Politecnico di Torino

Master's Degree in Aerospace Engineering

Master Thesis

Multi Objective Genetic Algorithm Optimization Of a Cubesats Constellation To Ensure Communication Services During Natural Disasters Over Europe

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Abstract

The thesis focuses on the study and optimisation of a coverage for communication service, based on the deployment of a CubeSats constellation, aiming to provide a continuous coverage of an area of interest, in the specific, Europe and to provide a communication within in every point of the selected region by using small transportable antennas on ground.
A market survey is performed and shows that in the communications market, the use of nano and/or micro satellites has had an exponential increase in the last two decades and is destined to grow in the future.
One of the driving aspects for this thesis is the provision of a continuous coverage in order to assist the Civil Protection operations, in case of emergencies, which need an up to date satellite communication system. In this sense a constellation could be particularly attractive and could solve some limitations of the current technologies.
Starting from the definitions of system requirements, during the project phase 0, a feasibility study is performed, based on the link budget equation and on the coverage problem. This analysis sets the initial conditions in terms of antenna system, for the optimization of the constellation.
The core of the work is the implementation of a genetic algorithm based on a multi-object optimisation, where the Keplerian orbital elements and constellation parameters where taken as inputs, to generate the different populations to be provided to the fitness function.
The scenario is built using MATLAB functions that works in STK, by running the algorithm on the latter. The study is conducted in an innovative way, using the interaction between MATLAB and STK.
Number of planes, number of satellites per plane, orbital planes inclination and satellites altitude are the output of the analysis. These parameters allow to establish a preliminary mass and cost estimation.
This thesis is developed thanks to a collaboration between the Politecnico of Torino and the company ALTEC S.p.A. The work was carried out at ALTEC headquarters , with the support of the University.

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Nomenclature

Acronyms / Abbreviations

$\vec{B}$	Magnetic Field
$\vec{E}$	Electric Field
AIT	Assembly Integration and Test
CDS	CubeSats Design Specification
CNR	Carrier-to-Noise Ratio
COTS	Commercial Off The Shelf
DV	Design Vector
ECSS	European Cooperation for Space Standardization
EIRP	Equivalent Isotropic Radiated Power
EM	Electro-Magnetic Field
ESA	European Space Agency
FOM	Figure Of Merit
GA	Genetic Algorithm

GEO Geostationary Earth Orbit

HPOP High Precision Orbit Propagator

ICRF International Celestial Reference Frame

IOT Internet of Things

LHCP Left Hand Circular Polarization

M2M Machine to Machine

NP Number of Planes

NSGA-II Non-dominated Sorting Genetic Algorithm II

NSP Number of Satellites per Plane

OLE Object Linking and Embedding

P-POD Poly Pico-satellite Orbital Deployer

RAAN Right Ascension of the Ascending Node

RHCP Right Hand Circular Polarization

ROI Region Of Interest

SNR Signal-to-Noise Ratio

STK Satellite Tool Kit

Chapter 1

Introduction

1.1 Motivation

Constellations of micro, nano and CubeSats are currently one of the major interest for future space applications, from Earth observation and service providers, such as communication service, to deep space exploration missions, including for example fly-by missions to the moon or randez-vous to orbiting objects. The ambition is to provide all these services through low cost and mass saving (in terms of volume and number of satellites), with a still increasing technological level. Therefore, the optimization of satellites constellations is essential for the design and support of the new space missions that will be based on the utilization of micro and nano satellites. These constellations because of their cost-effectiveness are becoming more attractive for a wide range of specific mission goals, increasing significantly the access to space also for scientific, non-governmental and private institutions at the same time.
From the market analysis the growing interest in satellite constellations was highlighted. Moreover, the need for a stable and high performance internet and communication network, for European Civil Protection purposes has been identified. Consequently it was decided to try to use these constellations to fulfill this need. Rescue operations in damaged areas are facilitated when forecasting and prevention actions are incisive and coordinated, reducing or

mitigating the effects of possible calamitous events and reduce the extent of damage. It is of fundamental importance, for the good functioning of the rescue machine, that an effective system of communication is established between all the actors involved in overcoming the emergency. Currently, emergency communications are supported by fixed and mobile telephone lines for audio-fax communications, by the Internet for sending data and videos, and by a radio communication system that allows to maintain contact with those areas where telephone networks are damaged or unusable. If the above methods do not work, it is useful to have a system capable of ensuring communication continuity, to replace and establish a base communication network. Nowadays the communication service used in current emergency situations is supported by GEO satellites with huge limits in terms of downlink and uplink data transfer. The aim is to use a constellation of micro, nano and CubeSats as an alternative to the current GEO satellites. The aim can be achieved starting from the requirements definition and proceeding with coverage definition, link budget evaluation, in order to define a feasible scenario, and the use of a multi-objective optimization. Finally the constellation is optimized in terms of orbital parameters, in order to reach the highest as possible coverage over the region of interest (ideally 100% time and space coverage).

1.2 Micro, Nano and Cube Sats

Micro-satellites often have a launch mass between 25 and 100 kg. Depending on technology used, the principal amount of power is in the 50-250 W range. Micro-satellites tend to be designed with COTS components, implementing simplified project management and AIT process: this allows to reduce the costs considerably. These satellites can be used alone or in distributed systems (e.g.*constellation* or *formation flying*), for remote sensing, telecommunications or science missions.

Nano-satellites have a dry launch mass in the 5 to 25 kg range. The on board DC power is in the 10 to 100 W range. They can be equipped with an attitude control in three axes and they offer sophisticated data communication capabilities. Nano-satellites are usually deployed for less than 3 years lifetimes in LEO, due to atmospheric drag or the use of COTS components. Like micro-satellites, they can be used to cheaply implement scientific, remote sensing, communication, technology research and educational missions, being characterized by a high affordability and efficiency.

MASS CATEGORY	**MASS RANGE**
Minisatellite	$\geq$ 100 kg
Microsatellite	10 - 100 kg
Nanosatellite	1 - 10 kg
Picosatellite	0.1 - 1 kg
Femtosatellite	0.01 - 0.1 kg

Table 1.1 Small Spacecraft Mass Categories [13]

CubeSats are a subclass of Nano satellite that has become a popular system for academic, research, and commercial institutions. The CubeSat is a standardized satellite bus defined by California Polytechnic State University's CubeSat Design Specfication (CDS) [4].

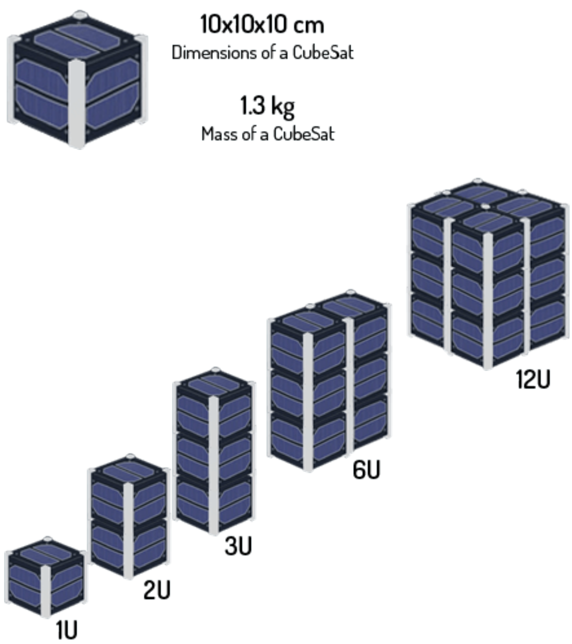

Fig. 1.1 CubeSats dimensions, mass and unit type.

These satellites, according to Table 1.1 mass ranges, take place in the Picosatellite and Nanosatellite mass ranges. CubeSats, as seen in Figure 1.1, are composed of one or multiple 10 cm x 10 cm x 10 cm cubes, also called U units, and are usually designed in a 1U, 1.5U, 2U, 3U, or 6U configuration. U's are conventionally limited to 1.33kg in mass. Figure 1.2 below illustrates some of these configurations.

Fig. 1.2 CubeSats are sized by number of units (U).

These satellites are generally launched into space as secondary or auxiliary payloads. Therefore the greatest merit of CubeSats is to allow to more organizations (public and private) to launch, deploy and test their novel spatial architectures at an increasingly accessible cost.

1.2.1 Launching

The CubeSat must be placed in a deployment mechanism, allowing launch. A standard launch interface or mechanism called the *Poly Pico-satellite Orbital Deployer* (**P-POD**) was developed, for example, by California Polytechnic State University [2]. The P-POD is then connected to an upper stage rocket body as a piggyback payload and deploys the cubes once the upper stage of the Launcher Vehicle has reached orbit. The P-POD provides and safe method to integrate CubeSats to the launch vehicle which increases the likelihood of approval by the primary payload.

