Altitude	Maximum Altitude	Mean Altitude
Orbit Altitude	[km]	25231.00	46340.00	35785.50
Orbit Radius	[km]	31609.14	52718.14	42163.64
Nadir angle	[Degrees]	6.92	11.60	8.67
Central angle	[Degrees]	73.40	78.08	76.33
Footprint length	[km]	16342.54	17383.11	16994.65
Footprint area	[km^2]	182596906.84	202799432.66	195209174.85
Velocity of the satellite	[m/s]	2380.82	3970.76	3074.68
Duration of Visibility	[minutes]	68.60	121.69	92.12
Number of satellite required for continuous coverage, N		**12**	**21**	**16**

Orbit type		Circular LEO, orbital period (T) = 97.73 minutes
Orbit Altitude	[km]	650.00
Orbit Radius	[km]	7028.14
Nadir angle	[Degrees]	64.70
Central angle	[Degrees]	20.30
Footprint length	[km]	4520.21
Footprint area	[km^2]	15880252.72
Velocity of the satellite	[m/s]	7530.94
Duration of Visibility	[minutes]	10.00
Number of satellite required for continuous coverage, N		**10**

Table III.13: Zone coverage, duration of visibility, and number of satellites required for continuous coverage under the orbit trace for different elevation angles at minimum satellite altitude of elliptical LEO

Elliptical LEO Elliptical LEO, orbital period (T) = 103.00 minutes					
Elevation Angle [Degrees]	Footprint length [km]	Footprint area [km^2]	Velocity [m/s]	Duration of Visibility [minutes]	Number of satellite required for continuous coverage, N
5	3183.34	7917743.81	7978.36	6.65	7
10	2468.83	4772173.12	7978.36	5.16	8
15	1953.71	2991997.38	7978.36	4.08	9
20	1578.85	1955314.94	7978.36	3.30	10
25	1299.00	1324138.92	7978.36	2.71	11

D. Time of Flight (TOF) from perigee to true anomaly initial

The results of time of Flight (TOF) from perigee to true anomaly initial for different orbit types in Table III.14 are obtained by applying the formulas in Annex II and computing in MATLAB. The time of flight from perigee to true anomaly initial is longer when the true anomaly initial of satellite result at position with higher mean anomaly.

Table III.14: Time of Flight from perigee to true anomaly initial for different orbit types

	Initial Value of eccentric (E) [rad]	Mean anomaly (M) [rad]	True anomaly initial (v) [degrees]	Time of Flight (TOF) [minutes]
Elliptical LEO	0.24	0.22	15	3.69
Elliptical VLEO	0.26	0.26	15	3.83
Elliptical MEO "Molnya"	0.11	0.03	15	3.55
Elliptical MEO "Tundra"	0.20	0.15	15	34.89
Circular LEO	0.79	0.79	45	12.22

III.7 Satellite constellation

Since one satellite can cover only a limited portion of the Earth at any particular instant, a satellite constellation which is a group of similar satellites that are synchronized to orbit the earth in some optimal way (the minimum total number of satellites required) in order to provide a (continuous) whole earth coverage or a (continuous) coverage for an area specific, is needed. Therefore, the constellation design problem is the question: "What combination of orbits which provide the optimum coverage for all ground stations?". The combination of orbits is related to many parameters which need to consider including the characteristics of orbits (eccentricity, inclinations, altitudes, etc.), the visibility time , the Relative spacing between satellites in adjacent planes or inter plane spacing F in a Walker constellation, the number of orbits, etc.

To simplifier the problem of satellite constellation, one or many parameters are fixed like inclination, the inter plane spacing F in a Walker constellation, satellite orbit altitude, etc to find the optimal constellation. The satellite constellations are classified into two categories: *circular orbit constellation* and *elliptical orbit constellation*.

III.7.1 Circular orbit constellation

The circular orbit constellation is used for the whole earth coverage because of their common altitude and inclination which provide a constant coverage or fixed satellite foot print size throughout the orbit. Recall that the coverage of satellite is greatly dependent on its altitude. There are two basic types of circular orbit constellation which have arisen from the street of coverage method: "Walker Star" and "Walker Delta" constellations [3].

The "*street of coverage*" method, which is shown in the Figure III.20, is a method which consists in lining up several satellites in an orbital plane to provide a dense set of overlapping coverage circles. One street of coverage will provide continuous coverage under the orbit trace, but is insufficient to provide complete Earth coverage. By using multiple streets of coverage from several satellites planes, (continuous) whole-Earth coverage can be achieved.

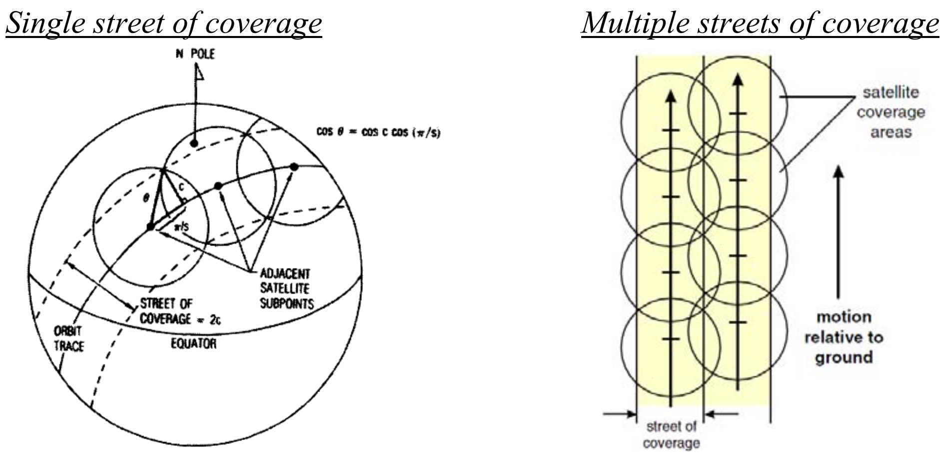


Figure III.20: Street of coverage

A. Walker Star

A-1. Principle

- This type of constellation requires that all orbits have a common inclination of 90 degrees or near 90 degrees.
- The "Walker Star" name comes from the fact that, if drawn on a polar map, the orbital planes intersect to make a star, as shown in Figure III.21. It can also be called as the π-constellation (RAAN Spread is 180°, the angle that is subtended in the plane of reference by the surface made by joining the evenly-spaced ascending nodes of the orbital planes).
- The characteristics of a Walker Star Constellation are shown in Table III.15.

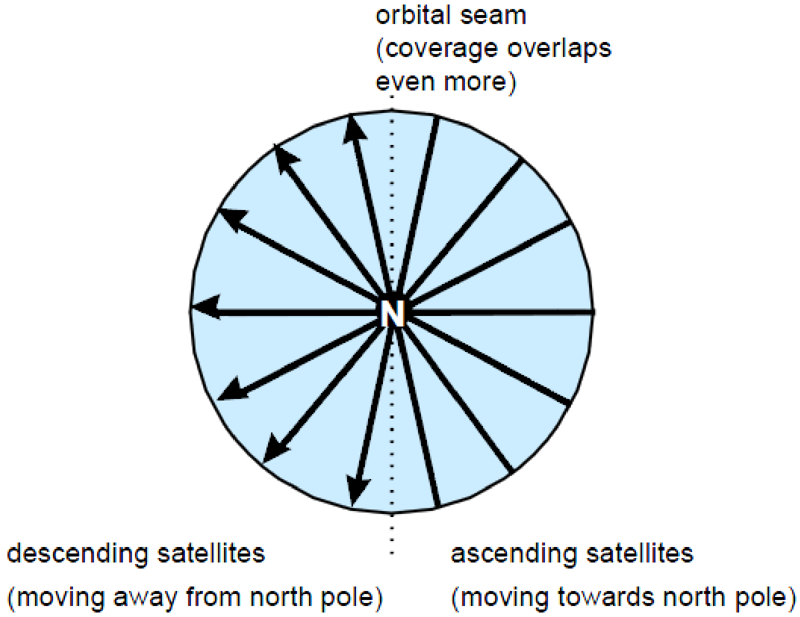


Figure III.21: Walker Star constellation

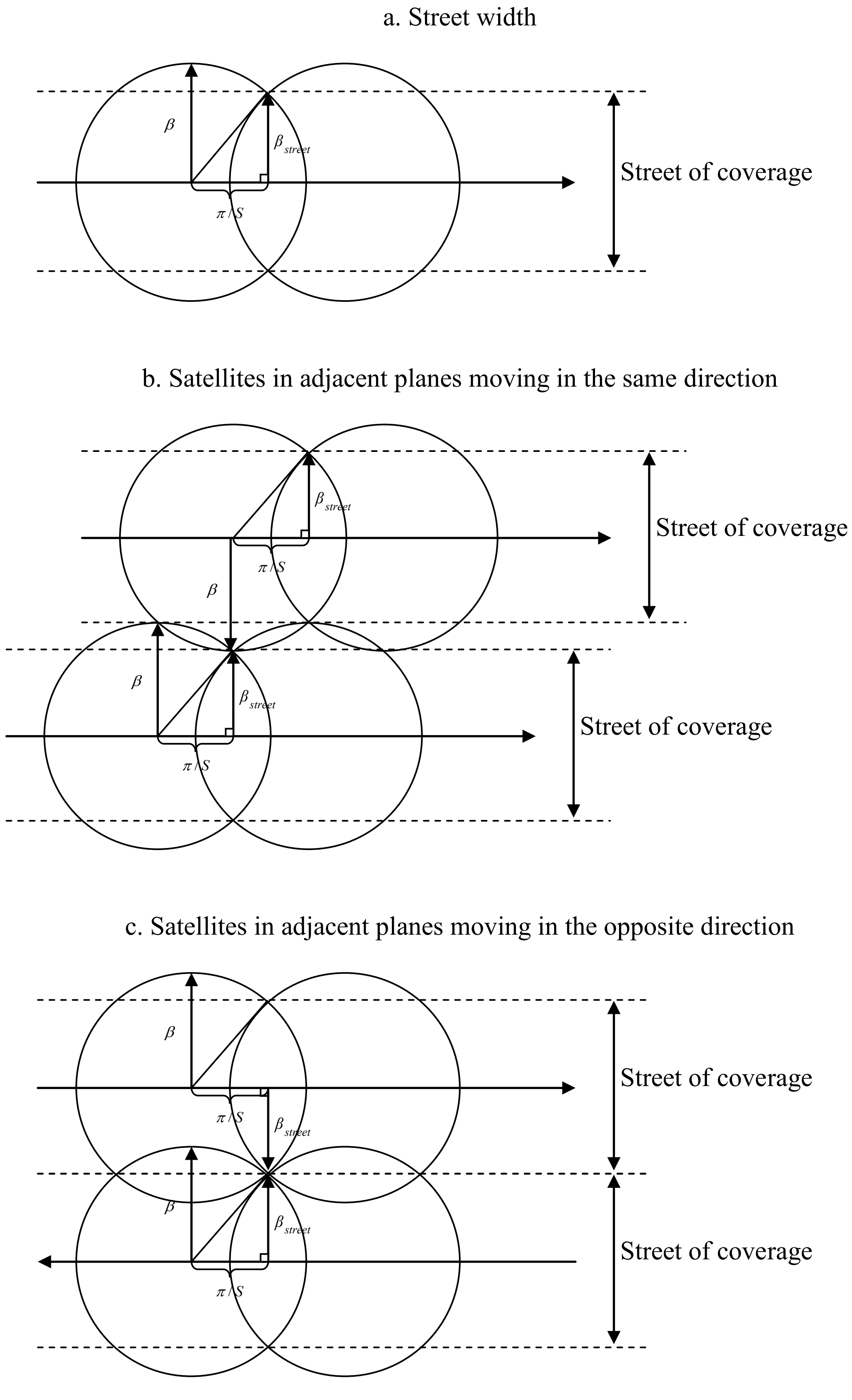


Figure III.22: Characteristics of a Walker Star constellation

Table III.15: Characteristics of a Walker Star constellation (β, S)

- β : Earth central angle
- S : Number of satellites per plane (evenly spaced)
- β_{street} : Street width

$$\cos(\beta_{street}) = \frac{\cos(\beta)}{\cos(\pi / S)}$$

(as shown in the Figure III.22.a)

- Street of coverage $= 2\beta_{street}$
- If the satellites in adjacent planes are going in the same direction as shown in Figure III.22.b, then the perpendicular separation, *D_SD*, between the orbit planes is:

$$D\_SD = \beta_{street} + \beta$$

- If the satellites in adjacent planes are going in the opposite direction as shown in Figure III.22.c, then the perpendicular separation, *D_OD*, between the orbit planes is:

$$D\_OD = 2\beta_{street}$$

- The approximated number of planes, P:

P = ceil([(180 - D_OD)/(D_SD)]+1)

- Total number of satellites, TNOS:

TNOS = N×P

A-2. Approximated number of planes and total number of satellites for different orbit types

The approximated number of planes and total number of satellites shown in Table III.16 are computed by MATLAB with the approximated value of central angle and number of satellites required per plane, *N* estimated from the section III.6.2.C, in Table III.12. As shown in Table III.16, the bigger size of orbit is the smaller number of planes and total number of satellites required.

Table III.16: Approximated number of planes and total number of satellites

Orbit type	Elliptical LEO		
	Minimum	Maximum	Mean
Central angle [degrees]	14.30	30.71	24.20
Number of satellite required per plane, N	**7**	**16**	**9**
Street width [degrees]	8.88	17.40	13.91
Street of coverage (SOC) [degrees]	17.76	34.79	27.82
D_SD [degrees]	23.18	48.11	38.11
D_SD [degrees]	17.76	34.79	27.82
Number of planes, P	**5**	**8**	**5**
Total number of satellite, TNOS	**35**	**128**	**45**
Orbit type	**Elliptical VLEO**		
	Minimum	Maximum	Mean
Central angle [degrees]	14.63	14.68	14.66

Number of satellite required per plane, N	**13**	**14**	**13**
Street width [degrees]	4.93	7.05	4.86
Street of coverage (SOC) [degrees]	9.87	14.10	9.72
D_SD [degrees]	19.57	21.73	19.52
D_SD [degrees]	9.87	14.10	9.72
Number of planes, P	**9**	**10**	**10**
Total number of satellite, TNOS	**117**	**140**	**130**

Orbit type	**Elliptical MEO "Molnya"**		
	Minimum	Maximum	Mean
Central angle [degrees]	28.60	76.97	71.16
Number of satellite required per plane, N	**4**	**64**	**11**
Street width [degrees]	28.47	71.41	70.33
Street of coverage (SOC) [degrees]	56.94	142.81	140.66
D_SD [degrees]	57.07	148.38	141.49
D_SD [degrees]	56.94	142.81	140.66
Number of planes, P	**2**	**4**	**2**
Total number of satellite, TNOS	**8**	**256**	**22**

Orbit type	**Elliptical MEO "Tundra"**		
	Minimum	Maximum	Mean
Central angle [degrees]	73.40	78.08	76.33
Number of satellite required per plane, N	**12**	**21**	**16**
Street width [degrees]	73.21	77.65	76.06
Street of coverage (SOC) [degrees]	146.42	155.30	152.12
D_SD [degrees]	146.61	155.73	152.39
D_SD [degrees]	146.42	155.30	152.12
Number of planes, P	**2**	**2**	**2**
Total number of satellite, TNOS	**24**	**42**	**32**

Orbit type	**Circular LEO**
Central angle [degrees]	20.30
Number of satellite required per plane, N	**10**
Street width [degrees]	9.55
Street of coverage (SOC) [degrees]	19.10
D_SD [degrees]	29.85
D_SD [degrees]	19.10
Number of planes, P	**7**
Total number of satellite, TNOS	**70**

A-3. Limitations of the Walker Star constellation

- The perpendicular separation distance D, is minimal at the pole and maximal at the equator. Therefore, for whole-Earth coverage, the street of coverage from each orbital plane needs to be evenly spaced about one half of the equator so that each coverage street is touching its neighbor.
- Walker Star constellation often requires significantly more satellites than other constellation types for whole-Earth coverage because of its common crossing point and the overlapping of satellite footprints.
- At the poles, the overlapping of satellite footprints will cause interference and multiple coverage, requiring some footprints to be disabled, and the high relative velocities of satellites travelling in neighboring planes will make maintaining Inter-Satellite Links (ISLs) very difficult due to Doppler shift, high tracking rate, and the need to swap neighbors and reestablish links as orbital planes cross.

B. Walker Delta

B-1. Principle

- This type of constellation of orbital planes is inclined with a constant inclination (generally less than 90°) and the even spacing of the right angles of the ascending nodes Ω1 ... Ωp across the full 360° of longitude, which means that ascending and descending planes of satellites and their coverage continuously overlap, rather than being separated as with the Walker Star constellation.
- The "Walker Delta" name comes from the fact that, if drawn on a polar map, at a minimum of three orbital planes, a rounded triangle, or Greek delta letter (Δ), is formed by the around the pole by the planes, as shown in Figure III.23. It can also be called as the 2π-constellation (RAAN Spread is 360°, the angle that is subtended in the plane of reference by the surface made by joining the evenly-spaced ascending nodes of the orbital planes).
- The characteristics of a Walker Delta constellation are shown in the Table III.17.

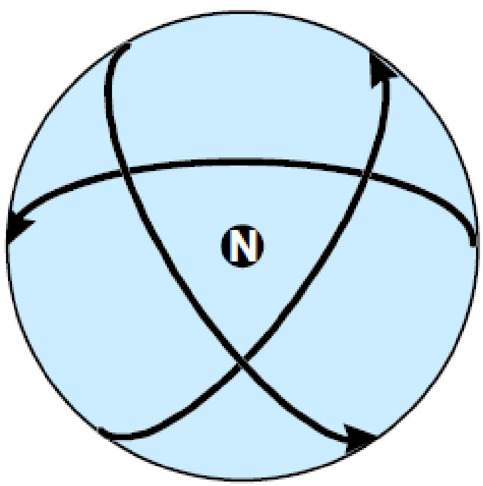


Figure III.23: Walker Delta constellation

Table III.17: Characteristics of a Walker Delta constellation (i:T/P/F)

▪ Walker Delta constellation is denoted by $$i:T/P/F \qquad (0 \le F \le P-1)$$ ▪ i : Inclination angle [deg.], i < 90° ▪ T : Number total of satellites ▪ P : Number of orbit planes evenly spaced in node ▪ F : Relative spacing between satellites in adjacent planes or Inter plane spacing ▪ S = T/P : Number of satellites per plane (evenly spaced) ▪ Pattern Unit : PU [deg.] = 360° /T ▪ Planes are spaced at Intervals of (PU × S) in node Node spacing [deg.] = PU × S=360°/P when i < 90° ▪ Satellites are spaced at intervals of (PU × P) within each plane. In-plane spacing between satellites [deg.] = PU × P = 360° /S ▪ If a satellite is at its ascending node, the next most easterly satellite will be (PU × F) past the node Phase difference between adjacent planes [deg.] = PU × F

Example: 55°: 25/5/1 constellation shown in Figure III.24.

- Inclination angle: i = 55°
- 25 satellites in 5 planes (T = 25, P = 5 and F = 1)
- 5 satellites per planes (S = T/5 = 5)
- Pattern Unit : PU = 360°/T = 14.4 deg.
- Node spacing [deg.] = PU × S = 14.4 × 5 = 72°
- In-plane spacing between satellites [deg.] = PU × P or = 360° /S = 72°
- Phase difference between adjacent planes [deg.] = PU × F = 14.4°

In Figure III.24, satellite one is positioned at its ascending node, with satellite six, therefore, one PU beyond its nodal position in the next most-Easterly plane.

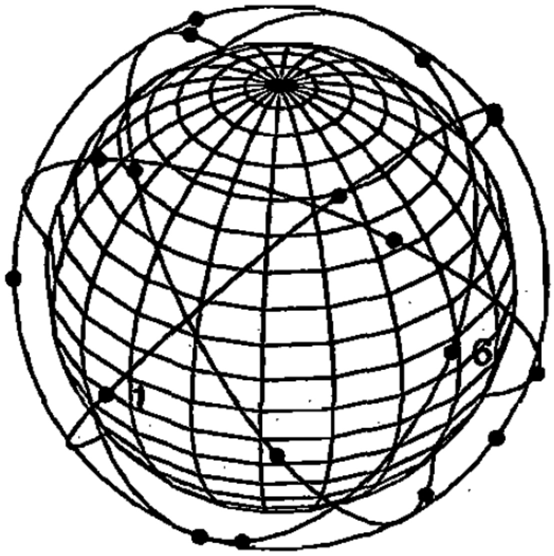


Figure III.24: Walker Delta constellation, defined by 55°: 25/5/1

Note: When i = 90°, the formula of Node Spacing in the Table III.17 is change to Node spacing [deg.] = 180°/P, and the Walker Delta constellation or 2π-constellation is become the Walker Star constellation or π-constellation.

B-2. Walker Delta constellation for the approximated number of planes and number of satellites required per plane for different orbit types

The results of Walker Delta constellation for the approximated number of planes and number of satellites required per plane for different orbit types is shown in Table III.18.

Table III.18: Walker Delta constellation for the approximated number of planes and number of satellites required per plane for different orbit types

Walker Delta constellation (i:TNOS/P/F)				
Orbit type	**Elliptical LEO**			
Inclination (i)	[degrees]	71		
Inter plane spacing (F)		1		
		Minimum	Maximum	Mean
Number of planes (P)		**5**	**8**	**5**
Total number of satellite (TNOS)		**35**	**128**	**45**
Pattern Unit (PU)	[degrees]	10.29	2.81	8
Node spacing	[degrees]	72	45	72
In-plane spacing between satellites	[degrees]	51.43	22.5	40
Phase difference between adjacent planes	[degrees]	10.29	2.81	8
Orbit type	**Elliptical VLEO**			
Inclination (i) Inter plane spacing (F)	[degrees]	40.02 1		
		Minimum	Maximum	Mean
Number of planes (P)		**9**	**10**	**10**
Total number of satellite (TNOS)		**117**	**140**	**130**
Pattern Unit (PU)	[degrees]	3.08	2.57	2.77
Node spacing	[degrees]	40.00	36.00	36
In-plane spacing between satellites	[degrees]	27.69	25.71	27.69
Phase difference between adjacent planes	[degrees]	3.08	2.57	2.77
Orbit type	**Elliptical MEO "Molnya"**			
Inclination (i) Inter plane spacing (F)	[degrees]	63.40 1		
		Minimum	Maximum	Mean
Number of planes (P) Total number of satellite (TNOS)		**2** **8**	**4** **256**	**2** **22**
Pattern Unit (PU) Node spacing In-plane spacing between satellites Phase difference between adjacent planes	[degrees] [degrees] [degrees] [degrees]	45.00 180.00 90.00 45.00	1.41 90.00 5.63 1.41	16.36 180.00 32.73 16.36
Orbit type	**Elliptical MEO "Tundra"**			
Inclination (i)	[degrees]	63.40		
Inter plane spacing (F)		1		
		Minimum	Maximum	Mean
Number of planes (P)		**2**	**2**	**2**

Total number of satellite (TNOS)		**24**	**42**	**32**
Pattern Unit (PU)	[degrees]	15.00	8.57	11.25
Node spacing	[degrees]	180.00	180.00	180.00
In-plane spacing between satellites	[degrees]	30.00	17.14	22.50
Phase difference between adjacent planes	[degrees]	15.00	8.57	11.25
Orbit type	**Circular LEO**			
Inclination (i)	[degrees]	72.00		
Inter plane spacing (F)		1		
Number of planes (P)		**7**		
Total number of satellite (TNOS)		**70**		
Pattern Unit (PU)	[degrees]	5.14		
Node spacing	[degrees]	51.43		
In-plane spacing between satellites	[degrees]	36.00		
Phase difference between adjacent planes	[degrees]	5.14		

B-3. Limitations of the Walker Delta constellation

There is no coverage above certain latitude depending upon the value of constant inclination *i*, generally neglect polar coverage.

III.7.2 Elliptical orbit constellation

The elliptical orbit constellation is used for an area specific coverage (between specified locations) because of the change of many parameters in constellation design with the altitude of satellite throughout the orbit such as the coverage footprint (with the largest coverage footprint at the apogee and the smallest coverage footprint at the perigee), the time of satellite visibility and the velocity of the satellite.

For elliptical orbit constellation, to limit the number of variables in constellation design, and thus its complexity, the Walker Star and Walker Delta constellation can be used. However, these two methods cannot provide a good optimal constellation for such elliptical orbit constellation for (continuous) whole Earth coverage, because there would have many overlapping of satellite footprints and no coverage above certain latitude depending upon the value of constant inclination *i*. But, when both methods were used for an area specific (continuous) coverage, it would provide a quite better optimal constellation for elliptical orbit than the circular orbit when the specific locations are well selected because the circular orbit doesn't loiter at apogee like the elliptical orbit.

Recall that the satellite constellation is related to many parameters such as the characteristics of orbits (eccentricity, inclinations, altitudes, etc.), the visibility time, the Relative spacing between satellites in adjacent planes or inter plane spacing F in a Walker constellation, the number of orbits, etc. To simplifier the problem of satellite constellation, one or many parameters are fixed like inclination, the inter plane spacing F in a Walker constellation, satellite orbit altitude, etc to find the optimal constellation.

III.8 Link Budget (EIRP, S/No, G/T)

The link budget is established to evaluate the system margin according to the qualities of the services required in terms of bit error rate, and the value of key parameters of the system such as the tr ansmitter pow er, the E IRP (Emitted Isotropic R adiated P ower), t he pr opagation losses, etc which allow us to determine and verify the quality of the communication link.

III.8.1 Architecture of link budget

The architecture of link budget of nanosatellite OUFTI-1 is shown in Figure III.25.

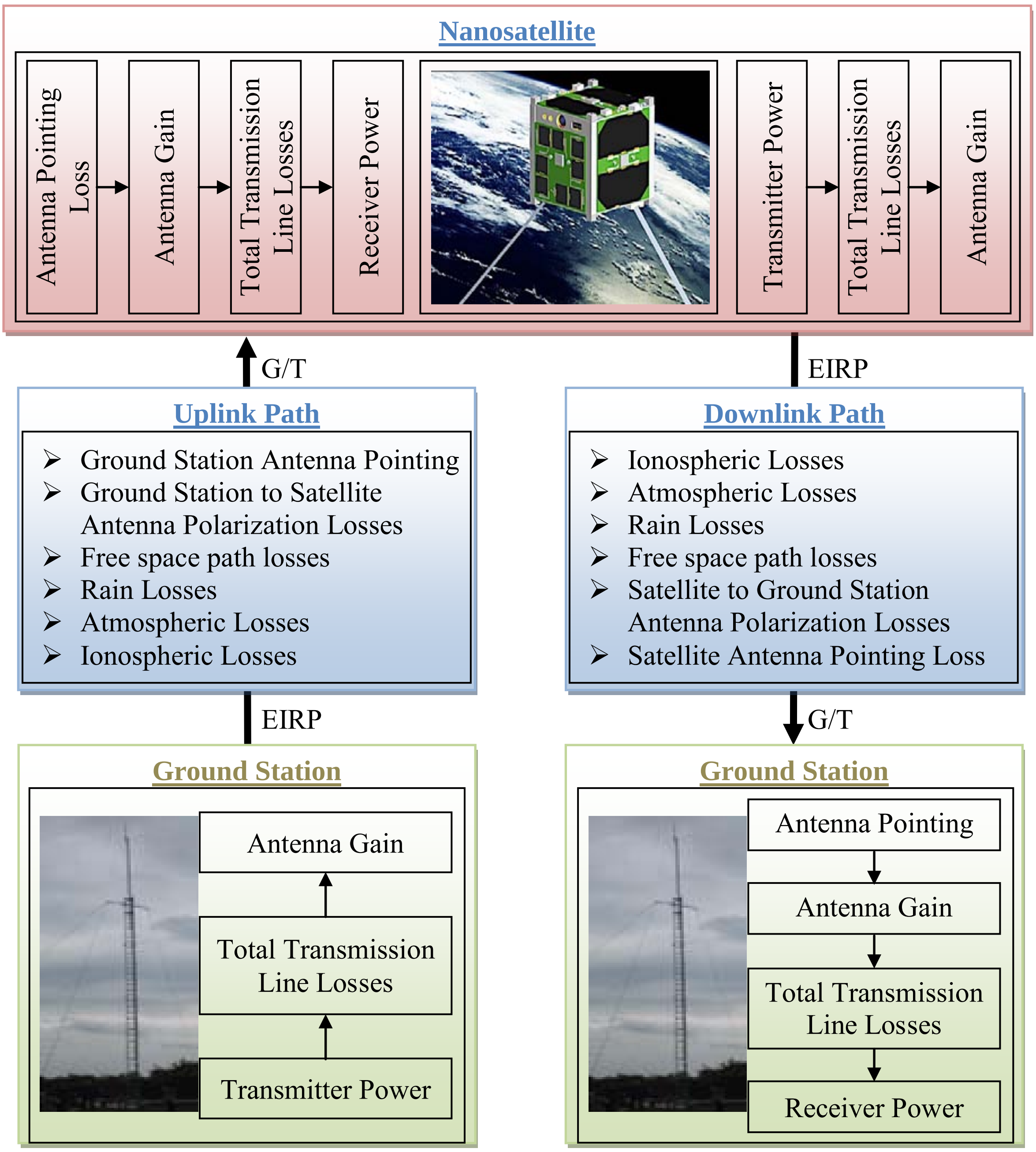


Figure III.25: Architecture of link budget

III.8.2 Link budget

In this section, we will observe the impacts of orbit types, frequency and modulation types with or without coding, on link budget of communication system of OUFTI-1 nanosatellite, especially the system margin.

A. Link budget between OUFTI-1 nanosatellite and Liege ground station

The characteristic of nanosatellite and ground station which is used to compute the link budget was shown in Annex II, A.II.3, in Table 1 and Table 2 respectively. Recall that the characteristic of OUFTI-1 nanosatellite has also been shown in Table III.1.

A-1. Excel sheet link budget calculator

In order to compute and get the result of link budget, the Excel sheet link budget calculator was developed. It is a powerful tool allowing to:

- configure the whole system between satellite and ground station;
- compute the downlink and uplink link budgets.

The Excel sheet is composed of 13 main window tabs which are the following:

1. "Title Page"
2. "I.I.R.R" (Introduction, Instructions for use, Reference, Revisions);
3. "Orbit & Frequency" (orbit properties and frequency choices);
4. "Uplink Budget";
5. "Downlink Budget";
6. "System Performance Summary";
7. "Transmitters" (System transmitters & line losses);
8. "Receivers" (System receivers & line losses);
9. "Antenna Gains";
10. "Antenna Pointing Losses";
11. "Antenna Polarization Loss";
12. "Atmos. & Ionos. Losses" (Atmosphere, ionosphere and rain losses);
13. "Modulation-Demodulation Method".

A view of the "Orbit & Frequency" and "Downlink Budget" tabs is provided in Figure III.26 and Figure III.27 respectively.

A-2. Result of link budget between OUFTI-1 nanosatellite and Liege ground station

By using the Excel sheet link budget calculator, the result of link budget between OUFTI-1 nanosatellite and Liege ground station was found in Table III.19.

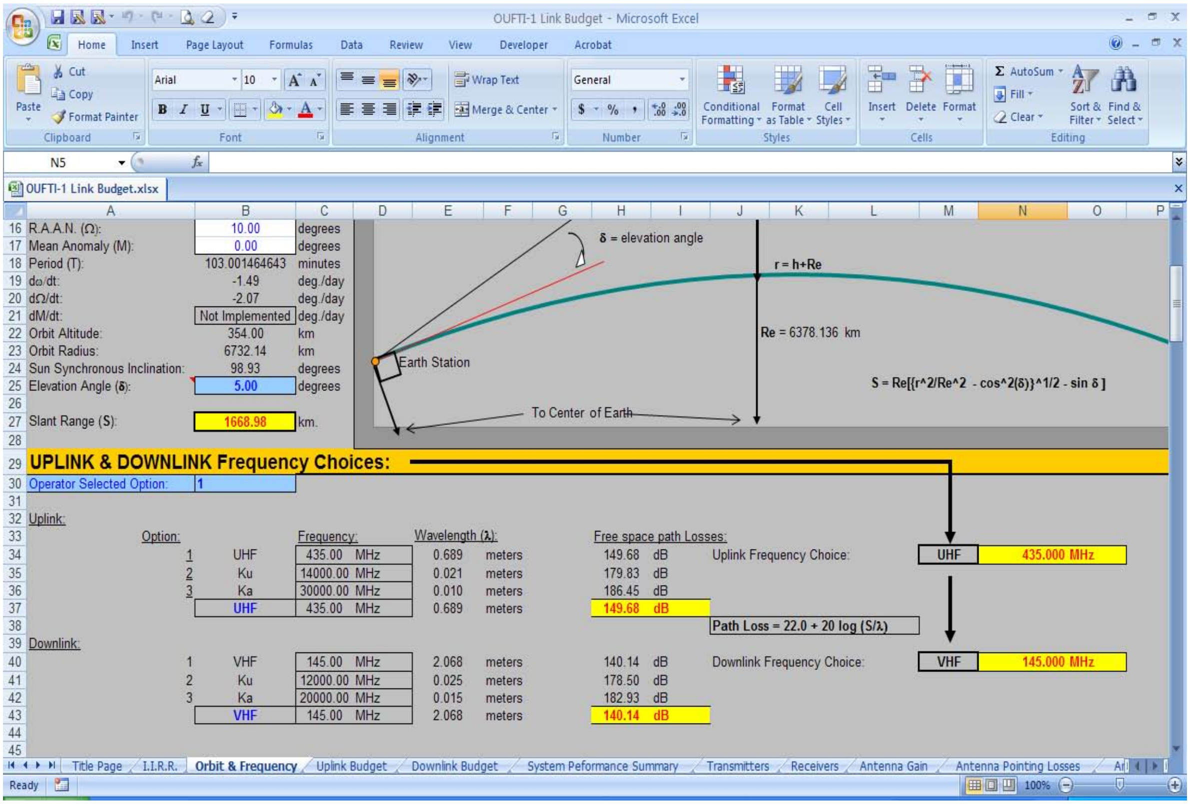


Figure III.26: Overview of the « Orbit & Frequency » tab of the Excel link budget tool

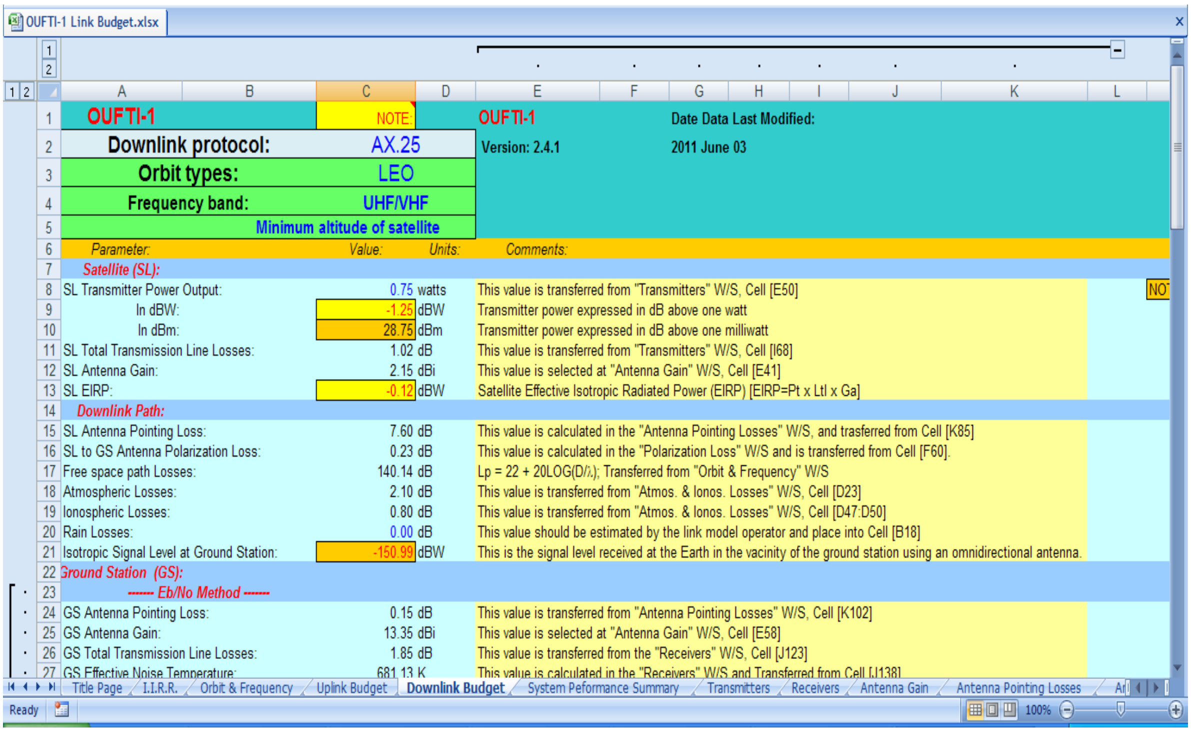


Figure III.27: Overview of the « Downlink Budget » tab of the Excel link budget tool

Table III.19: Result of link budget between OUFTI-1 nanosatellite and Liege ground station

Orbit type		**LEO (Minimum altitude of satellite)**				
Frequency band		**UHF/VHF**				
		Uplink (UHF)		**Downlink (VHF)**		
Protocol		AX.25	D-STAR	AX.25	D-STAR	Beacon
		Ground station (GS)		Satellite (SL)		
Transmitter power	[W]	20	20	0.75	0.75	0.10
	[dBW]	13.01	13.01	-1.25	-1.25	-10.00
Total Transmission Line Losses	[dB]	3.09	3.09	1.02	1.02	1.02
Antenna Gain	[dBi]	13.35	13.35	2.15	2.15	2.15
EIRP	[dBW]	**23.27**	**23.27**	**-0.12**	**-0.12**	**-8.87**
		Uplink path		Downlink path		
Antenna Pointing Loss	[dB]	0.15	0.15	7.60	7.60	7.60
Antenna Polarization Losses	[dB]	0.23	0.23	0.23	0.23	0.23
Free space path losses	[dB]	149.68	149.68	140.14	140.14	140.14
Atmospheric Losses	[dB]	2.10	2.10	2.10	2.10	2.10
Ionospheric Losses	[dB]	0.40	0.40	0.80	0.80	0.80
Rain Losses	[dB]	0.00	0.00	0.00	0.00	0.00
Isotropic Signal Level	[dBW]	**-129.29**	**-129.29**	**-150.99**	**-150.99**	**-159.74**
		Satellite (SL)		Ground station (GS)		
Antenna Pointing Loss	[dB]	7.60	7.60	0.15	0.15	0.15
Antenna Gain	[dBi]	2.15	2.15	13.35	13.35	13.35
Total Transmission Line Losses	[dB]	0.83	0.83	1.85	1.85	1.85
Effective Noise Temperature	[K]	219.66	219.66	681.13	681.13	681.13
Figure of Merit (G/T)	[dB/K]	**-22.10**	**-22.10**	**-16.83**	**-16.83**	**-16.83**
Signal-to-Noise Power Density (S/No)	[dBHz]	**69.60**	**69.60**	**60.62**	**60.62**	**51.87**
System Desired Data Rate	[bps]	9600.00	4800.00	9600.00	4800.00	20.00
	[dBHz]	39.82	36.81	39.82	36.81	13.01
System Eb/No for the Uplink	[dB]	**29.78**	**32.79**	**20.80**	**23.81**	**38.86**
Demodulation Method Selected		Non-Coherent FSK	GMSK	Non-Coherent FSK	GMSK	Non-Coherent FSK
Forward Error Correction Coding Used		None Coding	None Coding	None Coding	None Coding	None Coding
Specified Bit-Error-Rate (BER)		10-5	10-5	10-5	10-5	10-5
Demodulator Implementation Loss		1.00	1.00	1.00	1.00	1.00
System Eb/No	[dB]	13.35	9.72	13.35	9.72	13.35
Eb/No Threshold	[dB]	**14.35**	**10.72**	**14.35**	**10.72**	**14.35**
System link margin	[dB]	**15.43**	**22.07**	**6.45**	**13.09**	**24.51**
Desired link margin	[dB]	6.00	6.00	6.00	6.00	6.00
Available link margin	[dB]	**9.43**	**16.07**	**0.45**	**7.09**	**18.51**
Minimum transmitter power	[dB]	3.58	-3.06	-1.70	-8.34	-28.51
	[W]	**2.28**	**0.49**	**0.68**	**0.15**	**0.0014**

According to the Table III.19, we can observe that:

- The link margin of D-STAR is 6.46 dB better than the link margin of AX.25 because D-STAR protocol uses modulation GMSK which is better than Non-Coherent FSK and its transmitted data rate is lower than the one of AX.25.
- The link margin of Beacon is 18.06 dB and 11.42 dB better than the link margin of AX.25 and D-STAR respectively because Beacon use very low data rate which is just for sending 12 critical parameters in Morse code, giving the information about the status of satellite (safe mode, default mode, D-star mode, etc).

B. Impact of orbit types on link budget

This section will show the impact of changing the orbit type on link budget between OUFTI-1 nanosatellite and Liege ground station and also find the orbit types which can provide a valid communication link. Changing the orbit type (LEO → MEO, VLEO) will result in free space path losses change as shown in Table III.20.

Table III.20: Free space path losses with different orbit type

Frequency band	**UHF/VHF**	
	Downlink (VHF)	**Uplink** (UHF)
Frequency	145 MHz	435 MHz
Orbit type	**Free space path losses** [dB]	
	Downlink	**Uplink**
LEO	140.14	149.68
VLEO	140.36	149.90
MEO (Molnya)	146.97	156.51
MEO (Tundra)	165.35	174.89

The results of link budget between OUFTI-1 nanosatellite and Liege ground station for different orbit type with Beacon, AX.25 and D-STAR are shown in Table III.21, III.22 and III.23 respectively.