The amount of mass that the vehicle can lift in space is a fundamental parameter for evaluating launch performance. Generally the Spacecraft are divided in three categories as in fig 1.3:

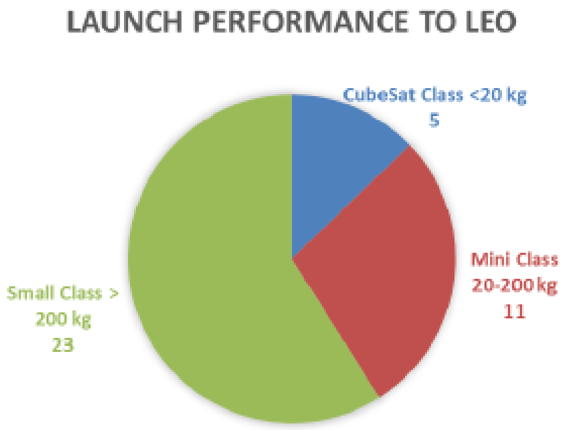

Fig. 1.3 Performance Classes for Launch Vehicles[14]

Perceived advantage in cost and cost containment are the key drivers to this market expansion of small launch vehicles. Nowadays the launch vehicles on the market seems to be too expensive in order to support the small satellite market expansion [14]

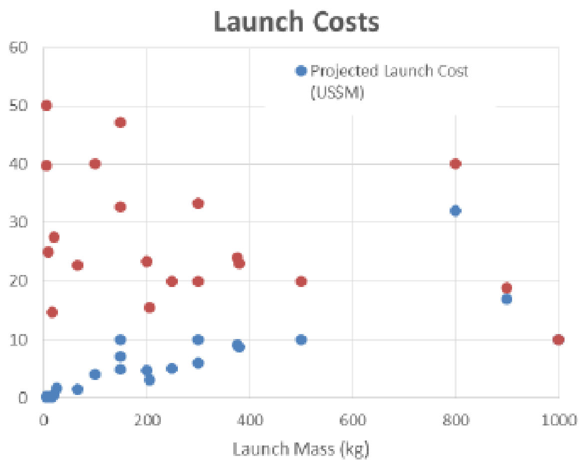

Fig. 1.4 Planned launch service price [14]

Figure 1.4 shows that for payloads with a mass of less than 500 kg the cost does not exceed 10 million. Anyway, none of these launchers come close to the much lower per kilogram

cost of bigger rockets like the Falcon 9 ($2.7k/kg for the reusable variant).
One of the most important objects of these small launch systems is to achieve high launch rates. Achieving this goal is essential to reduce costs.

1.2.2 Deployment

The P-POD main door is opened for the cubesat deployment, once the release mechanism of the P-POD door is actuated, a set of torsion springs at the door hinge swing the door open, and the CubeSats are deployed by the main spring, gliding on the P-POD's rails. The spring pushes out the satellites and gives them a speed that depends on their weight. The springs are all designed in the same way, so if the cubesats have different masses, they will be ejected at different speeds, usually between 1.2 and 1.7 m/s. The tubular design of the P-POD creates a predictable linear trajectory for the CubeSats resulting in a low spin rate upon deployment [5].

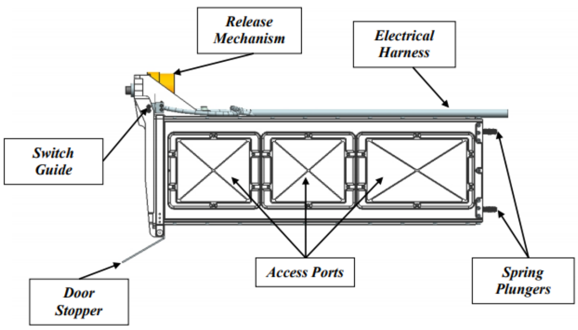

Fig. 1.5 Main P-POD Features [5]

1.3 Market Analysis and Forecast

Over 300 nano/microsatellites were launched in 2017, that represents an increase of 20 percent in nano/microsatellites launched compared to 2016. This market analysis has been performed for the microsatellites range up to 50 kg, due to the relatively large amount of satellites increasing in this mass range.

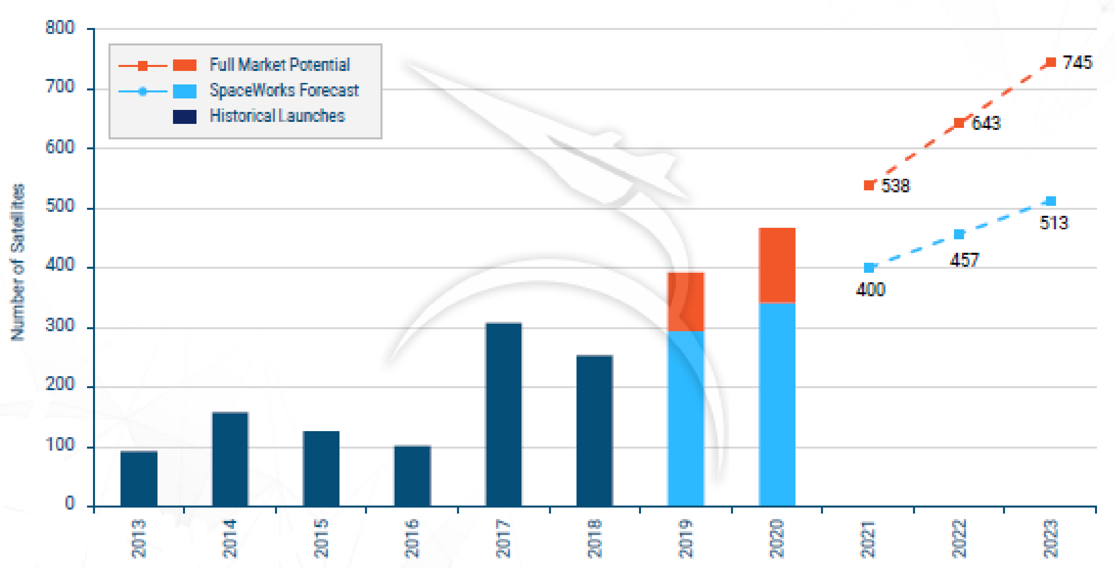

Fig. 1.6 2018-2019 Launch history and market forecast.[18]

The projection in figure 1.6 highlights that up to 2800 nano/micro satellites will be launched over next five years. In 2018, over 10 percent of all the nano/micro satellites launched were intended for communication applications [18]. In the next five years, communication satellites constellations are expected to represent over 20 percent of the nano/micro satellites market, where as many as 700 nano/micro satellites will be launched. For civil and commercial uses, these satellites will be useful. [18]

Much of the activity in this field is centred around serving the rapidly growing IOT/M2M market. Communications operators are still in the technology demonstration phase and will need to secure additional capital to execute on their deployment plans. Whether or not these predictions are met, it is possible to expect that the large number of satellites put into orbit will drive significant advancement both in commercial and in scientific applications.

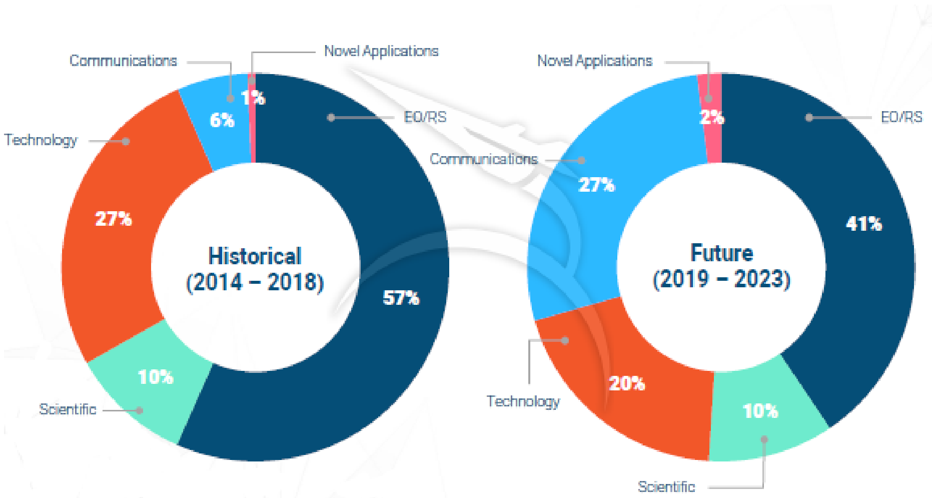

Fig. 1.7 Nano/Micro satellites trends by application.[18]

The global launch market demonstrated broader acceptance of small satellite ride shares. Traditional launch vehicles accommodated a record number of small satellites awaiting launch. Another growing market is that of small launchers, which allow smaller masses to be launched more frequently, reducing costs. About that, for example, Rocket Lab's Electron achieved its first successful launch in January of 2018, at an altitude of 500 km, marking a new era of responsiveness for small satellite launch [18].

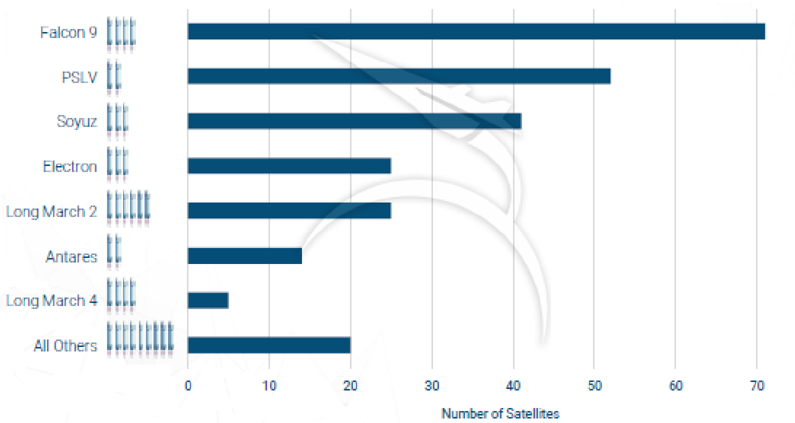

Fig. 1.8 Launcher efficiency. [18]

In Figure 1.7 the Electron is compared to other large launchers. It is shown how Electron is the fourth in terms of satellites launched in only its first year of operations [18]. These results bode well for an increasingly profitable use of these launchers.

1.4 Satellites Constellation

Traditionally, space missions have used only a single monolithic spacecraft to make measurements and communicate with land controllers. This architecture can sometimes fundamentally limit the activities of the spacecraft to a single point in space and time. For missions that needs more than one satellite and for more complex missions, satellite constellations are adopted. The most common targets are global and regional coverage for voice, data, communications relays, and science measurements. Large-scale Earth orbiting constellations of many satellites promise great operational benefits due to the spatial and temporal diversity they can achieve. With the technological advances of small satellites, these constellations are rapidly emerging. An example of a satellite constellation is **Iridium Satellite Constellation**, or upcoming private Iridium NEXT, that relays data for satellite phones and provides telephone connectivity worldwide using 66 low earth orbit satellites [9].