Table III.21: Impact of orbit types on link budget with Beacon protocol

Frequency band		**UHF/VHF**			
Protocol		**Beacon**			
Altitude of satellite		**Minimum altitude of satellite (at perigee)**			
		Downlink (VHF)			
Orbit type		LEO	VLEO	MEO (Molnya)	MEO (Tundra)
Free space path losses	[dB]	140.14	140.36	146.97	165.35
Isotropic Signal Level	[dBW]	-159.74	-159.96	-166.57	-184.95
Signal-to-Noise Power Density (S/No)	[dBHz]	51.87	51.66	45.04	26.66
System Eb/No for the Downlink	[dB]	**38.86**	**38.65**	**32.03**	**13.65**
Eb/No threshold	[dB]	**14.35**			
System link margin	[dB]	**24.51**	**24.29**	**17.68**	**-0.70**
Desired link margin	[dB]	6.00	6.00	6.00	6.00
Available link margin	[dB]	**18.51**	**18.29**	**11.68**	**-6.70**
Minimum transmitter power	[dB]	-28.51	-28.29	-21.68	-3.30
	[W]	**0.0014**	**0.0015**	**0.0068**	**0.4678**

Table III.22: Impact of orbit types on link budget with AX.25 protocol

Frequency band		**UHF/VHF**			
Protocol		**AX.25**			
Altitude of satellite		**Minimum altitude of satellite (at perigee)**			
		Uplink (UHF)			
Orbit type		LEO	VLEO	MEO (Molnya)	MEO (Tundra)
Free space path losses	[dB]	149.68	149.90	156.51	174.89
Isotropic Signal Level	[dBW]	-129.29	-129.51	-136.13	-154.51
Signal-to-Noise Power Density (S/No)	[dBHz]	69.60	69.39	62.77	44.39
System Eb/No for the Uplink	[dB]	**29.78**	**29.56**	**22.95**	**4.57**
Eb/No threshold	[dB]	**14.35**			
System link margin	[dB]	**15.43**	**15.21**	**8.59**	**-9.78**
Desired link margin	[dB]	6.00	6.00	6.00	6.00
Available link margin	[dB]	**9.43**	**9.21**	**2.59**	**-15.78**
Minimum transmitter power	[dB]	3.58	3.80	10.42	28.79
	[W]	**2.28**	**2.40**	**11.01**	**757.63**
		Downlink (VHF)			
Orbit type		LEO	VLEO	MEO (Molnya)	MEO (Tundra)
Free space path losses	[dB]	140.14	140.36	146.97	165.35
Isotropic Signal Level	[dBW]	-150.99	-151.20	-157.82	-176.20
Signal-to-Noise Power Density (S/No)	[dBHz]	60.62	60.41	53.79	35.41
System Eb/No for the Downlink	[dB]	**20.80**	**20.59**	**13.97**	**-4.41**
Eb/No threshold	[dB]	**14.35**			
System link margin	[dB]	**6.45**	**6.23**	**-0.38**	**-18.76**
Desired link margin	[dB]	6.00	6.00	6.00	6.00
Available link margin	[dB]	**0.45**	**0.23**	**-6.38**	**-24.76**
Minimum transmitter power	[dB]	-1.70	-1.48	5.13	23.51
	[W]	**0.68**	**0.71**	**3.26**	**224.53**

Table III.23: Impact of orbit types on link budget with D-STAR protocol

Frequency band		**UHF/VHF**			
Protocol		**D-STAR**			
Altitude of satellite		**Minimum altitude of satellite (at perigee)**			
		Uplink (UHF)			
Orbit type		LEO	VLEO	MEO (Molnya)	MEO (Tundra)
Free space path losses	[dB]	149.68	149.90	156.51	174.89
Isotropic Signal Level	[dBW]	-129.29	-129.51	-136.13	-154.51
Signal-to-Noise Power Density (S/No)	[dBHz]	69.60	69.39	62.77	44.39
System Eb/No for the Uplink	[dB]	**32.79**	**32.57**	**25.96**	**7.58**
Eb/No threshold	[dB]	**10.72**			
System link margin	[dB]	**22.07**	**21.85**	**15.24**	**-3.14**
Desired link margin	[dB]	6.00	6.00	6.00	6.00
Available link margin	[dB]	**16.07**	**15.85**	**9.24**	**-9.14**
Minimum transmitter power	[dB]	-3.06	-2.84	3.77	22.15
	[W]	**0.49**	**0.52**	**2.38**	**164.13**

		Downlink (VHF)			
Orbit type		LEO	VLEO	MEO (Molnya)	MEO (Tundra)
Free space path losses	[dB]	140.14	140.36	146.97	165.35
Isotropic Signal Level	[dBW]	-150.99	-151.20	-157.82	-176.20
Signal-to-Noise Power Density (S/No)	[dBHz]	60.62	60.41	53.79	35.41
System Eb/No for the Downlink	[dB]	**23.81**	**23.60**	**16.98**	**-1.40**
Eb/No threshold	[dB]	**10.72**			
System link margin	[dB]	**13.09**	**12.88**	**6.26**	**-12.12**
Desired link margin	[dB]	6.00	6.00	6.00	6.00
Available link margin	[dB]	**7.09**	**6.88**	**0.26**	**-18.12**
Minimum transmitter power	[dB]	-8.34	-8.12	-1.51	16.87
	[W]	**0.1465**	**0.1540**	**0.7066**	**48.6410**

As shown in Table III.21, III.22 and III.23, we can observe that:

- The bigger size of orbit has the higher value of free space path losses and as a result has the smaller value of link margin (better link budget). For example, the uplink or downlink free space path losses of LEO orbit is 0.22 dB, 6.84 dB, and 25.21 dB better than the free space path losses of VLEO, MEO "Molniya" and MEO "Tundra" orbit respectively. Hence, the link margin of LEO is 0.22 dB, 6.84 dB, and 25.21 dB better than the link margin of VLEO, MEO (Molnya) and MEO (Tundra) respectively.
- For downlink link budget with Beacon protocol, with the desired link budget 6 dB, the communication link is valid only for LEO, VEO and MEO "Molniya" orbit with the minimum tr ansmitter pow er of **0.0014 W, 0.0015 W and 0.0068 W** for each orbit respectively.
- For downlink link budget with AX.25 protocol, with the desired link budget 6 dB, the communication l ink i s va lid onl y f or LEO and V EO or bit w ith t he m inimum transmitter power (of satellite) of **0.68 W and 0.71 W** for each orbit respectively. While for upl ink l ink budg et w ith A X.25 pr otocol, w ith t he de sired l ink budge t 6 dB , t he communication l ink i s valid f or LEO, V EO a nd M EO " Molniya" or bit w ith t he minimum transmitter power (of ground station) of **2.28 W, 2.40 W and 11.01 W** for each orbit respectively.
- For downlink link budget with D-STAR protocol, with the desired link budget 6 d B, the communication link is valid only for LEO, VEO orbit, and MEO "Molniya" with the minimum transmitter power (of satellite) of **0.1465 W, 0.1540 W and 0.7066 W** for each orbit respectively. For upl ink l ink budg et w ith A X.25 pr otocol, w ith t he de sired link budg et 6 dB , t he c ommunication l ink is a lso va lid f or L EO, V EO a nd M EO "Molniya" orbit with the minimum transmitter power (of ground station) of **0.49 W, 0.52 W and 2.38 W** for each orbit respectively.
- Hence, with condition of the desired link budget 6 dB, there are two orbits, LEO and VLEO, which are v alid for t he c ommunication l ink f or any pr otocol. However, t he link budg et of LEO or bit is be tter t han t he one of V LEO or bit, c onsequently t he smaller minimum transmitter power. Therefore, the LEO orbit is the best choice for our communication link.

C. Impact of the frequency band on link budget

This s ection w ill s how the i mpact of c hanging t he f requency ba nd on l ink budg et between OUFTI-1 nanosatellite and Liege ground station with orbit LEO, satellite altitude at perigee, and w ith A X.25 pr otocol onl y. The reasons w hy w e j ust s tudy the impa ct of changing t he frequency band on link budget with AX.25 protocol only is that it is the case that the link budget result (value of link margin) is the worst among all the protocol using, and also for gaining time . Therefore, we can judge which frequency band that can provide a valid communication by the link budget result of this case.

Changing the frequency band (UHF/VHF → Ka or Ku) will result in changing total lines losses (cable type), antenna types and free space path losses. The free space path losses with different frequency bands are shown in Table III.24. The line losses, antenna gain and others losses are calculated in Excel.

Table III.24: Free space path losses with different frequency bands

Note: Satellite is located at the perigee of LEO orbit							
Frequency band		**UHF/VHF**		**Ku**		**Ka**	
		Downlink	Uplink	Downlink	Uplink	Downlink	Uplink
Frequency [MHz]		VHF 145	UHF 435	Ku 12000	Ku 14000	Ka 20000	Ka 30000
Free space path losses	[dB]	140.14	149.68	178.50	179.83	182.93	186.45
Atmospheric Losses	[dB]	2.10	2.10	0.71	0.86	3.38	2.77
Ionospheric Losses	[dB]	0.80	0.40	0.00	0.00	0.00	0.00
Rain Losses	[dB]	0.00	0.00	11.57	16.05	32.09	62.79

By using the Excel sheet link budget calculator with the characteristic data of nanosatellite and ground station in Annex II, A.II.3, in Table 1 and Table 2, the result of uplink and downlink link budget between OUFTI-1 nanosatellite and Liege ground station with AX.25 for different frequency bands were found in Table III.25.

Table III.25: Impact of frequency band on uplink link budget with AX.25 protocol

Orbit type		**LEO (Minimum altitude of satellite)**		
Protocol		**AX.25**		
Uplink				
Frequency band		**UHF/VHF**	**Ku**	**Ka**
		Ground station (GS)		
Transmitter power	[W]	20	20	20
	[dBW]	13.01	13.01	13.01
Total Transmission Line Losses	[dB]	3.09	9.40	14.85
Antenna Gain	[dBi]	13.35	54.20	60.82
EIRP	[dBW]	**23.27**	**57.81**	**58.98**
		Uplink path		
Antenna Pointing Loss	[dB]	0.15	1.03	5.27
Antenna Polarization Losses	[dB]	0.23	0.23	0.23
Free space path losses	[dB]	149.68	179.83	186.45
Atmospheric Losses	[dB]	2.10	0.86	2.77
Ionospheric Losses	[dB]	0.40	0.00	0.00
Rain Losses	[dB]	0.00	16.17	63.26
Isotropic Signal Level	[dBW]	**-129.29**	**-140.32**	**-198.99**

		Satellite (SL)		
Antenna Pointing Loss	[dB]	7.60	0.00	0.00
Antenna Gain	[dBi]	2.15	5.27	5.27
Total Transmission Line Losses	[dB]	0.83	1.70	2.40
Effective Noise Temperature	[K]	219.66	245.16	262.12
Figure of Merit (G/T)	[dB/K]	**-22.10**	**-20.33**	**-21.31**
Signal-to-Noise Power Density (S/No)	[dBHz]	**69.60**	**67.95**	**8.29**
System Desired Data Rate	[bps]	9600.00	9600.00	9600.00
	[dBHz]	39.82	39.82	39.82
System Eb/No for the Uplink	[dB]	**29.78**	**28.13**	**-31.53**
Demodulation Method Selected		Non-Coherent FSK	Non-Coherent FSK	Non-Coherent FSK
Forward Error Correction Coding Used		None Coding	None Coding	None Coding
Specified Bit-Error-Rate (BER)		10^{-5}	10^{-5}	10^{-5}
Demodulator Implementation Loss		1.00	1.00	1.00
System Eb/No	[dB]	13.35	13.35	13.35
Eb/No Threshold	[dB]	14.35	14.35	14.35
System link margin	[dB]	**15.43**	**13.78**	**-45.88**
Desired link margin	[dB]	6.00	6.00	6.00
Available link margin	[dB]	**9.43**	**7.78**	**-51.88**
Minimum transmitter power	[dB]	3.58	5.23	64.89
	[W]	**2.28**	**3.34**	**3085215.08**
Downlink				
Frequency band		**UHF/VHF**	**Ku**	**Ka**
		Ground station (GS)		
Transmitter power	[W]	0.75	0.75	0.75
	[dBW]	-1.25	-1.25	-1.25
Total Transmission Line Losses	[dB]	1.02	1.81	2.17
Antenna Gain	[dBi]	2.15	5.59	6.90
EIRP	[dBW]	**-0.12**	**2.53**	**3.48**
		Uplink path		
Antenna Pointing Loss	[dB]	7.60	0.00	0.00
Antenna Polarization Losses	[dB]	0.23	0.23	0.23
Free space path losses	[dB]	140.14	178.50	182.93
Atmospheric Losses	[dB]	2.10	0.71	3.38
Ionospheric Losses	[dB]	0.80	0.00	0.00
Rain Losses	[dB]	0.00	11.66	32.33
Isotropic Signal Level	[dBW]	**-150.99**	**-188.56**	**-215.40**
		Satellite (SL)		
Antenna Pointing Loss	[dB]	0.15	0.76	2.17
Antenna Gain	[dBi]	13.35	52.87	57.30

Total Transmission Line Losses	[dB]	1.85	5.38	7.00
Effective Noise Temperature	[K]	681.13	434.15	450.93
Figure of Merit (G/T)	[dB/K]	**-16.83**	**21.11**	**23.76**
Signal-to-Noise Power Density (S/No)	[dBHz]	**60.62**	**60.39**	**34.79**
System Desired Data Rate	[bps]	9600.00	9600.00	9600.00
	[dBHz]	39.82	39.82	39.82
System Eb/No for the Uplink	[dB]	**20.80**	**20.57**	**-5.03**
Demodulation Method Selected		Non-Coherent FSK	Non-Coherent FSK	Non-Coherent FSK
Forward Error Correction Coding Used		None Coding	None Coding	None Coding
Specified Bit-Error-Rate (BER)		10^{-5}	10^{-5}	10^{-5}
Demodulator Implementation Loss		1.00	1.00	1.00
System Eb/No	[dB]	13.35	13.35	13.35
Eb/No Threshold	[dB]	14.35	14.35	14.35
System link margin	[dB]	**6.45**	**6.22**	**-19.38**
Desired link margin	[dB]	6.00	6.00	6.00
Available link margin	[dB]	**0.45**	**0.22**	**-25.38**
Minimum transmitter power	[dB]	-1.70	-1.47	24.13
	[W]	**0.6764**	**0.7131**	**258.8751**

As shown in Table III.25, we can observe that:

- For downlink link budget with AX.25 protocol, with the desired link budget 6 dB, the communication link is valid only for UHF/VHF and Ku frequency band with the minimum transmitter power (of satellite) of **0.6764 W and 0.7131 W** for each frequency band respectively.
- For uplink link budget with AX.25 protocol, with the desired link budget 6 dB, the communication link is also valid for UHF/VHF and Ku frequency band with the minimum transmitter power (of ground station) of **2.28 W, and 3.34 W** for frequency band respectively.
- Hence, the link budget of communication link is better when it's used with the lower frequency, and the best choice of frequency band for our communication link is UHF/VHF as it is required the least minimum transmitter power.

D. Impact of the modulation types with/without coding on link budget

For the same reason as described in the section III.8.2.C, this section will only show the impact of changing the type of modulations with/without coding on link budget between OUFTI-1 nanosatellite and Liege ground station with AX.25 protocol.

The modulations with/without coding selection for computing link budget with AX.25 protocol are Non-Coherent FSK, Coherent FSK, GMSK, BPSK and BPSK with coding convolution. The theoretical required Eb/No for these modulation types which are computed in MATLAB are shown in Table III.25 and in Figure III.28.

Table III.26: Modulation, coding, BER and theoretical required Eb/No

	Modulation Type	Coding	Bit Error Rate	Required Eb/No (dB)
1	Non-Coherent FSK	No Coding	1.00E-05	13.35
2	Coherent FSK	No Coding	1.00E-05	12.60
3	GMSK	No Coding	1.00E-05	9.72
4	BPSK	No Coding	1.00E-05	9.59
5	BPSK	Convolutional (R=1/2, K=7)	1.00E-05	5.91

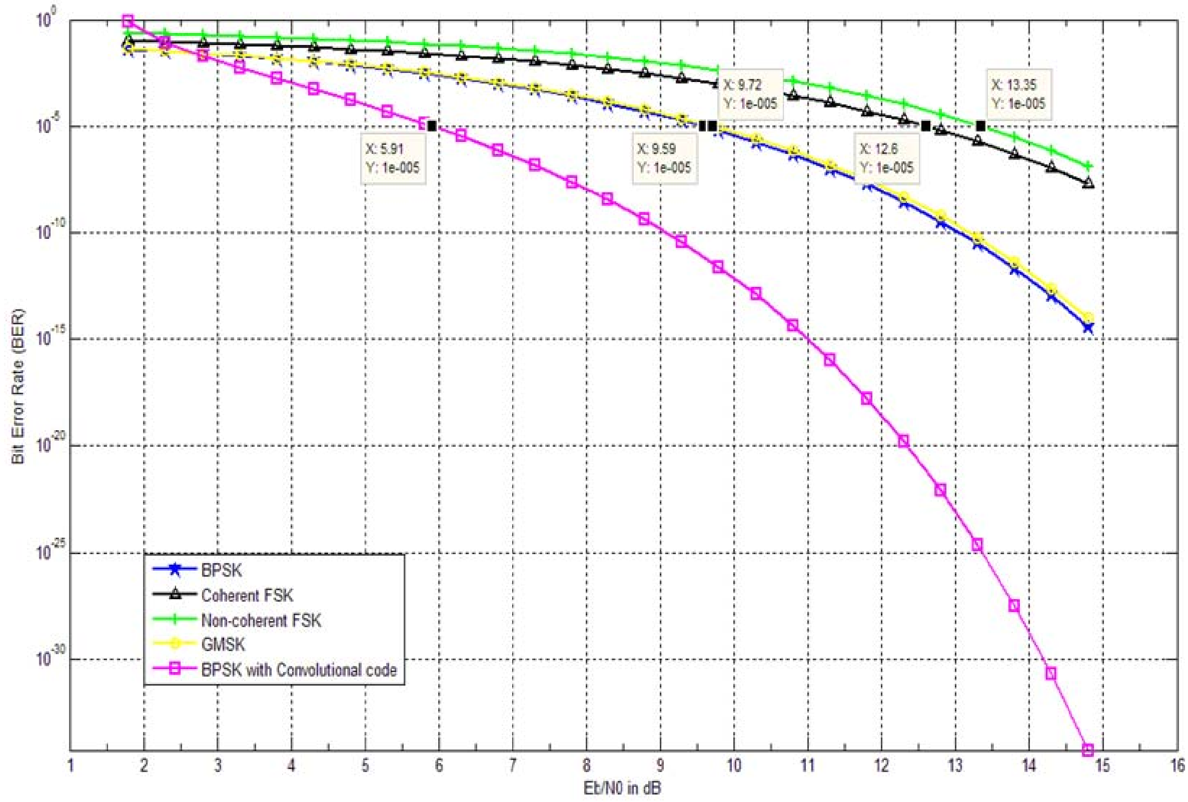


Figure III.28: Theoretical Eb/No vs. BER curve for different modulation types

By using the Excel sheet link budget calculator, the result of uplink and downlink link budget between OUFTI-1 nanosatellite and Liege ground station with AX.25 for different modulation types were found in Table III.27.

As shown in Table III.26, we can observe that:

- The communication link with modulation type with or without coding which required less Eb/No provides a better link budget, consequently, the less minimum transmitter power. For instance, the uplink communication link with modulation BPSK and with convolutional code which is the least required Eb/No for the BER of 10^-5, has the highest system link margin of 22.87, consequently, the least minimum transmitter power of 0.41 W.

Table III.27: Impact of modulation types on link budget with AX.25 protocol

Frequency band		**UHF/VHF**				
Orbit type		**LEO (Minimum altitude of satellite)**				
Protocol		**AX.25**				
		Uplink (UHF)				
Modulation type		Non-Coherent FSK	Coherent FSK	GMSK	BPSK	BPSK
Coding		None	None	None	None	Convolutional (R=1/2, K=7)
System Eb/No for the Uplink	[dB]	**29.78**				
Eb/No threshold	[dB]	**14.35**	**13.60**	**10.72**	**10.59**	**6.91**
System link margin	[dB]	**15.43**	**16.18**	**19.06**	**19.19**	**22.87**
Desired link margin	[dB]	6.00	6.00	6.00	6.00	6.00
Available link margin	[dB]	**9.43**	**10.18**	**13.06**	**13.19**	**16.87**
Minimum transmitter power	[dB]	3.58	2.83	-0.05	-0.18	-3.86
	[W]	**2.28**	**1.92**	**0.99**	**0.96**	**0.41**
		Downlink (VHF)				
Modulation type		Non-Coherent FSK	Coherent FSK	GMSK	BPSK	BPSK
Coding		None	None	None	None	Convolutional (R=1/2, K=7)
System Eb/No for the Downlink	[dB]	**20.80**				
Eb/No threshold	[dB]	**14.35**	**13.60**	**10.72**	**10.59**	**6.91**
System link margin	[dB]	**6.45**	**7.20**	**10.08**	**10.21**	**13.89**
Desired link margin	[dB]	6.00	6.00	6.00	6.00	6.00
Available link margin	[dB]	**0.45**	**1.20**	**4.08**	**4.21**	**7.89**
Minimum transmitter power	[dB]	-1.70	-2.45	-5.33	-5.46	-9.14
	[W]	**0.68**	**0.5685**	**0.2931**	**0.2843**	**0.1219**

Conclusion

Throughout this chapter, we have dealt with the conception elements of nanosatellite system such as:

1. Definition of missions: provides a summary of characteristic of OUFTI-1 nanosatellite;
2. Space segment: describes the nanosatellite subsystems;
3. Ground segment: presents the elements of ground segment;
4. Space environment: describes the regions of earth's atmosphere and the space environment effects on satellite;
5. Physical layer and data layer: understands the elements of a digital transmission system of OUFTI-1 and AX.25, D-STAR and Beacon protocol;
6. Orbital mechanic: studies about the classical orbital elements and the comparison of different orbit types on orbital parameters, slant range and free space path losses, zone coverage, duration of visibility, etc;
7. Satellite constellation: describes two categories of satellite constellation (circular orbit constellation and elliptical orbit constellation) and two method of satellite constellation (Walker Star and Walker Delta);

8. Link budget (EIRP, S/No, G/T): started by the architecture of link budget and ended by the link budget of nanosatellite including a study of impact of the orbit types, frequency bands and modulation on link budget.

All literature and theoretical studies carried out in this chapter will be completed in next chapter by the implementation under the simulation software program STK. Before going on with the next chapter, there are some important points that need to remember in this chapter:

- The bigger size of orbit will result in the smaller of time rate of change of ω ($d\omega$) and time variation of R.A.A.N ($d\Omega$), the bigger of zone coverage, the longer duration of visibility, hence the smaller number of satellite required for continuous coverage under the orbit trace, consequently, the smaller number of planes and total number of satellites required.
- The bigger size of orbit has the higher value of free space path losses and as a result has the smaller value of link margin (better link budget).
- The lower frequency provides the better link budget of communication link, hence less minimum transmitter power.
- The modulation type with or without coding that required less Eb/No provides a better link budget of communication link, consequently, the less minimum transmitter power.

CHAPTER IV

“Realization and simulation: realization of a simulator for orbital mechanics and communication performance analysis”

Literature and theoretical studies carried out in the previous chapters, especially the orbit elements, the constellation, and communication link budgets, will be completed in this chapter under the simulation software program STK. This chapter will be divided into 5 parts:

1. What is STK?
2. Orbital mechanics for different orbit types
3. Continuous whole Earth coverage constellation for different orbit types
4. Constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations
5. Link budget between OUFTI1 nanosatellite and Liege ground station for different orbit types

<u>Note</u>:

❖ All STK simulations, unless otherwise noted, were run over the same analysis period of 24 hours, beginning on 7 Jul 2011 10: 00:00.000 UTCG or 7 Jul 2011 12: 00:00.000 LCLG, and terminating 8 Jul 2011 10 :00:00.000 UTCG or 8 Jul 2011 12: 00:00.000 LCLG.

❖ The different orbit types used for all STK simulation scenarios, unless otherwise noted, are:
- Elliptical orbits: LEO, VLEO, MEO (Molniya) and MEO (Tundra) [all are inclined]
- Circular orbits: LEO (inclined), LEO (polar).

The characteristics of the different orbit types for STK simulations are shown in Table IV.1.

Table IV.1: Characteristics of the different orbit types for STK simulations

Orbital parameters \ Orbit types		Elliptical				Circular	
		LEO	VLEO	MEO “Molniya”	MEO “Tundra”	LEO “Inclined”	LEO “Polar”
Apogee altitude (ha)	[km]	1447.00	370.00	39105.00	46340.00	650.00	650.00
Perigee altitude (hp)	[km]	354.00	368.00	1250.00	25231.00	650.00	650.00
Inclination (i)	[degrees]	71.00°	40.02°	63.4°	63.4°	72°	90°
R.A.A.N (Ω)	[degrees]	45.00	45.00	45.00	45.00	45.00	45.00
Argument of perigee (ω)	[degrees]	30.00	30.00	30.00	30.00	0.00	0.00
True anomaly (v)	[degrees]	15.00	15.00	15.00	15.00	45.00	45.00

❖ There are no orbit plane constraints, and the satellites are assumed to be capable of attitude control as well as inter-satellite communication links.

❖ For all constellations in the STK simulation scenarios, the relative spacing between satellites in adjacent planes F is equal to 1.

IV.1 What is STK?

Satellite Tool Kit (STK), currently on version 9.2.2, is a comprehensive simulation software program developed by Analytical Graphics, Inc. (AGI). STK has an expansive range of capabilities, and for this reason it is widely used in the space community, especially for remote sensing applications. STK is used by all the arenas of research and development, from university research programs, to military development operations, to commercial investment agendas.

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

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

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

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

The STK product range has been reorganized into 3 Editions with supplemental STK modules as follows:

- STK Basic Edition is a free application that includes fundamental STK Professional capabilities that address most requirements for concept development and preliminary system or mission design. Generating content with STK Basic is easy. You can share modeling and analysis results through AGI's free, interactive 3D viewer; KML export for Google Earth; or AGI's open API.
- STK Professional Edition is a general-purpose engineering application that derives its power from AGI's patented spatial mechanics engine with integrated visualization capabilities. STK Professional has an intuitive user interface, tens of thousands of data output parameters and a modular structure for extending the application with specialized modeling and analysis capabilities.
- STK Expert Edition is a software bundle that combines STK Professional with all of STK's core analysis modules (STK/Analyzer, STK/Attitude, STK/Communications, STK/Coverage, STK/Radar, STK/Integration and STK/Terrain, Imagery, & Maps) at a reduced cost.
- Supplemental STK Modules are modules that can be added to the Basic, Professional or Expert editions.

A brief summary of the editions and modules is shown in Figure IV.1.

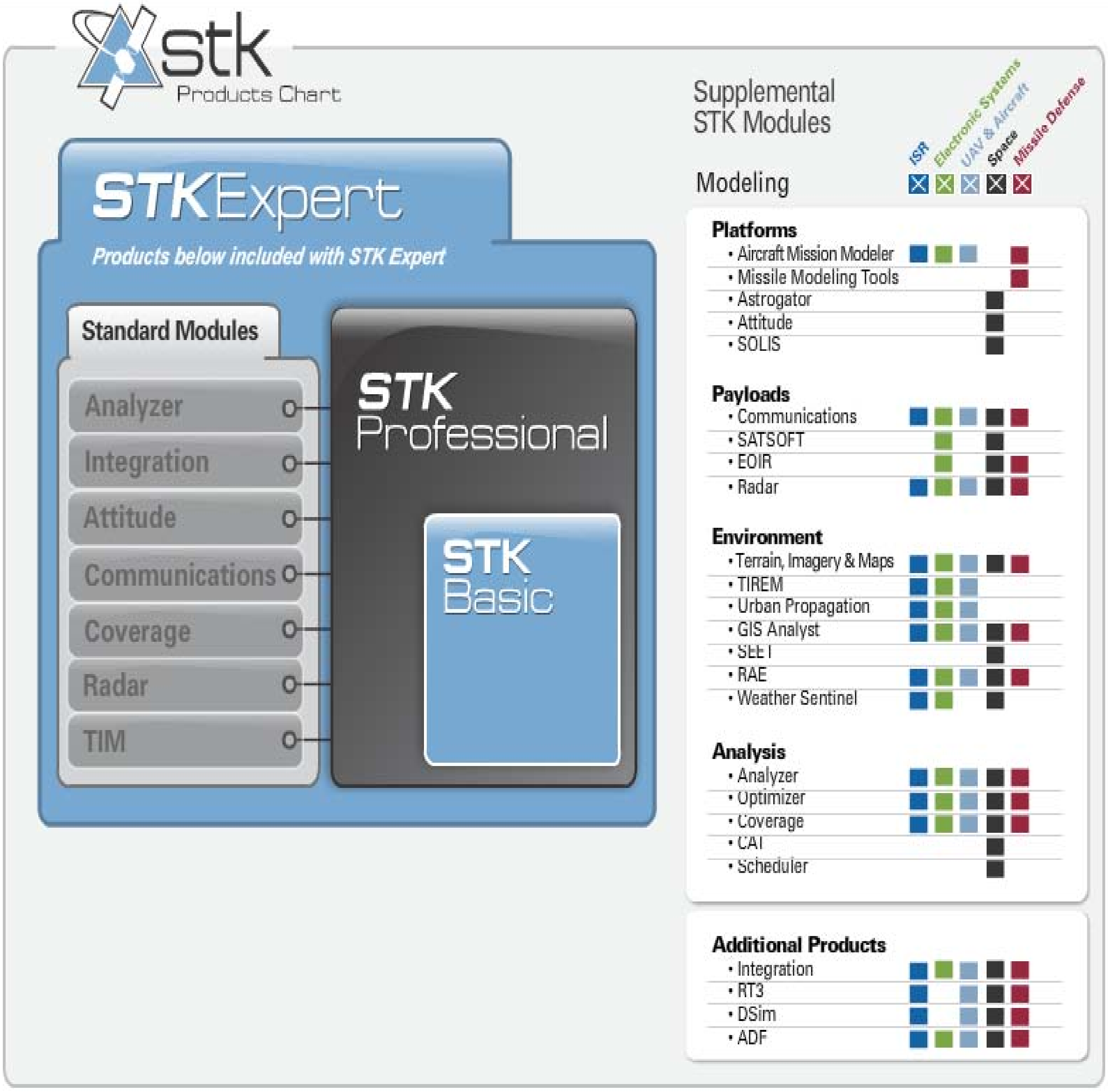


Figure IV.1: STK products chart

Each of the modules can be purchased individually and added to the STK/Basic Edition, the STK/Professional Edition or the STK/ Expert Editions. The product license of STK modules is very expensive. However, Analytical Graphics, Inc. (AGI) provides an educational use only version with free license for some STK modules with limited days, throughout the universities based on a program of academic research. The STK simulation program that was used in this thesis is an educational use only version granted to TéSA, and the modules that can be used is shown in Figure IV.2. And the STK workspace is shown in Figure IV.3.

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

Product Licenses			
Product	**Description**	**Version**	**Status**
AMM	Aircraft Mission Modeler **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
ASTG	Astrogator **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
ATT	Attitude **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
CAT	Conjunction Analysis Tool **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
COV	Coverage **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
Comm	Communications **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
Radar	Radar **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
SEET	Space Environment and Effects Tool **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
STK	STK Basic Edition	9.0	Nodelock(NIC)
STKIntegration	STK Integration Module **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
STKProfessional	STK Professional Edition **Expires in: 46 days**	9.0	LockDemo(30-aug-2011)
DIS	Distributed Interactive Simulation	9.0	**No License found**
EOIR	Electro-Optical Infrared Sensor Performance	9.0	**No License found**
MicrosoftVE	Microsoft Bing Maps	9.0	**No License found**
RT3Client	RT3 Client	9.0	**No License found**
RdrAdvEn	Radar Advanced Environment - Subject to ITAR	9.0	**No License found**
SOLIS	Spacecraft Object Library In STK	9.0	**No License found**
STKCAP	Civil Air Patrol Bundle		**No License found**
STKEDU	Educational Bundle		**No License found**
STKExpert	STK Expert Edition	9.0	**No License found**
STKTIM	Terrain, Imagery & Maps	9.0	**No License found**
TIREM	TIREM		**No License found**

Figure IV.2: Product licenses

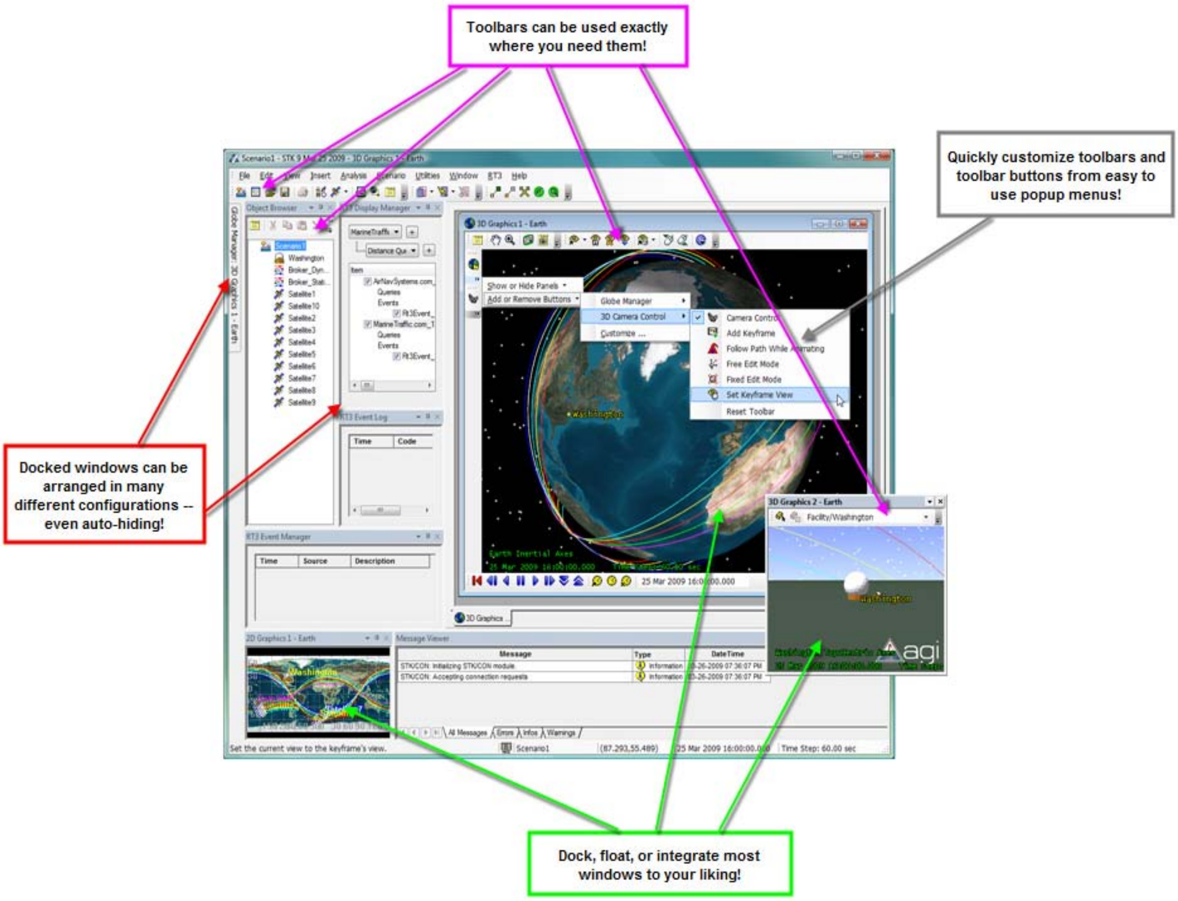


Figure IV.3: STK Workspace

IV.2 Orbital mechanics for different orbit types

IV.2.1 Description of the simulation scenarios of orbital mechanics

Facilities (ground stations) and nanosatellite having different orbit types are created using STK. The simulation software computation capabilities of STK are exploited in order to find the classical orbital elements, access, slant range and other orbit parameters for each orbit type. Whenever possible or applicable, comparisons with the results in chapter III will be done.

IV.2.2 Simulation scenarios and output results of orbital mechanics

A. Creating scenarios, satellites and facilities for different orbit types

❖ Steps to create a scenario:

- {Open STK→ Click File menu→ Click New} or Click Create a New Scenario icon → Input [Name, Description, Location, Analysis period (start time to stop time), Central Body] → Click Ok

❖ Steps to create a satellite by using the Define Properties:

- {Click Insert menu → Click New} or Click Insert New Object icon → Select Satellite → Select Define Properties → Click Insert to bring up the Satellite Properties page
- Go to satellite Basic-orbit page → Input [Propagator (Click → J2Perturbation), Step Size, Coord Type (Click → Classical), Coord System (Click → J2000), Apogee Altitude (Click → Apogee Altitude), Perigee Altitude (Click → Perigee Altitude), Inclination, Argument of Perigee, RAAN (Click → RAAN), True Anomaly (Click → True Anomaly)]
- Go to satellite 2D or 3D Graphics Settings to enhance the clarity, the realism and even the accuracy of your 2D and 3D visualizations.
- Go to satellite Constraints Settings to model the performance characteristics and limitations of objects in the scenario more accurately.
- Click OK to apply the changes and close
- Select the Satellite in the Object Browser
- Click F2 and rename the facility

Note:

- To find the orbital period for a pass (a pass is a complete orbit of a satellite around the Earth between successive node crossings) and eccentricity, Click next to Apogee Altitude to open the drop out list → select **Period** (see Figure IV.4)
- To find the satellite Cartesian position, Click at the **Coor Type** to open the drop out list → select **Cartesian** (see Figure IV.4)

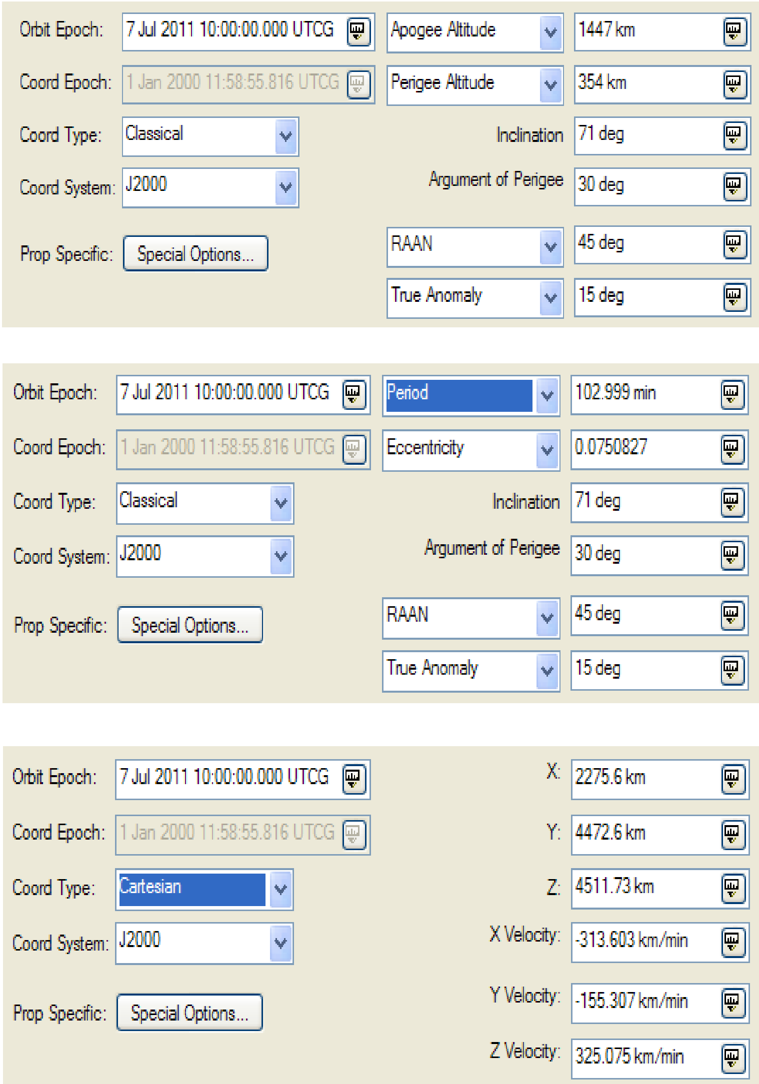


Figure IV.4: How to find orbital period and Cartesian position in STK

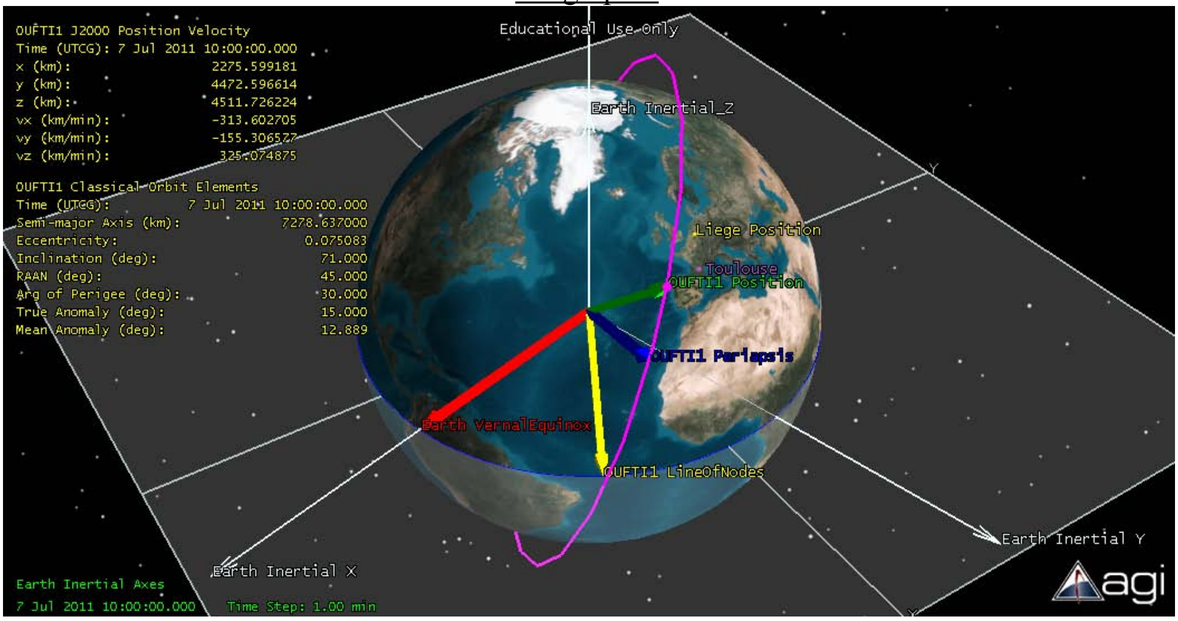
❖ <u>Steps to create a facility by using the City Database:</u>

- {Click Insert menu → Click New} or Click Insert New Object ( ) icon → Select Facility → Select Select from City Database → Click Insert to bring up the City Database
- Input [City name (Toulouse or Liege)] → Click Search → Select the right city from the search results list → Click Insert and Close
- Right-click on Facility in the Object Browser→ Properties → Go to 2D or 3D Graphics Settings to enhance the clarity, the realism and even the accuracy of your 2D and 3D visualizations
- Click OK to apply the changes and close
- Select the Satellite in the Object Browser
- Click F2 and rename the facility

For more detail about the steps to *create a scenario, a satellite and a facility* go to STK help.

The 3D and 2D graphics of the simulation scenarios for different orbit types are shown in Figure IV.4, IV.5, IV.6, IV.7, IV.8 and IV.9.

3D graphic



2D graphic

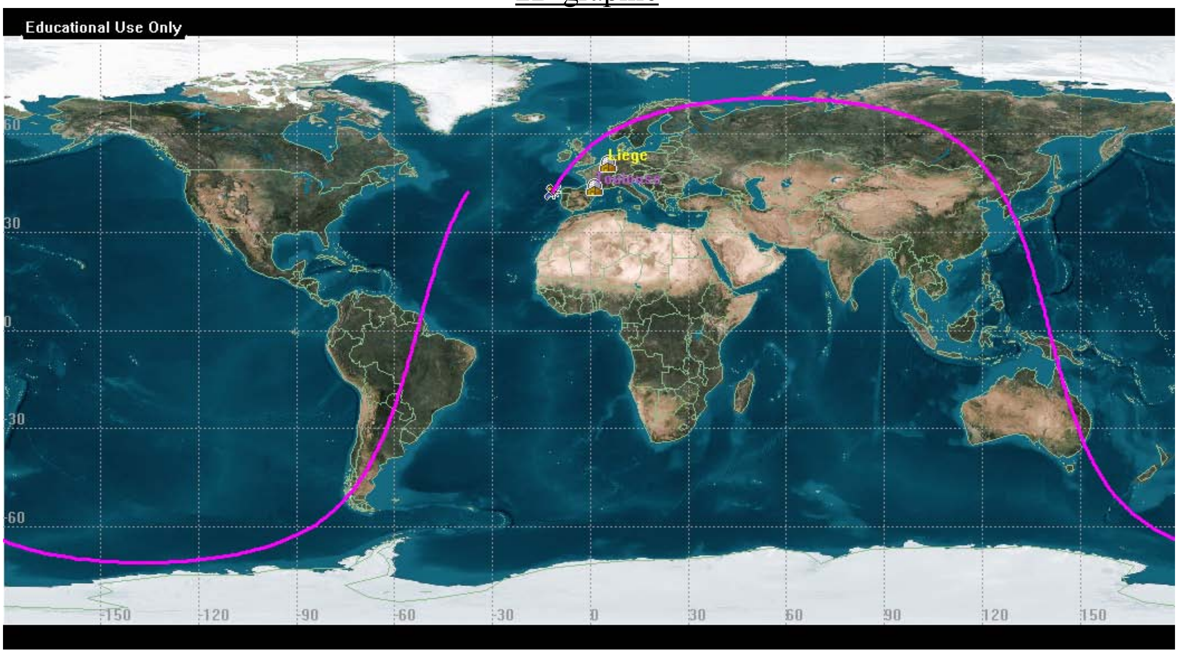
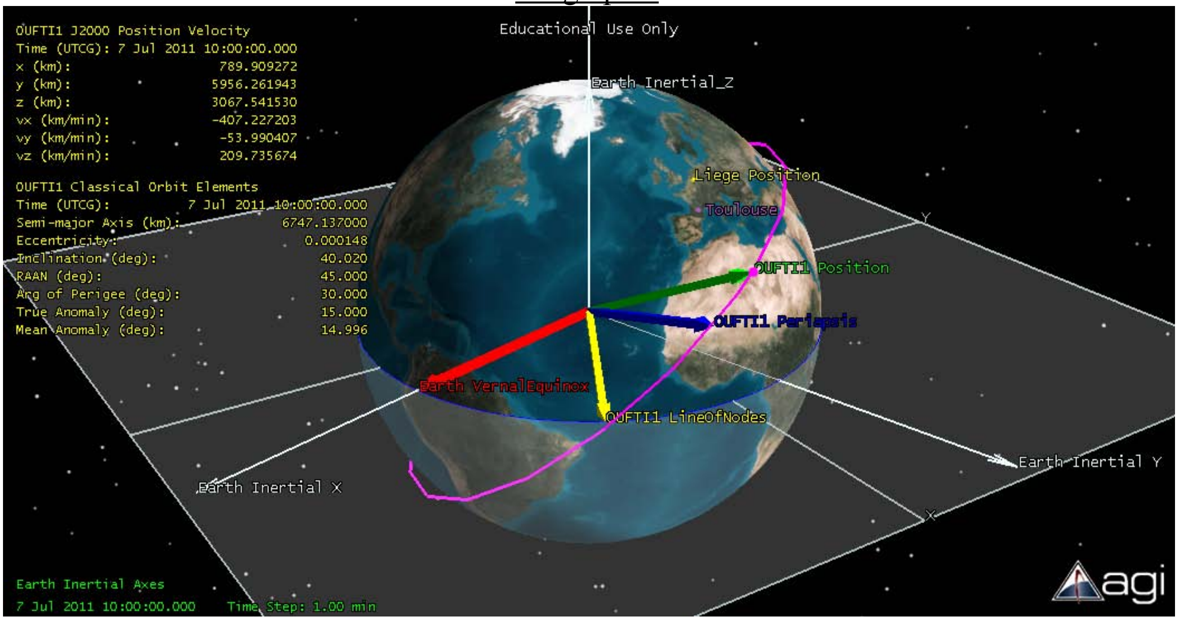


Figure IV.5: Simulation scenario for elliptical LEO orbit

The orbital period of elliptical LEO orbit calculated by STK is about 103 minutes for a pass as the results calculated in Chapter III.

3D graphic



2D graphic

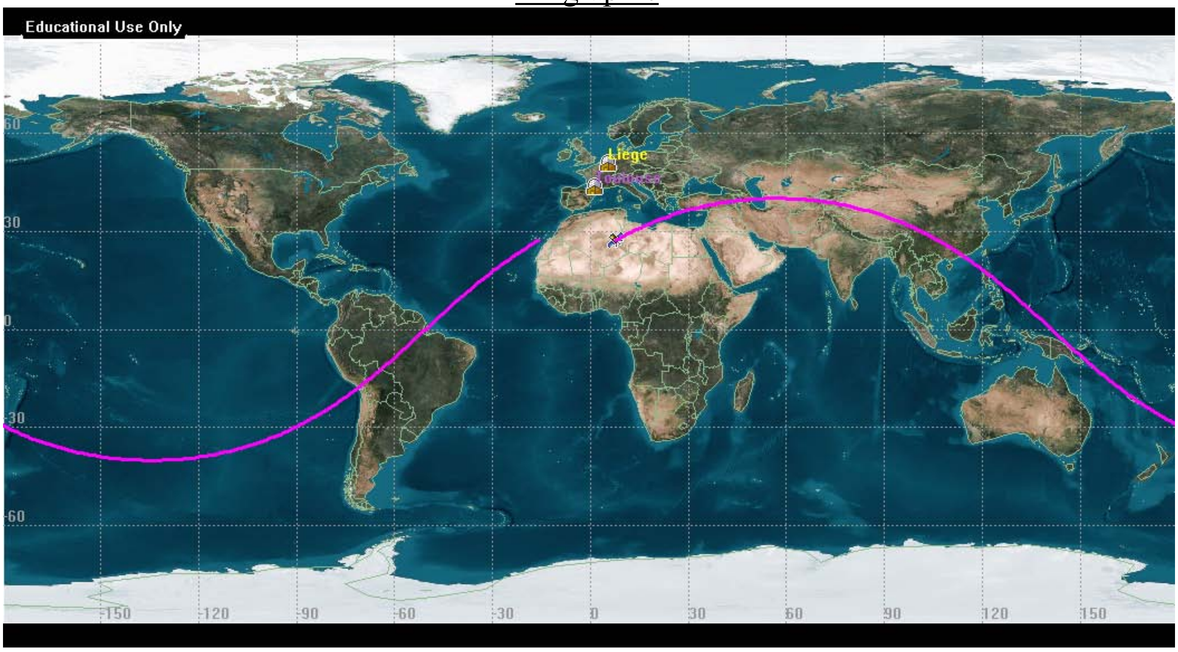
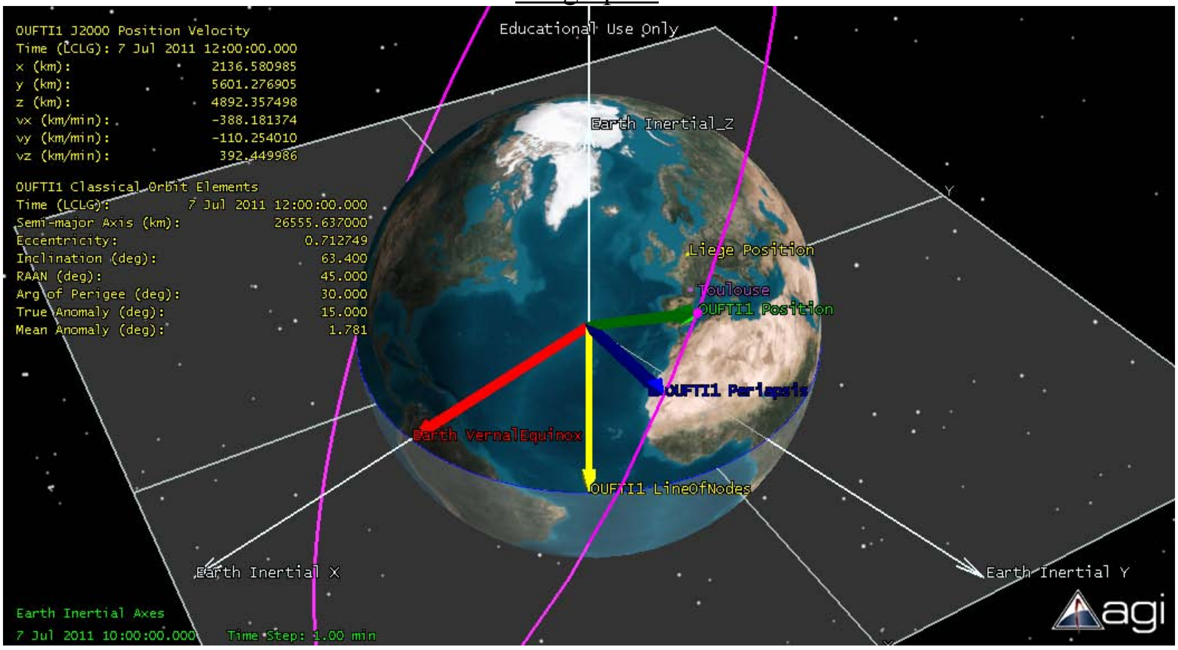


Figure IV.6: Simulation scenario for elliptical VLEO orbit

The orbital period of elliptical VLEO orbit calculated by STK is about 91.93 minutes for a pass as the results calculated in Chapter III.

3D graphic



2D graphic

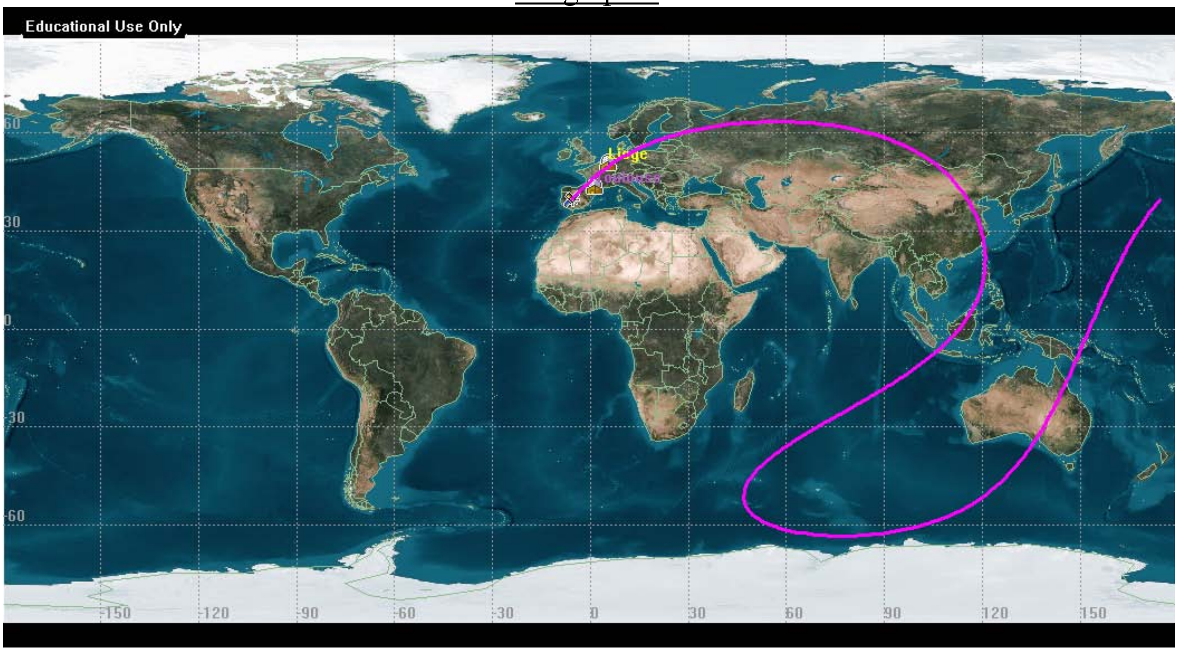
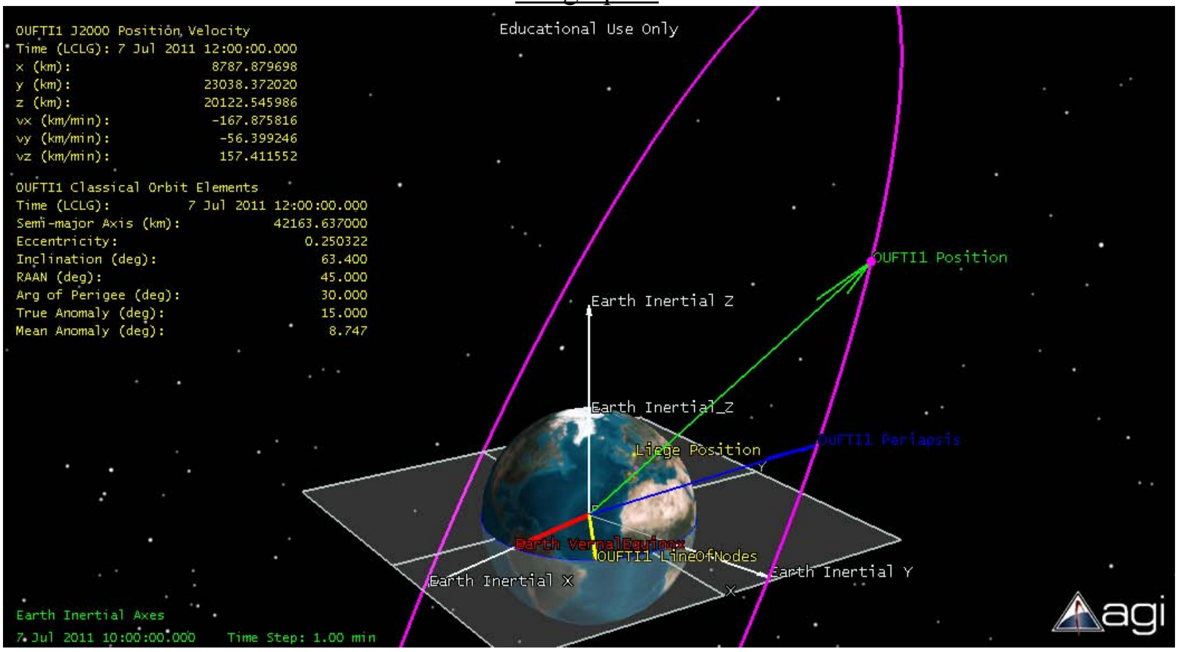


Figure IV.7: Simulation scenario for elliptical MEO “Molniya” orbit

The orbital period of elliptical MEO “Molniya” orbit calculated by STK is about 717.79 minutes for a pass as the results calculated in Chapter III.

3D graphic



2D graphic

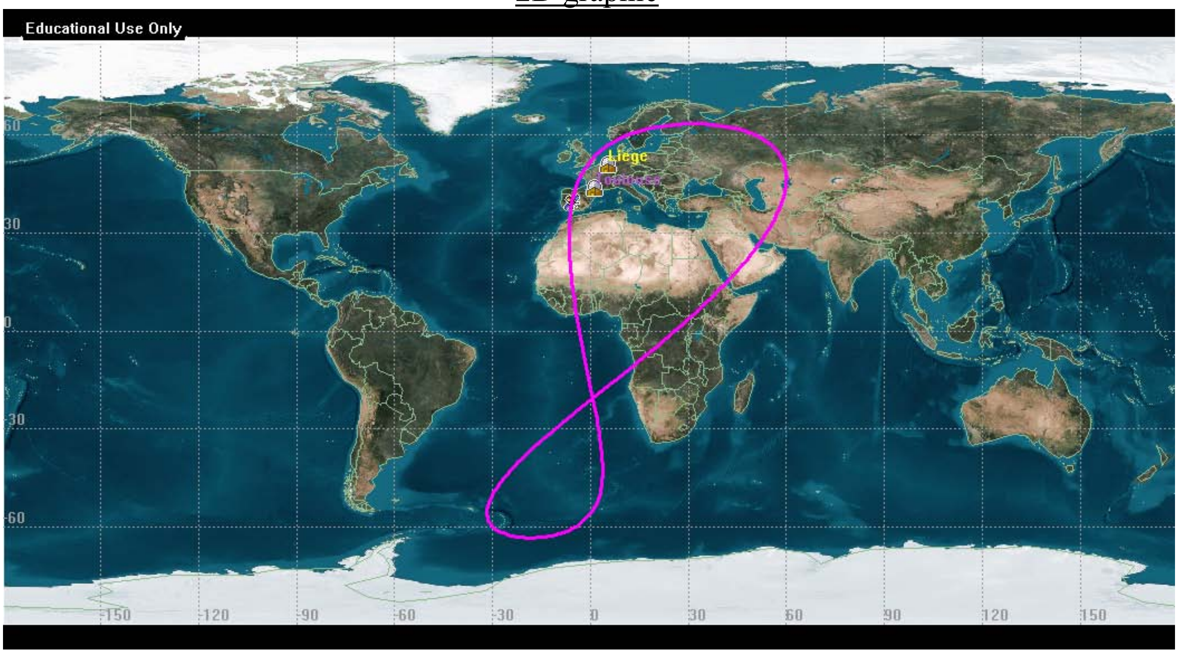
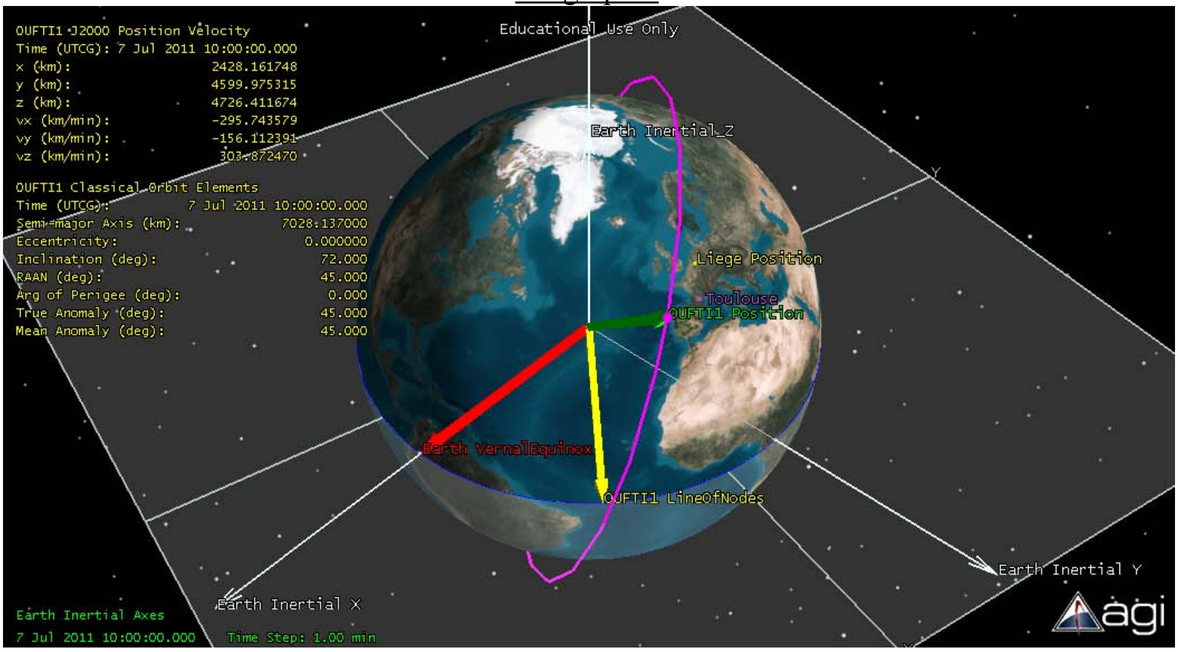


Figure IV.8: Simulation scenario for elliptical MEO "Tundra" orbit

The orbital period of elliptical MEO "Tundra" orbit calculated by STK is about 1436.04 minutes for a pass as the results calculated in Chapter III.

3D graphic



2D graphic

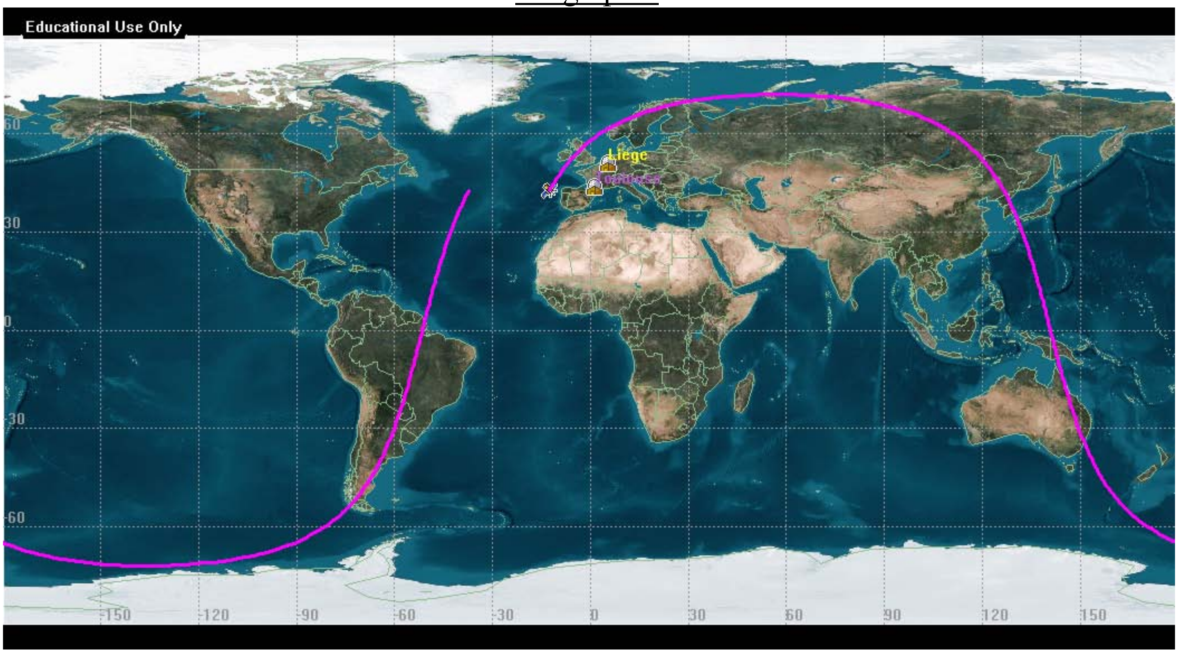
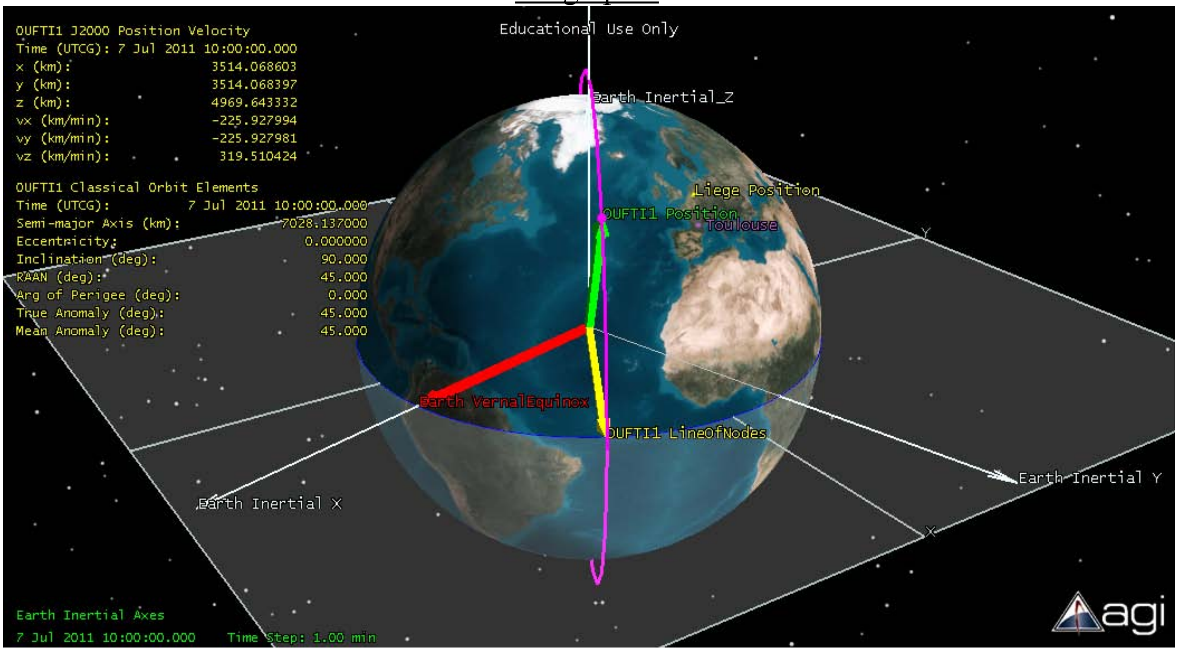


Figure IV.9: Simulation scenario for circular LEO “inclined” orbit

The orbital period of circular LEO “Inclined” orbit calculated by STK is about 97.73 minutes for a pass as the results calculated in Chapter III.

3D graphic



2D graphic

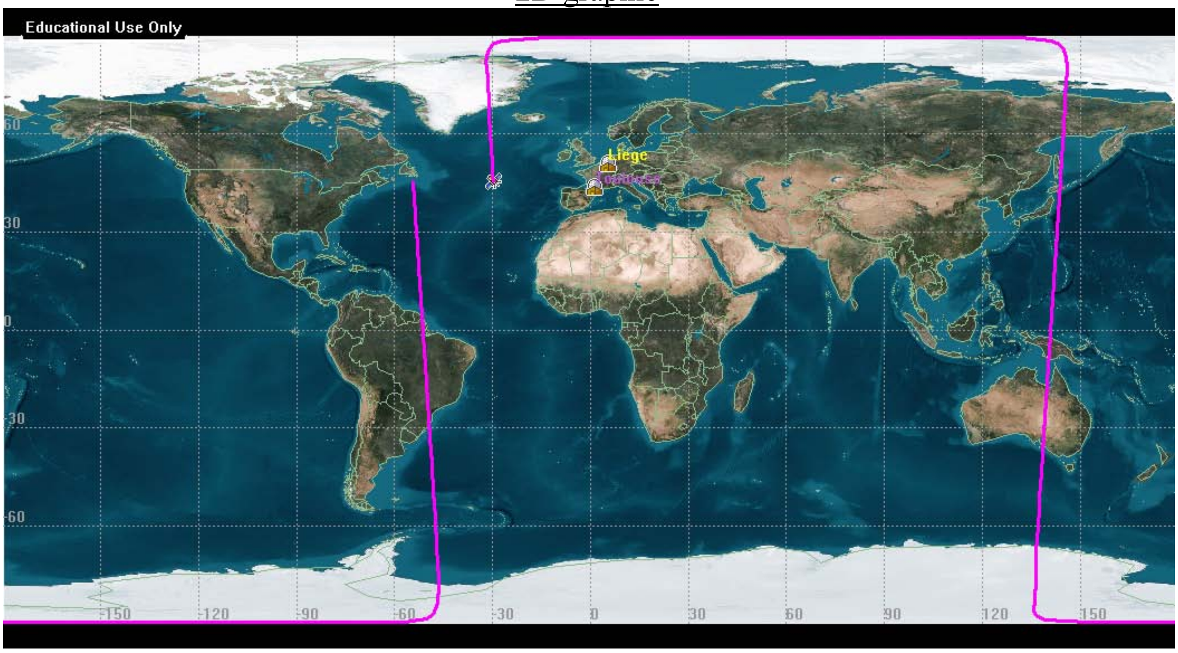


Figure IV.10: Simulation scenario for circular LEO "polar" orbit

The orbital period of circular LEO "Polar" orbit calculated by STK is about 97.73 minutes for a pass.

B. Propagator initial conditions for different orbit types

❖ Steps to get Propagator Initial Conditions report:

➢ {Right-click Satellite in the Object Browser→ Select Report & Graph Manager} or {Click Report & Graph Manager icon → Chose Satellite in object type → Select the Satellite which you want to get report} → Go to Styles → Select Show Reports and Unselect Show Graphs → Go to Installed Styles → Select Propagator Inputs → Go to Generate As → Select Report/Graph → Click Generate

The propagator initial conditions of the simulation scenarios for different orbit types are:

1. Elliptical LEO orbit

```
          Propagator Initial Conditions
------------------------------------------------
Propagator Name = J2Perturbation

Start Time = 7 Jul 2011 10:00:00.000000000 UTCG
Stop Time  = 8 Jul 2011 10:00:00.000000000 UTCG
Time interval tracks the scenario interval
Time Step = 300.000000

Orbit Epoch = 7 Jul 2011 10:00:00.000000000

Radius of Periapsis = 6732137.00000000
Eccentricity        = 0.07508274
Inclination         = 70.99999642
RAAN                = 44.99999567
Arg of Periapsis    = 30.00000816
True Anomaly        = 15.00000000

Reference Distance  = 6378137.00000000
Gravitational Param = 398600441800000.00000000
J2 Coefficient      = 0.00108263

Coordinate System = ICRF
Propagation Frame = ICRF
```

2. Elliptical VLEO orbit

```
          Propagator Initial Conditions
------------------------------------------------
Propagator Name = J2Perturbation

Start Time = 7 Jul 2011 10:00:00.000000000 UTCG
Stop Time  = 8 Jul 2011 10:00:00.000000000 UTCG
Time interval tracks the scenario interval
Time Step = 300.000000

Orbit Epoch = 7 Jul 2011 10:00:00.000000000

Radius of Periapsis = 6746137.00000000
Eccentricity        = 0.00014821
Inclination         = 40.01999642
RAAN                = 44.99998914
Arg of Periapsis    = 30.00001200
True Anomaly        = 15.00000000

Reference Distance  = 6378137.00000000
Gravitational Param = 398600441800000.00000000
J2 Coefficient      = 0.00108263

Coordinate System = ICRF
Propagation Frame = ICRF
```

3. Elliptical MEO “Molniya” orbit

```
          Propagator Initial Conditions
------------------------------------------------
Propagator Name = J2Perturbation

Start Time = 7 Jul 2011 10:00:00.000000000 UTCG
Stop Time  = 8 Jul 2011 10:00:00.000000000 UTCG
Time interval tracks the scenario interval
Time Step = 300.000000

Orbit Epoch = 7 Jul 2011 10:00:00.000000000

Radius of Periapsis = 7628137.00000000
Eccentricity        = 0.71274886
Inclination         = 63.39999642
RAAN                = 44.99999446
Arg of Periapsis    = 30.00000863
True Anomaly        = 15.00000000

Reference Distance  = 6378137.00000000
Gravitational Param = 398600441800000.00000000
J2 Coefficient      = 0.00108263

Coordinate System = ICRF
Propagation Frame = ICRF
```

4. Elliptical MEO “Tundra” orbit

```
          Propagator Initial Conditions
------------------------------------------------
Propagator Name = J2Perturbation

Start Time = 7 Jul 2011 10:00:00.000000000 UTCG
Stop Time  = 8 Jul 2011 10:00:00.000000000 UTCG
Time interval tracks the scenario interval
Time Step = 300.000000

Orbit Epoch = 7 Jul 2011 10:00:00.000000000

Radius of Periapsis = 31609137.00000000
Eccentricity        = 0.25032233
Inclination         = 63.39999642
RAAN                = 44.99999446
Arg of Periapsis    = 30.00000863
True Anomaly        = 15.00000000

Reference Distance  = 6378137.00000000
Gravitational Param = 398600441800000.00000000
J2 Coefficient      = 0.00108263

Coordinate System = ICRF
Propagation Frame = ICRF
```

5. <u>Circular LEO "Inclined" orbit</u>

```
        Propagator Initial Conditions
-----------------------------------------------
Propagator Name = J2Perturbation

Start Time = 7 Jul 2011 10:00:00.000000000 UTCG
Stop Time  = 8 Jul 2011 10:00:00.000000000 UTCG
Time interval tracks the scenario interval
Time Step = 300.000000

Orbit Epoch = 7 Jul 2011 10:00:00.000000000

Radius of Periapsis = 7028136.99999998
Eccentricity        = 0.00000000
Inclination         = 71.99999642
RAAN                = 44.99999582
Arg of Periapsis    = 0.00000000
True Anomaly        = 45.00000811

Reference Distance  = 6378137.00000000
Gravitational Param = 398600441800000.00000000
J2 Coefficient      = 0.00108263

Coordinate System = ICRF
Propagation Frame = ICRF
```

6. <u>Circular LEO "Polar" orbit</u>

```
        Propagator Initial Conditions
-----------------------------------------------
Propagator Name = J2Perturbation

Start Time = 7 Jul 2011 10:00:00.000000000 UTCG
Stop Time  = 8 Jul 2011 10:00:00.000000000 UTCG
Time interval tracks the scenario interval
Time Step = 300.000000

Orbit Epoch = 7 Jul 2011 10:00:00.000000000

Radius of Periapsis = 7028136.99999996
Eccentricity        = 0.00000000
Inclination         = 89.99999642
RAAN                = 44.99999832
Arg of Periapsis    = 0.00000000
True Anomaly        = 45.00000771

Reference Distance  = 6378137.00000000
Gravitational Param = 398600441800000.00000000
J2 Coefficient      = 0.00108263

Coordinate System = ICRF
Propagation Frame = ICRF
```

C. <u>Classical orbit elements</u>

- Steps to get Classical Orbit Elements report:
  - {Right-click Satellite in the Object Browser Select Report & Graph Manager} or {Click Report & Graph Manager icon→ Chose Satellite in object type → Select the Satellite which you want to get report} → Go to Styles → Select Show Reports and Unselect Show Graphs → Go to Installed Styles → Select Classical Orbit Elements → Go to Generate As → Select Report/Graph → Click Generate

The classical orbit elements of the simulation scenarios for different orbit types at start time 7/7/11 10:00 AM UTCG and stop time 7/8/11 10:00 AM UTCG (1 day time step) are shown in Table IV.2, IV.3, IV.4, IV.5, IV.6 and IV.7.

Table IV.2: Classical orbit elements of elliptical LEO orbit

Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of Perigee (deg)	True Anomaly (deg)	Mean Anomaly (deg)
7/7/11 10:00 AM	7278.637	0.075083	71	45	30	15	12.889
7/8/11 10:00 AM	7278.637	0.075083	71	42.934	28.509	4.392	3.768
Time variation of R.A.A.N ($d\Omega$), [degrees/day]				-2.066			
Time rate of change of ω ($d\omega$), [degrees/day]				-1.491			

For elliptical LEO orbit, as shown in Table IV.2, the time rate of change of ω (dω) is about -1.49 degrees per day, the time variation of R.A.A.N (dΩ) is about -2.07 degrees per day, and the mean anomaly at start time is about 12.89 degrees the same as the results calculated in Chapter III.

Table IV.3: Classical orbit elements of elliptical VLEO orbit

Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of Perigee (deg)	True Anomaly (deg)	Mean Anomaly (deg)
7/7/11 10:00 AM	6747.137	0.000148	40.02	45	30	15	14.996
7/8/11 10:00 AM	6747.137	0.000148	40.02	38.729	37.911	257.397	257.413
Time variation of R.A.A.N ($d\Omega$), [degrees/day]				-6.271			
Time rate of change of ω ($d\omega$), [degrees/day]				7.911			

For elliptical VLEO orbit, as shown in Table IV.3, the time rate of change of ω (dω) is about 7.91 degrees per day, the time variation of R.A.A.N (dΩ) is about -6.27 degrees per day, and the mean anomaly at start time is about 15 degrees the same as the results calculated in Chapter III.

Table IV.4: Classical orbit elements of elliptical MEO “Molniya” orbit

Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of Perigee (deg)	True Anomaly (deg)	Mean Anomaly (deg)
7/7/11 10:00 AM	26555.637	0.712749	63.4	45	30	15	1.781
7/8/11 10:00 AM	26555.637	0.712749	63.4	44.875	30	32.216	3.964
Time variation of R.A.A.N ($d\Omega$), [degrees/day]				-0.125			
Time rate of change of ω ($d\omega$), [degrees/day]				0.000			

For elliptical MEO “Molniya” orbit, as shown in Table IV.4, the time rate of change of ω (dω) is about 0 degrees per day, the time variation of R.A.A.N (dΩ) is about -0.13 degrees per day, and the mean anomaly at start time is about 1.78 degrees the same as the results calculated in Chapter III.

Table IV.5: Classical orbit elements of elliptical MEO “Molniya” orbit

Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of Perigee (deg)	True Anomaly (deg)	Mean Anomaly (deg)
7/7/11 10:00 AM	42163.637	0.250322	63.4	45	30	15	8.747
7/8/11 10:00 AM	42163.637	0.250322	63.4	44.993	30	16.679	9.737
Time variation of R.A.A.N ($d\Omega$), [degrees/day]				-0.007			
Time rate of change of ω ($d\omega$), [degrees/day]				0.000			

For elliptical MEO “Tundra” orbit, as shown in Table IV.5, the time rate of change of ω (dω) is about 0 degrees per day, the time variation of R.A.A.N (dΩ) is about -0.01 degrees per day, and the mean anomaly at start time is about 8.75 degrees the same as the results calculated in Chapter III.

Table IV.6: Classical orbit elements of circular LEO “Inclined” orbit

Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of Perigee (deg)	True Anomaly (deg)	Mean Anomaly (deg)
7/7/11 10:00 AM	7028.137	0	72	45	0	45	45
7/8/11 10:00 AM	7028.137	0	72	42.809	0	305.122	305.122
Time variation of R.A.A.N (*dΩ*), [degrees/day]				-2.191			
Time rate of change of *ω* (*dω*), [degrees/day]				0.000			

For circular LEO “Inclined” orbit, as shown in Table IV.6, the time variation of R.A.A.N (dΩ) is about -2.19 degrees per day, and the mean anomaly at start time is about 15 degrees the same as the results calculated in Chapter III. The time rate of change of *ω* (dω) is about 0.00 degrees per day, while the one from the results calculated in Chapter III is about -1.85. This is because for a circular orbit in STK, the value of Arg. Of Perigee is defined to be zero (i.e., periapsis at the ascending node).

Table IV.7: Classical orbit elements of circular LEO “Polar” orbit

Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	Arg. of Perigee (deg)	True Anomaly (deg)	Mean Anomaly (deg)
7/7/11 10:00 AM	7028.137	0	90	45	0	45	45
7/8/11 10:00 AM	7028.137	0	90	45	0	302.414	302.414
Time variation of R.A.A.N (*dΩ*), [degrees/day]				0.000			
Time rate of change of *ω* (*dω*), [degrees/day]				0.000			

For circular LEO “Inclined” orbit, as shown in Table IV.6, the time variation of R.A.A.N (dΩ) is 0.00 degrees per day, and the mean anomaly at start time is about 45 degrees the same as the results calculated by Matlab or Excel formulas. The time rate of change of *ω* (dω) is 0.00 degrees per day, while the one from the results calculated by Matlab or Excel formulas is about -3.55. This is because for a circular orbit in STK, the value of Arg. Of Perigee is defined to be zero (i.e., periapsis at the ascending node).

D. Access and AER

STK allows us to determine an “**access interval**”, the times period during which one object can "access," or see another object, or in other words the time during which line-of-sight visibility between two objects is possible. In addition, we can impose constraints on accesses between objects to define what constitutes a valid access. These constraints are defined as properties of the objects between which accesses are being calculated. STK can calculate access from all types of vehicles, facilities, targets, area targets, and sensors to all objects (including planets and stars) within a scenario.

STK also allows us to compute **AER** [Azimuth, Elevation and Range (the linear distance between two points)] between two objects during access for the interval start and end times and for each ephemeris point available.

❖ Steps to get Access report:

➢ {Right-click Satellite in the Object Browser → Select Access} or {Click on Select Access icon→ Choose the selected Satellite of your simulation in the Access for} → Go to Associated Object → Select Facility (ex. Liege or Toulouse) → Go to Report → Click Access

❖ Steps to get AER report of facility:

➢ {Right-click Facility (e. Liege or Toulouse) in the Object Browser → Select Access} or {Click on Select Access icon→ Choose the selected Facility of your simulation in the Access for} → Go to Associated Object → Select Satellite → Go to Report → Click AER

❖ Steps to add a minimum elevation angle constraint on facility:

➢ {Right-click Facility (e. Liege or Toulouse) in the Object Browser→ Select Properties → Go to Constraints-Basic page→ Go to Elevation Angle → Select Min → Input the constraint value → Click OK to apply and close.

For more detail about the steps to get Access report, AER report, and to add an elevation angle constraint go to STK help.