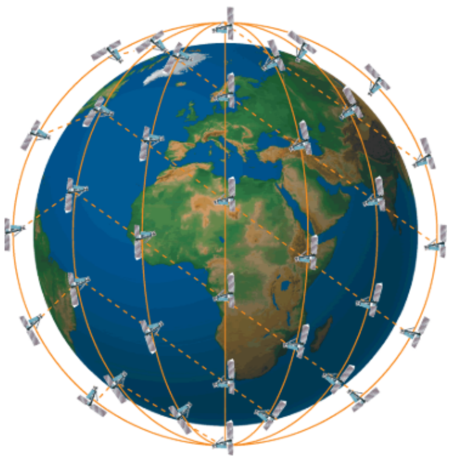

Fig. 1.9 Iridium LEO Constellation

The number of spacecrafts in a distributed space system can range from two to several hundreds or even thousands. An interesting feature of LEO communication constellation is it can be optimized for multiple factors. For example higher altitude means fewer satellites, but a much more severe radiation environment, so the satellite cost will be higher, operational life shorter and more power will be needed.

The constellation discussed in this thesis aims to provide the required coverage with the minimum number of satellites. The primary trade off is often coverage as a measure of performance versus number of satellites as a measure of cost. However, the system cost isn't represented only by the number of satellites. Launchers are the most expensive part. For example higher altitude constellations require fewer satellites, but more cost to take satellites into orbit.

Specifying a constellation by defining all of the orbit elements for each satellite is complex.[10]. In the analysis of this thesis, only some of the six orbital parameters were included in the optimization. This choice becomes from having adopted circular orbits at the same altitude and inclination. This means that the period, angular velocity, and node rotation rate will be the same for all of the satellites [10]. This work uses this approach to optimise the constellation using a Walker architecture.

Chapter 2

Preliminary Space Mission Analysis

Space Mission Engineering is the refinement of requirements and definition of mission parameters to meet the broad objectives of space mission in a timely manner at minimum cost and risks, looking at the system as a whole [10].
It is important to distinguish Mission Engineering by System Engineering, which is concerned primarily with the formal requirement definition process and how to achieve all requirements satisfaction.
This analysis starts with a need based mission, in which a specific set of objectives must be fulfilled. In this thesis the goal is to provide high availability communication service, in addition to the currently existing services, in the event of natural disasters.

2.1 Elements of a Space Mission

Each mission can be divided into different phases and elements. The latter are: space segment (S/C in orbit), Launch segment (the launchers) and ground segment (ground control stations). All of these several elements must interact with each other, so it is important to design them to satisfy mission requirements. What has been said merges in the space mission architecture definition, then on the basis of this architecture each individual segment is studied and sized, based on the function it must perform and what it needs to perform it.

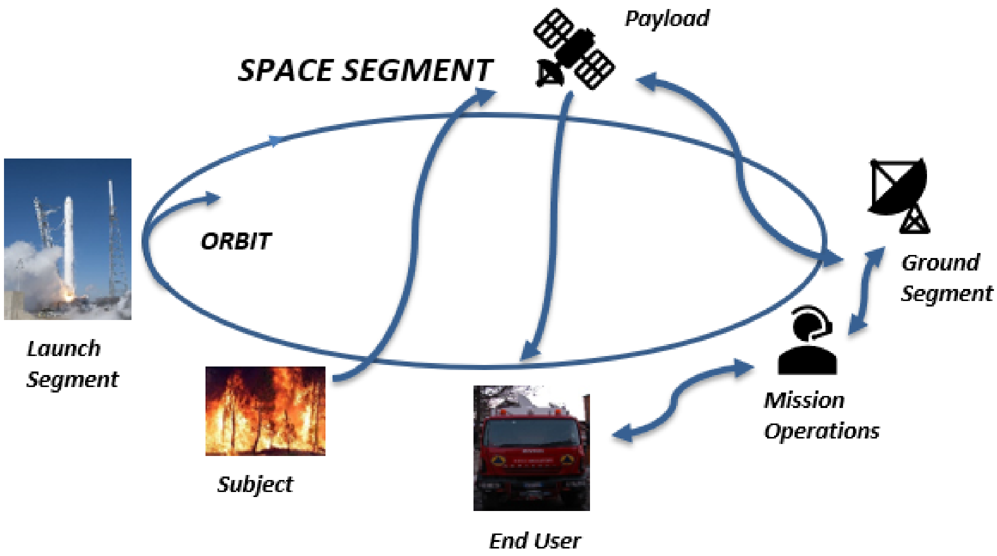

Fig. 2.1 Mission Architecture

The *launch segment* includes the facility, launch vehicle and its upper stage, required to place the spacecraft in orbit.

The *Orbit* is the spacecraft's trajectory or path, usually there is a separate ascending trajectory, final mission orbit and if it is planned, a disposal orbit or re-entry trajectory. The mission orbit critically influences every element of the mission.

The *Communication architecture* is the arrangement of components, which accomplish the mission's communication, command and control requirements. The key parameters on which it depends are: the amount of data to be transferred, as well as the bit rate, location, availability and readiness of communication of the space and ground assets.

The *ground system* consists of fixed and mobile ground stations in the region where service will must ensured.

Mission operations are carried out by the operators that deals with ground and space segments, procedures and data flow.
A relevant factors in the architecture of this mission are: command, control, and communications structure. The last one contains: spacecraft, communication architectures, ground segment, and mission operations elements.
The *mission subject* is what interacts, or is sensed by the S/C payload, it is the main focus of interest for the mission; e.g. for a communication mission: region of interest, equipment on the Earth such as ground terminals, ground facility, or equipment on S/C.
Providing continuous coverage of a specific region of interest is the subject of the mission.
The first step is to determine the subject element's key characteristics in two cases:

- If mission interacts with user equipment, we must define the subject characteristics either from known information for well-established services or by a trade study involving in the rest of the system

- the parameters necessary to specify passive subjects are largely the same as those use to specify user elements, except that there is no receiver to be characterized, and the EIRP specification for the transmitter is replaced by the object's emission intensity as a function of bandwidth.

2.2 V-Model and Project Phasing

System development life cycle is described by V-model, which is the graphical representation of the sequence of steps to be taken.

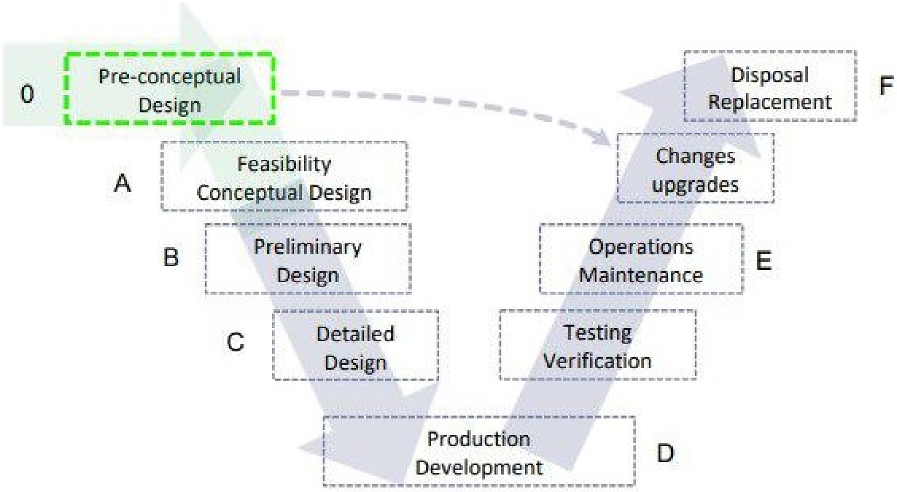

Fig. 2.2 V-Model

Following the direction of the arrows in the figure 2.2, the left side of the V represents the initialization and decomposition of requirements and formulation of system design, this is the project definition section with a Top-Down direction. The base of the graph depicts the actual implementation of the system (i.e. production). Finally, the right side of the V with a Bottom-Up evolution, represents the integration of parts and their validation up to operation and final phase of disposal or re-entry.
A comparable way of representing the development of a system lifecycle, based on V-model, is the project phasing. There are several organization of project phasing, but ESA guidelines (Fig. 2.3) are adopted for the purpose of this thesis, so the life cycle is divided into seven phases as follows:

A phase is a group of activities, in which a project advances from one milestone to another and the major activities are usually ended by a formal review, that confirms if the work has been carried out according to the requirements.