The Access and AER of the simulation scenarios for different orbit types from start time 7/7/11 10:00 AM UTCG to stop time 7/8/11 10:00 AM UTCG (1 day period of simulation and step 1 min) without any constraints are:

D-1. Elliptical LEO orbit

a. Access and AER for Satellite-Liege

OUFTI1-To-Liege

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:09:18.569	9.309
	2	7 Jul 2011 11:46:37.473	7 Jul 2011 11:54:53.176	8.262
	3	7 Jul 2011 13:34:41.441	7 Jul 2011 13:42:46.838	8.090
	4	7 Jul 2011 15:20:22.873	7 Jul 2011 15:33:18.326	12.924
	5	7 Jul 2011 17:05:17.944	7 Jul 2011 17:22:09.481	16.859
	6	7 Jul 2011 18:50:28.353	7 Jul 2011 19:07:24.975	16.944
	7	7 Jul 2011 20:37:28.949	7 Jul 2011 20:47:21.865	9.882
	8	8 Jul 2011 08:17:08.892	8 Jul 2011 08:27:05.187	9.938
Global Statistics				
Min Duration	3	7 Jul 2011 13:34:41.441	7 Jul 2011 13:42:46.838	8.090
Max Duration	6	7 Jul 2011 18:50:28.353	7 Jul 2011 19:07:24.975	16.944
Mean Duration				11.526
Total Duration				92.208

Liege-To-OUFTI1

Global Statistics

Min Elevation	8 Jul 2011 08:27:05.187	37.135	0.000	2608.550744
Max Elevation	7 Jul 2011 17:12:23.133	55.572	50.874	1108.195698
Mean Elevation			11.014	
Min Range	7 Jul 2011 10:03:23.909	306.739	29.162	800.860447
Max Range	7 Jul 2011 19:07:24.975	179.489	0.000	4169.070940
Mean Range				2374.614227

b. Access and AER for Satellite-Toulouse

```
OUFTI1-To-Toulouse
------------------

                  Access      Start Time (UTCG)           Stop Time (UTCG)         Duration (min)
                  ------    ------------------------    ------------------------    --------------
                       1    7 Jul 2011 10:00:00.000    7 Jul 2011 10:06:47.835             6.797
                       2    7 Jul 2011 11:48:19.414    7 Jul 2011 11:49:26.725             1.122
                       3    7 Jul 2011 15:23:02.393    7 Jul 2011 15:31:04.750             8.039
                       4    7 Jul 2011 17:06:47.185    7 Jul 2011 17:23:03.097            16.265
                       5    7 Jul 2011 18:51:36.327    7 Jul 2011 19:09:53.418            18.285
                       6    7 Jul 2011 20:38:13.612    7 Jul 2011 20:51:15.410            13.030
                       7    8 Jul 2011 08:15:16.542    8 Jul 2011 08:24:45.595             9.484
Global Statistics
-----------------
Min Duration           2    7 Jul 2011 11:48:19.414    7 Jul 2011 11:49:26.725             1.122
Max Duration           5    7 Jul 2011 18:51:36.327    7 Jul 2011 19:09:53.418            18.285
Mean Duration                                                                             10.432
Total Duration                                                                            73.022
```

```
Toulouse-To-OUFTI1
------------------

Global Statistics
-----------------
Min Elevation     7 Jul 2011 20:51:15.398          218.720             0.000    4204.463949
Max Elevation     7 Jul 2011 18:59:22.616          248.686            61.429    1137.549575
Mean Elevation                                                        11.528
Min Range         8 Jul 2011 08:19:38.647          108.201            23.135     851.403463
Max Range         7 Jul 2011 19:09:53.403          168.426             0.000    4268.751618
Mean Range                                                                      2531.463343
```

From *A. Creating scenarios, satellites and facilities for different orbit types*, the orbit period of elliptical LEO orbit is about 103 minutes for a pass. As a result, the satellite orbit the earth about 14 (24*60/103) passes per day. For these 14 passes per day, however, the satellite can access

- Liege facility 8 accesses per day with the minimum access duration 8.090 minutes, maximum access duration 16.944 minutes and total access duration 92.208 minutes per day.
- and Toulouse facility 7 accesses per day with the minimum access duration 1.122 minutes, maximum access duration 18.285 minutes and total access duration 73.022 minutes per day as shown in the text box above.

Hence, the total duration of access from OUFTI1 satellite to Liege facility is about 19.18 minutes bigger/better than the one from OUFTI1 satellite to Toulouse facility.

The mean range between Liege facility and OUFTI1 satellite is about 2374.61 km, while the one between Toulouse facility and OUFTI1 satellite is about 2531.46 km. Hence, the free space path looses between OUFTI1 satellite and Liege facility is smaller than the one between OUFTI1 and Toulouse facility, so that the communication between OUFTI1 and Toulouse facility will averagely worst than the one between OUFTI1 and Liege facility.

D-2. Elliptical VLEO orbit

a. Access and AER for Satellite-Liege

```
OUFTI1-To-Liege
---------------

                  Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (min)
                  ------    ------------------------    ------------------------    --------------
                       1    7 Jul 2011 11:34:53.508    7 Jul 2011 11:42:06.455             7.216
                       2    7 Jul 2011 13:09:51.496    7 Jul 2011 13:18:24.367             8.548
                       3    7 Jul 2011 14:45:47.757    7 Jul 2011 14:53:51.052             8.055
                       4    7 Jul 2011 16:23:04.186    7 Jul 2011 16:27:31.491             4.455
Global Statistics
-----------------
Min Duration           4    7 Jul 2011 16:23:04.186    7 Jul 2011 16:27:31.491             4.455
Max Duration           2    7 Jul 2011 13:09:51.496    7 Jul 2011 13:18:24.367             8.548
Mean Duration                                                                              7.068
Total Duration                                                                            28.274
```

```
Liege-To-OUFTI1
---------------

Global Statistics
-----------------
Min Elevation     7 Jul 2011 14:53:51.052          141.398             0.000    2220.988494
Max Elevation     7 Jul 2011 13:14:07.783          176.552            11.637    1284.078572
Mean Elevation                                                         3.891
Min Range         7 Jul 2011 13:14:07.630          176.603            11.637    1284.078111
Max Range         7 Jul 2011 14:45:47.757          245.035             0.000    2226.929480
Mean Range                                                                      1865.168284
```

b. Access and AER for Satellite-Toulouse

```
OUFTI1-To-Toulouse
------------------

                  Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (min)
                  ------    ------------------------    ------------------------    --------------
                       1    7 Jul 2011 10:00:00.000    7 Jul 2011 10:04:03.912             4.065
                       2    7 Jul 2011 11:32:25.878    7 Jul 2011 11:41:46.274             9.340
                       3    7 Jul 2011 13:08:10.381    7 Jul 2011 13:18:16.204            10.097
                       4    7 Jul 2011 14:44:27.783    7 Jul 2011 14:54:29.521            10.029
                       5    7 Jul 2011 16:21:04.371    7 Jul 2011 16:29:57.959             8.893
                       6    7 Jul 2011 18:00:10.337    7 Jul 2011 18:02:04.738             1.907
Global Statistics
-----------------
Min Duration           6    7 Jul 2011 18:00:10.337    7 Jul 2011 18:02:04.738             1.907
Max Duration           3    7 Jul 2011 13:08:10.381    7 Jul 2011 13:18:16.204            10.097
Mean Duration                                                                              7.388
Total Duration                                                                            44.331
```

```
Toulouse-To-OUFTI1
------------------

Global Statistics
-----------------
Min Elevation     7 Jul 2011 13:18:16.204           95.473             0.000    2226.885293
Max Elevation     7 Jul 2011 13:13:12.886          173.664            39.008     575.540323
Mean Elevation                                                         8.824
Min Range         7 Jul 2011 13:13:12.828          173.718            39.008     575.540178
Max Range         7 Jul 2011 11:41:46.274           92.217             0.000    2227.246824
Mean Range                                                                      1614.831731
```

From *A. Creating scenarios, satellites and facilities for different orbit types*, the orbit period of elliptical VLEO orbit is about 91.93 minutes for a pass. As a result, the satellite orbit the earth a bout 16 (24*60/91.93) pa sses p er d ay. For t hese 16 passes p er day, however, the satellite can access

- Liege f acility 4 accesses per da y with t he m inimum a ccess dur ation 4.455 minutes, maximum access duration 8.548 minutes and total access duration 28.274 minutes per day.

- and Toulouse facility 6 accesses per day with the minimum access duration 1.907 minutes, maximum access duration 10.097 minutes and total access duration 44.331 minutes per day as shown in the text box above.

Hence, the total duration of access from OUFTI1 satellite to Liege facility is about 16.06 minutes smaller/worst than the one from OUFTI1 satellite to Toulouse facility.

The mean range between Liege facility and OUFTI1 satellite is about 1865.17 km, while the one between Toulouse facility and OUFTI1 satellite is about 1614.83 km. Hence, the free space path looses between OUFTI1 satellite and Liege facility is bigger than the one between OUFTI1 and Toulouse facility, so that the communication between OUFTI1 and Toulouse facility will averagely better than the one between OUFTI1 and Liege facility.

D-3. Elliptical MEO "Molniya" orbit

a. Access and AER for Satellite-Liege

OUFTI1-To-Liege

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:32:25.550	32.426
	2	7 Jul 2011 22:15:36.168	8 Jul 2011 00:26:31.991	130.930
	3	8 Jul 2011 09:50:54.212	8 Jul 2011 10:00:00.000	9.096

Global Statistics

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
Min Duration	3	8 Jul 2011 09:50:54.212	8 Jul 2011 10:00:00.000	9.096
Max Duration	2	7 Jul 2011 22:15:36.168	8 Jul 2011 00:26:31.991	130.930
Mean Duration				57.484
Total Duration				172.453

Liege-To-OUFTI1

Global Statistics

	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)
Min Elevation	8 Jul 2011 00:26:31.991	256.404	0.000	33573.391555
Max Elevation	8 Jul 2011 09:59:13.424	131.716	87.063	1692.845094
Mean Elevation			15.613	
Min Range	7 Jul 2011 10:02:47.804	209.942	75.461	1646.655623
Max Range	8 Jul 2011 00:26:31.991	256.404	0.000	33573.391555
Mean Range				17604.454150

b. Access and AER for Satellite-Toulouse

OUFTI1-To-Toulouse

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:23:10.605	23.177
	2	7 Jul 2011 22:17:52.152	8 Jul 2011 00:48:20.986	150.481
	3	8 Jul 2011 09:48:55.438	8 Jul 2011 10:00:00.000	11.076

Global Statistics

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
Min Duration	3	8 Jul 2011 09:48:55.438	8 Jul 2011 10:00:00.000	11.076
Max Duration	2	7 Jul 2011 22:17:52.152	8 Jul 2011 00:48:20.986	150.481
Mean Duration				61.578
Total Duration				184.733

```
Toulouse-To-OUFTI1
------------------

Global Statistics
-----------------
                     Time (UTCG)           Azimuth (deg)    Elevation (deg)     Range (km)
                  -----------------------  -------------    ---------------    -----------
Min Elevation     7 Jul 2011 10:23:10.605         41.319              0.000    10063.034449
Max Elevation     7 Jul 2011 10:01:39.598        309.821             80.097     1512.258637
Mean Elevation                                                       15.903
Min Range         7 Jul 2011 10:01:08.688        262.202             75.480     1488.999031
Max Range         8 Jul 2011 00:48:20.986        254.630              0.000    36008.063340
Mean Range                                                                     19709.426453
```

From *A. Creating scenarios, satellites and facilities for different orbit types*, the orbit period of elliptical MEO "Molniya" orbit is about 717.79 minutes for a pass. As a result, the satellite orbit the earth about 2 (24*60/717.79) passes per day. For these 2 passes per day, however, the satellite can access

- Liege facility 3 accesses per day with the minimum access duration 9.096 minutes, maximum access duration 130.930 minutes and total access duration 172.453 minutes per day.
- and Toulouse facility 3 accesses per day with the minimum access duration 11.076 minutes, maximum access duration 150.481 minutes and total access duration 184.733 minutes per day as shown in the text box above.

Hence, the total duration of access from OUFTI1 satellite to Liege facility is about 12.28 minutes smaller/worst than the one from OUFTI1 satellite to Toulouse facility.

The mean range between Liege facility and OUFTI1 satellite is about 17604.45 km, while the one between Toulouse facility and OUFTI1 satellite is about 19709.43 km. Hence, the free space path looses between OUFTI1 satellite and Liege facility is smaller than the one between OUFTI1 and Toulouse facility, so that the communication between OUFTI1 and Toulouse facility will averagely worst than the one between OUFTI1 and Liege facility.

D-4. Elliptical MEO "Tundra" orbit

a. Access and AER for Satellite-Liege

```
OUFTI1-To-Liege
---------------

                  Access      Start Time (UTCG)           Stop Time (UTCG)        Duration (min)
                  ------   -----------------------    -----------------------     --------------
                       1   7 Jul 2011 12:00:00.000    7 Jul 2011 23:54:55.832            714.931
                       2   8 Jul 2011 08:43:56.990    8 Jul 2011 12:00:00.000            196.050

Global Statistics
-----------------
Min Duration           2   8 Jul 2011 08:43:56.990    8 Jul 2011 12:00:00.000            196.050
Max Duration           1   7 Jul 2011 12:00:00.000    7 Jul 2011 23:54:55.832            714.931
Mean Duration                                                                            455.490
Total Duration                                                                           910.981
```

```
Liege-To-OUFTI1
---------------

Global Statistics
-----------------
                      Time (UTCG)          Azimuth (deg)    Elevation (deg)     Range (km)
                  ----------------------   -------------    ---------------    -----------
Min Elevation     7 Jul 2011 23:54:55.832        194.881              0.000    52246.386292
Max Elevation     7 Jul 2011 12:42:29.696        302.408             85.475    26296.370590
Mean Elevation                                                       39.970
Min Range         8 Jul 2011 11:53:28.475        217.449             71.536    25689.673303
Max Range         7 Jul 2011 23:54:55.832        194.881              0.000    52246.386292
Mean Range                                                                     37868.385299
```

b. Access and AER for Satellite-Toulouse

```
OUFTI1-To-Toulouse
------------------

                  Access      Start Time (UTCG)          Stop Time (UTCG)         Duration (min)
                  ------   ----------------------    ----------------------      --------------
                       1   7 Jul 2011 12:00:00.000   8 Jul 2011 00:44:10.145            764.169
                       2   8 Jul 2011 08:17:00.162   8 Jul 2011 12:00:00.000            222.997

Global Statistics
-----------------
Min Duration           2   8 Jul 2011 08:17:00.162   8 Jul 2011 12:00:00.000            222.997
Max Duration           1   7 Jul 2011 12:00:00.000   8 Jul 2011 00:44:10.145            764.169
Mean Duration                                                                           493.583
Total Duration                                                                          987.166
```

```
Toulouse-To-OUFTI1
------------------

Global Statistics
-----------------
                      Time (UTCG)          Azimuth (deg)    Elevation (deg)     Range (km)
                  ----------------------   -------------    ---------------    -----------
Min Elevation     8 Jul 2011 00:44:10.145        196.243              0.000    51884.670582
Max Elevation     7 Jul 2011 12:16:29.325        289.010             84.771    25729.364885
Mean Elevation                                                       38.899
Min Range         8 Jul 2011 11:43:35.430        217.160             76.766    25463.743009
Max Range         8 Jul 2011 00:44:10.145        196.243              0.000    51884.670582
Mean Range                                                                     38291.898706
```

From *A. Creating scenarios, satellites and facilities for different orbit types*, the orbit period of elliptical MEO "Tundra" orbit is about 1436.04 minutes for a pass. As a result, the satellite orbit the earth about 1 (24*60/1436.04) pass per day. For these 1 pass per day, however, the satellite can access

- Liege facility 2 accesses per day with the minimum access duration 196.050 minutes, maximum access duration 714.931 minutes and total access duration 910.981 minutes per day.
- and Toulouse facility 2 accesses per day with the minimum access duration 222.997 minutes, maximum access duration 764.169 minutes and total access duration 987.166 minutes per day as shown in the text box above.

Hence, the total duration of access from OUFTI1 satellite to Liege facility is about 76.18 minutes smaller/worst than the one from OUFTI1 satellite to Toulouse facility.

The mean range between Liege facility and OUFTI1 satellite is about 37868.385299 km, while the one between Toulouse facility and OUFTI1 satellite is about 38291.898706 km. Hence, the free space path looses between OUFTI1 satellite and Liege facility is smaller than the one between OUFTI1 and Toulouse facility, so that the communication between OUFTI1 and Toulouse facility will averagely worst than the one between OUFTI1 and Liege facility.

D-5. Circular LEO "Inclined" orbit

a. Access and AER for Satellite-Liege

OUFTI1-To-Liege

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:10:33.440	10.557
	2	7 Jul 2011 11:39:40.713	7 Jul 2011 11:50:20.712	10.667
	3	7 Jul 2011 13:23:27.535	7 Jul 2011 13:31:21.675	7.902
	4	7 Jul 2011 15:04:54.648	7 Jul 2011 15:14:56.410	10.029
	5	7 Jul 2011 16:44:46.810	7 Jul 2011 16:57:59.556	13.212
	6	7 Jul 2011 18:24:36.779	7 Jul 2011 18:38:15.344	13.643
	7	7 Jul 2011 20:05:47.985	7 Jul 2011 20:14:24.149	8.603
	8	8 Jul 2011 07:07:26.620	8 Jul 2011 07:18:05.934	10.655
	9	8 Jul 2011 08:44:49.165	8 Jul 2011 08:58:42.307	13.886
Global Statistics				
Min Duration	3	7 Jul 2011 13:23:27.535	7 Jul 2011 13:31:21.675	7.902
Max Duration	9	8 Jul 2011 08:44:49.165	8 Jul 2011 08:58:42.307	13.886
Mean Duration				11.017
Total Duration				99.155

Liege-To-OUFTI1

Global Statistics

	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)
Min Elevation	7 Jul 2011 10:10:33.440	24.481	-0.000	2998.598077
Max Elevation	8 Jul 2011 08:51:43.036	115.441	78.393	675.124510
Mean Elevation			11.395	
Min Range	8 Jul 2011 08:51:42.764	116.287	78.392	675.121807
Max Range	7 Jul 2011 11:50:20.712	21.699	0.000	2998.981415
Mean Range				2206.952610

b. Access and AER for Satellite-Toulouse

OUFTI1-To-Toulouse

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:08:15.658	8.261
	2	7 Jul 2011 11:39:21.350	7 Jul 2011 11:46:50.959	7.493
	3	7 Jul 2011 16:46:49.035	7 Jul 2011 16:57:57.196	11.136
	4	7 Jul 2011 18:26:02.191	7 Jul 2011 18:39:55.383	13.887
	5	7 Jul 2011 20:06:49.534	7 Jul 2011 20:17:19.428	10.498
	6	8 Jul 2011 07:05:53.480	8 Jul 2011 07:15:27.138	9.561
	7	8 Jul 2011 08:42:41.437	8 Jul 2011 08:56:33.354	13.865
Global Statistics				
Min Duration	2	7 Jul 2011 11:39:21.350	7 Jul 2011 11:46:50.959	7.493
Max Duration	4	7 Jul 2011 18:26:02.191	7 Jul 2011 18:39:55.383	13.887
Mean Duration				10.672
Total Duration				74.701

Toulouse-To-OUFTI1

Global Statistics

	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)
Min Elevation	7 Jul 2011 20:06:49.534	313.636	0.000	2988.515831
Max Elevation	8 Jul 2011 08:49:34.554	111.739	81.494	666.658184
Mean Elevation			12.613	
Min Range	8 Jul 2011 08:49:34.270	112.955	81.493	666.655203
Max Range	7 Jul 2011 11:46:50.959	358.303	0.000	2995.151081
Mean Range				2185.873205

From *A. Creating scenarios, satellites and facilities for different orbit types*, the orbit period of circular LEO "Inclined" orbit is about 97.73 minutes for a pass. As a result, the satellite orbit the earth about 15 (24*60/97.73) passes per day. For these 15 passes per day, however, the satellite can access

- Liege facility 9 accesses per day with the minimum access duration 7.902 minutes, maximum access duration 13.886 minutes and total access duration 99.155 minutes per day.
- and Toulouse facility 7 accesses per day with the minimum access duration 7.493 minutes, maximum access duration 13.887 minutes and total access duration 74.701 minutes per day as shown in the text box above.

Hence, the total duration of access from OUFTI1 satellite to Liege facility is about 24.45 minutes smaller/worst than the one from OUFTI1 satellite to Toulouse facility.

The mean range between Liege facility and OUFTI1 satellite is about 2206.95 km, while the one between Toulouse facility and OUFTI1 satellite is about 2185.87 km. Hence, the free space path looses between OUFTI1 satellite and Liege facility is bigger than the one between OUFTI1 and Toulouse facility, so that the communication between OUFTI1 and Toulouse facility will averagely better than the one between OUFTI1 and Liege facility.

D-6. Circular LEO "Polar" orbit

a. Access and AER for Satellite-Liege

OUFTI1-To-Liege

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:06:25.238	6.421
	2	7 Jul 2011 16:51:00.151	7 Jul 2011 16:53:58.371	2.970
	3	7 Jul 2011 18:25:38.472	7 Jul 2011 18:38:17.613	12.652
	4	7 Jul 2011 20:03:15.004	7 Jul 2011 20:16:31.392	13.273
	5	7 Jul 2011 21:42:15.658	7 Jul 2011 21:50:33.051	8.290
	6	8 Jul 2011 05:32:24.630	8 Jul 2011 05:41:48.049	9.390
	7	8 Jul 2011 07:07:04.207	8 Jul 2011 07:20:32.449	13.471
	8	8 Jul 2011 08:45:49.057	8 Jul 2011 08:57:59.715	12.178
Global Statistics				
Min Duration	2	7 Jul 2011 16:51:00.151	7 Jul 2011 16:53:58.371	2.970
Max Duration	7	8 Jul 2011 07:07:04.207	8 Jul 2011 07:20:32.449	13.471
Mean Duration				9.831
Total Duration				78.645

Liege-To-OUFTI1

Global Statistics

	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)
Min Elevation	7 Jul 2011 21:50:33.051	260.558	0.000	2976.031658
Max Elevation	8 Jul 2011 07:13:45.617	83.402	57.652	770.403948
Mean Elevation			10.259	
Min Range	8 Jul 2011 07:13:45.236	83.801	57.651	770.399088
Max Range	8 Jul 2011 07:20:32.449	2.135	0.000	3000.458618
Mean Range				2258.115130

b. Access and AER for Satellite-Toulouse

OUFTI1-To-Toulouse

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (min)
	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:03:51.197	3.853
	2	7 Jul 2011 18:28:06.465	7 Jul 2011 18:39:32.846	11.440
	3	7 Jul 2011 20:05:11.836	7 Jul 2011 20:18:37.952	13.435
	4	7 Jul 2011 21:44:39.765	7 Jul 2011 21:52:26.497	7.779
	5	8 Jul 2011 05:33:39.124	8 Jul 2011 05:37:40.825	4.028
	6	8 Jul 2011 07:05:29.235	8 Jul 2011 07:18:28.486	12.988
	7	8 Jul 2011 08:43:30.538	8 Jul 2011 08:56:01.003	12.508
Global Statistics				
Min Duration	1	7 Jul 2011 10:00:00.000	7 Jul 2011 10:03:51.197	3.853
Max Duration	3	7 Jul 2011 20:05:11.836	7 Jul 2011 20:18:37.952	13.435
Mean Duration				9.433
Total Duration				66.031

Toulouse-To-OUFTI1

Global Statistics

	Time (UTCG)	Azimuth (deg)	Elevation (deg)	Range (km)
Min Elevation	7 Jul 2011 20:05:11.836	357.305	0.000	2995.151370
Max Elevation	7 Jul 2011 20:11:57.633	276.150	56.743	774.233813
Mean Elevation			10.408	
Min Range	7 Jul 2011 20:11:58.026	275.750	56.742	774.228658
Max Range	7 Jul 2011 20:05:11.836	357.305	0.000	2995.151370
Mean Range				2236.930788

From *A. Creating scenarios, satellites and facilities for different orbit types*, the orbit period of circular LEO "Polar" orbit is about 97.73 minutes for a pass. As a result, the satellite orbit the earth about 15 (24*60/97.73) passes per day. For these 15 passes per day, however, the satellite can access

- Liege facility 8 accesses per day with the minimum access duration 2.970 minutes, maximum access duration 13.471 minutes and total access duration 78.645 minutes per day.
- and Toulouse facility 7 accesses per day with the minimum access duration 3.853 minutes, maximum access duration 13.435 minutes and total access duration 66.031 minutes per day as shown in the text box above.

Hence, the total duration of access from OUFTI1 satellite to Liege facility is about 12.61 minutes smaller/worst than the one from OUFTI1 satellite to Toulouse facility.

The mean range between Liege facility and OUFTI1 satellite is about 2258.115130 km, while the one between Toulouse facility and OUFTI1 satellite is about 2236.930788 km. Hence, the free space path looses between OUFTI1 satellite and Liege facility is bigger than the one between OUFTI1 and Toulouse facility, so that the communication between OUFTI1 and Toulouse facility will averagely better than the one between OUFTI1 and Liege facility.

IV.2.3 Summary of output results of orbital mechanics

According the Tables IV.8, we can notice that

- The time variation of R.A.A.N (dΩ) and the time rate of change of ω (dω) are bigger for the orbit with smaller orbital altitude/semi-major axis like elliptical LEO and VLEO orbit. And they are equal 0 for the circular orbit "Polar". With such bigger value of both parameters, it can cause the satellite lifetime shorter.
- The number access and hence the total duration of visibility depends on the inclination and the orbital altitude. The total duration of visibility for one location is high when the orbital altitude is high or when the inclination of satellite makes the satellite at right position above the ground station.
- By comparing with the orbit with lower altitude like LEO and VLEO, the orbit with higher altitude like MEO orbit has a higher orbital period, and hence has lower number of passes per day and lower number of accesses per day, but higher duration of visibility with higher range, with higher free space path looses.
- As there are no any elevation angle constraints on a ground-based location in our simulation, the minimum elevation is 0 degrees. Actually, we know that when we are on the ground trying to see something in space the lower we look along the horizon, the more atmospheres you have to look through and the better the chance that something will be in the way. To help avoid the elevation angle problem, STK allows you to put an elevation angle constraint on a ground-based location. A good typical minimum elevation is 6-8 degrees, but it can be more depending on the area, the surrounding terrain, and even buildings. A summary of output results of orbital mechanics with a minimum elevation constraint of 6 degrees is shown in Table IV.9. By adding a minimum elevation angle constraint of 6 degrees, it decreases the total duration of visibility or the number of accesses, and also the maximum and mean range.

Table IV.8: Summary of output results of orbital mechanics without an elevation constraint

Propagator Initial Conditions							
Propagator Name = J2Perturbation							
Start Time = 7 Jul 2011 10:00:00.000000000 UTCG							
Stop Time = 8 Jul 2011 10:00:00.000000000 UTCG							
		Elliptical				Circular	
		LEO	VLEO	MEO "Molniya"	MEO "Tundra"	LEO "Inclined"	LEO "Polar"
Radius of Periapsis	[km]	6732.14	6746.14	7628.14	31609.14	7028.14	7028.14
Eccentricity		0.08	0.00015	0.71	0.25	0.00	0.00
Inclination	[deg]	71.00	40.02	63.40	63.40	72.00	90.00
RAAN	[deg]	45.00	45.00	45.00	45.00	45.00	45.00
Arg of Periapsis	[deg]	30.00	30.00	30.00	30.00	0.00	0.00
True Anomaly	[deg]	15.00	15.00	15.00	15.00	45.00	45.00
Orbital Period	[min]	103.00	91.93	717.79	1436.04	97.73	97.73
Time variation of RAAN ($d\Omega$)	[deg/day]	-2.066	-6.271	-0.125	-0.007	-2.191	0.000
Time rate of change of ω ($d\omega$)	[deg/day]	-1.491	7.911	0.000	0.000	0.000	0.000
Number of Passes per day		14	16	2	1	15	15
Satellite-Liege							
Number of Accesses per day		8	4	3	2	9	8
Min Duration	[min]	8.090	4.455	9.096	196.050	7.902	2.970
Max Duration	[min]	16.944	8.548	130.930	714.931	13.886	13.471
Mean Duration	[min]	11.526	7.068	57.484	455.490	11.017	9.831
Total Duration	[min]	92.208	28.274	172.453	910.981	99.155	78.645
Min Elevation	[deg]	0.000	0.000	0.000	0.000	0.000	0.000
Max Elevation	[deg]	50.874	11.637	87.063	85.475	78.393	57.652
Mean Elevation	[deg]	11.014	3.891	15.613	39.970	11.395	10.259
Min Range	[km]	800.860	1284.078	1646.656	25689.673	675.122	770.399
Max Range	[km]	4169.071	2226.929	33573.392	52246.386	2998.981	3000.459
Mean Range	[km]	2374.614	1865.168	17604.454	37868.385	2206.953	2258.115
Satellite-Toulouse							
Number of Accesses per day		7	6	3	2	7	7
Min Duration	[min]	1.122	1.907	11.076	222.997	7.493	3.853
Max Duration	[min]	18.285	10.097	150.481	764.169	13.887	13.435
Mean Duration	[min]	10.432	7.388	61.578	493.583	10.672	9.433
Total Duration	[min]	73.022	44.331	184.733	987.166	74.701	66.031
Min Elevation	[deg]	0.000	0.000	0.000	0.000	0.000	0.000
Max Elevation	[deg]	61.429	39.008	80.097	84.771	81.494	56.743
Mean Elevation	[deg]	11.528	8.824	15.903	38.899	12.613	10.408
Min Range	[km]	851.403	575.540	1488.999	25463.743	666.655	774.229
Max Range	[km]	4268.75	2227.247	36008.063	51884.671	2995.151	2995.151
Mean Range	[km]	2531.46	1614.832	19709.426	38291.899	2185.873	2236.931

Table IV.9: Summary of output results of orbital mechanics with a minimum elevation constraint of 6 degrees

Propagator Initial Conditions							
Propagator Name = J2Perturbation							
Start Time = 7 Jul 2011 10:00:00.000000000 UTCG							
Stop Time = 8 Jul 2011 10:00:00.000000000 UTCG							
		Elliptical				Circular	
		LEO	VLEO	MEO "Molniya"	MEO "Tundra"	LEO "Inclined"	LEO "Polar"
Radius of Periapsis	[km]	6732.14	6746.14	7628.14	31609.14	7028.14	7028.14
Eccentricity		0.08	0.00015	0.71	0.25	0.00	0.00
Inclination	[deg]	71.00	40.02	63.40	63.40	72.00	90.00
RAAN	[deg]	45.00	45.00	45.00	45.00	45.00	45.00
Arg of Periapsis	[deg]	30.00	30.00	30.00	30.00	0.00	0.00
True Anomaly	[deg]	15.00	15.00	15.00	15.00	45.00	45.00
Orbital Period	[min]	103.00	91.93	717.79	1436.04	97.73	97.73
Time variation of RAAN ($d\Omega$)	[deg/day]	-2.066	-6.271	-0.125	-0.007	-2.191	0.000
Time rate of change of ω ($d\omega$)	[deg/day]	-1.491	7.911	0.000	0.000	0.000	0.000
Number of Passes per day		14	16	2	1	15	15
Satellite-Liege							
Number of Accesses per day		6	3	3	2	8	5
Min Duration	[min]	2.082	1.741	7.737	175.588	0.202	4.179
Max Duration	[min]	13.533	4.912	98.930	676.328	10.924	10.545
Mean Duration	[min]	8.676	3.546	43.778	425.958	7.174	8.603
Total Duration	[min]	52.057	10.638	131.334	851.916	57.393	43.014
Min Elevation	[deg]	6.000	6.000	6.000	6.000	6.000	6.000
Max Elevation	[deg]	50.874	11.637	87.063	85.475	78.393	57.652
Mean Elevation	[deg]	17.409	7.689	19.324	42.487	17.548	17.282
Min Range	[km]	800.860	1284.078	1646.656	25689.673	675.122	770.399
Max Range	[km]	3463.247	1657.202	29184.522	51648.059	2403.863	2403.825
Mean Range	[km]	1923.877	1537.389	15494.984	37338.468	1818.369	1796.127
Satellite-Toulouse							
Number of Accesses per day		5	4	3	2	6	4
Min Duration	[min]	5.061	5.498	9.555	200.736	4.201	7.557
Max Duration	[min]	14.957	7.281	118.055	725.892	10.922	10.508
Mean Duration	[min]	9.256	6.542	48.399	463.314	7.580	9.290
Total Duration	[min]	46.279	26.168	145.198	926.628	45.483	37.159
Min Elevation	[deg]	6.000	6.000	6.000	6.000	6.000	6.000
Max Elevation	[deg]	61.429	39.008	80.097	84.771	81.494	56.743
Mean Elevation	[deg]	17.637	14.317	19.347	41.289	19.072	17.459
Min Range	[km]	851.403	575.540	1488.999	25463.743	666.655	774.229
Max Range	[km]	3577.479	1657.769	32070.421	51531.301	2398.205	2398.286
Mean Range	[km]	2101.613	1249.361	17851.096	37796.872	1801.832	1767.512

IV.3 Continuous whole Earth coverage constellation for different orbit types

IV.3.1 Description of the simulation scenarios of continuous whole Earth coverage constellation

A constellation of nanosatellites is considered. The purpose of this simulation scenario is to answer the question whether a constellation (Walker Star or Walker Delta method) which provides a continuous whole Earth coverage (24h/day) for the different orbit types envisaged in Table IV.1 can be devised, and if so, find the optimum constellation for each orbit type.

IV.3.2 Simulation scenarios and output results of continuous whole Earth coverage constellation

A. Method to find the optimal satellite constellation

Facilities (ground stations) and nanosatellite having different orbit types are firstly created using STK. Then, in order to find the optimal satellite constellation for elliptical or circular orbit, inclined or polar, Walker Star or Walker Delta constellation, we use two programs. One is C to help outputting the combination of the number of planes P and number of satellites per plane N to be tested. Another is STK which is used to test and find the combination of number of planes P and number of satellites per plane N, whether it can provide a continuous whole Earth coverage (24h/day).

A-1. *Working with STK instruction*

❖ Steps to get create a satellite constellation in STK:

- ➢ Create facilities (ground stations) and nanosatellite which is described in IV.2.2 A.
- ➢ Right-click Satellite in the Object Browser→ Go to Satellite → Select Walker → Input (Type: Delta, Number of Planes, Number of Sats per Plane, Inter-Plane Spacing is the relative spacing between satellites in adjacent planes *F* which is equal to 1 for all constellations in this thesis, RAAN Spread is equal to 180 degrees for Walker Star constellation (usually for polar or near polar orbit, inclination of 90 degrees or near 90 degrees) and 360 degrees for Walker Delta constellation (for orbit with an inclination generally less than 90°), Select Color by Plane, Select Create unique names for sub-objects, Select Create Constellation to have STK automatically create a Constellation object that includes all of the satellites in the Walker constellation. Enter the constellation's name in the text box) → Click Create Walker and Close.

To address area coverage capabilities, the Coverage module of STK provides two STK object classes: coverage definition ( ) and figure of merit ( ). Coverage definition objects allow to define and maintain an area of coverage, to define the STK objects providing coverage for the area (such as satellites, aircraft and sensors), to define the time period of interest, and to calculate accesses to the region. The figure of merit objects attaching to a coverage definition object provide the means for evaluating the quality of coverage provided by the assigned objects (or assets).

❖ Steps to define the Coverage Region and Assign Assets

➢ Double-click the icon in the Object Catalog to add a coverage definition to the scenario.

➢ Open the Basic - Grid page for the coverage definition properties, and set the following options:

- Grid Area of Interest Type: Global
- Point Granularity: Lat/Lon
- Point Granularity Value: 6.0 deg

➢ Open the Assets page. Select the satellite constellation, click Assign, make sure that Status is set to Active, and click Apply.

➢ Open the 2D Graphics - Attributes page, and set the following options as shown in Figure IV.12:

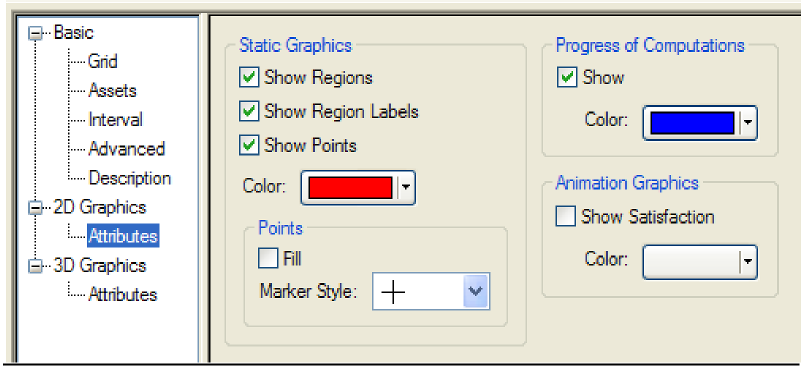


Figure IV.11: 2D Graphics - Attributes page of Coverage Region

➢ Click OK, then select the coverage definition in the Object Browser, select Compute Accesses from the CoverageDefinition Tools menu.

❖ Steps to assess the Quality of Coverage with a Figure of Merit

➢ Select the coverage definition in the Object Browser, and double-click the icon in the Object Catalog to add a figure of merit.

➢ Open the Definition page for the Figure of Merit. Choose Simple Coverage for the Type.

➢ Open the 2D Graphics - Attributes page for the figure of merit, and set the following options as shown in Figure IV.13:

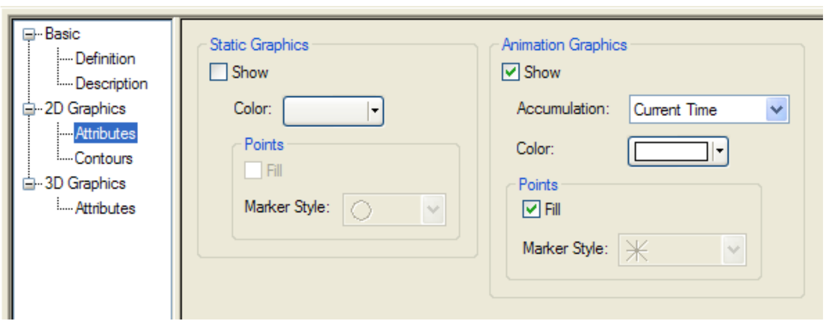


Figure IV.12: 2D Graphics - Attributes page of Figure of Merit

- Click OK, and animate the scenario.

❖ Steps to get Global Coverage report:

- {Right-click CoverageDefinition in the Object Browser → Select Report & Graph Manager} or {Click Report & Graph Manager icon → Chose CoverageDefinition in object type → Select the CoverageDefinition} → Go to Styles → Select Show Reports and Unselect Show Graphs → Go to Installed Styles → Select Global Coverage → Go to Generate As → Select Report/Graph → Click Generate

For more detail about the steps how to create a satellite constellation, to define a Coverage Region and Assign Assets, to assess a Quality of Coverage with a Figure of Merit, and a Global Coverage report go to STK help.

A-2. *Flow chart to find the optimal satellite constellation*

A flow chart to find the optimal satellite constellation for continuous whole Earth coverage is shown in Figure IV.11. This flow chart is programmed in C to help out putting the combination of the number of planes P and number of satellites per plane N to be tested in STK. The C code for this flow chart is provided in Annex III, A.III.1.

In order to find the optimal satellite constellation, the value of P_min, P_max, N_min and N_max are chosen around or equal the approximated value calculated in Chpater II, II.1.1.B. Review that the approximated values of P_min, P_max, N_min and N_max is calculated for different orbit types at minimum, maximum and mean satellite altitude (for elliptical orbit) or at a constant satellite altitude (for circular orbit), with an elevation angle 5 degrees, and for a constant velocity of satellite throughout the orbit. The value of P_min, P_max, N_min and N_max chosen for finding the optimal constellation for different orbit type are shown in Table IV.10.

Table IV.10: Value of P_min, P_max, N_min and N_max chosen for finding the optimal constellation for different orbit type

Orbit type	**Approximated value**				**Chosen value**			
	P_min	P_max	N_min	N_max	P_min	P_max	N_min	N_max
Elliptical LEO	5	8	7	16	5	8	7	16
Elliptical VLEO	9	10	13	14	9	10	13	14
Elliptical MEO “Molniya”	2	4	4	64	2	4	4	64
Elliptical MEO “Tundra”	2		12	21	2		4	21
Circular LEO “Inclinded”	7		10		6	8	7	12
Circular LEO “Polar”	7		10		6	8	7	12

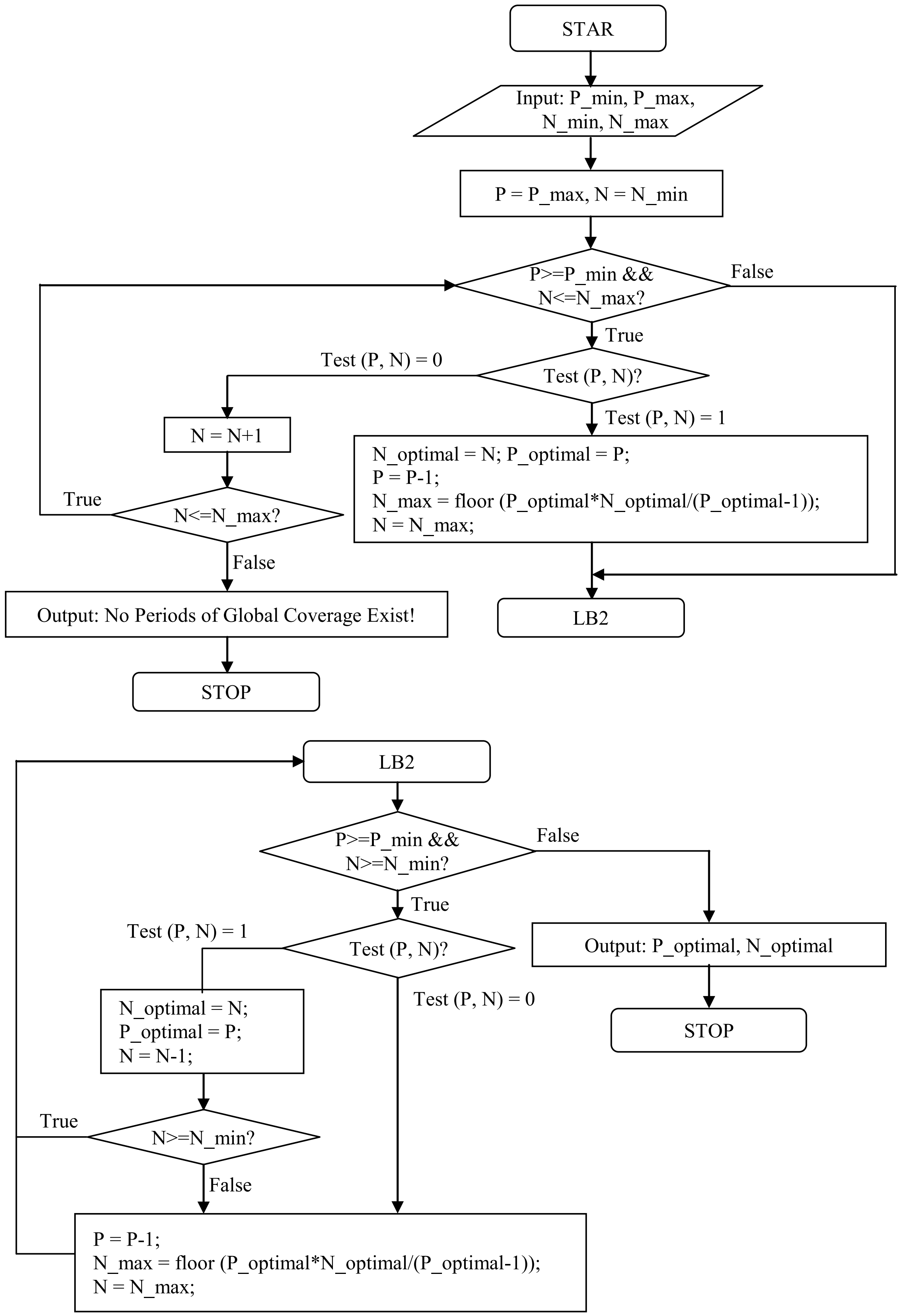


Figure IV.13: Flow chart to find the optimal satellite constellation for continuous whole Earth coverage

B. <u>Output results of continuous whole Earth coverage constellation for different orbit types</u>

B-1. Elliptical LEO orbit

By using the C code in Annex III, A.III.1 of the flow chart in Figure IV.11 and the simulation software computation capabilities of STK, we got the results in Table IV.11.

Table IV.11: Results of Walker Delta constellation for continuous whole Earth coverage for elliptical LEO orbit during one day period of simulation

Constellation defined by	Total duration (min)	Total percent	Possible continuous whole Earth coverage?
71°: 8/7/1	1440	100	Yes
71°: 7/8/1	1440	100	Yes
71°: 7/7/1	1440	100	Yes
71°: 6/8/1	1440	100	Yes
71°: 6/7/1	1371.928	95.272780	No
71°: 5/9/1	92.829	6.446480	No
The optimal constellation is defined by define by 71°: 6/8/1 (inclination: 71°, number of planes: 6, and number of satellites per plane: 8, inter plane spacing: 1), hence the minimum total number of satellites is 48.			

As shown in Table IV.11, the Walker Delta constellation of elliptical LEO orbit which is define by 71°: 6/8/1 (inclination: 71°, number of planes: 6, and number of satellites per plane: 8, with the total number of satellite only 48) is the optimal constellation which can provide a continuous whole Earth coverage since its total duration is 1440 minutes per day or 100 percent of coverage per day. Whereas, the Walker Delta constellation of elliptical LEO orbit which is defined by 71°: 6/7/1 and 71°: 5/9/1, it exists a global coverage but cannot provide a continuous whole Earth coverage as its total duration is less than 1440 minutes per day or less than 100 percent of coverage per day. The testing screen of satellite constellation, P and N in C code for elliptical LEO orbit is shown in Figure IV.14. The 2D and 3D graphics of Walker Delta constellation for elliptical LEO orbit defined by 71°: 6/8/1 and defined by 71°: 5/9/1 are shown in Figure IV.15 and Figure IV.16 respectively.

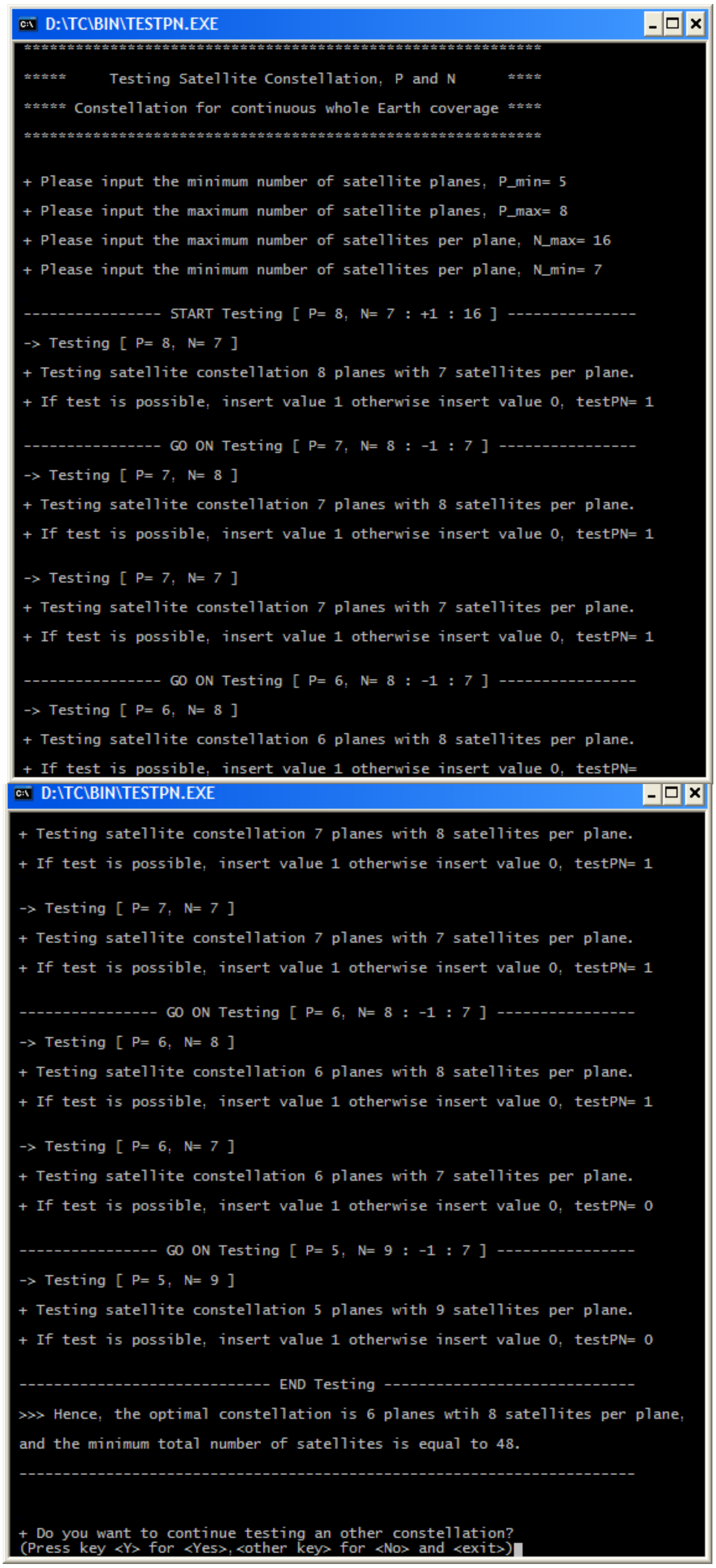
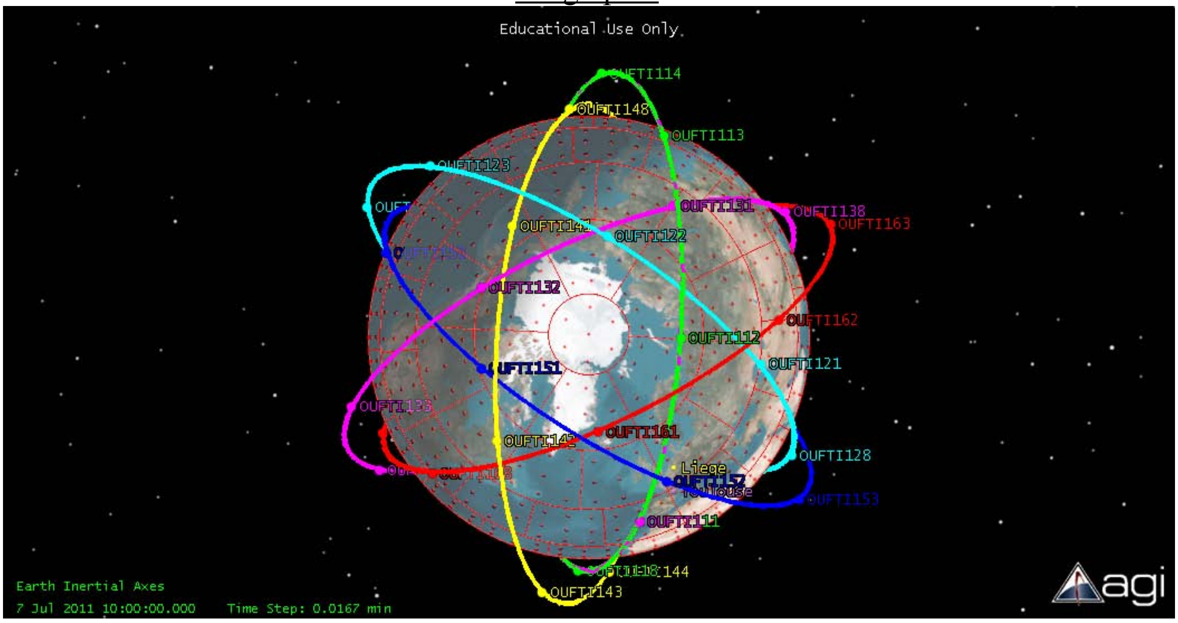


Figure IV.14: Testing satellite constellation, P and N in C code for elliptical LEO orbit

3D graphic



2D graphic

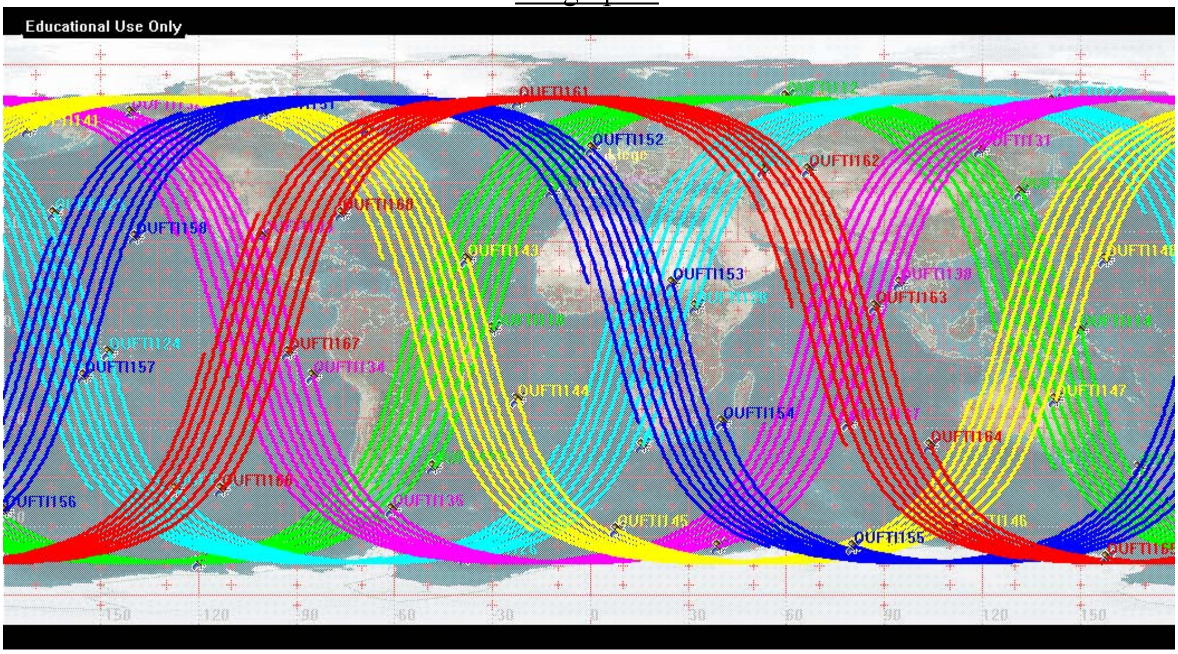
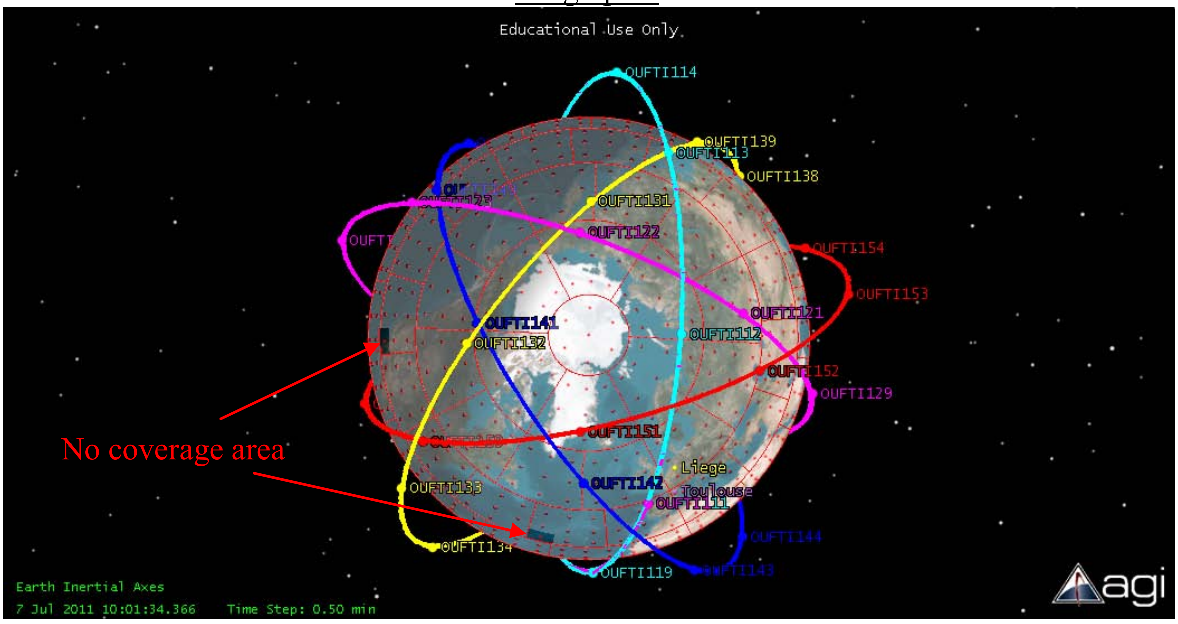


Figure IV.15: Walker Delta constellation 2D and 3D graphics for elliptical LEO orbit defined by 71°: 6/8/1

3D graphic



2D graphic

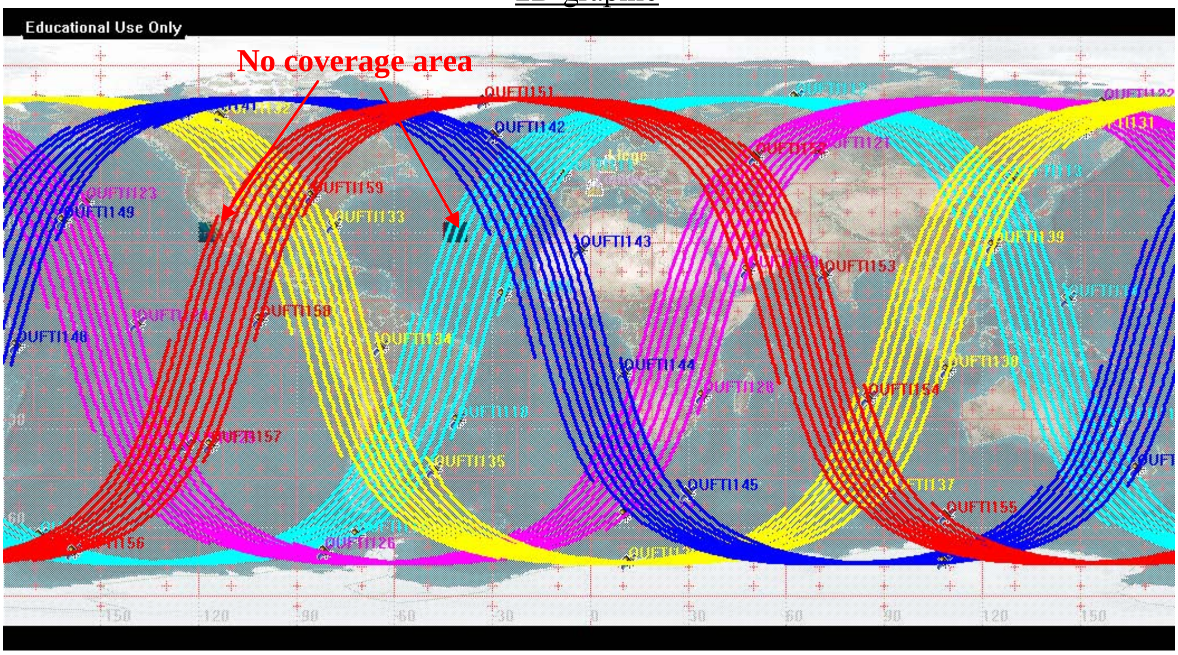


Figure IV.16: Walker Delta constellation 2D and 3D graphics for elliptical LEO orbit defined by 71°: 5/9/1

B-2. Elliptical VLEO orbit

By using the C code of the flow chart in Figure IV.11 and the simulation software computation capabilities of STK, we got the results in Table IV.12.

Table IV.12: Results of Walker Delta constellation for continuous whole Earth coverage for elliptical VLEO orbit during one day period of simulation

Constellation defined by	Total duration (min)	Total percent	Possible continuous whole Earth coverage?
71°: 10/13/1	No periods of global coverage exist		No
71°: 10/14/1	No periods of global coverage exist		No
Hence, no periods of global coverage exist.			

The testing screen of satellite constellation, P and N in C code for elliptical VLEO orbit is shown in Figure IV.17. The 2D and 3D graphics of Walker Delta constellation for elliptical VLEO orbit defined by are shown in Figure IV.18.

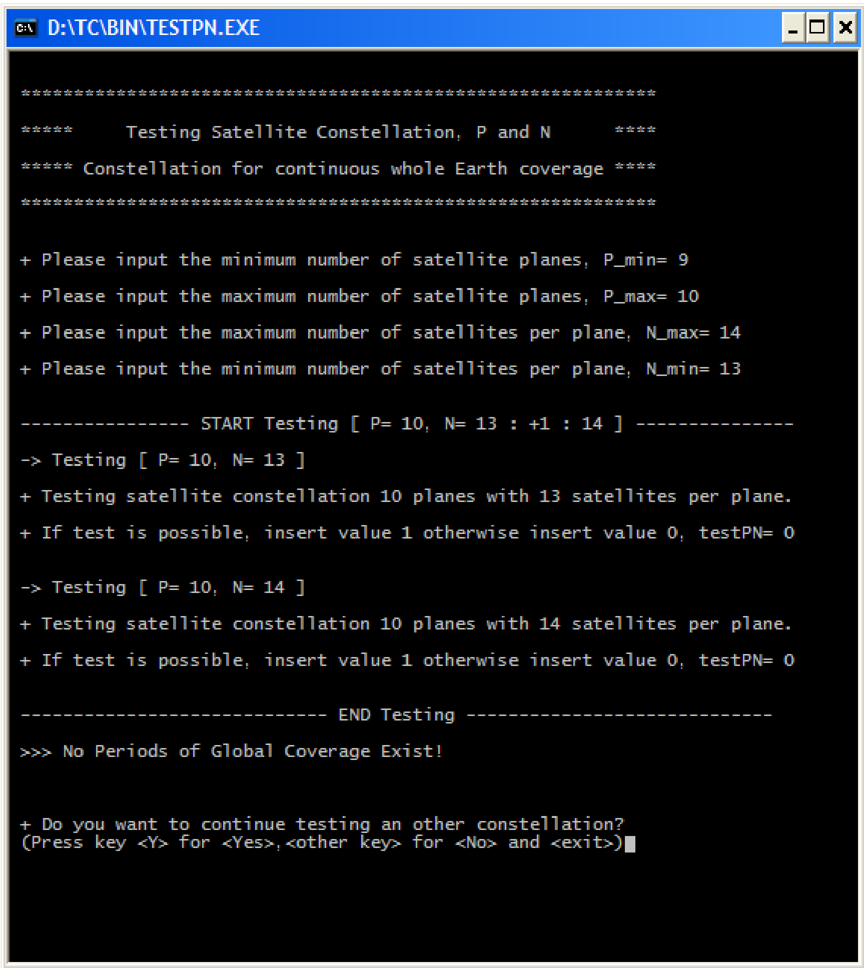
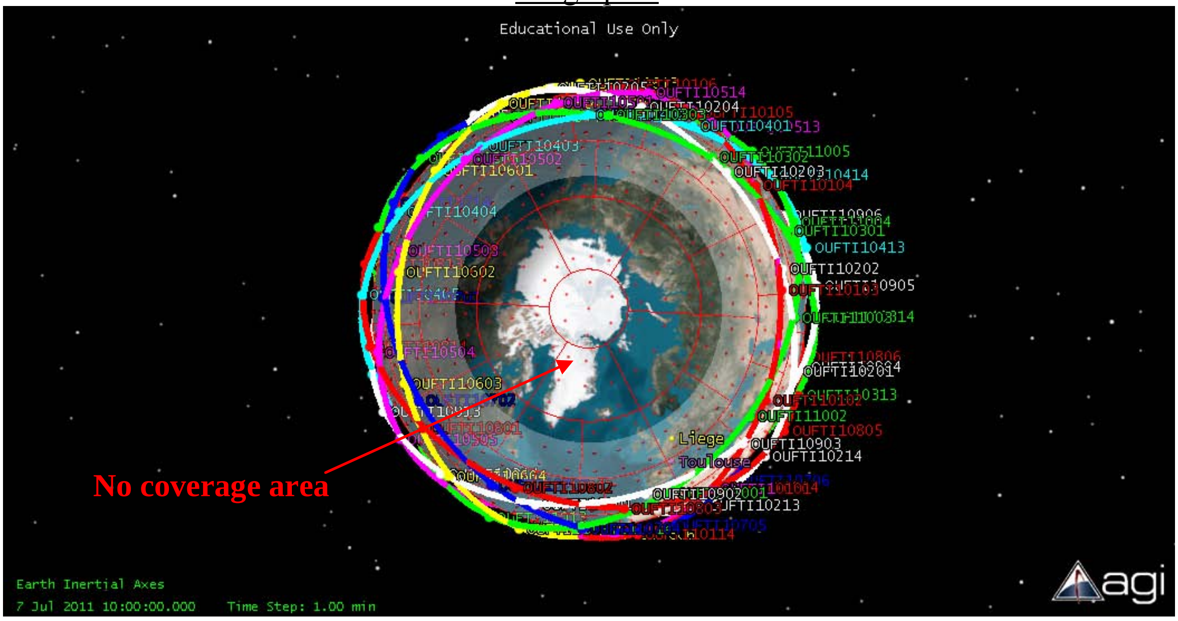


Figure IV.17: Result of constellation test in C code and the global coverage report of Walker Delta constellation for elliptical VLEO orbit defined by 40.02°: 10/14/1

3D graphic



2D graphic

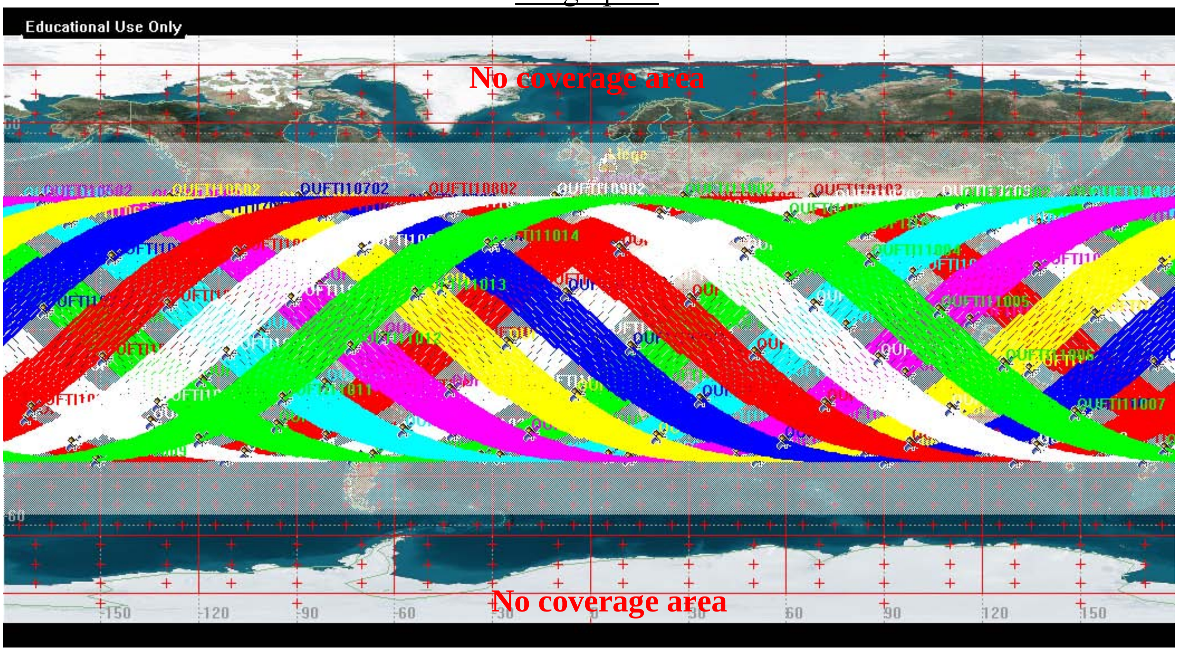


Figure IV.18: Walker Delta constellation 2D and 3D graphics for elliptical VLEO orbit defined by 40.02°: 10/14/1

As shown in the Figure IV.18, there are no periods of global coverage because of the value of inclination which cannot provide the coverage at the latitude upper than about 60 degrees and lower than about -60 degrees (See II.1.2.C Limitations of the Walker Delta Constellation).

B-3. Elliptical MEO "Molniya" orbit

By using the C code of the flow chart in Figure IV.11 and the simulation software computation capabilities of STK, we got the results in Table IV.13.

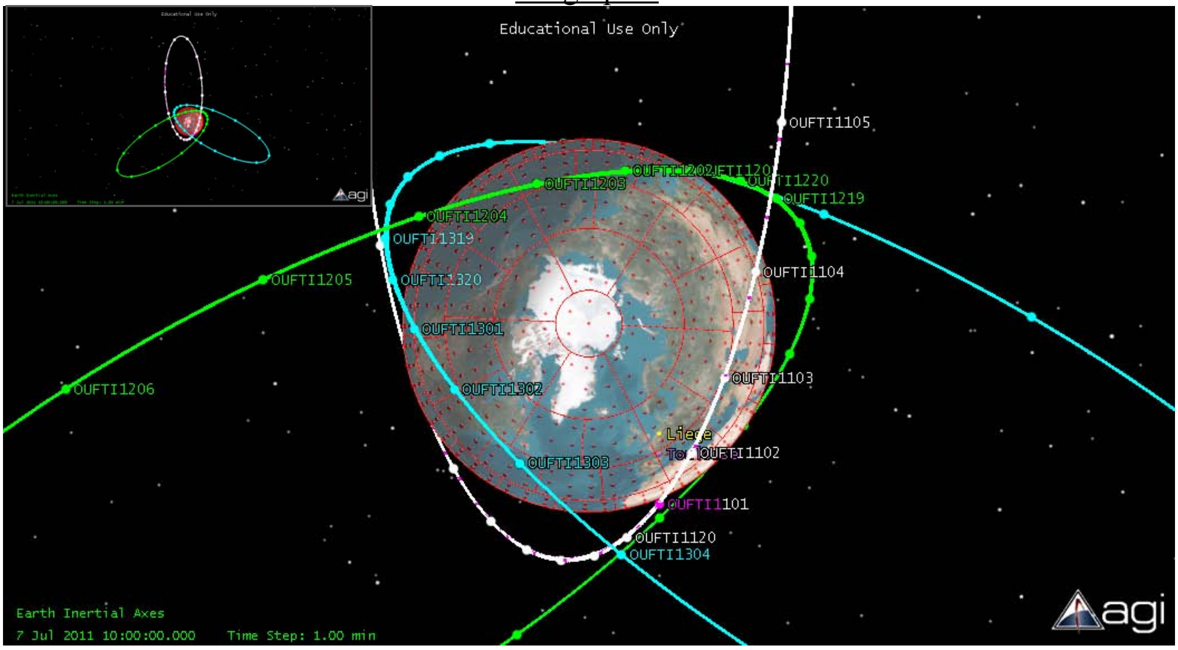
Table IV.13: Global coverage report of Walker Delta constellation for continuous whole Earth coverage for elliptical MEO "Molniya" orbit for one day period of simulation

Constellation defined by	Total duration (min)	Total percent	Possible continuous whole Earth coverage?
63.40°: 4/4/1	538.915	37.424653	No
63.40°: 4/5/1	635.808	44.153303	No
63.40°: 4/6/1	791.077	54.935909	No
63.40°: 4/7/1	910.259	63.212463	No
63.40°: 4/8/1	1006.084	69.866934	No
63.40°: 4/9/1	1109.005	77.014246	No
63.40°: 4/10/1	1222.556	84.899721	No
63.40°: 4/11/1	1279.465	88.851745	No
63.40°: 4/12/1	1344.929	93.397838	No
63.40°: 4/13/1	1386.057	96.253983	No
63.40°: 4/14/1	1423.231	98.835482	No
63.40°: 4/15/1	1440.000	100.000000	Yes
63.40°: 3/20/1	1440.000	100.000000	Yes
63.40°: 3/19/1	1432.046	99.447618	No
63.40°: 2/30/1	704.671	48.935509	No
The optimal constellation is defined by define by 63.40°: 3/20/1 (inclination: 63.40°, number of planes: 3, and number of satellites per plane: 20, inter plane spacing: 1), hence the minimum total number of satellites is 60.			

As shown in Table IV.13, the optimal Walker Delta constellation of elliptical LEO orbit which is define by 63.40°: 3/20/1 (inclination: 63.40°, number of planes: 3, and number of satellites per plane: 20, inter plane spacing: 1, total number of satellites is 60) is quite high. This is not abnormal because as we have discussed in Chapter III.7, at section III.7.2 *Elliptical Constellation*, for the elliptical orbit, the Walker Delta constellation cannot provide a good optimal constellation for elliptical orbit for (continuous) whole earth coverage, because there would have many overlapping of satellite footprints. For elliptical orbit constellation, the method Walker Delta constellation is about to use for an area specific coverage to offer a quite better optimal constellation.

The 2D and 3D graphics of Walker Delta constellation for elliptical MEO "Molniya" orbit defined by 63.40°: 3/20/1 is shown in Figure IV.19.

3D graphic



2D graphic

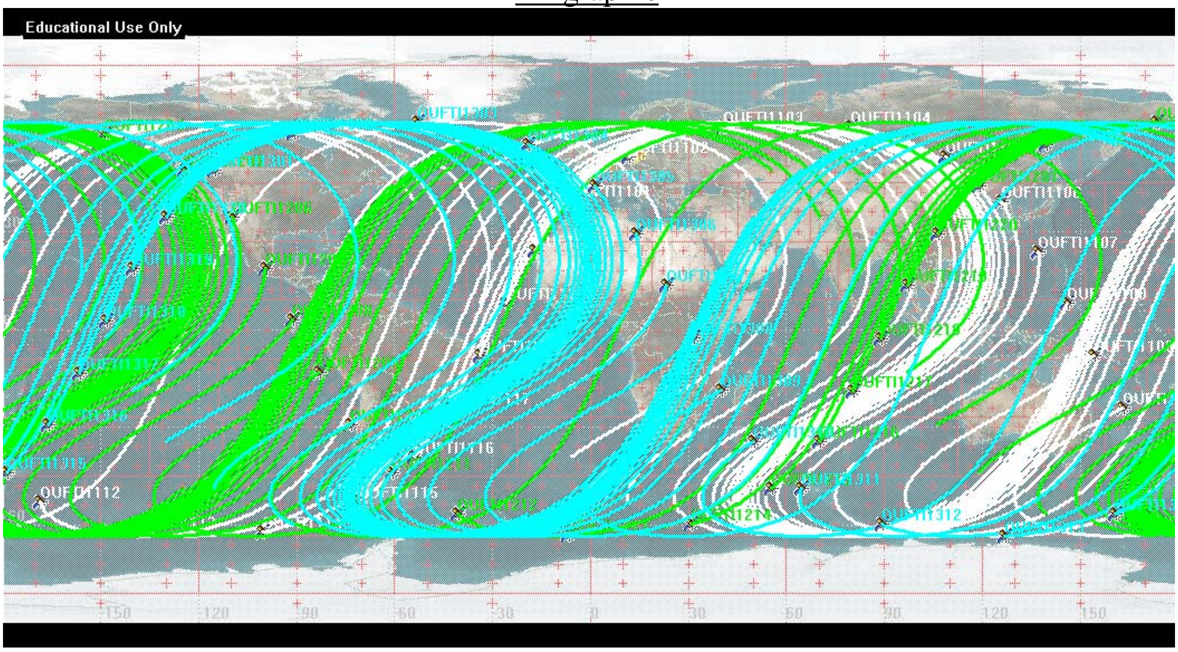


Figure IV.19: Walker Delta constellation 2D and 3D graphics for elliptical MEO "Molniya" orbit defined by 63.40°: 3/20/1

B-4. Elliptical MEO "Tundra" orbit

By using the C code of the flow chart in Figure IV.11 and the simulation software computation capabilities of STK, we got the results in Table IV.14.

Table IV.14: Global coverage report of Walker Delta constellation for continuous whole Earth coverage for elliptical MEO “Tundra” orbit for one day period of simulation

Constellation defined by	Total duration (min)	Total percent	Possible continuous whole Earth coverage?
63.40°: 2/4/1	1334.764	92.691951	No
63.40°: 2/5/1	1440.000	100.000000	Yes
The optimal constellation is defined by define by 63.40°: 2/5/1 (inclination: 63.40°, number of planes: 2, and number of satellites per plane: 5, inter plane spacing: 1), hence the minimum total number of satellites is 10.			

The 2D and 3D graphics of Walker Delta constellation for elliptical MEO “Tundra” orbit defined by 63.40°: 2/5/1 is shown in Figure IV.20.

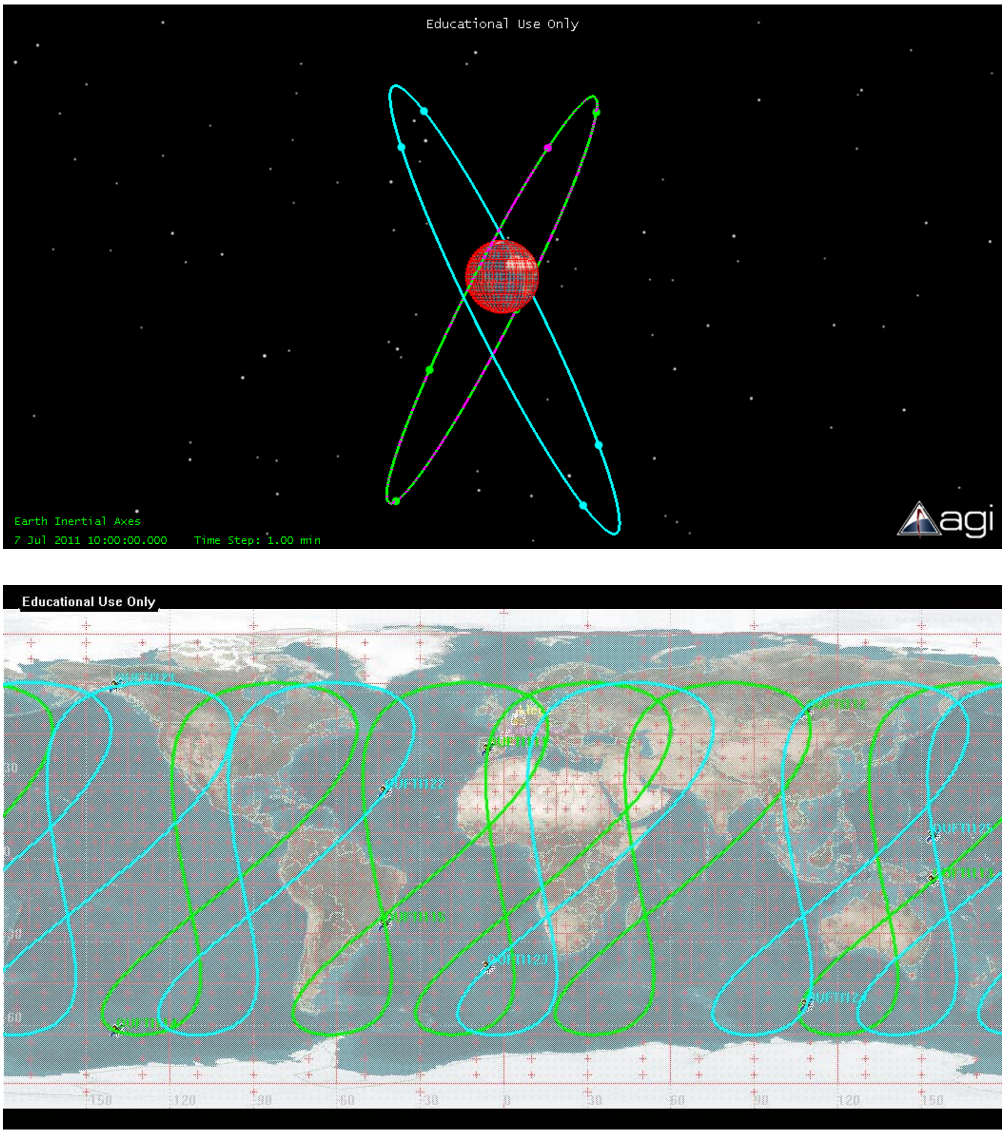


Figure IV.20: Walker Delta constellation 2D and 3D graphics for elliptical MEO “Tundra” orbit defined by 63.40°: 2/5/1

B-5. *Circular LEO orbit "Inclined"*

By using the C code of the flow chart in Figure IV.11 and the simulation software computation capabilities of STK, we got the results in Table IV.15.

Table IV.15: Results of Walker Delta constellation for continuous whole Earth coverage for circular LEO orbit "Inclined" during one day period of simulation

Constellation defined by	Total duration (min)	Total percent	Possible continuous whole Earth coverage?
72°: 8/7/1	No periods of global coverage exist		No
72°: 8/8/1	1440	100	Yes
72°: 7/9/1	1440	100	Yes
72°: 7/8/1	No periods of global coverage exist		No
72°: 6/10/1	No periods of global coverage exist		No
The optimal constellation is defined by define by 72°: 7/9/1 (inclination: 72°, number of planes: 7, and number of satellites per plane: 9, inter plane spacing: 1), hence the minimum total number of satellites is 63.			

The 2D and 3D graphics of Walker Delta constellation for circular LEO "Inclined" orbit defined by 72°: 7/9/1 is shown in Figure IV.21.

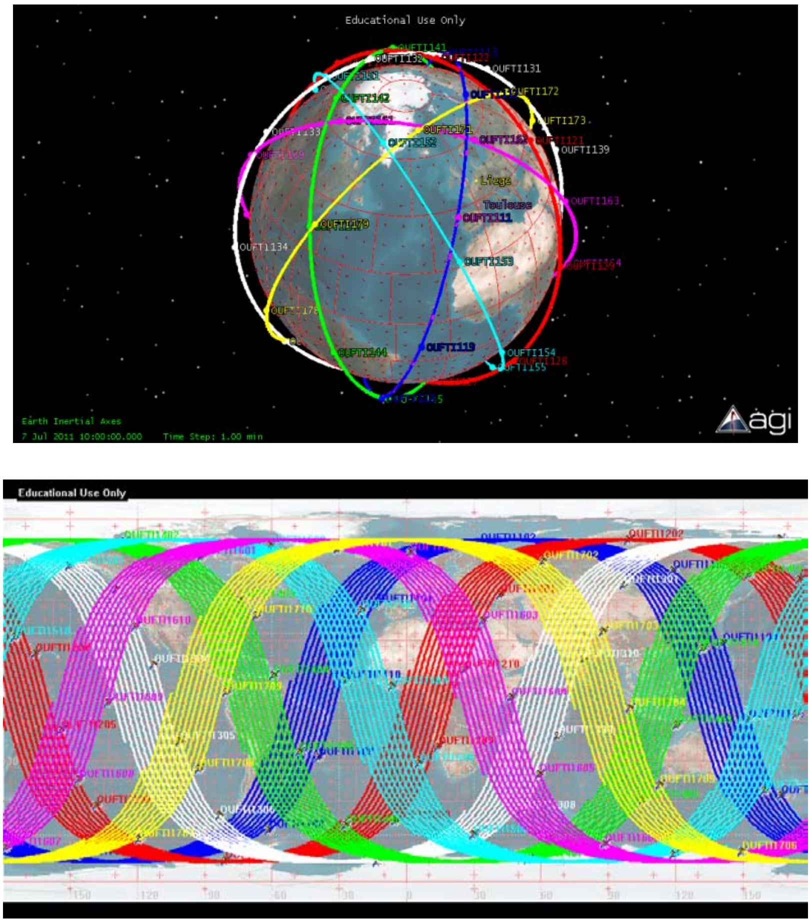


Figure IV.21: Walker Delta constellation 2D and 3D graphics for circular LEO "Inclined" orbit defined by 72°: 7/9/1

B-6. Circular LEO orbit “Polar”

By using the C code of the flow chart in Figure IV.11 and the simulation software computation capabilities of STK, we got the results in Table IV.16.

Table IV.16: Results of Walker Delta constellation for continuous whole Earth coverage for circular LEO orbit “Polar” during one day period of simulation

Constellation defined by	Total duration (min)	Total percent	Possible continuous whole Earth coverage?
90°: 8/7/1	1.252	0.086975	No
90°: 8/8/1	1440	100	Yes
90°: 7/9/1	1440	100	Yes
90°: 7/8/1	1440	100	Yes
90°: 7/7/1	No periods of global coverage exist		No
90°: 6/9/1	1440	100	Yes
90°: 6/8/1	1329.139	92.301286	No
The optimal constellation is defined by define by 72°: 6/9/1 (inclination: 72°, number of planes: 6, and number of satellites per plane: 9, inter plane spacing: 1), hence the minimum total number of satellites is 54.			

The 2D and 3D graphics of Walker Delta constellation for circular LEO “Polar” orbit defined by 72°: 6/9/1 is shown in Figure IV.22.