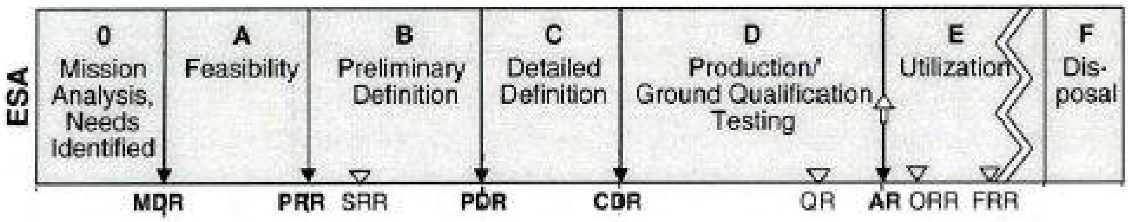

Fig. 2.3 Project phasing - ESA guidelines

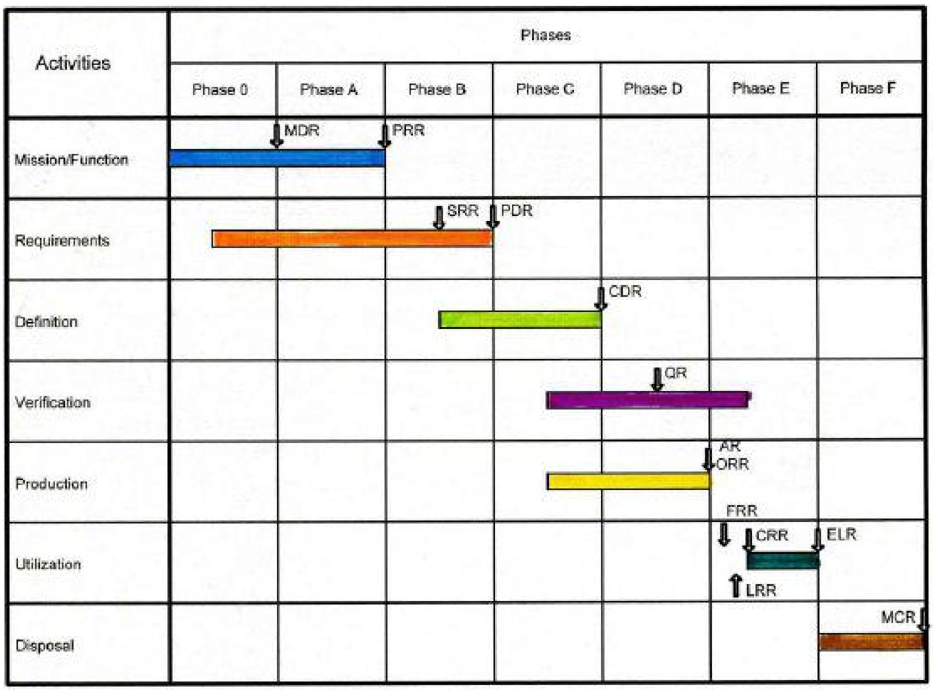

Fig. 2.4 Phases vs Activities

According to ECSS, phases 0, A and B are focused mainly on :

- the elaboration of system functional and technical requirements and identification of system concepts to comply with the mission statement, taking into account the technical and programmatic constraints identified by the project initiator and top-level customer
- the identification of all activities and resources to be used to develop the space and ground segments of the project
- the initial assessment of technical and programmatic risk

- initiation of pre-development activities.

Phases C and D comprise all activities to be performed in order to develop and qualify the space and ground segments and their products.
Phase E comprises all activities to be performed in order to launch, commission, utilize, and maintain the orbital elements of the space segment and utilize and maintain the associated ground segment.
Phase F comprises all activities to be performed in order to safely dispose all products launched into space as well as ground segment.[1]
For the purpose of this thesis, only a first approach of phase 0 has been addressed, the activities in this phase are conducted by the project initiator, top level costumer and representatives of end users; it is oriented to:

- The analysis of the mission by defining the mission statement in terms of identification an characterization of mission needs, expected performance, dependability and safety goals, and mission operating constraints due to physical and operational environment.
- Development of preliminary technical requirements specification.
- Identifying possible mission concepts.
- Performing preliminary assessment of programmatic aspects supported by market and economic studies as appropriate and preliminary risk assessment.
- The MDR is held at the end of phase 0, the output of this review is used to determine the readiness of the project to move into phase A. The main goal of the MDR is to release the mission statement and assess the preliminary technical requirements specification.

The most common space missions fall into five general areas: science and exploration, public services, commercial, military and human. Each of these categories is funded differently and

has disparate characteristics and objectives.
The mission designed for this thesis is mainly a commercial mission, but contains aspects that also concern the public interest and this is held in the stakeholders definition.

2.3 Stakeholders

Referring to R.E.Freeman's definition, a stakeholder is any person or organization who can be positively or negatively impacted by, or cause an impact on the actions of a company. Going into detail, Post Preston and Sachs, in their book "Redefining the corporation" say : "The stakeholders are the individuals and constituencies that contribute, either voluntarily or involuntarily, to wealth creating capacity and activities of a company, and are therefore its potential beneficiaries and/or risk bearers".

Stakeholders are classified by several standards, the new SMAD considers:

- **User/Operator** is the institution that uses the output data of the space project.
- **Sponsor**is the institution that pays for the space project.
- **Developer**is the institution that builds it.

Mapping the stakeholders, with respect to influence, power and interest, as shown in figure 2.5, can help to understand who to take more into consideration, this activity is called stakeholder prioritization.

- *Promoters* have both great interest in the mission and the power to contribute to its success.
- *Defenders* have a vested interest and can voice their support in the community but have little actual power to influence the mission in any way

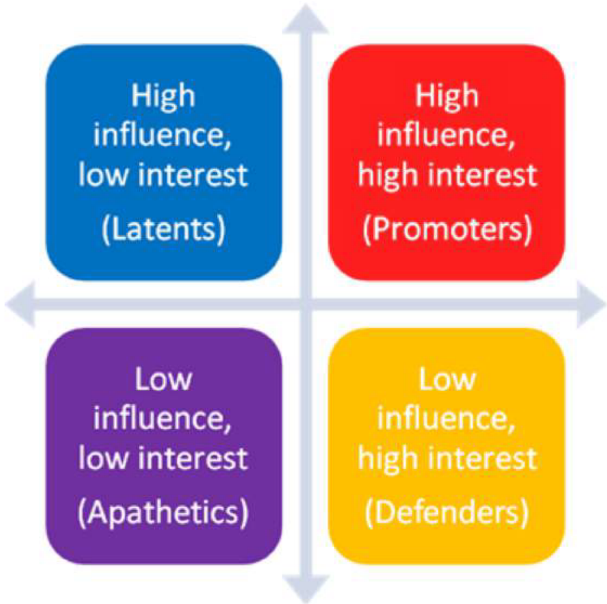

Fig. 2.5 Stakeholders mapping

- *Latent* haven't particular interest and can voice their support in the community but have little actual power to influence the mission in any way.
- *Apathetic* have little interest and little power and may not even know the project exist.

After a market survey that highlighted the opportunities of a constellation of CubeSats in a communication mission, it was decided to use them to study if they are able to guarantee continuous geometric coverage and subsequently achieve continuity of communication. For this project, civil protection is a candidate as possible promoter. Civil protection is interested in improving its satellite communication service for the proper functioning of relief efforts. The goal is extended to the whole of the European continent, involving the civil protection agencies of different nations.

The defenders in this case may be the universities that may be interested in exploiting this project as a possibility of training for the students, or to test new technologies. In this category also falls public opinion, which can perceive the public utility of the service given the numerous disasters afflict the territory and cause enormous damages.

2.4 Mission Statement

The mission statement is a clear and concise sentence that explains why the mission exists. It defines the high level objectives of a mission, i.e. why the mission is required and for which purpose the system that shall perform the mission exist. It doesn't include lower level implementation aspects, like orbit or required bandwidth, but it is the source from which the top level mission and system requirements can be generated; the level of information included in the mission statement shall be sufficient to begin the requirements definition process.
A typical logical sequence of questions that shall be answered to define the mission statement is the follow:

1. What is the root problem? Who is the end user?
2. How can the problem be solved?
3. Are there other significant objectives imposed by the top level scenario?
4. What is the need defined by the identified problem and solution?

"To provide a broadcast services of voice, text and video data, to the European civil protection agencies; by deploying a LEO, low-cost, satellite constellation, with small and transportable ground stations. To achieve a complete coverage of region of interest for at least twelve months"

PRIMARY OBJECTIVE ***To provide continuous real-time telecommunication and internet service at low cost for Civil Protection operations.***
SECONDARY OBJECTIVE ***To allow service access for on request users under certain economic conditions.***

It is important to clarify that the mission statement concerns the purpose of the mission arising from this thesis. The objective of this thesis is mainly to optimize the constellation in terms of geometric coverage of the ROI and provide the basis for a future more in-depth analysis of the communication system.

2.5 Requirements Definition

Mission Requirements: The mission requirements and constraints derive straight from the mission objectives, just answering questions such as Why? When? Where? What? How many satellites? For how long? Mission Requirements generally address orbit requirement, duration, assembly, utilization timing and needs, scientific objectives and define the mission success criteria.

	REQUIREMENT
MIS-1	The mission lifetime shall be at least 12 months.
MIS-2	The mission shall have (TBD) S/Cs in (TBD) orbital planes.
MIS-3	The orbital planes inclination shall be e (TBD).
MIS-4	The S/Cs constellation shall be deployed in LEO.
MIS-5	The constellation shall provide broadcast and internet service.
MIS-5	Each S/C shall be replaceable.
MIS-6	The Constellation shall be failure tolerant.
MIS-7	Each S/C shall be compliant with the related space debris mitigation guidelines.
MIS-8	The mission shall have a disposal strategy.

Table 2.1 Mission Requirements

The identified mission requirements are listed in table 2.1.

Functional Requirements: they stem directly from the functional analysis. This class of requirements establishes which functions the product shall carry out and how well they shall be performed to accomplish the intended mission. Performance requirements are included. They provide inputs for the selection or development of the required components and subsystems.

The identified functional requirements are listed in table 2.2. In the thesis FUN-4 is guaranteed only for the image and text data.

Environmental Requirements:This class of requirements derives from the environmental conditions during the life cycle of the product. It includes the vibration and acoustic

	REQUIREMENT
FUN-1	The constellation shall cover whole European geographic area.
FUN-2	The constellation shall provide down-link communication.
FUN-3	The constellation shall provide up-link communication.
FUN-4	Each S/C shall broadcast Image, voice,text and video data
FUN-5	The constellation shall be operable by Mission Control Center.
FUN-6	The constellation shall insure continuous coverage in selected ROI.
FUN-7	The data rate shall be at least 50 Mbps (with a goal of 100Mbps).

Table 2.2 Functional Requirements

environment encountered during the launch phase, the thermal and radiation environment during lifetime in orbit.

	REQUIREMENT
ENV-1	The constellation shall survive in LEO environment.

Table 2.3 Environmental Requirements

For this mission has been identified only the requirement in table 2.3, due to the lack of detailed data relating to vibration, thermal and radiation forces.