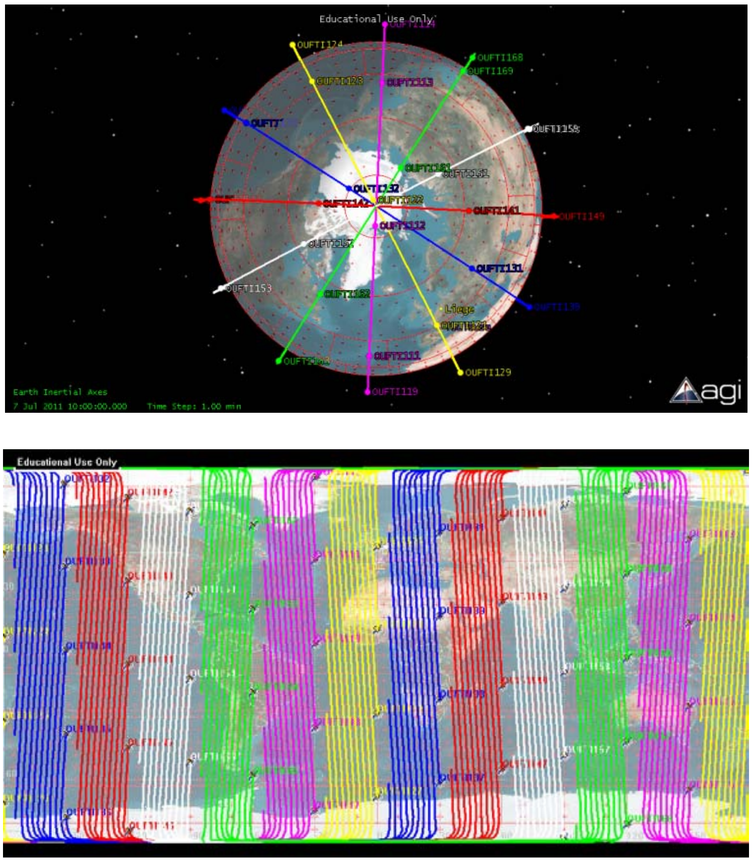


Figure IV.22: Walker Star constellation 2D and 3D graphics for circular LEO “Polar” orbit defined by 72°: 6/9/1

IV.3.3 Summary of output results of continuous whole Earth coverage constellation

Table IV.17: Summary of output results of continuous whole Earth coverage constellation

Orbit type	Possible continuous whole Earth coverage?	Optimal constellation defined by	Total number of satellites
Elliptical LEO	Yes	71°: 6/8/1	48
Elliptical VLEO	No	40.02°: xx/xx/xx	xx
Elliptical MEO “Molniya”	Yes	63.40°: 3/20/1	60
Elliptical MEO “Tundra”	Yes	63.40°: 2/5/1	10
Circular LEO “Inclined”	Yes	72°: 7/9/1	63
Circular LEO “Polar”	Yes	90°: 6/9/1	54

According the Tables IV.17, we can observe that:

Orbit size concerning:

- The orbit with the bigger size required less total number of satellites for constellation for continuous whole Earth coverage constellation. For example, the total number of satellites required for constellation for continuous whole Earth coverage for the elliptical MEO “Molniya” orbit is 50 satellites higher than the one for elliptical MEO “Tundra”. This is because the size of the elliptical MEO “Tundra” orbit is bigger than the elliptical MEO “Molniya” orbit.
- For elliptical MEO “Molniya”, the optimal constellation is defined by 63.40°: 3/20/1 requiring 60 satellites in total. By comparing with elliptical LEO or circular LEO orbit with the smaller orbit size, we observe that the optimal constellation of elliptical MEO “Molniya” with the bigger orbit size is required much higher total number of satellites. This would make the first observation sentence not right, but it’s not abnormal or wrong. According to what we have discussed in Chapter III, at section III.7 *Satellite Constellation*, the Walker Delta or Walker Star constellation is about to use for the circular orbit which can provide a good optimal constellation for (continuous) whole earth coverage. But, if both method is used with elliptical orbit, it would somehow provide a good result or a bad result of optimal constellation depend on whether or not the orbit has many overlapping of satellite footprints in the orbit. For elliptical orbit constellation, the method Walker Delta constellation is about to use for an area specific coverage to offer a quite better optimal constellation.

Orbit inclination concerning:

- The orbit with very smaller inclination, for example the elliptical VLEO orbit with inclination 40°, cannot provide a (continuous) whole Earth coverage.
- For the same orbit size, the Walker Star constellation (used for inclination 90° or near 90°) provides a better optimal constellation than the Walker Delta constellation (used for inclination less than 90°). For instance, the total number of satellites required for constellation for continuous whole Earth coverage for the circular LEO “Polar” orbit is 9 satellites lower than the one for circular LEO “Inclined”.

IV.4 Constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations

IV.4.1 Description of the simulation scenarios of constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations

The purpose of the simulation scenarios in this section is to find the optimum constellation which provides a continuous coverage (24h/day) over a specific area. Two scenarios, one for circular LEO "Inclined" orbit and other one for elliptical LEO orbit, are created in order to validate a continuous coverage case for a specific area between Liege (latitude: 50.62°, longitude: 5.5667°) and Toulouse (latitude: 43.6°, longitude: 1.43333°). The communication between Toulouse and Liege facility is accomplished via one satellite. These two scenarios of satellite constellation are demonstrated and compared.

IV.4.2 Simulation scenarios and output results of constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations

A. Method to find the optimal satellite constellation

Facilities (ground stations) and nanosatellite having different orbit types are firstly created using STK. Then, in order to find the optimal satellite constellation for elliptical or circular orbit, inclined or polar, Walker Star or Walker Delta constellation, we use two programs. One is C to help outputting the combination of the number of planes P and number of satellites per plane N and intersatellite to be tested. Another is STK which is used to test and find the combination of number of planes P and number of satellites per plane N, whether it can provide a continuous whole Earth coverage (24h/day).

A-1. *Working with STK instruction*

We have already presented about:

- How to create a scenario, a satellite, a facility
- How to get Access report, AER report, to add an elevation angle constraint
- How to create a satellite constellation, to define a Coverage Region and Assign Assets, to access a Quality of Coverage with a Figure of Merit, and Global Coverage report.

To simulate with the scenarios in this section, we have to know how to create a Chain and get a Complete Chain Access report.

❖ Steps to create a Chain and get a Complete Chain Access report:

➢ Set up your scenario with at least three different assets. These can be satellites, ground vehicles, facilities, targets, or aircraft.
➢ Insert a Chain object and open up its properties browser.
➢ On the Basic Definition page for the Chain, highlight the object that starts the communications link and click to move it from Available Objects to Assigned Objects.
➢ Next, select the object that will relay your communications and click.
➢ Finally, select and assign the object that will receive communications.
➢ Once finished, click OK to close the Chain property browser.

- Right-click the Chain object, select Chain Tools—> Report, and create the Complete Chain Access report. This gives the times and durations that the complete chain has access.
- Click to reset the animation and then click to animate the scenario. A yellow line will connect the objects in the Chain during periods of access in the 3D Graphics window.

For more detail about the steps how to create a satellite constellation, to define a Coverage Region and Assign Assets, to assess a Quality of Coverage with a Figure of Merit, and a Global Coverage report go to STK help.

A-2. *Flow chart to find the optimal satellite constellation*

Similarly to section IV.3.2 A, a flow chart to find the optimal satellite constellation for continuous coverage for an area specific is shown in Figure IV.23. This flow chart is programmed in C to help outputting the combination of the number of planes P and number of satellites per plane N to be tested in STK. The C code for this flow chart is provided in Annex III, A.III.2.

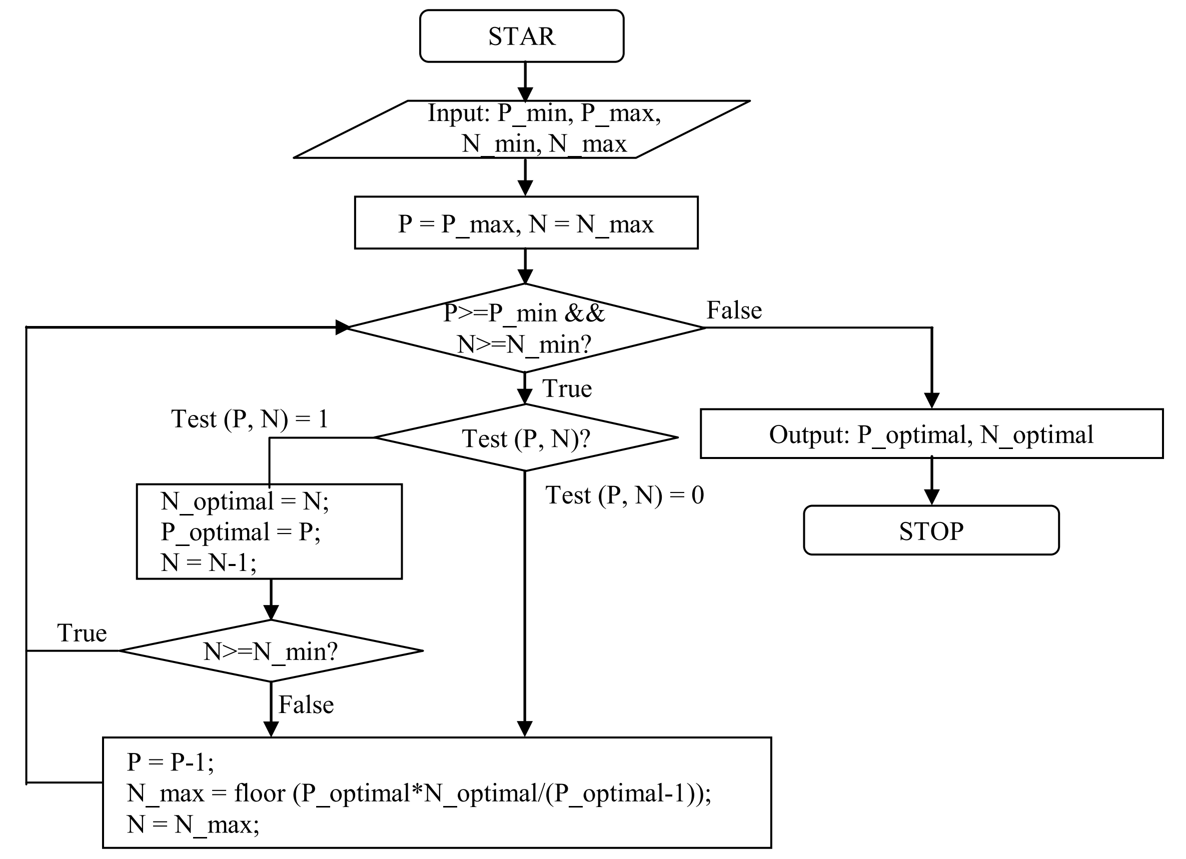


Figure IV.23: Flow chart to find the optimal satellite constellation for continuous coverage for an area specific

In order to find the optimal satellite constellation, the value of P_min, P_max, N_min and N_max are carefully chosen.

The P_max and N_max is chosen to be equal the optimal value P and N of constellation for continuous whole Earth coverage, in Table IV.17 at section IV.3.3, because the value of P and N required for constellation for continuous coverage for an area specific would required less than the value of P and N required for constellation for continuous whole Earth coverage.

The value P_min and N_min of constellation for continuous coverage for an area specific is chosen to be lower than the chosen value P_min and N_min of constellation for continuous whole Earth coverage, because the value of P_min and N_min required for constellation for continuous coverage for an area specific would required less than the value of P_min and N_min required for constellation for continuous whole Earth coverage.

The value of P_min, P_max, N_min and N_max chosen for finding the optimal constellation for circular LEO "Inclined" orbit and elliptical LEO orbit are shown in Table IV.10.

Table IV.18: Value of P_min, P_max, N_min and N_max chosen for finding the optimal constellation for different orbit type

Orbit type	**Elliptical LEO**	**Circular LEO "Inclinded"**
Chosen value of P_min, P_max, N_min and N_max for constellation for continuous whole Earth coverage	P_min = 5 P_max = 8 N_min = 7 N_max = 16	P_min = 6 P_max = 8 N_min = 7 N_max = 12
Optimal value P and N of constellation for continuous whole Earth coverage	P = 6 N = 8	P = 7 N = 9
Chosen value of P_min, P_max, N_min and N_max for constellation for continuous coverage for an area specific	P_max = 6 N_max = 8 P_min = 5 N_min = 5	P_max = 7 N_max = 9 P_min = 5 N_min = 5

B. Output results of continuous coverage for an area specific for continuous coverage constellation circular LEO "Inclined" orbit and elliptical LEO orbit

B-1. Elliptical LEO orbit

By using the C code in Annex III, A.III.2 of the flow chart in Figure IV.23 and the simulation software computation capabilities of STK, we got the results in Table IV.19.

Table IV.19: Results of Walker Delta constellation for continuous coverage for an area specific (Toulouse-Liege) for elliptical LEO orbit during one day period of simulation

Constellation Defined by	Total Duration (min)	Possible continuous coverage for an area specific (Toulouse-Liege)?
71°: 6/8/1	1440	Yes
71°: 6/7/1	1440	Yes
71°: 6/6/1	1438.130	No
71°: 5/8/1	1434.229	No
The optimal constellation is defined by define by 71°: 6/7/1. Hence, the minimum total number of satellites is 42.		

For elliptical LEO orbit, by comparing with the Walker Delta constellation for continuous whole Earth coverage, the Walker Delta constellation for continuous coverage for an area specific (Toulouse-Liege) can save up to 6 satellites as shown in Table IV.19.

B-2. Circular LEO orbit "Inclined"

By using the C code of the flow chart in Figure IV.23 and the simulation software computation capabilities of STK, we got the results in Table IV.20.

Table IV.20: Results of Walker Delta constellation for continuous coverage for an area specific (Toulouse-Liege) for circular LEO orbit "Inclined" during one day period of simulation

Constellation Defined by	Total Duration (min)	Possible continuous coverage for an area specific (Toulouse-Liege)?
72°: 7/9/1	1440	Yes
72°: 7/8/1	1440	Yes
72°: 7/7/1	1440	Yes
72°: 7/6/1	1440	Yes
72°: 7/5/1	1437.483	No
72°: 6/7/1	1440	Yes
72°: 6/6/1	1439.986	No
72°: 5/8/1	1403.304	No
The optimal constellation is defined by define by 72°: 6/7/1. Hence, the minimum total number of satellites is 42.		

For circular LEO orbit, by comparing with the Walker Delta constellation for continuous whole Earth coverage, the Walker Delta constellation for continuous coverage for an area specific (Toulouse-Liege) can save up to 21 satellites as shown in Table IV.20.

IV.4.3 Summary of output results of constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations

Table IV.21: Summary of output results of constellation for continuous coverage for an area specific between Liege and Toulouse

Orbit type	For continuous whole Earth coverage, optimal constellation defined by	For continuous coverage for an area specific (Toulouse-Liege), optimal constellation defined by	Saving Number of satellite
Elliptical LEO	71°: 6/8/1	71°: 6/7/1	6
Circular LEO "Inclined"	72°: 7/9/1	72°: 6/7/1	21

According to Table IV.21, we can notice that:

- The constellation for (continuous) coverage for an area specific required less satellites than the constellation for (continuous) whole Earth coverage.
- For circular LEO "Inclined", the constellation for continuous coverage for an area specific between Liege and Toulouse can save more satellites than the one for elliptical LEO. This depends on the area specific selection. Such constellation would

provide a quite better optimal constellation for elliptical orbit than the circular orbit when the specific locations are well selected because the circular orbit doesn't loiter at apogee like the elliptical orbit as have discussed in chapter III, at section III.7.2.

IV.5 Link budget between one nanosatellite and Liege ground station for Low Earth Orbit satellite system

IV.5.1 Description of the simulation scenarios for Low Earth Orbit satellite system

These scenarios aim at determining the link budgets for elliptical LEO orbit and circular LEO "Inclined" orbit between a nanosatellite and a ground station located in Liege, Belgium.

A summary of characteristic of the communication system studied is shown in Table IV.22.

Table IV.22: Summary of characteristic of the communication system studied

"Transmitter"			
		At SL	**At GS**
Frequency Band (UHF/VHF)			
		Downlink (VHF)	Uplink (UHF)
Frequency	[MHz]	145	435
Power			
Protocol		AX.25 And D-STAR	
Transmitter Power	[W]	0.75	20
	[dBw]	-1.25	13.01
Protocol		Beacon	
Transmitter Power	[W]	0.1	0.1
	[dBw]	-10	-10
Antenna			
Antenna Type		Monopole	Yagi
Antenna Gain	[dBi]	2.15	13.35
Antenna Pointing Loss	[dB]	7.6	0.15
Antenna Polarization Loss	[dB]	0.2283	0.2283
Transmission Losses			
Total Line Losses	[dB]	1.02	3.09
Data Rate And Modulation Type			
Protocol	Beacon	AX.25	D-STAR
Data Rate	12 wpm or 20 bps	9.6 kbps	DV Mode: 4.8 kbps
Modulation Type	FSK Non-Coherent	FSK Non-Coherent	GMSK
Coding	None	None	None
"Path Losses"			
		Downlink (VHF)	Uplink (UHF)
Frequency	[MHz]	145	435
Free Space Path Losses For Minimum Altitude Of Satellite	[dB]	140.14	149.68
Atmospheric Losses	[dB]	2.10	2.10
Ionospheric Losses	[dB]	0.80	0.40
Rain Losses	[dB]	0.00	0.00

“Receiver”			
		At GS	**At SL**
Frequency Band (UHF/VHF)			
		Downlink (VHF)	Uplink (UHF)
Frequency	[MHz]	145	435
Antenna			
Antenna Type		Yagi	Monopole
Antenna Gain	[dBi]	13.35	2.15
Antenna Pointing Loss	[dB]	0.15	7.6
Transmission Losses			
Total In-Line Losses From Antenna To LNA	[dB]	1.85	0.83
LNA Gain	[dB]	20	20
LNA To Receiver Line Loss	[dB]	0.5	0
System Noise Temperature	[K]	681.13	219.66
Data Rate And Modulation Type			
Protocol	Beacon	AX.25	D-STAR
Data Rate	12 wpm or 20 Bps	9.6 kbps	DV Mode: 4.8 kbps
Modulation Type	FSK Non-Coherent	FSK Non-Coherent	GMSK
Coding	None	None	None
BER	10^{-5}	10^{-5}	10^{-5}
System Require Eb/No	13.35 dB	13.35 dB	9.72 dB
Demodulator Implementation Loss	1 dB	1 dB	1 dB
Eb/No Threshold	14.35 dB	14.35 dB	10.72 dB

IV.5.2 Simulation scenarios and output results of link budget for Low Earth Orbit satellite system

STK is firstly used to create the scenarios, the facility (ground station) and the nanosatellite for different orbit types, and then for each scenario, STK/Communications antenna, transmitter and receiver objects are exploited to model the communications involved in the system and evaluate the link budget.

A. Working with STK instruction

As we have already known how to create the scenarios, the facility and the satellite, in this section we have to know how to add a sensor, an antenna, a transmitter, a receiver to facility, satellite or satellite’s sensor, and how to generate a link budget report and add a minimum link budget constraint.

The satellite will be tracking the facility so it can transmit data to the facility. To do this, we need to attach a sensor that will act as a pointing mechanism for the antenna. Let’s start by adding a sensor to the satellite.

❖ Steps to add an Sensor:

- ➢ Attach a sensor ( ) to the Satellite.
- ➢ Rename the sensor.
- ➢ Open sensor’s ( ) Properties.
- ➢ Select the Basic – Pointing page.

- Set the Pointing Type to Targeted, set the Track Mode to Transpond, and set the About Boresight to Rotate.

Note: Transpond tracking mode means that the antenna points to the true location of the target object. This mode is the most appropriate for 2-way communications and is typically sufficient for all non-laser communications. Older scenarios are interpreted as using the Transpond tracking mode. Access computations including the computation of targeting times are performed based on the sensor being the transmitter of the signal.

- Select Station () in the Available Targets section.
- Move () Station to the Assigned Targets section.
- Click OK.

❖ Steps to add an Antenna:

- Select whether satellite's sensor or facility in the Object Browser that you want to attach the antenna to → Double-click the antenna icon in the Object Catalog to add an antenna.
- Rename the antenna's name in the Object Browser to a proper name by press F2 on the selected antenna.
- Open Antenna's () Properties Browser ( ).
- Select Basic – Definition page.
- Set the Type to Isotropic, and set the design frequency according to your system

Note: In fact, the type of our system antennas is whether Monopole (for satellite) or Yagi (for ground station). But, there has no such model/type of antenna in STK. To set such model/type of antenna in STK, we have to set the Type to Antenna Script and add a whether MATLAB or Visual Basic script file of such type of antenna. Also, STK must have a license to integrate with MATLAB or Visual Basic, for example the STK/MATLAB license. So, to simplifier the problem and as we don't have a STK/MATLAB license for our educational used only version of STK, we will set the Type to Isotropic with the antenna gain equal to zero dB, and we will set the antenna gain of Monopole or Yagi in the Additional Transmitter Gains/Losses tab of Transmitter or Receiver.

- Leave all other defaults.
- Click OK.

❖ Steps to add a Transmitter (Figure IV.24):

- Select whether satellite or facility in the Object Browser that you want to add a transmitter → Double-click a transmitter icon in the Object Catalog to add a transmitter.
- Rename the receiver's name to a proper name you want.
- Open the receiver () Properties Browser ( ).
- Select the Basic – Definition page.
- Set the Type to Complex TransmitterModel.
- Select Model Specs tab and set the value of frequency and power.
- Click on the Antenna Tab and set the Reference Type to Link. Note that Sensor/ "*Sensor's name*"/Antenna/ "*Antenna's name*" is the Antenna Name.
- Select Modulator tab, enter the value at Data Rate and choose the NFSK (for AX.25 and Beacon protocol) or BPSK (for D-STAR protocol) for Modulation Type, and make sure the Auto Scale is selected for Signal Bandwidth.

- Select Filter tab, and make sure the Use is unselected.

Note: As in STK, it doesn't have a GMSK modulation type and also as we don't have a STK/MATLAB license to integrate the MATLAB script file with STK for our educational used only version of STK, so to facility the simulation we will choose the BPSK instead of GMSK for D-STAR protocol.

- Select the Additional Gains and Losses tab and add and set the value of Antenna gain, and Total transmission line losses into the Pre-Receive Gains/Losses.
- Click OK.

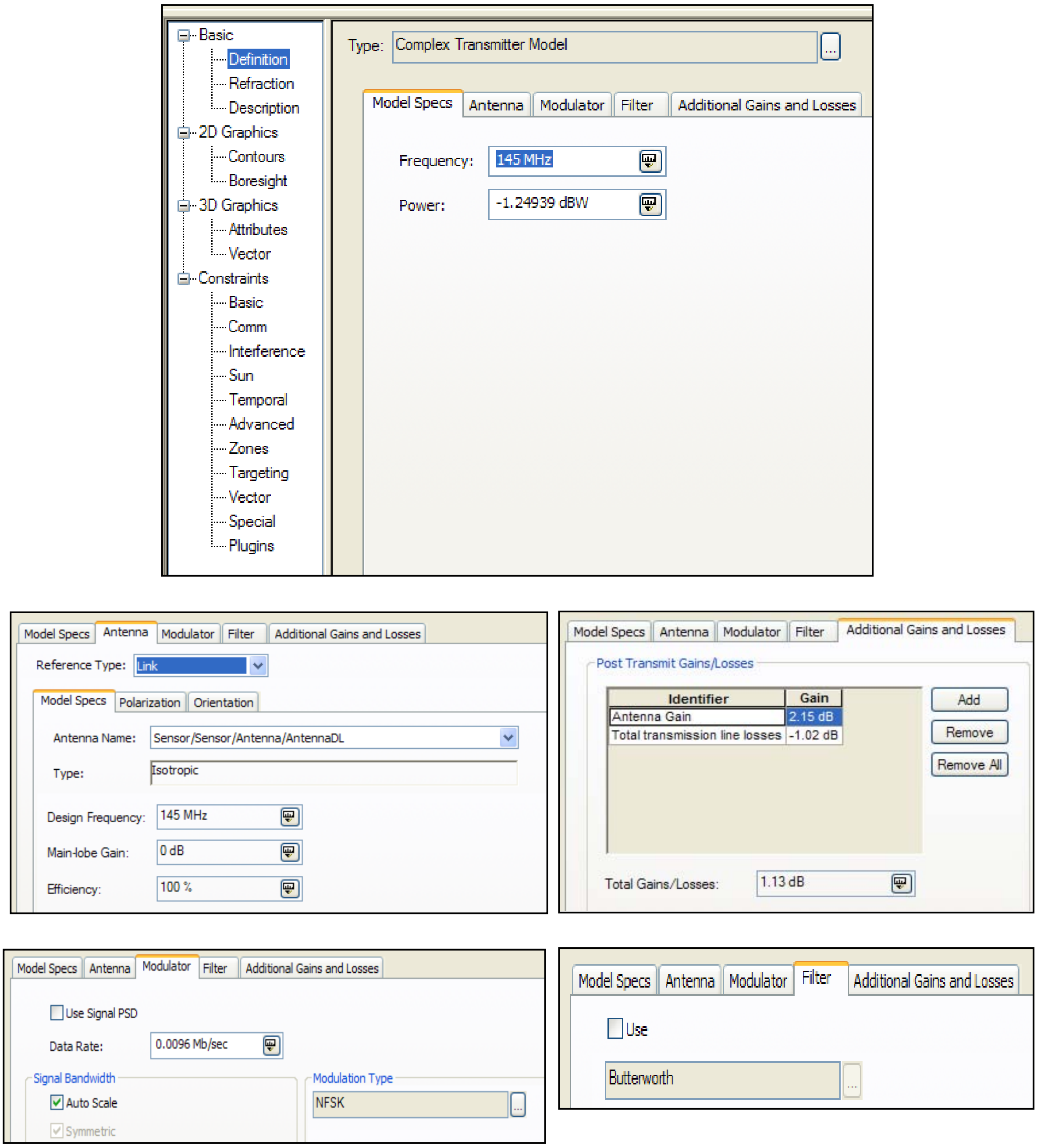


Figure IV.24: Adding a Transmitter in STK

❖ Steps to add a Receiver (Figure IV.25):

- Select whether satellite or facility in the Object Browser that you want to add a receiver → Double-click a receiver icon in the Object Catalog to add a receiver.
- Rename the receiver's name to a proper name you want.
- Open the receiver ( ) Properties Browser ( ).
- Select the Basic – Definition page.
- Set the Type to Complex Receiver Model.
- Select Model Specs tab and set all parameters in this tab. For example, set frequency to 145 MHz for downlink and make sure the Auto Track is selected, Eb/N_0 threshold to 14.35 dB for modulation NFSK as shown in Figure IV.25.
- Select the Antenna tab and set the Reference Type to Link. Note that Antenna/ "*Antenna's name*" is the Antenna Name.

<u>Note</u>: The linked antennas are independent of any receiver or transmitter and thus facilitate the sharing of the antenna by several transmitters and receivers. If you have multiple transponders attached to communication satellite, you can create an antenna object and have the transmitters or receivers reference it.

- Select the System Noise Temperature tab, select Constant and set the value.
- Select the Filter tab and make sure the Auto Scale is selected.
- Select the Additional Gains and Losses tab and add and set the value of Antenna pointing loss at TX, Antenna polarization loss at TX, Antenna pointing loss at RX, Antenna gain, Atmosphere losses, Ionosphere losses, Rain losses, and Total transmission line losses at RX into the Pre-Receive Gains/Losses.

<u>Note</u>: As in STK, it doesn't have the model of our antenna type (so as the antenna pointing loss, the antenna polarization loss), atmosphere losses, ionosphere losses, rain losses, and also as we don't have a STK/MATLAB license to integrate the MATLAB script file with STK for our educational used only version of STK, we'll add all these parameters as a constant value in the Additional Gains and Losses tab of the Receiver in order to simplifier the simulation.

- Click OK.

❖ Generating a Link Budget Report

You will be concentrating on an examination of the antenna Eb/No and the Bit Error Rate (BER). To check these values, you will create a Link Budget Report.

- Select Receiver ( ) in the Object Browser.
- Click Access Tool ( ).
- Select the selected Transmitter of your simulation in the Associated Objects panel.
- Click the Report & GraphManager…button.
- Turn off the Show Graphs option.
- If it not already expanded, expand the Installed Styles folder.
- Select the Link Budget – Detailed report.
- Click Generate…

<u>Note</u>: The link budget detailed report shows several more communication parameters than just the simple link budget report. But, in our case, the gain antenna, the atmosphere losses, the ionosphere losses, and etc, their value is not equal to zero dB. Hence, to generate the report for our simulation, we will create our report style that will hide the column of gain antenna, atmosphere looses, ionosphere losses, and etc.

➢ Close the Link Budget report.
➢ Close the Report & GraphManager.
➢ Close the Access Panel.

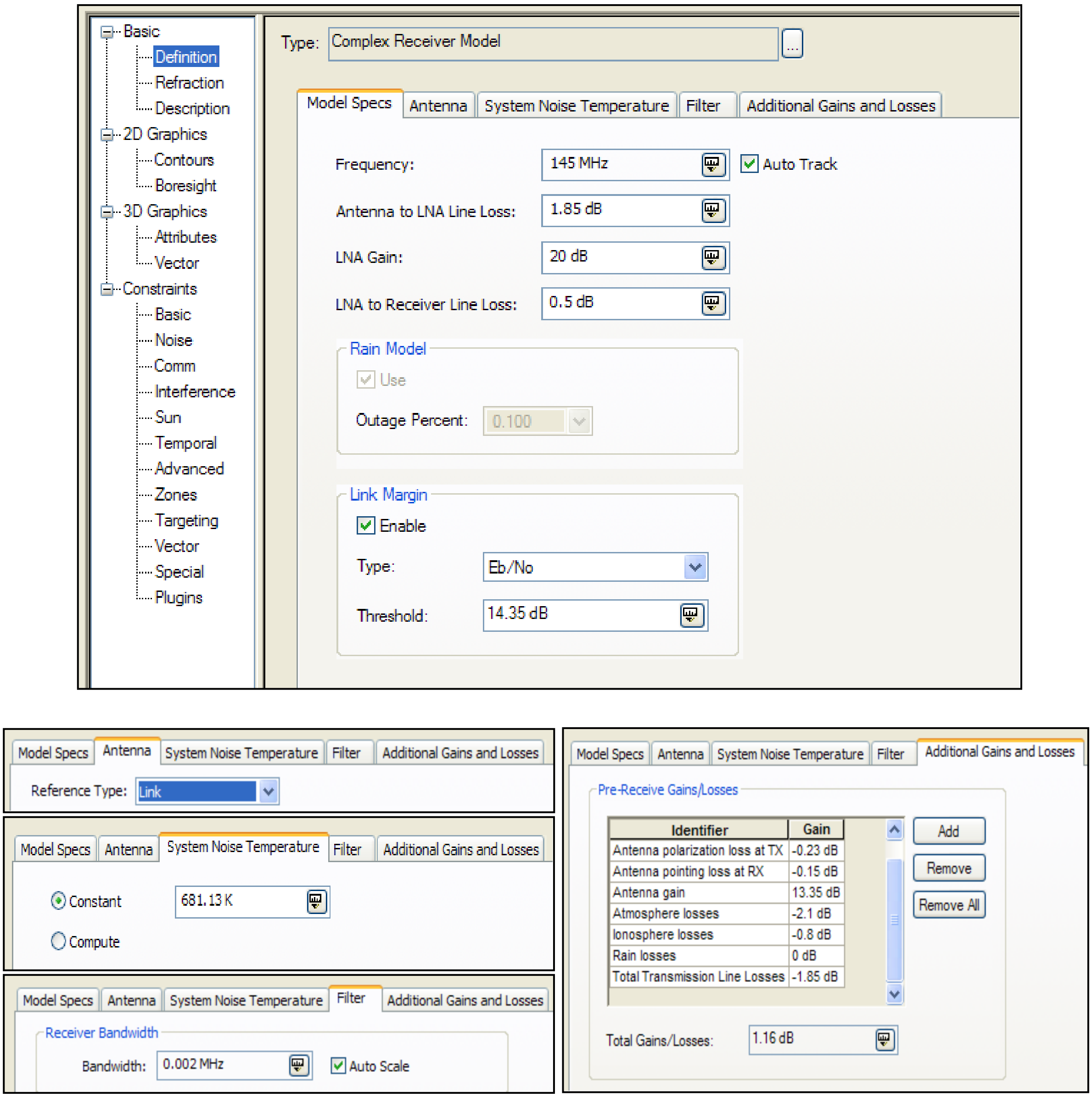


Figure IV.25: Adding a Receiver in STK

❖ To create a new Report Style of Link Budget (Figure IV.26):

➢ Select Receiver ( ) in the Object Browser.
➢ Click Access Tool ( ).
➢ Select the selected Transmitter of your simulation in the Associated Objects panel.
➢ Click the Report & GraphManager…button.
➢ Turn off the Show Graphs option.
➢ Select My Styles folder, click on icon to create a new report style and enter the name of the new report style for example KKBER

- Select Content page, type “Link information” below the Data Providers and click Filter button
- Select the “Time”, “Xmtr Power”, etc of the Link information data and click to the lists below the Report Contents as shown in Figure
- Click on Units… button to set the unit of the parameter
- Click Ok to apply and close.
- Select the KKBER report.
- Click Generate…
- Close the Link Budget report.
- Close the Report & GraphManager.
- Close the Access Panel.

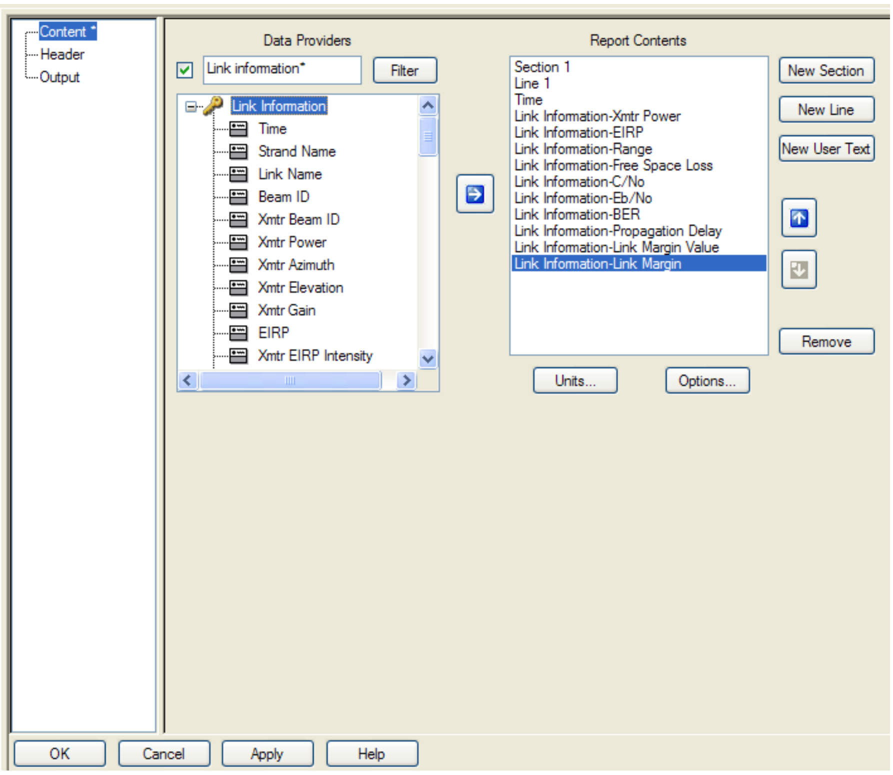


Figure IV.26: Creating a new Report Style of Link Budget in STK

- Steps to add a minimum Link Budget constraint on the receiver:
  - {Right-click Receiver in the Object Browser→ Select Properties → Go to Constraints-Basic page→ Go to Link Budget → Select Min → Input the constraint value → Click OK to apply and close.

B. <u>Output results of link budget for Low Earth Orbit satellite system</u>

B-1. Elliptical LEO orbit

By using the simulation software computation capabilities of STK and the characteristic data of the communication system studied in Table IV.22, we got the results of link budget for Elliptical LEO orbit in Table IV.23 and Table IV.24.

Table IV.23: Link budget results of elliptical LEO orbit with AX.25 and D-STAR protocol

AX.25 protocol	Downlink			Uplink		
		Min Eb/No	Max Eb/No		Min Eb/No	Max Eb/No
Time (UTCG)	7-Jul-11 10:00:00 AM	7-Jul-11 7:07:25 PM	7-Jul-11 10:03:24 AM	7-Jul-11 10:00:00 AM	7-Jul-11 7:07:25 PM	7-Jul-11 10:03:24 AM
Xmtr Power (dBW)	-1.249	-1.249	-1.249	14:24.0	13.01	13.01
EIRP (dBW)	-0.119	-0.119	-0.119	23.27	23.27	23.27
Range (km)	1721.897021	4169.070898	800.860447	1721.8561	4169.070972	800.859346
Free Space Loss (dB)	-140.3953	-148.0759	-133.7463	-149.9375	-157.6184	-143.2887
C/No (dB*Hz)	60.912165	53.231523	67.561171	69.354424	61.673575	76.003236
Eb/No (dB)	21.0895	13.4088	27.7385	29.5317	21.8509	36.1805
BER	6.21E-29	8.68E-06	1.00E-30	1.00E-30	1.00E-30	1.00E-30
Propagation Delay (sec)	0.006	0.014	0.003	0.006	0.014	0.003
Link Margin Value (dB)	14.35	14.35	14.35	14.35	14.35	14.35
Link Margin (dB)	6.7395	-0.9412	13.3885	15.1817	7.5009	21.8305
Without any constraint						
Number of access	8			8		
Total Duration of access (min)	92.208			92.207		
With a mininum link budget constraint of 6 dB						
Number of access	4			8		
Total Duration of access (min)	28.063			92.207		

D-STAR protocol	Downlink			Uplink		
		Min Eb/No	Max Eb/No		Min Eb/No	Max Eb/No
Time (UTCG)	7-Jul-11 10:00:00 AM	7-Jul-11 7:07:25 PM	7-Jul-11 10:03:24 AM	7-Jul-11 10:00:00 AM	7-Jul-11 7:07:25 PM	7-Jul-11 10:03:24 AM
Xmtr Power (dBW)	-1.249	-1.249	-1.249	14:24.0	13.01	13.01
EIRP (dBW)	-0.119	-0.119	-0.119	23.27	23.27	23.27
Range (km)	1721.897021	4169.070898	800.860447	1721.8561	4169.070972	800.859346
Free Space Loss (dB)	-140.3953	-148.0759	-133.7463	-149.9375	-157.6184	-143.2887
C/No (dB*Hz)	60.912165	53.231523	67.561171	69.354424	61.673575	76.003236
Eb/No (dB)	24.0998	16.4191	30.7488	32.542	24.8612	39.1908
BER	1.00E-30	3.83E-21	1.00E-30	1.00E-30	1.00E-30	1.00E-30
Propagation Delay (sec)	0.006	0.014	0.003	0.006	0.014	0.003
Link Margin Value (dB)	10.72	10.72	10.72	10.72	10.72	10.72
Link Margin (dB)	13.3798	5.6991	20.0288	21.822	14.1412	28.4708
Without any constraint						
Number of access	8			8		
Total Duration of access (min)	92.208			92.207		
With a mininum link budget constraint of 6 dB						
Number of access	8			8		
Total Duration of access (min)	91.681			92.207		

Table IV.24: Link budget results of elliptical LEO orbit with Beacon protocol

Beacon protocol	Downlink		
		Min Eb/No	Max Eb/No
Time (UTCG)	7-Jul-11 10:00:00 AM	7-Jul-11 7:07:25 PM	7-Jul-11 10:03:24 AM
Xmtr Power (dBW)	-10	-10	-10
EIRP (dBW)	-8.87	-8.87	-8.87
Range (km)	1721.897021	4169.070898	800.860447
Free Space Loss (dB)	-140.3953	-148.0759	-133.7463
C/No (dB*Hz)	52.161552	44.48091	58.810559
Eb/No (dB)	39.1513	31.4706	45.8003
BER	1.00E-30	1.00E-30	1.00E-30
Propagation Delay (sec)	0.006	0.014	0.003
Link Margin Value (dB)	14.35	14.35	14.35
Link Margin (dB)	24.8013	17.1206	31.4503
Without any constraint			
Number of access	8		
Total Duration of access (min)	92.208		
With a mininum link budget constraint of 6 dB			
Number of access	8		
Total Duration of access (min)	92.208		

According to the Table IV.23 and IV.24, we can observe that:

- The uplink and downlink total access is nearly the same, about 92.21 minutes. A slightly difference 0.001 minutes is because in STK the Access computations including the computation of targeting times are performed based on the sensor being the transmitter of the signal.
- There is no effect of the total access with the minimum link budget constraint of 6 dB when the minimum link margin is bigger than 6 dB.
- For uplink of Elliptical LEO orbit with AX.25 protocol, the minimum link margin is 7.5009 dB and the maximum link margin is 21.8305 dB.
- For downlink of Elliptical LEO orbit with AX.25 protocol, the minimum link margin is -0.9412 dB and the maximum link margin is 13.3885 dB. So, with the minimum link budget constraint of 6 dB, the total duration of access is reduced from 92.208 minutes to 28.063 minutes.
- For uplink of Elliptical LEO orbit with D-STAR protocol, the minimum link margin is 5.6991 dB and the maximum link margin is 20.0288 dB. So, with the minimum link budget constraint of 6 dB, the total duration of access is reduced from 92.208 minutes to 91.681 minutes.
- For downlink of Elliptical LEO orbit with D-STAR protocol, the minimum link margin is 14.1412 dB and the maximum link margin is 28.4708 dB.
- For uplink of Elliptical LEO orbit with Beacon protocol, the minimum link margin is 17.1206 dB and the maximum link margin is 31.4503 dB.
- The higher range is the higher propagation delay.
- Without changing the orbit, the link margin can be improved by whether increasing the receiver or transmitter gain and consequently EIRP and C/N_0, or by reducing the data rate.

Table IV.25: Link budget results of circular LEO "Inclined" orbit with AX.25 and D-STAR protocol

AX.25 protocol	Downlink			Uplink		
		Min Eb/No	Max Eb/No		Min Eb/No	Max Eb/No
Time (UTCG)	7-Jul-11 10:00:00 AM	7-Jul-11 11:50:21 AM	8-Jul-11 8:51:43 AM	7-Jul-11 10:00:00 AM	7-Jul-11 11:50:21 AM	8-Jul-11 8:51:43 AM
Xmtr Power (dBW)	-1.249	-1.249	-1.249	14:24.0	13.01	13.01
EIRP (dBW)	-0.119	-0.119	-0.119	23.27	23.27	23.27
Range (km)	1867.728014	2998.980326	675.121807	1867.68903	2998.982503	675.122047
Free Space Loss (dB)	-141.1014	-145.2146	-132.2628	-150.6437	-154.757	-141.8052
C/No (dB*Hz)	60.206035	56.092836	69.044665	68.648269	64.534882	77.486715
Eb/No (dB)	20.3833	16.2701	29.222	28.8256	24.7122	37.664
BER	9.56E-25	3.16E-10	1.00E-30	1.00E-30	1.00E-30	1.00E-30
Propagation Delay (sec)	0.006	0.01	0.002	0.006	0.01	0.002
Link Margin Value (dB)	14.35	14.35	14.35	14.35	14.35	14.35
Link Margin (dB)	6.0333	1.9201	14.872	14.4756	10.3622	23.314
Without any constraint						
Number of access	9			9		
Total Duration of access (min)	99.154			99.154		
With a mininum link budget constraint of 6 dB						
Number of access	4			9		
Total Duration of access (min)	30.63			99.154		

D-STAR protocol	Downlink			Uplink		
		Min Eb/No	Max Eb/No		Min Eb/No	Max Eb/No
Time (UTCG)	7-Jul-11 10:00:00 AM	7-Jul-11 11:50:21 AM	8-Jul-11 8:51:43 AM	7-Jul-11 10:00:00 AM	7-Jul-11 11:50:21 AM	8-Jul-11 8:51:43 AM
Xmtr Power (dBW)	-1.249	-1.249	-1.249	14:24.0	13.01	13.01
EIRP (dBW)	-0.119	-0.119	-0.119	23.27	23.27	23.27
Range (km)	1867.728014	2998.980326	675.121807	1867.68903	2998.982503	675.122047
Free Space Loss (dB)	-141.1014	-145.2146	-132.2628	-150.6437	-154.757	-141.8052
C/No (dB*Hz)	60.206035	56.092836	69.044665	68.648269	64.534882	77.486715
Eb/No (dB)	23.3936	19.2804	32.2323	31.8359	27.7225	40.6743
BER	1.00E-30	1.00E-30	1.00E-30	1.00E-30	1.00E-30	1.00E-30
Propagation Delay (sec)	0.006	0.01	0.002	0.006	0.01	0.002
Link Margin Value (dB)	10.72	10.72	10.72	10.72	10.72	10.72
Link Margin (dB)	12.6736	8.5604	21.5123	21.1159	17.0025	29.9543
Without any constraint						
Number of access	9			9		
Total Duration of access (min)	99.154			99.154		
With a mininum link budget constraint of 6 dB						
Number of access	9			9		
Total Duration of access (min)	99.154			99.154		

Table IV.26: Link budget results of circular LEO "Inclined" orbit with Beacon protocol

Beacon protocol	Downlink		
		Min Eb/No	Max Eb/No
Time (UTCG)	7-Jul-11 10:00:00 AM	7-Jul-11 11:50:21 AM	8-Jul-11 8:51:43 AM
Xmtr Power (dBW)	-10	-10	-10
EIRP (dBW)	-8.87	-8.87	-8.87
Range (km)	1867.728014	2998.980326	675.121807
Free Space Loss (dB)	-141.1014	-145.2146	-132.2628
C/No (dB*Hz)	51.455423	47.342223	60.294053
Eb/No (dB)	38.4451	34.3319	47.2838
BER	1.00E-30	1.00E-30	1.00E-30
Propagation Delay (sec)	0.006	0.01	0.002
Link Margin Value (dB)	14.35	14.35	14.35
Link Margin (dB)	24.0951	19.9819	32.9338
Without any constraint			
Number of access	9		
Total Duration of access (min)	99.154		
With a mininum link budget constraint of 6 dB			
Number of access	9		
Total Duration of access (min)	99.154		

B-2. Circular LEO "Inclined" orbit

By using the simulation software computation capabilities of STK and the characteristic data of the communication system studied in Table IV.22, we got the results of link budget for Circular LEO "Inclined" orbit in Table IV.25 and Table IV.26 above.

According to the Table IV.25 and IV.26, we can observe that:

- There is no effect of the total access with the minimum link budget constraint of 6 dB when the minimum link margin is bigger than 6 dB.
- For uplink of circular LEO "Inclined" orbit with AX.25 protocol, the minimum link margin is 10.3622 dB and the maximum link margin is 23.314 dB.
- For downlink of circular LEO "Inclined" orbit with AX.25 protocol, the minimum link margin is 1.9201 dB and the maximum link margin is 14.872 dB. So, with the minimum link budget constraint of 6 dB, the total duration of access is reduced from 99.154 minutes to 30.63 minutes.
- For uplink of circular LEO "Inclined" with D-STAR protocol, the minimum link margin is 17.0025 dB and the maximum link margin is 29.9543 dB.
- For downlink of circular LEO "Inclined" with D-STAR protocol, the minimum link margin is 8.5604 dB and the maximum link margin is 21.5123 dB.
- For uplink of circular LEO "Inclined" with Beacon protocol, the minimum link margin is 17.1206 dB and the maximum link margin is 31.4503 dB.
- The higher range is the higher propagation delay.
- Without changing the orbit, the link margin can be improved by whether increasing the receiver or transmitter gain and consequently EIRP and C/N_0, or by reducing the data rate.

IV.5.3 Summary of output link budget results for Low Earth Orbit satellite system

According to the Table IV.28, we can notice that:

- The smaller size of orbit is the better link margin of the system. For instance, the circular LEO "inclined" orbit has a better link margin than the elliptical LEO orbit.

Table IV.27: Summary of output link budget results for Low Earth Orbit satellite system

	AX.25 protocol	Min Eb/No	Max Eb/No
	Downlink		
Elliptical LEO Orbit	Link Margin (dB)	-0.9412	13.3885
Circular LEO "Inclined" Orbit	Link Margin (dB)	1.9201	14.872
	Uplink		
Elliptical LEO Orbit	Link Margin (dB)	7.5009	21.8305
Circular LEO "Inclined" Orbit	Link Margin (dB)	10.3622	23.314
	D-STAR protocol	Min Eb/No	Max Eb/No
	Downlink		
Elliptical LEO Orbit	Link Margin (dB)	5.6991	20.0288
Circular LEO "Inclined" Orbit	Link Margin (dB)	8.5604	21.5123
	Uplink		
Elliptical LEO Orbit	Link Margin (dB)	14.1412	28.4708
Circular LEO "Inclined" Orbit	Link Margin (dB)	17.0025	29.9543
	Beacon protocol	Min Eb/No	Max Eb/No
	Downlink		
Elliptical LEO Orbit	Link Margin (dB)	17.1206	31.4503
Circular LEO "Inclined" Orbit	Link Margin (dB)	19.9819	32.9338

Conclusion

Throughout this chapter, we have demonstrated the orbital mechanics, the constellation for continuous whole Earth coverage, the constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations and the link budget between OUFTI1 nanosatellite and Liege ground station for different orbit types by the implementation under the simulation software program STK. We have verified that:

- The orbit with the smaller size will result in higher time rate of change of ω ($d\omega$) and time variation of R.A.A.N ($d\Omega$), shorter duration of visibility hence required more total number of satellites for constellation for continuous whole Earth coverage constellation, and smaller value of free space path losses hence providing a better value of link margin (better link budget);
- The orbit with very smaller inclination, for example the elliptical VLEO orbit with inclination 40°, cannot provide a (continuous) whole Earth coverage;
- The constellation for (continuous) coverage for an area specific required less satellites than the constellation for (continuous) whole Earth coverage;
- The constellation for (continuous) coverage for an area specific for elliptical orbit would provide a quite better optimal constellation than the constellation for circular orbit when the specific locations are well selected because the circular orbit doesn't loiter at apogee like the elliptical orbit.

CHAPTER V

"Conclusion"

V.1 Conclusion

In this thesis, we have dealt with many things about nanosatellites by going through three main parts: literature part, theoretical part, and the realization and simulation part.

- Literature part: state of the art of the development of the nanosatellites – technologies and applications. We have going through an overview of nanosatellite system including history of nanosatellite, general characteristic of nanosatellite system, characteristic of nanosatellite, nanosatellite subsystem, advantages and disadvantages of nanosatellite, nanosatellite challenges and application of nanosatellites.

- Theoretical part: conception elements of nanosatellite systems. We have studied about the conception elements of nanosatellite system: the definition of missions, the space segment, the ground segment, the space environment, the physical layer and data layer, and particularly the orbital mechanic, the satellite constellation and the link budget. We have noticed the effect of the orbit size, the frequency and the modulation types on nanosatellite communications. The orbit with bigger size has smaller time rate of change of ω ($d\omega$) and the time variation of R.A.A.N ($d\Omega$), bigger zone coverage, longer duration of visibility, requires smaller number of planes and total number of satellites for constellation, and has a better link budget. For the effect of frequency on nanosatellite communications, we have seen that the lower frequency provides the better link budget of communication link, hence less minimum transmitter power. As for the effect of modulation type, the modulation with or without coding which required less Eb/No provides a better link budget of communication link, consequently, the less minimum transmitter power.

- Realization and simulation: realization of a simulator for orbital mechanics and communication performance analysis. Throughout this chapter, we have demonstrated the orbital mechanics, the constellation for continuous whole Earth coverage, the constellation for optimized, cost-effective Low Earth Orbit satellite system between two specified locations and the link budget between OUFTI1 nanosatellite and Liege ground station for different orbit types by the implementation under the simulation software program STK.

The study of nanosatellite system achieved in this thesis is hard to obtain, but also an interesting subject that can lead to further researches in various disciplines of the sciences engineering, especially in space communication for example the research of the efficiency modulation type, the data management protocol, the signal processing, and etc. In the end, the nanosatellite is a better choice for a "Faster, Better, Smaller, Cheaper" space communication.

REFERENCES

[1] MARAL Gérard; BOUSQUET Michel. *SATELLITE COMMUNICATIONS SYSTEMS-Systems, Techniques and Technology*, 5^{e} edition. New York: John Wiley & Sons Ltd, 2009.

[2] ITU-R Study Group 4 (SG 4). *HANDBOOK ON SATELLITE COMMUNICATIONS (HSC)*, 3^{e} edition. Geneva, 1995.

[3] Wiley J. LARSON; James R. WERTZ. *Space Mission Analysis and Design, 3^{e} edition*. California: Microcosm Press, 2005.

[4] A. Denis; J. Pisane. *OUFTI-1 Phase A : Mission definition, Space and ground systems description*. Université de Liège, Septembre 2009.

[5] Howard D. Curtis, " Orbital Mechanics for Engineering Students", 2e édition, Butterworth-Heinemann / Elsevier, 2010, 740 pages.

[6] "Air University Space Primer", Air University, Maxwell AFB, AL, USA, Auhust 2003.

[7] William A. Beech; Douglas E. Nielsen, Jack Taylor. *AX.25 Link Access Protocol for Amateur Packet Radio*, version 2.2. American Radio Relay League, Inc, 1993.

[8] Nicolas CROSSET. *Implémentation du relais D-STAR à bord du nanosatellite OUFTI-1*. Université de Liège, 28 juin 2010.

[9] Innovative Solutions In Space. <http://www.isispace.nl/>

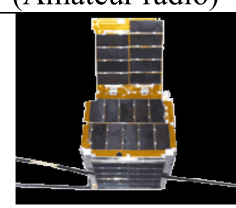
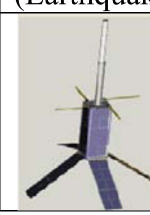
[10] A Brief Chronology of Amateur Satellites. <http://www.amsat.org/amsat-new/satellites/history.php>

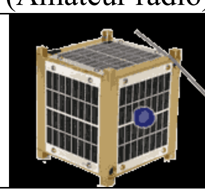
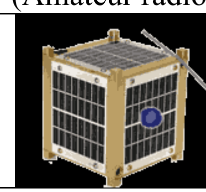
[11] BURLACU Maria-Mihaela; LORENZ Pascal, 09/24/2010, A survey of small satellites domain: challenges, applications and communications key issues. <http://icast-magazine.org/2010/09/survey-small-satellites-domain-challenges-applications-and-communications-key-issues>

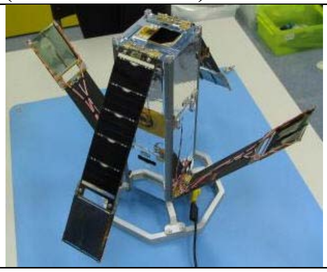
[12] <http://space.au.af.mil/primer/index.htm>.

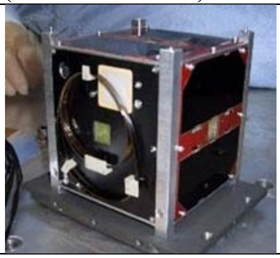
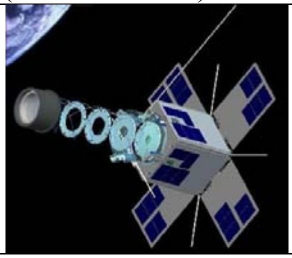
ANNEX I

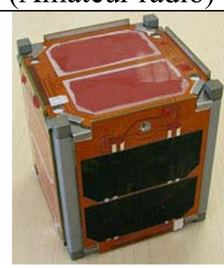
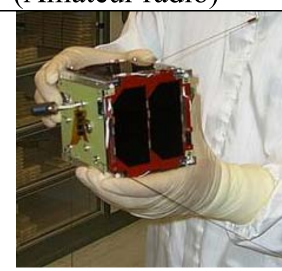
Table 1: History of nanosatellites

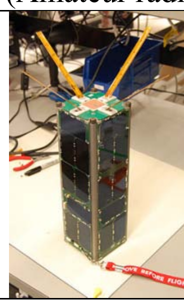
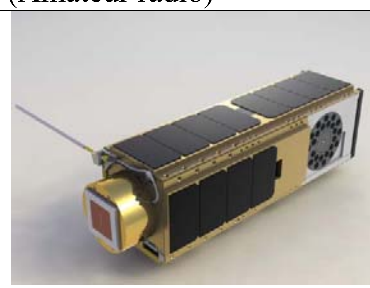
Year	**1961**	**2000**	**2003**	
Name	OSCAR	ASU-OSCAR 37 (ASUSAT)	Cubesat-OSCAR 55	Quakesat
Date	12 December, 1961	27 January, 2000	30 June, 2003	June 30, 2003 on Rockot
Mass	4.5 kg	6 kg	1 kg	5 kg
Size	?	?	10 x 10 x 10 cm	10×10×32 cm
Types of orbit	VLEO Apogee:431.00 km Perigee:245.30 km	LEO Apogee: 799.00 km Perigee: 746.30 km	LEO Apogee: 831.00 km Perigee: 816.39 km	LEO Apogee: 837.9 km Perigee: 824.1km
Inclination	81.14°	100.19°	98.72°	98.72°
Period [minutes]	91.30	100.30	101.37	101.53
Launch vehicle	?	Minotaur-1	Dnepr	Rokot/Briz-KM
Launch location	Vandenberg Air Force Base, California, in United States	Vandenberg Air Force Base, California, in United States	Baikonur Cosmodrome, Kazakhstan	Plesetsk Cosmodrome, Arkhangelsk Oblast
Project/organization	OSCAR	Arizona State University	Tokyo Institute of Technology Matunaga LSS	Stanford University
Nation/Country	USA	USA	Japan	USA
Frequency band	VHF (Downlink 144.9830 MHz)	UHF?	UHF (Downlink 437.4000 MHz AFSK 1200 BPS)	UHF (436.675MHz 9600 bps FSK)
Application	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Earth observation (Earthquake detection)
Image				

Year	**2003**		**2005**	**2006**
Name	CubeSat-OSCAR 57 (CubeSat XI-IV)	RS-22	CubeSat-OSCAR 58 (Cubesat XI-V)	GeneSat-1
Date	30 June, 2003	27 September, 2003	27 October, 2005	16 December, 2006
Mass	1 kg	1 kg?	1 kg	4.500 kg
Size	10 x 10 x 10 cm	10 x 10 x 10 cm?	10 x 10 x 10 cm	10cm x 10cm x 30cm
Types of orbit	LEO Apogee: 832.00 km Perigee: 817.00 km	LEO Apogee: 693.00 km Perigee: 675.00 km	LEO Apogee: 709.00 km Perigee: 682.00 km	VLEO Apogee: 370.00 km Perigee: 368.00 km
Inclination	98.72 °	98.10°	98.18°	40.02°
Period [minutes]	101.39	98.44	98.68	91.93
Launch vehicle	Dnepr	Dnepr	Cosmos	Minotaur-1
Launch location	Baikonur Cosmodrome, Kazakhstan	Baikonur Cosmodrome, Kazakhstan	Plesetsk MSC (Multi Space Camera)	NASA Wallops Flight Facility, Mid-Atlantic Regional Spaceport (MARS)
Project/organization	University of Tokyo	Mozhaisky Military Space University	University of Tokyo	National Aeronautics and Space Administration (NASA)
Nation/Country	Japan	Russia	Japan	USA
Frequency band	UHF (Downlink 437.4900 MHz AFSK 1200 BPS)	UHF (Downlink 435.3520 MHz)	UHF (Downlink 437.3450 MHz AFSK 1200 BPS)	UHF (Downlink 437.0750 MHz AFSK 1200 BPS)
Application	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)
Image				

Year	2007	2008		
Name	CAPE-1	Delfi OSCAR-64 (Delfi-C3)	Cubesat Oscar-65 (Cute-1.7 + APD II)	Cubesat Oscar - 66 (SEEDS II)
Date	2007-04-17	28 April, 2008	28 April, 2008	28 April, 2008
Mass	?	2.2 kg	3 kg	1 kg
Size	CubeSat (1U)	10cm x 10cm x 34cm	20cmx15cmx10cm	10 x 10 x 10 cm
Types of orbit	LEO	LEO Apogee: 642.10 km Perigee: 621.60 km	LEO Apogee: 641.90 km Perigee: 622.30 km	LEO Apogee: 642.90 km Perigee: 621.80 km
Inclination	?	98.00°	98.00°	98.00 °
Period [minutes]	?	97.35	97.36	97.36
Launch vehicle	Dnepr	PSLV	PSLV	PSLV
Launch location	Baikonur Cosmodrome, Kazakhstan	Satish Dawan Space Center, India	Satish Dawan Space Center, India	Satish Dawan Space Center, India
Project/organization	University of Louisiana at Lafayette (Students)	Delft University of Technology	Tokyo Institute of Technology	Nihon University
Nation/Country	?	Netherlands	Japan	Japan
Frequency band	?	VHF (Downlink 145.8700 MHz BPSK 1200 BPS)	UHF (437.4750 MHz GMSK 9600 BPS)	UHF (Downlink 437.4850 MHz FM)
Application	Technology Demonstration	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)
Image	?			

Year	**2008**	**2009**		
Name	COMPASS-1	PRISM	KKS-1	STARS
Date	28 April, 2008	23 January, 2009	23 January, 2009	23 January, 2009
Mass	1 kg	8 kg	3 kg	8 kg
Size	1U CubeSat	19cm x 19cm x 30cm	15cm x 15cm x 15cm	16cm x 16cm x 16cm
Types of orbit	LEO Apogee: 642.30 km Perigee: 621.50 km	LEO Apogee: 670.00 km Perigee: 660.00 km	LEO Apogee: 670.00 km Perigee: 660.00 km	LEO Apogee: 670.00 km Perigee: 660.00 km
Inclination	98.00°	98.03°	98.00 °	98.00°
Period [minutes]	97.35	98.04	98.04	98.04
Launch vehicle	PSLV	H-IIA F15	H-IIA F15	H-IIA F15
Launch location	Satish Dawan Space Center, India	Tanegashima Space Center, Tanegashima	Tanegashima Space Center, Tanegashima	Tanegashima Space Center, Tanegashima
Project/organization	Aachen University of Applied Sciences	Intelligent Space Systems Laboratory (ISSL) of University of Tokyo	Tokyo Metropolitan College of Industrial Technology	Kagawa University
Nation/Country	Germany	Japan	Japan	Japan
Frequency band	UHF (Downlink 437.4050 MHz AFSK 1200 BPS)	UHF (Downlink 437.4250 MHz AFSK 1200 BPS)	UHF (Downlink 437.4450 MHz AX.25)	UHF (Downlink 437.4850 MHz AX.25)
Application	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)
Image			?	

Year	**2009**			
Name	SwissCube	ITUpSAT1	UWE-2	BEESAT
Date	23 September, 2009	23 September, 2009	23 September, 2009	23 September, 2009
Mass	1 kg	1 kg	1 kg	1 kg
Size	10cm cube	10cm cube	10cm cube	10cm cube
Types of orbit	LEO Apogee: 752.00 km Perigee: 726.00 km	LEO Apogee: 752.00 km Perigee: 726.00 km	LEO Apogee: 752.00 km Perigee: 726.00 km	LEO Apogee: 752.00 km Perigee: 726.00 km
Inclination	98.28°	98.29°	98.30°	98.30°
Period [minutes]	99.59	99.59	99.59	99.59
Launch vehicle	PSLV-C14	PSLV-C14	PSLV-C14	PSLV-C14
Launch location	Satish Dawan Space Center, India	Satish Dawan Space Center, India	Satish Dawan Space Center, India	Satish Dawan Space Center, India
Project/organization	Ecole Polytechnique Federale De Lausanne	Istanbul Teknik Universitesi	Universitat Wurzburg	Technische Universitat Berlin
Nation/Country	Switzerland	Turkey	Germany	Germany
Frequency band	UHF (Downlink 437.5050 MHz FSK 1200 BPS)	UHF (Downlink 437.3250 MHz)	UHF (Downlink 437.3850 MHz FSK 9600 BPS)	UHF (Downlink 436.0000 MHz GMSK 9600 BPS)
Application	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)
Image				

Year	2010			
Name	RAX	O/OREOS		
Date	20 November, 2010	20 November, 2010		
Mass	2.8 kg	5.5 kg		
Size	10cmx10cmx34cm	10cmx10cmx34cm		
Types of orbit	LEO Apogee: 650.00 km Perigee: 650.00 km	LEO Apogee: 650.00 km Perigee: 650.00 km		
Inclination	72.00°	72.00°		
Period [minutes]	97.73	97.73		
Launch vehicle	Minotaur IV	Minotaur IV		
Launch location	Kodiak, Alaska, USA	Kodiak, Alaska, USA		
Project/organization	University of Michigan and SRI International	NASA Ames and Santa Clara University		
Nation/Country	USA	USA		
Frequency band	UHF (Downlink 437.5050 MHz GMSK 9600 BPS)	UHF (Downlink 437.3050 MHz AX.25 1200 BPS)		
Application	Telecommunications (Amateur radio)	Telecommunications (Amateur radio)		
Image				

ANNEX II

A.II.1 Formulas of orbital mechanics

Input parameters				
Variable inputs		Fixed inputs		
Name : Name of orbit type		Earth gravity constant	u =398600.607	[km^3/s^2]
f_up : Frequency uplink	[MHz]	Earth Radius	Re = 6378.136	[km]
f_down : Frequency downlink	[MHz]	Second zonal harmonic of the Earth planet	J2 = 1.08263*10^-3	[Unit less]
elev : Elevation angle	[degrees]	Radians to degrees	rad2deg = 180/pi	[Unit less]
ha : Height of apogee	[km]	Degrees to radians	deg2rad = pi/180	[Unit less]
hp : Height of perigee	[km]	Seconds to minutes	sec2mn = 1/60	[Unit less]
Relative spacing between satellites in adjacent planes F (0<= F <= P-1)	[Unit less]			
Inclination (i)	[degrees]			
Argument of perigee (w)	[degrees]			
R.A.A.N: Right Ascension of the Ascending node (o)	[degrees]			
True anomaly initial (v)	[degrees]			

Calculation parameters		
1/ Orbital Parameters		
Semimajor axis (a)	a = (ha+hp+2*Re)/2	[km]
Eccentricity (e)	e = [(ha+Re)-(hp+Re)]/[(ha+Re)+(hp+Re)]	[Unit less]
Orbit period (T)	T = (2*pi) * a* sqrt(a/u)*sec2mn	[minutes]
Initial Value of eccentric (E)	E_ini = 2*atan(sqrt((1-e)/(1+e))*tan(v/2*deg2rad));	[rad]
Mean anomaly (M)	M_ini = E_ini-e*sin(E_ini);	[rad]
Time rate of change of w (dw)	dw = -[3/2*(sqrt(u)*J2*Re^2)/((1-e^2)^2*(a^(7/2)))]*(5/2*(sin(i*deg2rad))^2-2)	[rad/s]
	dw_DegPerDay = dw*rad2deg*3600*24	[deg/day]
Time variation of R.A.A.N (do)	do = -[3/2*(sqrt(u)*J2*Re^2)/((1-e^2)^2*(a^(7/2)))]*cos(i*deg2rad)	[rad/s]
	do_DegPerDay = do*rad2deg*3600*24;	[deg/day]

Sun-synchronous inclination	X=-0.098919152*(1-e^2)^2*(a/Re)^3.5;
	if -1<=X && X<=1
	i_SunSynchro = acos(X)*rad2deg;
	fprintf('\n Sun-synchronous inclination \t\t %.2f \t\t degrees', i_SunSynchro);
	else
	fprintf('\n Sun-synchronous inclination \t\t None');
	end;
		[degrees]

	Orbit radius	
Minimum orbit radius	r_min = hp+Re	[km]
Maximum orbit radius	r_max = ha+Re	[km]
Mean orbit radius	r_mean = a	[km]
2/ Slant Range and Free Space Path Loss		
	Slant range	
Slant range	S = sqrt(r^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad)	[km]
Minimum slant range	S_min = sqrt(r_min^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad)	[km]
Maximum slant range	S_max = sqrt(r_max^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad)	[km]
Mean slant range	S_mean = sqrt(r_mean^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad)	[km]
	Wavelength	
Wavelength uplink	Lambda_up = c/(f_up*10^6)	[m]
Wavelength Downlink	Lambda_down = c/(f_down*10^6)	[m]

Free Space (FS) path loss		
Uplink		
Uplink FS path loss	L_up=22+20*log10((S*1000)/Lambda_up)	[dB]
Minimum FS path loss	L_min_up=22+20*log10((S_min*1000)/Lambda_up)	[dB]
Maximum FS path loss	L_max_up=22+20*log10((S_max*1000)/Lambda_up)	[dB]
Mean FS path loss	L_mean_up=22+20*log10((S_mean*1000)/Lambda_up)	[dB]
Downlink		
Downlink FS path loss	L_down=22+20*log10((S*1000)/Lambda_down)	[dB]
Minimum FS path loss	L_min_down=22+20*log10((S_min*1000)/Lambda_down)	[dB]
Maximum FS path loss	L_max_down=22+20*log10((S_max*1000)/Lambda_down)	[dB]
Mean FS path loss	L_mean_down=22+20*log10((S_mean*1000)/Lambda_down)	[dB]
3/ Zone Coverage, Duration of Visibility and Number of Satellite Required for Continuous Coverage		
Nadir angle		
Nadir angle	alpha = asin(Re/r*cos(elev*deg2rad))*rad2deg	[degrees]
Minimum nadir angle	alpha_min = asin(Re/r_max*cos(elev*deg2rad))*rad2deg	[degrees]
Maximum nadir angle	alpha_max = asin(Re/r_min*cos(elev*deg2rad))*rad2deg	[degrees]
Mean nadir angle	alpha_mean = asin(Re/r_mean*cos(elev*deg2rad))*rad2deg	[degrees]
Central angle		
Central angle	beta = acos((Re/r*cos(elev*deg2rad)))*rad2deg-elev	[degrees]
Minimum central angle	beta_min = acos((Re/r_min*cos(elev*deg2rad)))*rad2deg-elev	[degrees]
Maximum central angle	beta_max = acos((Re/r_max*cos(elev*deg2rad)))*rad2deg-elev	[degrees]
Mean central angle	beta_mean = acos((Re/r_mean*cos(elev*deg2rad)))*rad2deg-elev	[degrees]
Footprint length		
Footprint length	FPL = 2*Re*beta*deg2rad	[km]
Minimum footprint length	FPL_min = 2*Re*beta_min*deg2rad	[km]
Maximum footprint length	FPL_max = 2*Re*beta_max*deg2rad	[km]
Mean footprint length	FPL_mean = 2*Re*beta_mean*deg2rad	[km]
Footprint area		
Footprint area	FPA = 2*pi*Re^2*(1-cos(beta*deg2rad))	[km^2]
Minimum footprint area	FPA_min = 2*pi*Re^2*(1-cos(beta_min*deg2rad))	[km^2]
Maximum footprint area	FPA_max = 2*pi*Re^2*(1-cos(beta_max*deg2rad))	[km^2]
Mean footprint area	FPA_mean = 2*pi*Re^2*(1-cos(beta_mean*deg2rad))	[km^2]
Velocity of the satellite		
Velocity of satellite	V = sqrt(u*10^6*(2/r-1/a))	[m/s]
Minimum velocity of satellite	V_min = sqrt(u*10^6*(2/r_max-1/a))	[m/s]
Maximum velocity of satellite	V_max = sqrt(u*10^6*(2/r_min-1/a))	[m/s]
Mean velocity of satellite	V_mean = sqrt(u*10^6*(2/r_mean-1/a))	[m/s]
Duration of Visibility		
Duration of visibility	t = FPL*10^3/V*sec2mn	[minutes]
Minimum duration of visibility	t_min = FPL_min*10^3/V_max*sec2mn	[minutes]
Maximum duration of visibility	t_max = FPL_max*10^3/V_min*sec2mn	[minutes]
Mean duration of visibility	t_mean = FPL_mean*10^3/V_mean*sec2mn	[minutes]
Number of satellites required for continuous coverage		
Number of satellite required	N = ceil(T/t)	[Unit less]
Minimum number of satellite required	N_min = ceil(T/t_max)	[Unit less]
Maximum number of satellite required	N_max = ceil(T/t_min)	[Unit less]
Mean number of satellite required	N_mean = ceil(T/t_mean)	[Unit less]
4/ Time of Flight (TOF) from perigee to true anomaly initial		
Initial Value of eccentric (E)	E = 2*atan(sqrt((1-e)/(1+e))*tan(v/2*deg2rad))	[rad]
Mean anomaly (M)	M = E-e*sin(E*deg2rad)	[rad]
Time of Flight (TOF)	if E>=0 TOF = M*T/(2*pi); else TOF = T+(M*T/(2*pi)); end	[minutes]

		5/ Constellation
Walker Star constellation ==========================		
Street width		
Street width	beta_street = acos(cos(beta*deg2rad)/cos(pi/N))	[rad]
Minimum street width	beta_street_min = acos(cos(beta_min*deg2rad)/cos(pi/N_max))	[rad]
	beta_street_min_deg = beta_street_min*rad2deg	[degrees]
Maximum street width	beta_street_max = acos(cos(beta_max*deg2rad)/cos(pi/N_min))	[rad]
	beta_street_max_deg = beta_street_max*rad2deg	[degrees]
Mean street width	beta_street_mean = acos(cos(beta_mean*deg2rad)/cos(pi/N_mean))	[rad]
	beta_street_mean_deg = beta_street_mean*rad2deg	[degrees]

`if beta_street_min>beta_street_max`
`temp=beta_street_min;`
`beta_street_min=beta_street_max;`
`beta_street_max=temp;`
`end`		

Street of coverage (SOC)		
SOC	SOC_rad = 2*beta_street	[rad]
Minimum SOC	SOC_min_rad = 2*beta_street_min	[rad]
	SOC_min_km = 2*Re*beta_street_min	[km]
Maximum SOC	SOC_max_rad = 2*beta_street_max	[rad]
	SOC_max_km = 2*Re*beta_street_max	[km]
Mean SOC	SOC_mean_rad = 2*beta_street_mean	[rad]
	SOC_mean_km = 2*Re*beta_street_mean	[km]
Perpendicular separation distance between adjacent planes moving in the same direction, D_SD		
D_SD	D_SD = beta_street*rad2deg + beta	[degrees]
Minimum	D_min_SD = beta_street_min*rad2deg + beta_min	[degrees]
Maximum	D_max_SD = beta_street_max*rad2deg + beta_max	[degrees]
Mean	D_mean_SD = beta_street_mean*rad2deg + beta_mean	[degrees]
Perpendicular separation distance between adjacent planes moving in the opposite direction, D_OD		
D_OD	D_OD = 2*beta_street*rad2deg	[degrees]
Minimum	D_min_OD = 2*beta_street_min*rad2deg	[degrees]
Maximum	D_max_OD = 2*beta_street_max*rad2deg	[degrees]
Mean	D_mean_OD = 2*beta_street_mean*rad2deg	[degrees]
Number of planes		
Number of planes	P = round([(180 - D_OD)/(D_SD)]+1)	[Unit less]
Minimum number of planes	P_min = round([(180 - D_max_OD)/(D_max_SD)]+1)	[Unit less]
Maximum number of planes	P_max = round([(180 - D_min_OD)/(D_min_SD)]+1)	[Unit less]
Mean number of planes	P_mean = round([(180 - D_mean_OD)/(D_mean_SD)]+1)	[Unit less]
Total number of satellite, TNOS		
Total number of satellite	TNOS = N*P	[Unit less]
Minimum total number of satellite	TNOS_min = N_min*P_min	[Unit less]
Maximum total number of satellite	TNOS_max = N_max*P_max	[Unit less]
Mean total number of satellite	TNOS_mean = N_mean*P_mean	[Unit less]
Walker Delta constellation (i:TNOS/P/F) ==========================		
Pattern Unit (PU)		
PU	PU = 360/TNOS	[degrees]
Minimum PU	PU_min = 360/TNOS_min	[degrees]
Maximum PU	PU_max = 360/TNOS_max	[degrees]
Mean PU	PU_mean = 360/TNOS_mean	[degrees]
Node spacing		
Node spacing	NodeSpacing= PU* N	[degrees]
Minimum Node spacing	NodeSpacing_min= PU_min * N_min	[degrees]
Maximum Node spacing	NodeSpacing_max= PU_max * N_max	[degrees]
Mean Node spacing	NodeSpacing_mean= PU_mean * N_mean	[degrees]

In-plane spacing between satellite		
In-plane spacing between satellite	IPS = PU * P	[degrees]
Minimum	IPS_min = PU_min * P_min	[degrees]
Maximum	IPS_max = PU_max * P_max	[degrees]
Mean	IPS_mean = PU_mean * P_mean	[degrees]
Phase difference between adjacent planes		
Phase difference between adjacent planes	APS = PU * F	[degrees]
Minimum	APS_min = PU_min * F	[degrees]
Maximum	APS_max = PU_max * F	[degrees]
Mean	APS_mean = PU_mean * F	[degrees]