Operational Requirements: Requirements related to system operability. This class of requirements refers to the operation phase and includes operative modes implementation from ground, on orbit operations in general, communication between the space and ground systems and related aspects (frequencies licences and coordination).

	REQUIREMENT
OPS-1	The constellation shall be tolerant to be deployed in either sunlight or eclipse.
OPS-2	The ground segment shall be constituites by mobile and trasportable antennae.
OPS-3	Communication shall be in X-band.
OPS-4	The space segment shall ensure a continuous coverage.
OPS-5	The ground segment shall ensure a continuous communications.

Table 2.4 Operational Requirements

The OPS-4 in table 2.4 is satisfied from this work. Otherwise OPS-5 and OPS-3 need a detailed designed of communication system.

Interface Requirements [tab. 2.5]: This class of requirements applies to the product's interfaces with other elements of the mission. It includes physical, electrical, thermal and communications interfaces.

	REQUIREMENT
INT-1	The S/Cs shall survive thermal loads at launch phase.
INT-2	The satellite shall dialogue with ground segments using telemetry.
INT-3	The S/Cs vibrational response shall not interfere with launcher response.
INT-4	The deployment system shall be a P-POD.
INT-5	The satellite communication system shall be compatible with ground mobile antennae.

Table 2.5 Interface Requirements

Physical Requirements[tab. 2.6]: Establish the boundary conditions to ensure physical compatibility (not covered by the interface requirements, design and construction requirements, or referenced drawings). This class of requirements applies (but it is not limited) to the product's geometry (dimensions, interfaces), its mass and inertia properties (mass, moments of inertia, CoM location), to the materials used for manufacturing.

	REQUIREMENT
PHY-1	The S/C shall be between 3U and 12U category.
PHY-2	The S/C mass shall be up to 20kg.

Table 2.6 Physical Requirements

Design Requirements[tab 2.7]:Related to the imposed design and construction standards such as design standards, selection list of components or materials, interchangeability, safety margins.

	REQUIREMENT
DES-1	The S/C shall use COTS components.

Table 2.7 Design Requirements

2.6 Mission Phases and Scenarios

After specifying the mission phases, to describe dynamically the interaction of the system with external environment or other systems, a set of mission scenario can be defined. Mission Phases definition and scenarios development allows to obtain a better description of the mission, identify additional requirements and constraints, analyse operation feasibility and identify potential off-nominal events.

For the mission of this thesis a first subdivision in Phases on the left and scenarios on the right is shown in fig 2.6:

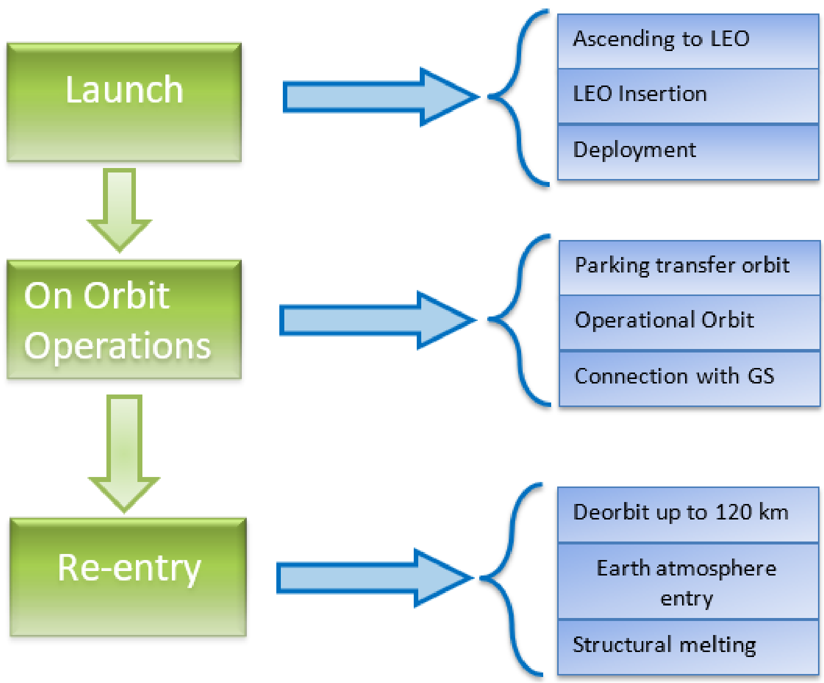

Fig. 2.6 Mission Phases and Scenarios derivation

The first phase involves the launch of satellites on board a launcher. As soon as the upper stage reaches the operating orbit, the release mechanism allows the satellites to be placed along the orbit. So the satellites are in the operational orbit. Now they can establish a connection with GS, starting to provide the communication service. During the operational life the satellites suffer a continuous deorbit, due to gravity. Below 120 km the satellite is considered lapsed. Thus the re-entry into the atmosphere and the destruction of the structure due to the impact with the atmosphere.

Chapter 3

Feasibility Study of a Communication Link

Today, satellites form an essential asset of communication system worldwide. From this perspective it is important to describe how this communication function is performed, focusing on communication as a primary mission objective.

Before starting to develop a communication architecture, it is useful to define the context in which the communication load must work. subsequently it is possible to determine the feasibility of a communication architecture on which the constellation, described in this thesis, is based.

Space mission communication architecture are usually divided in a ground segment and space segment in which those are included: ground terminals, network of satellites, control facilities and user terminals, that are connected by communications links.

The space mission communications architecture provides all the information needed to understand the number of communications link that each satellite's communication payload must support, whether the satellite beams support can be fixed, or whether it may be necessary to modify either the shape or the direction of satellite beams while on-orbit.

In the design of a communication space mission, the number of satellite and the orbit type

are strongly interrelated, i.e. they have a fundamental impact on the design.Focusing on this thesis, multiple satellites are used in a coordinated way. Orbit type also plays an important role in choosing the payload for communication, e.g. the altitude is fundamental in determining the power and sensitivity that will be required for the communications payload to achieve a stable link with ground terminals. Orbit and altitude also determines the delay between passes over a region of interest. Mission life time affects instead the choice of the main components, taking into account their operative and functional degradation.
The LEO constellation has been chosen for this work. It has several advantages:

- Highly survivable and multiple paths.
- Reduced jamming susceptibility due to limited Earth view area.
- Reduced transmitter power due to low altitude.
- Low cost launch per satellite.
- High latitudes coverage with inclined orbit.

and some disadvantages :

- Complex link acquisition ground terminals (antenna pointing, frequency and time).
- Complex dynamic network control.
- Many satellite required for high link availability.

3.1 Communication Link Analysis

An RF communication link occurs between a transmitter and receiver divided by a free space distance. The transmitter antenna radiates an electromagnetic wave into free space, and the receiver antenna collects the portion of radiated energy which falls on it.

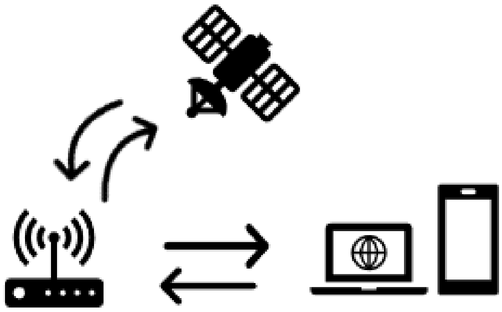

Fig. 3.1 Forward and Return Link

The overall link is composed by a *downlink* from satellite to Earth and a *uplink* from Earth to satellite. In turn, within these two categories it is possible to distinguish *forward links* (transmissions directed toward end users) and *return links* (transmission directed away from the end users).

Another feature that distinguishes a space mission of communication are the *Intersatellite links*, with which it is possible to exchange information between two satellites that belonging to the same constellation, this is useful to transmit information between two users who are not simultaneously in sight with the same satellite.

3.1.1 Physics of Satellite Communication Links

In this section, due to their importance in satellite communications, an overview is given on the physical principles of electromagnetic waves.

3.1.1.1 Electromagnetic wave

Each communication link used in a space mission is based on the propagation of electromagnetic radiation. The propagation occurs through the Earth's atmosphere and the space beyond the atmosphere, as we will see later, in this path the signal will suffer multiple losses. Almost all communication links use the spectrum of radio frequency of the electromagnetic wave and this spectrum is divided into a number of bands, as are listed in the following table.

Band	Frequency GHz
V-Band (ISL)	40 to 75
Q-Band	30 to 40
K_a-Band	18 to 30
K_u-Band	11 to 18
X-Band	7 to 11
C-Band	4 to 7
S-Band	2 to 4
L-Band	1 to 2

Table 3.1 Band in the Electromagnetic Spectrum

Electromagnetic radiation is generated by accelerating electric charges and by changing electric currents. A current oscillating at a frequency *f*, generates electromagnetic radiation in the form of propagating waves whose frequency match that of source [10]. Electric component of these waves, can be described by the following relations:

$$e = |E|\,sin(\omega t)$$

$$\omega = 2\pi f$$

$$\Phi = \omega t$$

$$\lambda = \frac{v}{f} = \frac{c}{f}$$

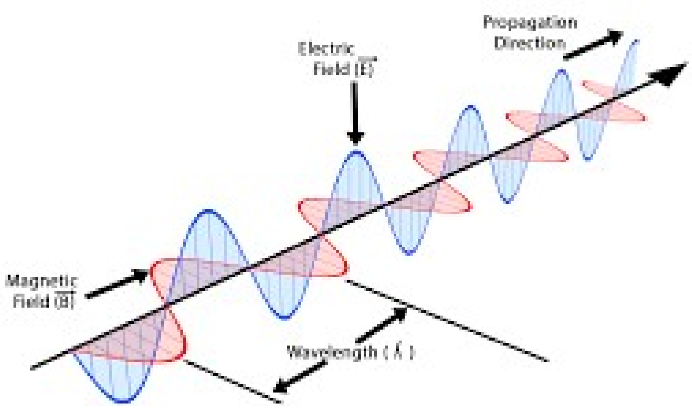

Fig. 3.2 Electromagnetic Wave

Figure 3.1 illustrates an electromagnetic wave with the electric and magnetic field vectors orthogonal both to one another and to the direction of propagation.