A.II.2 MATLAB Code of orbital mechanics

```
%-------------------------------------------------------------------------
%   Orbital Mechanics with MATLAB
%-------------------------------------------------------------------------

function [] = orbit_prop (Name, ha, hp, i, elev, w, o, v, f_up, f_down, F)

% Elliptical orbit:
% LEO  :          orbit_prop ('LEO', 1447, 354, 71, 5, 30, 45, 15, 435, 145, 1)
% VLEO :          orbit_prop ('VLEO', 370, 368, 40.02, 5, 30, 45, 15, 435, 145, 1)
% MEO (Molnya):   orbit_prop ('MEO (Molnya)', 39105, 1250, 63.4, 5, 30, 45, 15, 435, 145,
1)
% MEO (Tundra):   orbit_prop ('MEO (Tundra)', 46340, 25231, 63.4, 5, 30, 45, 15, 435,
145, 1)
% Circular orbit:
% LEO :           orbit_prop ('LEO', 650, 650, 72, 5, 0, 45, 45, 435, 145, 1)

%%I%%       >>>>>>>>>>>>>>>>>>>> The input parameters <<<<<<<<<<<<<<<<<<<<

            %%I.1%%     >>> Variable inputs

% Name, ha, hp, i are chosen to vary for comparison in our case.

% Name      :   Name of orbit type
% f_up      :   Frequency uplink                               [MHz]
% f_down    :   Frequency downlink                             [MHz]
% elev      :   Elevation Angle                                [degrees]
% ha        :   Height of Apogee                               [km]
% hp        :   Height of Perigee                              [km]
% Relative spacing between satellites in adjacent planes F; % 0<= F <= P-1      [unit
less]

                          % i, w, o, and v: Obtain by satellite measurement system
% i         :   Inclination                                    [degrees]
% w         :   Argument of Perigee                            [degrees]
% o         :   R.A.A.N: Right Ascension of the Ascending node [degrees]
% v         :   True anomaly initial                           [degrees]


            %%I.2%%     >>> Fix inputs

u = 398600.607;           % Earth gravity constant                            [km^3/s^2]
Re = 6378.136;            % Earth Radius                                      [km]
J2 = 1.08263*10^-3;       % Second zonal harmonic of the Earth planet         [unit less]
c=299.8*10^6;             % Speed of light                                [m/s]
rad2deg = 180/pi;         % Radians to degrees
deg2rad = pi/180;         % Degrees to radians
sec2mn = 1/60;            % Seconds to minutes
```

```
                          % The Keplerian elements are:
                          %   a  :  semimajor axis                             [km]
                          %   e  :  eccentricity                               [unit less]
                          %   i  :  inclination                                [degrees]
                          %   o  :  right ascension of the ascending node      [degrees]
                          %   w  :  argument of perigee                        [degrees]
                          %   v  :  true anomaly                               [degrees]


%%II%%      >>>>>>>>>>>>>>>>>>>>>> Orbit Properties <<<<<<<<<<<<<<<<<<<<<<

            %%II.1%%    >>> Orbital Parameters

% Input parameters: ha, hp, Re, i, o, w, v

a = (ha+hp+2*Re)/2;                         %   a : Semimajor Axis          [km]
e = [(ha+Re)-(hp+Re)]/[(ha+Re)+(hp+Re)];    %   e : Eccentricity            [unit less]
T = (2*pi) * a* sqrt(a/u)*sec2mn;           %   T : Orbit period            [minutes]

% Initial Value of eccentric (E) [rad]
E_ini = 2*atan(sqrt((1-e)/(1+e))*tan(v/2*deg2rad));
% Mean anomaly (M) [rad]
M_ini = E_ini-e*sin(E_ini);

% fprintf('+ Initial Value of eccentric, E_ini = %.5f radians = %.5f degrees \n', E_ini,
radtodeg(E_ini));
% fprintf('+ Mean anomaly, M_ini = %.5f radians = %.5f degrees \n', M_ini,
% radtodeg(M_ini));

% The time rate of change of the argument of perigee [rad/s]
dw = -[3/2*(sqrt(u)*J2*Re^2)/((1-e^2)^2*(a^(7/2)))]*(5/2*(sin(i*deg2rad))^2-2);

% The time rate of change of the argument of perigee [deg/day]
dw_DegPerDay = dw*rad2deg*3600*24;                                              %
dw_DegPerDay = 19.92770307*1/(1-e^2)^2*(Re/a)^3.5*(1-1.25*(sin(i))^2)
                                                                                %
dw_DegPerDay > 0, or 0°<=i<63.4° or 116.6°<i<=180°  : the perigee advances in the
direction of the motion of the satellite (hence, the name advance of perigee for this
phenomenon).
                                                                                %
dw_DegPerDay < 0, or 63.4°<=i<116.6°                : the perigee regresses, moving
opposite to the direction of motion.
                                                                                %
dw_DegPerDay = 0 when J2=0, or i= 63.4° or i=116.6° : are the critical inclinations at
which the apse line does not move.


% The time variation of the right ascension o or the rate of drift [rad/s]
do = -[3/2*(sqrt(u)*J2*Re^2)/((1-e^2)^2*(a^(7/2)))]*cos(i*deg2rad);

% The time variation of the right ascension o or the rate of drift [deg/day]
do_DegPerDay = do*rad2deg*3600*24;                                              %
do_DegPerDay = -9.963851533*1/(1-e^2)^2*(Re/a)^3.5*cos(i)
                                                                                %
do_DegPerDay < 0, or 0°<=i<90°          : Prograde orbits, the node line drifts westward.
                                                                                %
do_DegPerDay > 0, or 90°<i<=180°        : Retrograde orbits, the node line drifts
eastward.
                                                                                %
do_DegPerDay = 0 when J2=0, or i=90°    : Polar orbits, the node line is stationary.


fprintf('\n The Orbit Properties of %s orbit are in the list below: \n\n', Name);
```

```
fprintf('\n--------------------------------------------------------------------------------------------------------------------');
fprintf('\n \t\t\t\t\t ***** The Orbit Properties of %s orbit *****', Name);
fprintf('\n--------------------------------------------------------------------------------------------------------------------');
fprintf('\n Parameter \t\t\t\t\t\t\t Value ');
fprintf('\n--------------------------------------------------------------------------------------------------------------------');

fprintf('\n 1/ Orbital Parameters ');
fprintf('\n--------------------------------------------------------------------------------------------------------------------');

fprintf('\n Earth radius (Re) \t\t\t\t\t %.2f \t km', Re);
fprintf('\n Height of apogee (ha) \t\t\t\t %.2f \t km', ha);
fprintf('\n Height of perigee (hp) \t\t\t %.2f \t km', hp);
fprintf('\n Elevation angle (elev) \t\t\t %.2f \t\t degrees', elev);
fprintf('\n Inclination (i) \t\t\t\t\t %.2f \t\t degrees', i);
fprintf('\n R.A.A.N (o) \t\t\t\t\t\t %.2f \t\t degrees', o);
fprintf('\n Argument of perigee (w) \t\t\t %.2f \t degrees', w);
fprintf('\n True anomaly (v) \t\t\t\t\t %.2f \t\t degrees', v);

fprintf('\n Mean anomaly (M) \t\t\t\t\t %.2f \t\t degrees', radtodeg(M_ini));
fprintf('\n Semimajor axis (a) \t\t\t\t %.2f \t km', a);
fprintf('\n Eccentricity (e) \t\t\t\t\t %e \t\t unit less', e);
fprintf('\n Orbit period (T) \t\t\t\t\t %.2f  \t minutes', T);
fprintf('\n Time rate of change of w (dw) \t\t %.2f \t\t degrees/day', dw_DegPerDay);
fprintf('\n Time variation of R.A.A.N (do) \t %.2f \t\t degrees/day', do_DegPerDay);

% The sun-synchronous inclination [deg]
X=-0.098919152*(1-e^2)^2*(a/Re)^3.5;
if -1<=X && X<=1
    i_SunSynchro = acos(X)*rad2deg;
    fprintf('\n Sun-synchronous inclination \t\t %.2f \t\t degrees', i_SunSynchro);
else
    fprintf('\n Sun-synchronous inclination \t\t None');
end;

fprintf('\n--------------------------------------------------------------------------------------------------------------------');

% return;

            %%II.2%%    >>> Slant Range and Free Space Path Loss

% We calculate the Slant Range and Free Space Path Loss for r_min, r_max and r_mean by
assuming the elevation angle 5 degrees.
% Input parameters: ha, hp, Re, elev, f_up, f_down

if ha==hp
    H=ha;   % Orbit altitude [km]
    r = H+Re; % orbit radius [km]
    S = sqrt(r^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad);     % Slant range [km]
    Lambda_up = c/(f_up*10^6);           % Wavelenght uplink     [m]
    Lambda_down = c/(f_down*10^6);       % Wavelenght downlink   [m]
    L_up=22+20*log10((S*1000)/Lambda_up);            % Minimum Free Space Path Loss of
uplink [dB]
    L_down=22+20*log10((S*1000)/Lambda_down);        % Minimum Free Space Path Loss of
uplink [dB]

    fprintf('\n 2/ Slant Range and Free Space Path Loss ');
    fprintf('\n--------------------------------------------------------------------------------------------------------------------');
```

```
    fprintf('\n Orbit altitude \t\t\t\t\t %.2f \t km ', H);
    fprintf('\n Orbit radius \t\t\t\t\t\t %.2f \t km ', r);
    fprintf('\n Slant range \t\t\t\t\t\t %.2f \t km ', S);

    fprintf('\n \t\t\t\t\t Uplink ');
    fprintf('\n \t\t\t\t\t ------ ');
    fprintf('\n Frequency uplink \t\t\t\t\t %.2f \t MHz', f_up);
    fprintf('\n Wavelength uplink \t\t\t\t\t %.2f \t\t m', Lambda_up);
    fprintf('\n Free Space (FS) path loss \t\t\t %.2f \t dB ', L_up);

    fprintf('\n \t\t\t\t\t Downlink ');
    fprintf('\n \t\t\t\t\t ------ ');
    fprintf('\n Frequency downlink \t\t\t\t %.2f \t MHz', f_down);
    fprintf('\n Wavelength downlink \t\t\t\t %.2f \t\t m', Lambda_down);
    fprintf('\n Free Space (FS) path loss \t\t\t %.2f \t dB ', L_down);

    fprintf('\n-----------------------------------------------------------------------
------------------------------------------');

else
    H_min = hp;                         % Minimum orbit altitude [km]
    H_max = ha;                         % Maximum orbit altitude [km]
    H_mean = (ha+hp)/2;                 % Mean orbit altitude [km]

    r_min = hp+Re;                      % Minimum orbit radius [km]
    r_max = ha+Re;                      % Maximum orbit radius [km]
    r_mean = a;                         % Mean orbit radius    [km]
    % Elevation angle assume to be 5 degrees anywhere of satellite orbiting the Earth

    S_min = sqrt(r_min^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad);     % Minimum
slant range [km]
    S_max = sqrt(r_max^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad);     % Maximum
slant range [km]
    S_mean = sqrt(r_mean^2-Re^2*(cos(elev*deg2rad))^2)-Re*sin(elev*deg2rad);   % Mean
slant range    [km]

    Lambda_up = c/(f_up*10^6);           % Wavelenght uplink     [m]
    Lambda_down = c/(f_down*10^6);       % Wavelenght downlink   [m]

    L_min_up=22+20*log10((S_min*1000)/Lambda_up);            % Minimum Free Space Path
Loss of uplink [dB]
    L_max_up=22+20*log10((S_max*1000)/Lambda_up);            % Minimum Free Space Path
Loss of uplink [dB]
    L_mean_up=22+20*log10((S_mean*1000)/Lambda_up);          % Mean Free Space Path Loss
of uplink    [dB]

    L_min_down=22+20*log10((S_min*1000)/Lambda_down);        % Minimum Free Space Path
Loss of uplink [dB]
    L_max_down=22+20*log10((S_max*1000)/Lambda_down);        % Minimum Free Space Path
Loss of uplink [dB]
    L_mean_down=22+20*log10((S_mean*1000)/Lambda_down);      % Mean Free Space Path Loss
of uplink    [dB]

    fprintf('\n 2/ Slant Range and Free Space Path Loss ');
    fprintf('\n-----------------------------------------------------------------------
------------------------------------------');

    fprintf('\n Orbit altitude \t\t\t\t\t Minimum orbit altitude \t Maximum orbit
altitude \t Mean orbit altitude');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t km \t\t\t %.2f \t km \t\t\t %.2f \t km',
H_min, H_max, H_mean);
    fprintf('\n Orbit radius \t\t\t\t\t\t Minimum orbit radius \t\t Maximum orbit radius
\t\t Mean orbit radius');
```

```
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t km \t\t\t %.2f \t km \t\t\t %.2f \t km',
r_min, r_max, r_mean);
    fprintf('\n Slant range \t\t\t\t\t\t Minimum slant range \t\t Maximum slant range
\t\t Mean slant range');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t km \t\t\t %.2f \t km \t\t\t %.2f \t km',
S_min, S_max, S_mean);

    fprintf('\n \t\t\t\t\t\t\t\t\t\t\t\t\t\t\t Uplink ');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t\t\t\t\t\t ------ ');
    fprintf('\n Frequency uplink \t\t\t\t\t %.2f \t MHz', f_up);
    fprintf('\n Wavelength uplink \t\t\t\t\t %.2f \t\t m', Lambda_up);
    fprintf('\n Free Space (FS) path loss \t\t\t Minimum FS path loss \t\t Maximum FS
path loss \t\t Mean FS path loss');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t dB \t\t\t %.2f \t dB \t\t\t %.2f \t dB',
L_min_up, L_max_up, L_mean_up);

    fprintf('\n \t\t\t\t\t\t\t\t\t\t\t\t\t\t\t Downlink ');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t\t\t\t\t\t ------ ');
    fprintf('\n Frequency downlink \t\t\t\t %.2f \t MHz', f_down);
    fprintf('\n Wavelength downlink \t\t\t\t %.2f \t\t m', Lambda_down);
    fprintf('\n Free Space (FS) path loss \t\t\t Minimum FS path loss \t\t Maximum FS
path loss \t\t Mean FS path loss');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t dB \t\t\t %.2f \t dB \t\t\t %.2f \t dB',
L_min_down, L_max_down, L_mean_down);

    fprintf('\n-----------------------------------------------------------------------
------------------------------------------');

end

% << Slant Range and Free Space Path Loss vs. elevation angle >>
%
% kk = 5:5:90;
%
%     S_min = sqrt(r_min^2-Re.^2.*(cos(kk.*deg2rad)).^2)-Re.*sin(kk.*deg2rad);     %
Minimum slant range [km]
%     S_max = sqrt(r_max^2-Re.^2.*(cos(kk.*deg2rad)).^2)-Re.*sin(kk.*deg2rad);     %
Maximum slant range [km]
%     S_mean = sqrt(r_mean^2-Re.^2.*(cos(kk.*deg2rad)).^2)-Re.*sin(kk.*deg2rad);   % Mean
slant range    [km]
%
%     L_min_up=22+20*log10((S_min*1000)/Lambda_up);            % Minimum Free Space Path
Loss of uplink [dB]
%     L_max_up=22+20*log10((S_max*1000)/Lambda_up);            % Minimum Free Space Path
Loss of uplink [dB]
%     L_mean_up=22+20*log10((S_mean*1000)/Lambda_up);          % Mean Free Space Path
Loss of uplink    [dB]
%
%     L_min_down=22+20*log10((S_min*1000)/Lambda_down);        % Minimum Free Space Path
Loss of uplink [dB]
%     L_max_down=22+20*log10((S_max*1000)/Lambda_down);        % Minimum Free Space Path
Loss of uplink [dB]
%     L_mean_down=22+20*log10((S_mean*1000)/Lambda_down);      % Mean Free Space Path
Loss of uplink    [dB]
%
%
%     fprintf('\n \t\t\t << Slant Range and Free Space Path Loss vs. elevation angle at
minimum altitude >> \n');
%     fprintf('%s \t\t\t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t
%.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f
\t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \n', 'Elevation angle:',
kk(:));
%     fprintf('%s \t\t\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t
%.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t
%.2f \t\t %.2f \t\t %.2f \n', 'Minimum slant range:', S_min(:));
```

```
%     fprintf('%s \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \n', 'Uplink free space path looses:', L_min_up(:));
%     fprintf('%s \t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
%     \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \n', 'Downlink free space path looses:',
L_min_down(:));
%
%     fprintf('\n-------------------------------------------------------------------------
---------------------------------------------');
%     fprintf('\n \t\t\t << Slant Range and Free Space Path Loss vs. elevation angle at
maximum altitude >> \n');
%     fprintf('%s \t\t\t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t
%.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f
\t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \n', 'Elevation angle:',
kk(:));
%     fprintf('%s \t\t\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t
%.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t
%.2f \t\t %.2f \t\t %.2f \n', 'Maximum slant range:', S_max(:));
%     fprintf('%s \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \n', 'Uplink free space path looses:', L_max_up(:));
%     fprintf('%s \t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \n', 'Downlink free space path looses:', L_max_down(:));
%
%     fprintf('\n-------------------------------------------------------------------------
---------------------------------------------');
%     fprintf('\n \t\t\t << Slant Range and Free Space Path Loss vs. elevation angle at
maximum altitude >> \n');
%     fprintf('%s \t\t\t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t
%.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f
\t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \t\t\t %.2f \n', 'Elevation angle:',
kk(:));
%     fprintf('%s \t\t\t\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t
%.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t
%.2f \t\t %.2f \t\t %.2f \n', 'Mean slant range:', S_mean(:));
%     fprintf('%s \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \n', 'Uplink free space path looses:', L_mean_up(:));
%     fprintf('%s \t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f \t\t %.2f
\t\t %.2f \t\t %.2f \n', 'Downlink free space path looses:', L_mean_down(:));
%
%     fprintf('\n-------------------------------------------------------------------------
---------------------------------------------');

%  return;

            %%II.3%%    >>> Zone Coverage and Duration of Visibility

% Input parameters: >>> r_min, r_max, r_mean, a (From II.2 and II.1 get by ha, hp, Re);
Re; elev
% The zone coverage and duration of visibility depends on two parameters:
% orbit altitude and elevation angle.
% - The zone coverage is estimated at the minimum altitude, maximum altitude, and mean
altitude with the
% elevation angle 5 degrees.
% - The duration of visibility is estimated for a constant velocity of
% satellite with the elevation angle 5 degrees during orbiting.



if ha==hp

    % Nadir Angle [degrees]
```

```
    alpha = asin(Re/r*cos(elev*deg2rad))*rad2deg;

    % Central Angle [degrees]
    beta = acos((Re/r*cos(elev*deg2rad)))*rad2deg-elev;

    % Footprint Length [km]
    FPL = 2*Re*beta*deg2rad;

    % Footprint Area [km^2]
    FPA = 2*pi*Re^2*(1-cos(beta*deg2rad));

    % Velocity of the Satellite [m/s]
    V = sqrt(u*10^6*(2/r-1/a));

    % Duration of Visibility [minutes]
    t = FPL*10^3/V*sec2mn;

    fprintf('\n 3/ Zone Coverage and Duration of Visibility ');
    fprintf('\n----------------------------------------------------------------------------------------------------------------------');

    fprintf('\n Orbit radius \t\t\t\t\t\t %.2f \t km ', r);
    fprintf('\n Nadir angle \t\t\t\t\t\t %.2f \t\t degrees ', alpha);
    fprintf('\n Central angle \t\t\t\t\t\t %.2f \t\t degrees ', beta);
    fprintf('\n Footprint length \t\t\t\t\t %.2f \t km ', FPL);
    fprintf('\n Footprint area \t\t\t\t\t %.2f km^2 ', FPA);
    fprintf('\n Velocity of the satellite \t\t\t %.2f \t m/s ', V);
    fprintf('\n Duration of Visibility \t\t\t %.2f \t\t minutes ', t);

    % The number of satellites required for the area specific coverage in one repeat
cycle period T
    N = ceil(T/t);

    fprintf('\n Orbit period (T) \t\t\t\t\t %.2f \t\t minutes', T);
    fprintf('\n\n Number of satellites required');
    fprintf('\n for continuous coverage \t\t\t %d', N);

    fprintf('\n----------------------------------------------------------------------------------------------------------------------');

else

    % Nadir Angle [degrees]
    alpha_max = asin(Re/r_min*cos(elev*deg2rad))*rad2deg;           % (Maximum) Nadir
angle of minimum altitude          [degrees]
    alpha_min = asin(Re/r_max*cos(elev*deg2rad))*rad2deg;           % (Minimum) Nadir
angle of maximum altitude          [degrees]
    alpha_mean = asin(Re/r_mean*cos(elev*deg2rad))*rad2deg;         % Mean nadir angle
of mean altitude                  [degrees]

    % Central Angle [degrees]
    beta_min = acos((Re/r_min*cos(elev*deg2rad)))*rad2deg-elev;     % Minimum central
angle         [degrees]
    beta_max = acos((Re/r_max*cos(elev*deg2rad)))*rad2deg-elev;     % Maximum central
angle         [degrees]
    beta_mean = acos((Re/r_mean*cos(elev*deg2rad)))*rad2deg-elev;   % Mean central angle
[degrees]

    % Footprint Length [km]
    FPL_min = 2*Re*beta_min*deg2rad;                                 % Minimum footprint
length      [km]
    FPL_max = 2*Re*beta_max*deg2rad;                                 % Maximum footprint
length      [km]
```

```
    FPL_mean = 2*Re*beta_mean*deg2rad;                              % Mean footprint 
length         [km]

    % Footprint Area [km^2]
    FPA_min = 2*pi*Re^2*(1-cos(beta_min*deg2rad));                  %  Minimum footprint 
area       [km^2]
    FPA_max = 2*pi*Re^2*(1-cos(beta_max*deg2rad));                  %  Maximum footprint 
area       [km^2]
    FPA_mean = 2*pi*Re^2*(1-cos(beta_mean*deg2rad));                %  Mean footprint 
area          [km^2]

    % Velocity of the Satellite [m/s]
    V_max = sqrt(u*10^6*(2/r_min-1/a));                             % (Maximum) velocity 
of the satellite of minimum altitude [m/s]
    V_min = sqrt(u*10^6*(2/r_max-1/a));                             % (Minimum) velocity 
of the satellite of maximum altitude [m/s]
    V_mean = sqrt(u*10^6*(2/r_mean-1/a));                           % Mean velocity of 
the satellite of mean altitude         [m/s]

    % Duration of Visibility [minutes]
    t_max = FPL_max*10^3/V_min*sec2mn;                              % Minimum duration 
of visibility [minutes]
    t_min = FPL_min*10^3/V_max*sec2mn;                              % Maximum duration 
of visibility [minutes]
    t_mean = FPL_mean*10^3/V_mean*sec2mn;                           % Mean duration of 
visibility    [minutes]

    fprintf('\n 3/ Zone Coverage and Duration of Visibility ');
    fprintf('\n--------------------------------------------------------------------------
------------------------------------------');

    fprintf('\n Orbit radius \t\t\t\t\t\t Minimum orbit radius \t\t Maximum orbit radius 
\t\t Mean orbit radius');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t km \t\t\t %.2f \t km \t\t\t %.2f \t km', 
r_min, r_max, r_mean);
    fprintf('\n Nadir angle \t\t\t\t\t\t Minimum nadir angle \t\t Maximum nadir angle 
\t\t Mean nadir angle');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t %.2f 
\t\t degrees', alpha_min, alpha_max, alpha_mean);
    fprintf('\n Central angle \t\t\t\t\t\t Minimum central angle \t\t Maximum central 
angle \t\t Mean central angle');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t %.2f 
\t\t degrees', beta_min, beta_max, beta_mean);
    fprintf('\n Footprint length \t\t\t\t\t Minimum footprint length \t Maximum footprint 
length \t Mean footprint length');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t km \t\t\t %.2f \t km \t\t\t %.2f \t km', 
FPL_min, FPL_max, FPL_mean);
    fprintf('\n Footprint area \t\t\t\t\t Minimum footprint area \t Maximum footprint 
area \t Mean footprint area');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f  km^2 \t\t\t %.2f km^2 \t\t\t %.2f km^2', 
FPA_min, FPA_max, FPA_mean);
    fprintf('\n Velocity of the satellite \t\t\t Minimum velocity \t\t\t Maximum velocity 
\t\t\t Mean velocity');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t m/s \t\t\t %.2f \t m/s \t\t\t %.2f \t m/s', 
V_min, V_max, V_mean);
    fprintf('\n Duration of Visibility \t\t\t Minimum duration \t\t\t Maximum duration 
\t\t\t Mean duration');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t\t minutes \t\t %.2f\t\t minutes \t\t %.2f \t\t 
minutes', t_min, t_max, t_mean);

    % The number of satellites required for continuous coverage in one repeat cycle 
period T
    N_min = ceil(T/t_max);            % Minimum number of satellites required
    N_max = ceil(T/t_min);            % Maximum number of satellites required
    N_mean = ceil(T/t_mean);          % Mean number of satellites required
```

```
    fprintf('\n Orbit period (T) \t\t\t\t\t %.2f \t minutes', T);
    fprintf('\n Number of satellites required \t\t Minimum number \t\t\t Maximum number
\t\t\t Mean number');
    fprintf('\n for continuous coverage \t\t\t %d \t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d',
N_min, N_max, N_mean);

    fprintf('\n--------------------------------------------------------------------------
------------------------------------------');

end

% return;

            %%II.4%%    >>> Time of Flight (TOF) from perigee to true anomaly initial

% Input parameters: >>> true anomaly initial (v), eccentricity (e), period (T)

% Initial Value of eccentric (E) [rad]
E = 2*atan(sqrt((1-e)/(1+e))*tan(v/2*deg2rad));

% Mean anomaly (M) [rad]
M = E-e*sin(E);

% Time of flight from perigee to true anomaly (TOF) [minutes]
if E>=0
    TOF = M*T/(2*pi);
else
    TOF = T+(M*T/(2*pi));
end

fprintf('\n 4/ Time of Flight (TOF) from perigee to true anomaly initial ');
fprintf('\n------------------------------------------------------------------------------
--------------------------------------');

fprintf('\n True anomaly (v) \t\t\t\t\t %.2f \t\t degrees', v);
fprintf('\n Eccentricity (e) \t\t\t\t\t %.2f \t\t unit less', e);
fprintf('\n Orbit period (T) \t\t\t\t\t %.2f  \t minutes', T);
fprintf('\n Initial Value of eccentric (E) \t %.2f \t\t radians', E);
fprintf('\n Mean anomaly (M) \t\t\t\t\t %.2f \t\t radians', M);
fprintf('\n Time of Flight (TOF) \t\t\t\t %.2f\t\t minutes', TOF);

fprintf('\n------------------------------------------------------------------------------
--------------------------------------');

%  return;

            %%II.5%%    >>> Constellation

% Input parameters: >>> period (T), Duration of Visibility (t)

if ha==hp

    fprintf('\n 5/ Constellation ');
    fprintf('\n--------------------------------------------------------------------------
------------------------------------------');
    %=================================================
    % Walker Star Constellation : Approximated number of planes and total number of
satellites
    %=================================================

    % Input parameters: Number of satellite per plane (N), the earth central angle (beta)
```

```
    % Recall that: this constellation is used for the circular orbit with the
    % same altitude and the same coverage throughout the orbit

    %----------- FPL (coverage), Duration of visibility (T), Number of satellite required
--------------

    beta_street = acos(cos(beta*deg2rad)/cos(pi/N)); % Street width [rad]
    beta_street_deg = beta_street*rad2deg; % Street width [deg.]
    SOC_deg = 2*beta_street_deg; % Street of coverage [deg]
    SOC_km = 2*Re*beta_street; % Street of coverage [km]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the same direction
    D_SD = beta_street*rad2deg + beta; % [deg]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the opposite direction
    D_OD = 2*beta_street*rad2deg; % [deg]



    % We have: 2*beta_street + (P-1)*(beta_street+beta) = 180 [deg.]
    P = ceil([(180 - D_OD)/(D_SD)]+1); % Number of planes
    TNOS = N*P; % Total number of satellites

    fprintf('\n \t\t\t Walker Star constellation : Approximated number of planes and
total number of satellites ');
    fprintf('\n \t\t\t
========================================================================================\
n');

    fprintf('\n Central angle \t\t\t\t\t\t %.2f \t\t degrees ', beta);
    fprintf('\n\n Number of satellites required');
    fprintf('\n for continuous coverage \t\t\t %d ', N);
    fprintf('\n (Number of satellites per plane)\n');
    fprintf('\n Street width \t\t\t\t\t\t %.2f \t\t degrees ', beta_street_deg);
    fprintf('\n\n Street of coverage (SOC) \t\t\t %.2f \t\t deg ', SOC_deg);
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t km \n', SOC_km);
    fprintf('\n\n Perpendicular separation (D)');
    fprintf('\n between adjacent planes moving  \t %.2f \t\t degrees ', D_SD);
    fprintf('\n in the same direction\n');
    fprintf('\n Perpendicular separation (D)');
    fprintf('\n between adjacent planes moving  \t %.2f \t\t degrees ', D_OD);
    fprintf('\n in the different direction\n');
    fprintf('\n Number of planes \t\t\t\t\t %d ', P);
    fprintf('\n Total number of satellite \t\t\t %d ', TNOS);

    %===============================================
    % Walker Delta Constellation
    %===============================================

    % Input parameters: i:T/P/F (i:TNOS/P/F), In our case: i:45/5/1
    % TNOS: Totalnumber of satellites
    % P: Number of planes
    % F: Relative spacing between satellites in adjacent planes

    % Relative spacing between satellites in adjacent planes
    % F = 1; % 0<= F <= P-1

    %----------- Number of satellite required per plane (N), Pattern Unit (PU), Node
spacing,
    %----------- In-plane spacing between satellites, Phase difference between adjacent
planes
```

```
    % Number of satellite required per plane
    N = TNOS/P;
    % Pattern Unit [deg.]
    PU = 360/TNOS;
    % Node spacing [deg.]
    NodeSpacing= PU * N;
    % In-plane spacing between satellites [deg.]
    IPS = PU * P;
    % Phase difference between adjacent planes [deg.]
    APS = PU * F;

    fprintf('\n\n\n \t\t\t\t\t\t\t\t\t\t\t Walker Delta constellation (i:TNOS/P/F)');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t\t =========================\n');

    fprintf('\n Inclination (i) \t\t\t\t\t %.2f \t\t degrees', i);
    fprintf('\n Relative spacing between \t\t\t %.2f \t\t', F);
    fprintf('\n satellites in adjacent planes (F)\n');
    fprintf('\n Number of planes (P) \t\t\t\t %d ', P);
    fprintf('\n Total number of satellite (TNOS) \t %d ', TNOS);
    fprintf('\n Pattern Unit (PU) \t\t\t\t\t %.2f \t\t degrees ', PU);
    fprintf('\n Node spacing \t\t\t\t\t\t %.2f \t\t degrees ', NodeSpacing);
    fprintf('\n In-plane spacing between \t\t\t %.2f \t\t degrees ', IPS);
    fprintf('\n satellites');
    fprintf('\n Phase difference between \t\t\t %.2f \t\t degrees ', APS);
    fprintf('\n adjacent planes');

    fprintf('\n-----------------------------------------------------------------------------
------------------------------------------');

else


    fprintf('\n 5/ Constellation ');
    fprintf('\n-----------------------------------------------------------------------------
------------------------------------------');

    %=============================================
    % Walker Star Constellation : Approximated number of planes and total number of
satellites
    %=============================================

    % Input parameters: Number of satellite per plane (N), the earth central angle (beta)
    % Recall that: this constellation is used for the circular orbit with the
    % same altitude and the same coverage throughout the orbit

    %----------- Minimum FPL (coverage), Minimum duration of visibility (T), Minimum
number of satellite required --------------
    %----------- Maximum FPL (coverage), Maximum duration of visibility (T), Maximum
number of satellite required --------------
    beta_street_min = acos(cos(beta_min*deg2rad)/cos(pi/N_max)); % Street width [rad]
    beta_street_max = acos(cos(beta_max*deg2rad)/cos(pi/N_min)); % Street width [rad]

    if beta_street_min>beta_street_max
        temp=beta_street_min;
        beta_street_min=beta_street_max;
        beta_street_max=temp;
    else
        %beta_street_min;
        %beta_street_max;
    end

    beta_street_min_deg = beta_street_min*rad2deg; % Street width [deg.]
    beta_street_max_deg = beta_street_max*rad2deg; % Street width [deg.]
```

```
    SOC_min_deg = 2*beta_street_min_deg; % Street of coverage [rad]
    SOC_min_km = 2*Re*beta_street_min; % Street of coverage [km]

    SOC_max_deg = 2*beta_street_max_deg; % Street of coverage [rad]
    SOC_max_km = 2*Re*beta_street_max; % Street of coverage [km]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the same direction
    D_min_SD = beta_street_min*rad2deg + beta_min; % [deg]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the different direction
    D_min_OD = 2*beta_street_min*rad2deg; % [deg]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the same direction
    D_max_SD = beta_street_max*rad2deg + beta_max; % [deg]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the different direction
    D_max_OD = 2*beta_street_max*rad2deg; % [deg]

    % We have: 2*beta_street + (P-1)*(beta_street+beta) = 180 [deg.]
    P_min = ceil([(180 - D_max_OD)/(D_max_SD)]+1); % Number of planes

    % We have: 2*beta_street + (P-1)*(beta_street+beta) = 180 [deg.]
    P_max = ceil([(180 - D_min_OD)/(D_min_SD)]+1); % Number of planes

    %----------- Mean FPL (coverage), Mean duration of visibility (T), Mean number of
satellite required --------------

    beta_street_mean = acos(cos(beta_mean*deg2rad)/cos(pi/N_mean)); % Street width [rad]
    beta_street_mean_deg = beta_street_mean*rad2deg; % Street width [deg.]
    SOC_mean_deg = 2*beta_street_mean_deg; % Street of coverage [rad]
    SOC_mean_km = 2*Re*beta_street_mean; % Street of coverage [km]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the same direction
    D_mean_SD = beta_street_mean*rad2deg + beta_mean; % [deg]

    % The perpendicular separation or Phase difference between adjacent planes moving in
the different direction
    D_mean_OD = 2*beta_street_mean*rad2deg; % [deg]


    % We have: 2*beta_street + (P-1)*(beta_street+beta) = 180 [deg.]
    P_mean = ceil([(180 - D_mean_OD)/(D_mean_SD)]+1); % Number of planes



    TNOS_min = N_min*P_min; % Total number of satellites
    TNOS_max = N_max*P_max; % Total number of satellites
    TNOS_mean = N_mean*P_mean; % Total number of satellites


    fprintf('\n \t\t\t Walker Star constellation : Approximated number of planes and
total number of satellites ');
    fprintf('\n \t\t\t
=========================================================================================\
n');
```

```
    fprintf('\n Central angle \t\t\t\t\t\t Minimum central angle \t\t Maximum central
angle \t\t Mean central angle');
    fprintf('\n \t\t\t\t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t %.2f
\t\t degrees', beta_min, beta_max, beta_mean);
    fprintf('\n Number of satellites required \t\t Minimum number \t\t\t Maximum number
\t\t\t Mean number');
    fprintf('\n for continuous coverage \t\t\t %d \t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d',
N_min, N_max, N_mean);
    fprintf('\n (Number of satellites per plane)\n');
    fprintf('\n Street width \t\t\t\t\t\t Minimum street width \t\t Maximum street width
\t\t Mean street width');
    fprintf('\n \t\t\t\t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t %.2f
\t\t degrees', beta_street_min_deg, beta_street_max_deg, beta_street_mean_deg);
    fprintf('\n Street of coverage (SOC) \t\t\t Minimum SOC \t\t\t\t Maximum SOC \t\t\t\t
Mean SOC');
    fprintf('\n \t\t\t\t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t %.2f
\t\t degrees', SOC_min_deg, SOC_max_deg, SOC_mean_deg);
    fprintf('\n \t\t\t\t\t\t\t\t\t %.2f \t km \t\t\t %.2f \t km \t\t\t %.2f \t km\n',
SOC_min_km, SOC_max_km, SOC_mean_km);
    fprintf('\n Perpendicular separation (D) \t\t Minimum \t\t\t\t\t Maximum \t\t\t\t\t
Mean');
    fprintf('\n between adjacent planes moving  \t %.2f \t\t degrees \t\t %.2f \t\t
degrees \t\t %.2f \t\t degrees', D_min_SD, D_max_SD, D_mean_SD);
    fprintf('\n in the same direction\n');
    fprintf('\n Perpendicular separation (D) \t\t Minimum \t\t\t\t\t Maximum \t\t\t\t\t
Mean');
    fprintf('\n between adjacent planes moving  \t %.2f \t\t degrees \t\t %.2f \t\t
degrees \t\t %.2f \t\t degrees', D_min_OD, D_max_OD, D_mean_OD);
    fprintf('\n in the different direction\n');
    fprintf('\n Number of planes \t\t\t\t\t Minimum number \t\t\t Maximum number \t\t\t
Mean number');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d', P_min, P_max,
P_mean);
    fprintf('\n Total number of satellite \t\t\t Minimum number \t\t\t Maximum number
\t\t\t Mean number');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %d \t\t\t\t\t\t %d \t\t\t\t\t\t %d', TNOS_min,
TNOS_max, TNOS_mean);

    %=============================================
    % Walker Delta Constellation
    %=============================================

    % Input parameters: i:T/P/F (i:TNOS/P/F), In our case: i:45/5/1
    % TNOS: Totalnumber of satellites
    % P: Number of planes
    % F: Relative spacing between satellites in adjacent planes

    % Relative spacing between satellites in adjacent planes
    % F = 1; % 0<= F <= P-1

    %----------- Number of satellite required per plane (N), Pattern Unit (PU), Node
spacing,
    %----------- In-plane spacing between satellites, Phase difference between adjacent
planes

    % Number of satellite required per plane
    N_min = TNOS_min/P_min;
    % Pattern Unit [deg.]
    PU_min = 360/TNOS_min;
    % Node spacing [deg.]
    NodeSpacing_min= PU_min * N_min;
    % In-plane spacing between satellites [deg.]
    IPS_min = PU_min * P_min;
    % Phase difference between adjacent planes [deg.]
    APS_min = PU_min * F;
```

```
    %----------- Number of satellite required per plane (N), Pattern Unit (PU), Node
spacing,
    %----------- In-plane spacing between satellites, Phase difference between adjacent
planes

    % Number of satellite required per plane
    N_max = TNOS_max/P_max;
    % Pattern Unit [deg.]
    PU_max = 360/TNOS_max;
    % Node spacing [deg.]
    NodeSpacing_max= PU_max * N_max;
    % In-plane spacing between satellites [deg.]
    IPS_max = PU_max * P_max;
    % Phase difference between adjacent planes [deg.]
    APS_max = PU_max * F;


    %----------- Number of satellite required per plane (N), Pattern Unit (PU), Node
spacing,
    %----------- In-plane spacing between satellites, Phase difference between adjacent
planes

    % Number of satellite required per plane
    N_mean = TNOS_mean/P_mean;
    % Pattern Unit [deg.]
    PU_mean = 360/TNOS_mean;
    % Node spacing [deg.]
    NodeSpacing_mean= PU_mean * N_mean;
    % In-plane spacing between satellites [deg.]
    IPS_mean = PU_mean * P_mean;
    % Phase difference between adjacent planes [deg.]
    APS_mean = PU_mean * F;

    fprintf('\n\n\n \t\t\t\t\t\t\t\t\t\t\t Walker Delta constellation (i:TNOS/P/F)');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t\t ===========================\n');

    fprintf('\n Inclination (i) \t\t\t\t\t %.2f \t\t degrees', i);
    fprintf('\n Relative spacing between \t\t\t %.2f \t\t', F);
    fprintf('\n satellites in adjacent planes (F)\n');
    fprintf('\n Number of planes (P) \t\t\t\t Minimum number \t\t\t Maximum number \t\t\t
Mean number');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d', P_min, P_max,
P_mean);
    fprintf('\n Total number of satellite (TNOS) \t Minimum number \t\t\t Maximum number
\t\t\t Mean number');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d \t\t\t\t\t\t\t %d', TNOS_min,
TNOS_max, TNOS_mean);
    fprintf('\n Pattern Unit (PU) \t\t\t\t\t Minimum PU \t\t\t\t Maximum PU \t\t\t\t Mean
PU');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t %.2f
\t\t degrees', PU_min, PU_max, PU_mean);
    fprintf('\n Node spacing \t\t\t\t\t\t Minimum \t\t\t\t\t Maximum \t\t\t\t\t Mean');
    fprintf('\n \t\t\t\t\t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t %.2f
\t\t degrees', NodeSpacing_min, NodeSpacing_max, NodeSpacing_mean);
    fprintf('\n In-plane spacing between \t\t\t Minimum \t\t\t\t\t Maximum \t\t\t\t\t
Mean');
    fprintf('\n satellites \t\t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t
%.2f \t\t degrees', IPS_min, IPS_max, IPS_mean);
    fprintf('\n Phase difference between \t\t\t Minimum \t\t\t\t\t Maximum \t\t\t\t\t
Mean');
    fprintf('\n adjacent planes \t\t\t\t\t %.2f \t\t degrees \t\t %.2f \t\t degrees \t\t
%.2f \t\t degrees', APS_min, APS_max, APS_mean);
```

```
    fprintf('\n---------------------------------------------------------------------------
-------------------------------------------');

end
return;
```

A.II.3 Characteristic of nanosatellite and ground station studied

Table 1: Characteristic of nanosatellite studied

Frequency band, altitude of satellite, and elevation angle

Frequency band		UHF/VHF	Ku	Ka
Uplink frequency	[MHz]	435	14000	30000
Downlink frequency	[MHz]	145	12000	20000
Altitude of satellite	[km]	At perigee		
Elevation angle	[°]	5	5	5

Orbit type

Orbit type		LEO	VLEO	MEO "Molniya"	MEO "Tundra"
Apogee altitude (ha)	[km]	1447.00	370.00	39105.00	46340.00
Perigee altitude (hp)	[km]	354.00	368.00	1250.00	25231.00

Antenna type

Frequency band	UHF/VHF	Ku	Ka
Antenna type	Monopole	Patch	Patch

Monopole antenna

Frequency band		**UHF/VHF**	
Frequency	[MHz]	12000	14000
Antenna gain	**[dB]**	**2.15**	**2.15**

Patch antenna

Frequency band		**Ku**		**Ka**	
Frequency	[MHz]	12000	14000	20000	30000
Dielectric constant	[Unit less]	2.10	2.10	2.10	2.10
Substrate thickness	[m]	0.000642	0.000642	0.0003	0.000642
Antenna gain	**[dB]**	**5.59**	**5.27**	**6.90**	**5.27**

Protocol, transmitter power, data rate and modulation type

Protocol		AX.25	D-STAR	Beacon
Transmitter power	[W]	0.75	0.75	0.1
Data rate	[bps]	20	9600	4800
Modulation type		FSK non-coherent	FSK non-coherent	GMSK
Coding		None	None	None
BER		10^{-5}	10^{-5}	10^{-5}
System required Eb/No	[dB]	13.35	13.35	9.72

Table 2: Characteristic of ground station studied

Ground station type and its location			
Type	Gateway		
City	Liege		
Country	Belgium		
Latitude [°N]	50.62		
Longitude [°E]	5.5667		
Altitude at sea level [km]	0.00		
Antenna type			
Frequency band	UHF/VHF	Ku	Ka
Antenna type	Yagi	Parabolic	Parabolic

Yagi antenna	
Frequency band	**UHF/VHF**
Boom Length (λ): [m]	1.5
Optimum Elements	7
Antenna gain [dB]	**13.35**

Parabolic antenna				
Frequency band	**Ku**		**Ka**	
Frequency [MHz]	12000	14000	20000	30000
Dish diameter [m]	4.5	4.5	4.5	4.5
Dish Aperture efficiency [%]	60.50	60.50	60.50	60.50
Antenna gain [dB]	**52.87**	**54.20**	**57.30**	**60.82**

Protocol, transmitter power, data rate and modulation type		
Protocol	AX.25	D-STAR
Transmitter power [W]	20	20
Data rate [bps]	4800	9600
Modulation type	FSK non-coherent	GMSK
Coding	None	None
BER	10^{-5}	10^{-5}
System require Eb/No [dB]	13.35	9.72

ANNEX III

A.III.1 C code to find the optimal satellite constellation for continuous whole Earth coverage

```
#include <math.h>
#include <stdio.h>
#include <conio.h>

int P, N, N_min, N_max, P_min, P_max, testPN;
int N_optimal, P_optimal, count;
char ch;

main()
{
LB1:
clrscr();
printf("\n\n ********************************************************** ");
printf("\n\n *****     Testing Satellite Constellation, P and N      **** ");
printf("\n\n ***** Constellation for continuous whole Earth coverage **** ");
printf("\n\n ********************************************************** ");


printf("\n\n\n + Please input the minimum number of satellite planes, P_min= ");
scanf("%d",&P_min);
printf("\n + Please input the maximum number of satellite planes, P_max= ");
scanf("%d",&P_max);
printf("\n + Please input the maximum number of satellites per plane, N_max= ");
scanf("%d",&N_max);
printf("\n + Please input the minimum number of satellites per plane, N_min= ");
scanf("%d",&N_min);


P=P_max;
N=N_min;
printf("\n\n ---------------------------- START Testing ----------------------------");


while (P>=P_min&&N<=N_max)
{
printf("\n\n -> Testing [ P= %d, N= %d ] ", P, N);
printf("\n\n + Testing satellite constellation %d planes with %d satellites per plane." , P, N);
printf("\n\n + If test is possible, insert value 1 otherwise insert value 0, testPN= ");
scanf("%d",&testPN);
        if (testPN==1)
        {
          N_optimal= N;
          P_optimal= P;
          P=P-1;
          N_max=floor(P_optimal*N_optimal/P);
          N=N_max;
```

```
            goto LB2;
          }
          else if (testPN==0)
          {
            N=N+1;
            if (N<=N_max)
            continue;
            else
            printf("\n\n ----------------------------- END Testing ----------------------------- ");
            printf("\n\n >>> No Periods of Global Coverage Exist!");
            goto LB3;
          }
}

LB2:
while (P>=P_min&&N>=N_min)
{
  printf("\n\n -> Testing [ P= %d, N= %d ] ", P, N);
  printf("\n\n + Testing satellite constellation %d planes with %d satellites per plane." , P, N);
  printf("\n\n + If test is possible, insert value 1 otherwise insert value 0, testPN= ");
  scanf("%d",&testPN);
  if (testPN==1)
  {
    N_optimal= N;
    P_optimal= P;
    N=N-1;
    if (N>=N_min)
          continue;
    else
          P=P-1;
          N_max=floor(P_optimal*N_optimal/P);
          N=N_max;
          continue;
  }
  else if(testPN==0)
  {
          P=P-1;
          N_max=floor(P_optimal*N_optimal/P);
          N=N_max;
          continue;
  }
}

printf("\n\n ----------------------------- END Testing ----------------------------- ");
printf("\n\n  >>> H ence,  the op timal con stellation i s % d  planes w tih  %d sat ellites pe r pl ane,  "
,P_optimal,N_optimal);
printf("\n\n and the minimum total number of satellites is equal to %d.", P_optimal*N_optimal);
printf("\n\n -------------------------------------------------------------------- ");

LB3:
printf("\n\n\n\n + Do you want to continue testing an other constellation?");
```

```
printf("\n (Press key <Y> for <Yes>,<other key> for <No> and <exit>)");
ch=getch();
        if (ch=='Y'||ch=='y')
        goto LB1;
        else
        while(1)
        break;
        return (0);
}
```

A.III.2 <u>C code to find the optimal satellite constellation for continuous coverage for an area specific</u>

```
#include <math.h>
#include <stdio.h>
#include <conio.h>

int P, N, N_min, N_max, P_min, P_max, testPN;
int N_optimal, P_optimal, count;
char ch;

main()
{
LB1:
clrscr();
printf("\n\n *********************************************************** ");
printf("\n\n ********* Testing Satellite Constellation, P and N ********* ");
printf("\n\n *********   Constellation for continuous coverage  ********* ");
printf("\n\n *********           for an area specific           ********* ");
printf("\n\n *********************************************************** ");

printf("\n\n\n + Please input the minimum number of satellite planes, P_min= ");
scanf("%d",&P_min);
printf("\n + Please input the maximum number of satellite planes, P_max= ");
scanf("%d",&P_max);
printf("\n + Please input the maximum number of satellites per plane, N_max= ");
scanf("%d",&N_max);
printf("\n + Please input the minimum number of satellites per plane, N_min= ");
scanf("%d",&N_min);

P=P_max;
N=N_max;

printf("\n\n ---------------------------- START Testing ----------------------------");

while (P>=P_min&&N>=N_min)
{
  printf("\n\n -> Testing [ P= %d, N= %d ] ", P, N);
  printf("\n\n + Testing satellite constellation %d planes with %d satellites per plane." , P, N);
```

```
  printf("\n\n + If test is possible, insert value 1 otherwise insert value 0, testPN= ");
  scanf("%d",&testPN);
  if (testPN==1)
  {
    N_optimal= N;
    P_optimal= P;
    N=N-1;
    if (N>=N_min)
        continue;
    else
        P=P-1;
        N_max=floor(P_optimal*N_optimal/P);
        N=N_max;
        continue;
  }
  else if (testPN==0)
  {
        P=P-1;
        N_max=floor(P_optimal*N_optimal/P);
        N=N_max;
        continue;
  }
}

printf("\n\n ----------------------------- END Testing ----------------------------- ");
printf("\n\n  >>> H ence,  the op timal con stellation i s % d  planes w tih  %d sat ellites pe r pl ane,  "
,P_optimal,N_optimal);
printf("\n\n and the minimum total number of satellites is equal to %d.", P_optimal*N_optimal);
printf("\n\n ------------------------------------------------------------------------ ");

printf("\n\n\n\n + Do you want to continue testing an other constellation?");
printf("\n (Press key <Y> for <Yes>,<other key> for <No> and <exit>)");
ch=getch();
        if (ch=='Y'||ch=='y')
        goto LB1;
        else
        while(1)
        break;
        return (0);
}
```