3.1.1.2 Polarization

Orientation of Electric and Magnetic field vectors are very important in radio wave communication, *Polarization* is the spatial alignment of the E vector. Usually polarization assignment is based on the orientation of E with respect to the Earth's surface.

- **Horizontal polarization**: $\vec{E}$ is parallel to the Earth's surface, signals oscillate from left to right.
- **Vertical polarization**: $\vec{E}$ is perpendicular to the Earth's surface, signals oscillate from top to bottom. .
- **Circular/Elliptical polarization**: two superimposed wave with same frequency, same direction and $\vec{E}$ perpendicular to one other. If the constituent waves are of equal amplitude we have Circular polarization, otherwise with unequal amplitude Elliptical polarization. In each case if $\vec{E}$ rotates clockwise as viewed in the direction of propagation, the polarization sense is **RHCP**, and **LHCP** otherwise.

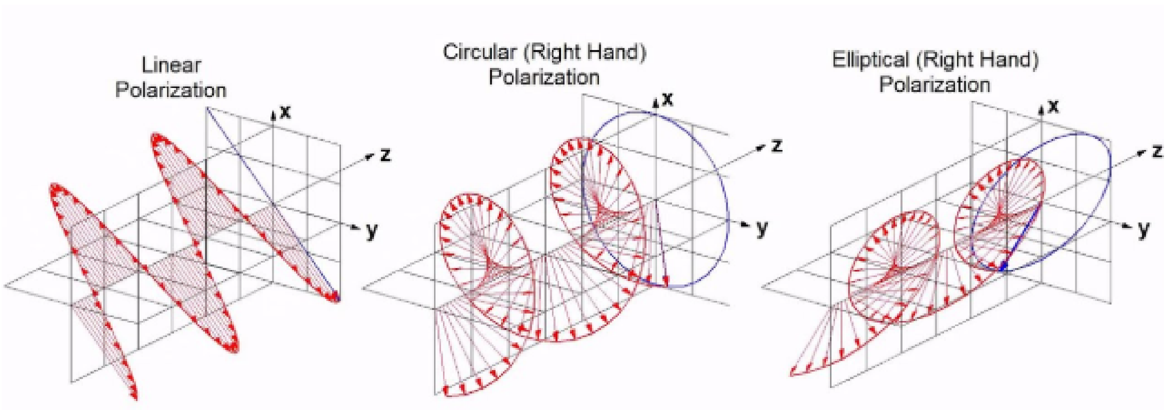

Fig. 3.3 Linear, Circular and Elliptical Polarization

In order to make communication link work effectively, both transmitting and receiving antennas should be in the same polarization.

3.1.2 Antennas

Antennas are used to launch an EM wave into space or receive an EM wave, to amplify the Tx or Rx signals that travel in a particular directions relative to the antenna [10]. There are several types of antennas and it is difficult to determine which antennas are likely to be useful for a given application. It is important to take in account any factors like operating frequency, coverage or pattern requirements and amplification factor.

The antenna *Gain*, **G**, gives the amplification factor of an antenna. It includes *directivity*, **D**, the focusing effect of the antenna which is a measure of the antenna's ability to concentrate energy is a given in a fixed direction, to which the losses L are subtracted.

$$G = D - L$$

The gain of an antenna can be calculated using different formulations involving frequency, efficiency and size:

$$G = \eta \left(\frac{4\pi}{\lambda^2}\right) A = \eta \left(\frac{\pi D}{\lambda}\right)^2 = \eta \left(\pi D \frac{f}{c}\right)^2$$

Or using the decibel based arithmetic, expressing the gain in dB:

$$G = 20.4 + 20log(f) + 20log(D) + 10log(\eta)$$

These relationships can be applied in a wide range of design situations, pertinent to communication payload architecture.

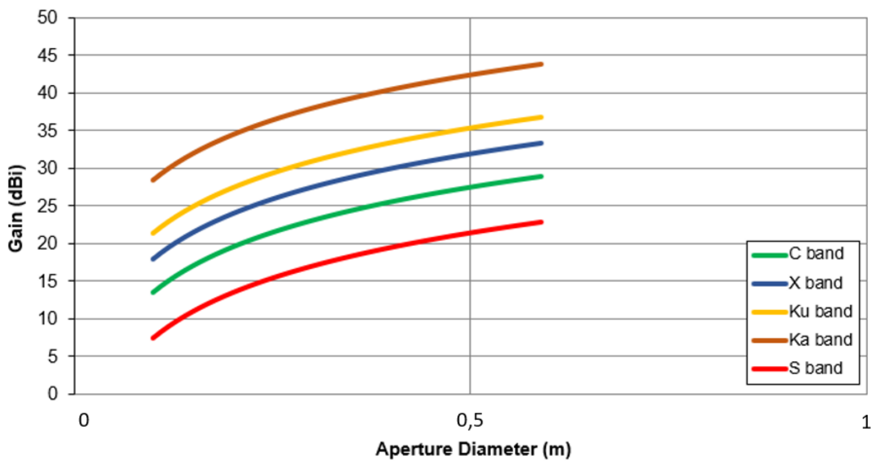

Fig. 3.4 Gain vs. Aperture Diameter for Several Frequencies and aperture Diameters

Assuming an antenna efficiency of 55%, in Fig 3.3, is shown how the gain varies according to frequency and aperture size.

The *half-power beamwidth* is the angle with respect to boresight, within which the gain is within 3dB, or 50% of the peak. Supposing an antenna with circular symmetric aperture the half-power beamwidth (deg) is:

$$\Theta = 21/(fD)$$

3.1.3 Pointing Errors

Pointing errors affect all antennas. Antenna pointing errors is caused by a pointing offset between the beam of the two antennas and it strictly depends on the ADCS performance. The most considerable causes of pointing error in satellites are linked to thermal distortion that results from variable heating of different antenna and spacecraft structures, which changes when the orientation of the satellites and antenna changes. When examining a communication link, it is significant to remember that the antennas on both ends of the link contribute to pointing errors. A graphical description of pointing error is represented in figure 3.4. It shows that in the direction of the ground receiver/transmitter the signal intensity is maximum. However, if the satellite receiver/transmitter is not in the direction of maximum intensity the performances degrade. The angle between the direction of the satellite and the ground receiver/transmitter is called angular pointing error.

3.1.4 Noise Temperature

The link analysis must also account for all significant sources of noise, evenly important for signal power computation. In the broadest sense, noise includes all in-band sources of EM energy received other than those that are desired to support the communications mission [10]. These incorporate black body thermal noise irradiated from environment, noise produced from within the link, and non thermal origins of interference from the outside the system,

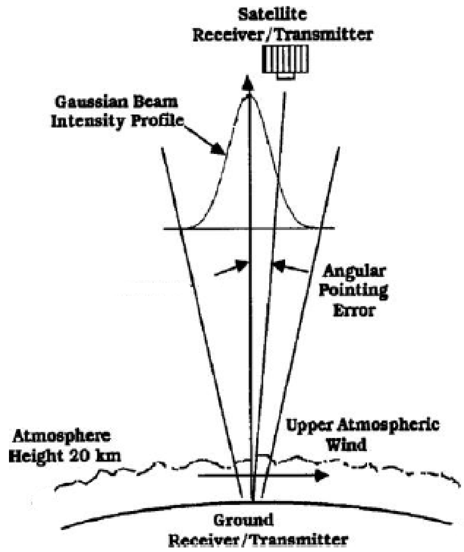

Fig. 3.5 Pointing Errors

including other RF transmitters that are not part of the space mission communications system being designed (usually accounted for separately).

Every object in nature emits EM radiation. Therefore, as a first contribution to noise, the EM radiation, approximated by that of a black body, produced by the objects in the field of view of the receiving antenna is considered.

$$N_0 = kT$$

Where N_0 is in W/Hz, k is the Boltzmann constant and T is the object's effective brightness temperature (K) the temperature that would be required of a black body in equilibrium with its environment to exhibit a similar radiation spectrum [10]. The overall *System Noise Temperature* is given by:

$$T_s = T_{ant} + \left(\frac{T_0(1-L_r)}{L_r}\right) + \left(\frac{T_0(F-1)}{L_r}\right)$$

The first term represents the *Antenna Noise Temperature*, estimated based on a general understanding of the antennas intended coverage and simpler models of the Earth's brightness temperature. The second term depends on the line losses between antenna and Low Noise Amplifier. These losses are proportional to cable length and cable type. I third term, the numerator is T_{LNA} anf F = 1+T_r/T_0, where T_r is the receiver noise temperature and $T_0 = 290K$ is reference temperature.

To maintain the correct temperature, a solution may be to cool the receiving equipment, e.g. for smaller stations, the solutions are based in the use of low noise equipment and a careful design. In the spacecraft is normally impossible to deeply reduce the temperature because the receiving equipment is usually around 290 K. This is one of the main reasons because uplink and downlink do not perform at the same way.

3.1.5 Modulation and Coding

To transmit data content between transmitter and receiver, the EM that enclose the working bands of the communication system are adjusted to encode data. *Modulation* is the name given to the process of changing a particular property of the carrier wave, typically a high-frequency periodic waveform, through the modulating signal, which typically contains information to be transmitted. *Demodulation* is the method by which signals are recovered from modulated carriers.

Nowadays communications transmits in digital format, at data rates measured in bps, with MODEM that operate on symbols, with a number of bits per symbol. Amplitude modulation seldom appears in satellite systems because it requires larger and more costly transmitters. Phase (*Phase Shift Keying*) or frequency modulation techniques are preferred, because the transmitter can operate at maximum power efficiency.

The simplest modulation scheme *Binary Phase Shift Keying* (BPSK), encodes information onto carriers through the use of two phase states per symbol (1 bit per symbol). Higher order modulations are: *Quadrature Phase Shift Keying* (QPSK), 8-PSK and 16-PSK that employees 4, 8, and 16 phase states per symbol, or the corresponding 2, 3, 4 bits per symbol. Higher order modulation involves in higher susceptibility of the communication links to the phase noise induced errors.

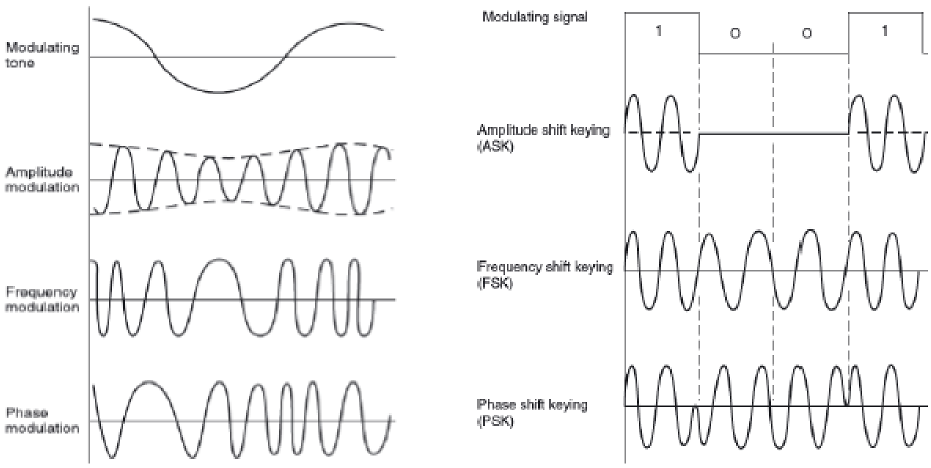

Fig. 3.6 Carrier features that the modulating signal changes

3.1.6 Bit Energy to Noise Ratio

The *Bit Error Rate* (BER) is a measure of quantization error in digital communications links [10]. As the bit energy is lowered and it increases and approaches the noise level that characterizes the communication link. It is possible to predict the BER of a communications link as a function of the bi energy to noise spectral density ratio (E_b/N_0) for a given modulation scheme and code rate [10]. BER is approximated by:

$$BER \approx \frac{1}{m} erfc\left(\sqrt{\frac{mE_b}{N_0}}\sin\left(\frac{\pi}{M}\right)\right)$$

where the M-ary PSK modulation scheme encodes m bits per symbol with M = 2^m.

Figure 3.6 exposes that for fixed bit energy quantization error grows as the number of bits per symbol increases, and that it is necessary to increase bit energy, to keep a unchanging BER as the symbol rates increases.

3.1.7 Atmospheric Effects

The atmosphere represents one of the sources of attenuation of EM radiation.
In Fig 3.7 is depicted the total attenuation resulting from atmospheric gases as a function of frequency. There are a contribution due to dry air and a second due to water vapor in the atmosphere. The first peak of total attenuation, due to water vapour is at 22GHz and second

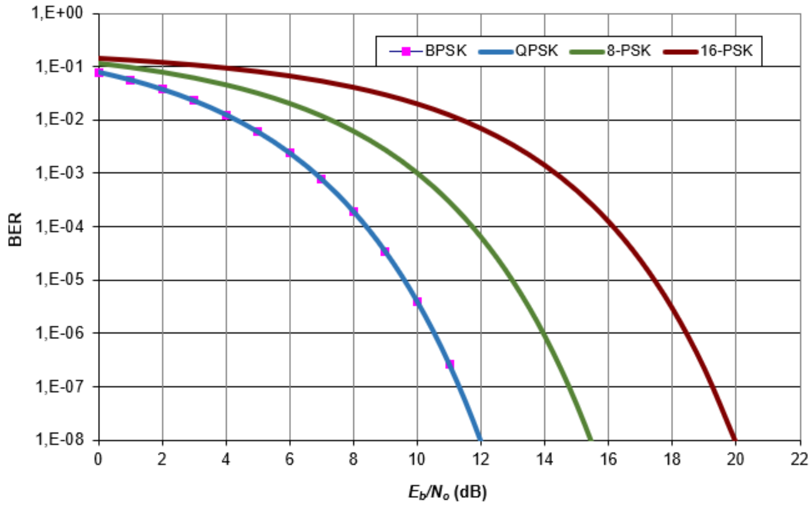

Fig. 3.7 Predicted BER Curves as a Function of Eb/N0 [10].

one is at 60 GHz due to molecular oxygen. There are also losses due to rainfall (rain and snow) that act through absorption and scattering. These losses vary depending on the season and the geographical area, as they are highly dependent on the concentration of water in the atmosphere. To predict rain precipitation effects, ITU has created a geographic database of rainfall rates [10]. Scintillation is the variation of signal amplitude, phase and angle of arrival due to refractive index of troposphere and ionosphere. But this effect doesn't represent significant constraint to the design of satellite communication links above 1 GHz.

3.2 Link Equations

Link analysis is fundamentally for detailed communication payload design. The link is divided into three main parts: Transmission , EM wave propagation and Receiving, these are included in the link equation:

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - L_{Tx+Rx}$$

where P_{Rx} and P_{Tx} are respectively the power at the receiver and from amplifier, G_{Rx} and G_{Tx} are the gains of receiver and transmitter antennas and L_{Tx+Rx} represents all losses.

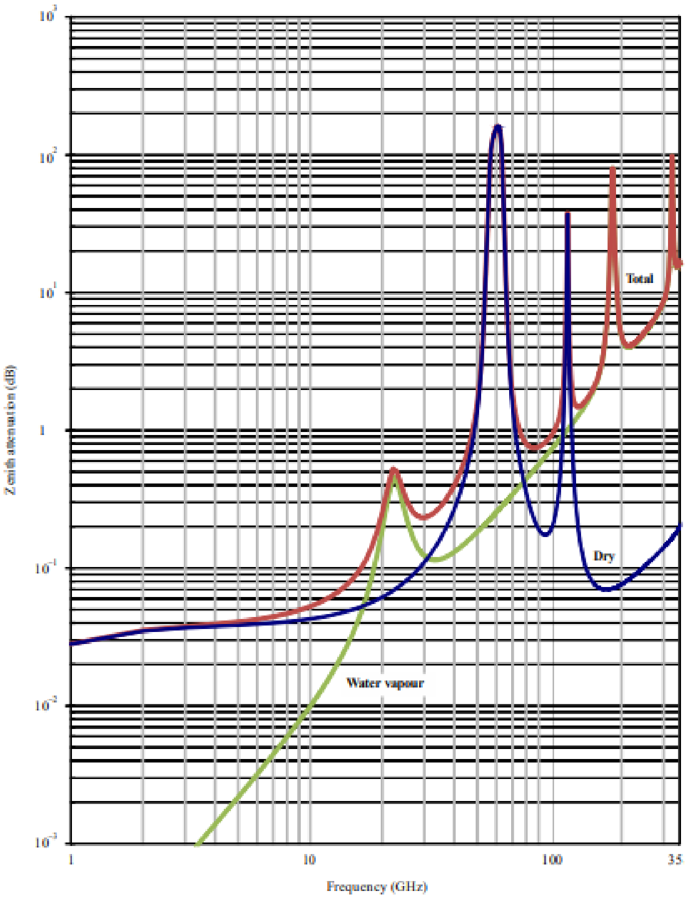

Fig. 3.8 Attenuation of EM Radiation vs. Frequency [8]

Starting from this equation the analysis continues by accounting for increments an decrements in power over each part of the link from the transmitter antenna, through space, to the receiver antenna and electronics where the signal is computed and decoded. In this way the analysis is done as a budget, where the positive allocations represent the sources of power, while the negative ones the losses. In the end the positive allocations must balance the negative allocations for the link to close.

The value to consider is the margin or excess on the threshold in received signal to noise power ratio at the receiver, required to close the link. The link is closed if the margin to the requirements is greater than or equal to zero. These requirements are determined or tabulated according to the modulation scheme and data rate that are to be used for the link.

Using the Shannon–Hartley theorem we can compute the maximum rate at which information can be transmitted over a communications channel of a specified bandwidth in the presence of noise, in other words a bound on the maximum amount of error-free information per time unit.

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

where C is the channel capacity, B is the bandwidth of the channel in Hz, S is the average received signal power over the bandwidth, N is the average power of the noise and interference over the bandwidth and S/N is the SNR or the CNR of the communication signal to the noise and interference at the receiver which is what you want to obtain.

3.2.1 Transmitted Power and Output Losses

The principal metric to evaluate for the transmitter work is the EIRP, a measure of the power radiated in the direction of the beam peak of the transmit antenna. The EIRP is the difference between the power of the transmitter and losses between transmitter and antenna, plus the transmit antenna gain. The result corresponds to the power that an isotropic radiator, with no output losses, requires to radiate wit power flux density equivalent to that at the beam peak of the transmit antenna.

$$EIRP = P_{Tx} + G_{Tx} - L_{output+Txantenna}$$

3.2.2 Free Space and Atmospheric Losses

The signal that reaches the receive antenna is reduced by atmospheric and free-space losses. These losses represents the reduction in power flux density that comes from the geometric dispersion of the EM radiation that travels into space.

$$L_s = \left(\frac{4\pi r}{\lambda}\right)^2$$

where r is the distance between Tx an Rx antenna and λ is the wave-length of the RF carrier. Furthermore the signal received, is reduced by atmospheric losses.

3.2.3 Received Power

The signal is increased by the gain of the Rx antenna , then reduced by the losses before the signal reaches the Rx amplifier. This process is complementary to that described for the signal path of the Tx.

$$C = EIRP + G_r - L_s - L_{atm+prec} - L_{in} - L_{Tx+Rx}$$

L_{in} are the input losses to the receiver and L_{Tx+Rx} is the sum of Tx and Rx pointing losses.

3.2.4 Receiver G \T

The Rx antenna gain to the noise temperature of the receiver is the principal FOM used to characterize receiver sensitivity and it is used to compute SNR. It is usually expressed in dB and computed as:

$$\frac{G}{T} = G_R - T$$

3.2.5 Available E_b\N_0 and Link Performance

The final step of the link analysis is to determine the value of E_b/N_0 for both downlnk and uplink, defining the relatioship amng data rate, antenna size, propagation path length and Tx power.

$$\frac{E_b}{N_0} = \frac{PL_tG_tL_sL_aG_r}{kT_sR}$$

Once the E_b/N_0 has been computed for the appropriate link, this value is compared against the value required for the modulation scheme. The difference between these two values is the *Link Margin*, the principal metric of link quality.

3.3 Feasibility Study

This section shows the analysis of the link budget of the case study, analyzing the downlink first and then the uplink. For this study, the calculations are made considering parabolic antennas with the related relationships. The work shows how the diameters of the transmitting and receiving antennas are connected with the data rate.

3.3.1 Downlink

In this case the diameter of the Tx (diam t) is vectorized in a range from 10cm to 50cm by choosing these limit values relative to the requirement to use cubesats.

Altitude [km]	500
Channel Bandwidth [GHz]	0.375
Channel Capacity [Mbit/s]	100
Tx Power [W]	5
Tx frequency [GHz]	8
Tx antenna efficiency	0.55
Elevation angle [deg]	20
Pointing error [deg]	1
Link margin	10

Table 3.2 Downlink Analysis Input

This input set was partly derived from the requirements and partly estimated after reading several similar articles. The Data rate has also been vectorized to highlight its influence within the solution.

The analysis has been carried out in such a way that in output the ground antenna diameter (diam_r) is provided and the solution will be shown in such a way as to highlight the variation of the output as the transmitter diameter and the data rate changes. Initially, the Eb / N0_req was calculated using Shannon's theorem in input Channel capacity and channel bandwidth. Calculation G_t and EIRP considering null the line losses of the tx system (L_tx = 0). Losses computation: antenna pointing loss, path loss and atmospheric loss (stimate 0.8 dB).

The System Noise Temperature has also been " estimated " not having a thorough knowledge of the Rx system; the estimate was made on the basis of some articles dealing with the same topic: Ts = 1380 K = 31.4 dB, This parameter strongly influences the final result.

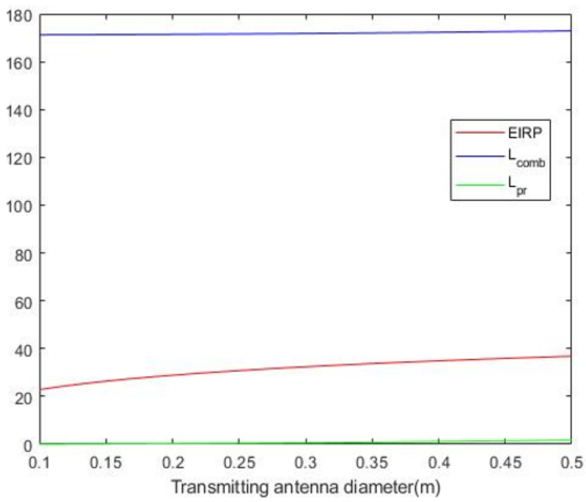

Fig. 3.9 Losses and EIRP when varying diam tx

In the next figure is shown the receiving antenna diameter when varying the transmitting antenna diameter and data rate. At high value of Data Rate (50 Mbps), the required receiving antenna diameter is 1.7 meters.

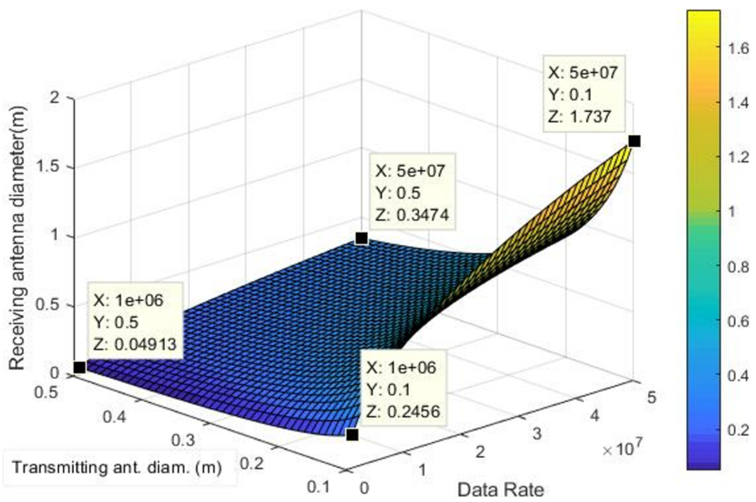

Fig. 3.10 diam r when varying diam t and Data Rate down-link

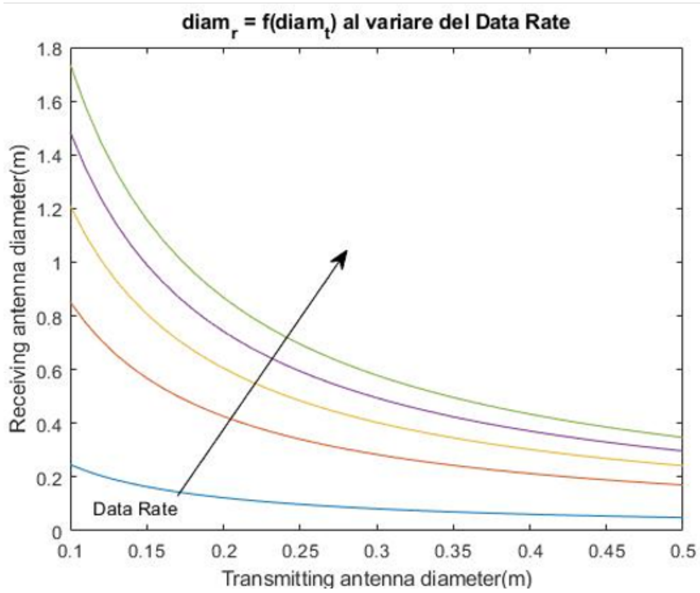

Fig. 3.11 Data Rate influence downlink

In the next figure the Data Rate varies between 1 Mbps to 50 Mbps.

3.3.2 Up-link Analysis

For this analysis Transmitting Power is 15W and the System Noise Temperature is 114K = 30.6 dB. In the up-link analysis the same method is used to vary diam_t in the range between 0.1 and 0.5 m.

In the previous figure is shown the receiving antenna diameter when varying the transmitting antenna diameter and data rate. At high value of Data Rate (50 Mbps), the required receiving antenna diameter is 0.2 meters.

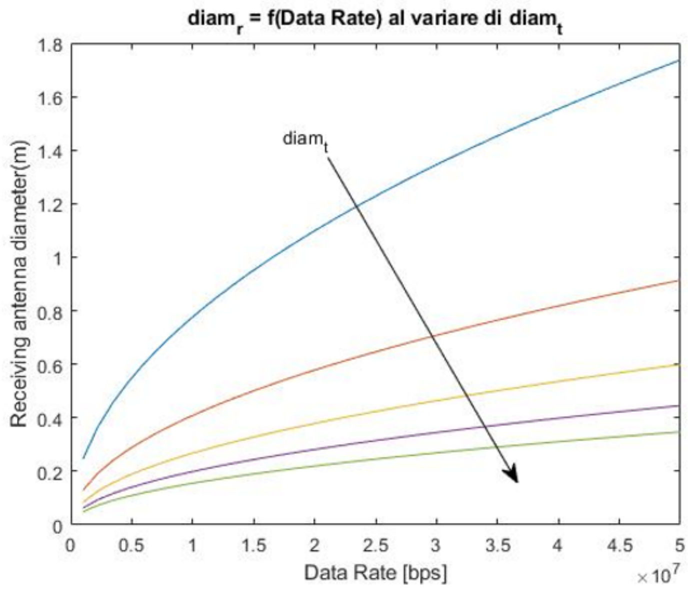

Fig. 3.12 diam t influence down-link

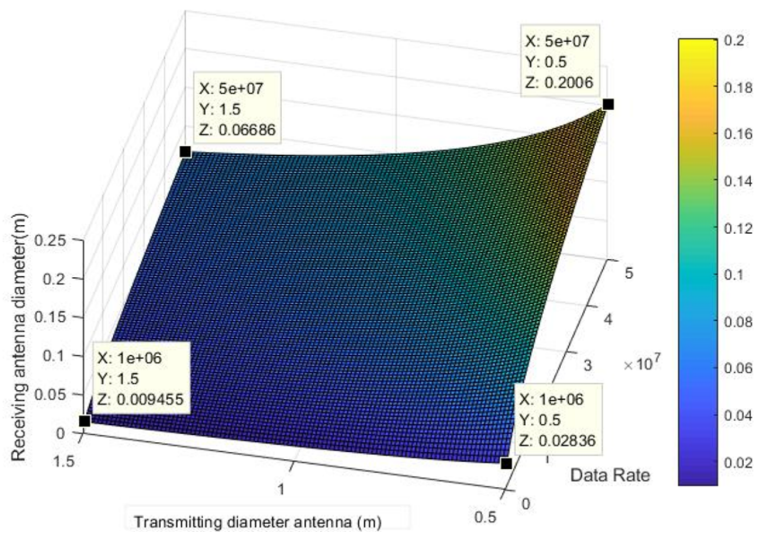

Fig. 3.13 diam r when varying diam t and Data Rate

In the previous figure is shown the receiving antenna diameter when varying the transmitting antenna diameter and data rate. At high value of Data Rate (50 Mbps), the required recieving antenna diameter is 0.2 meters.

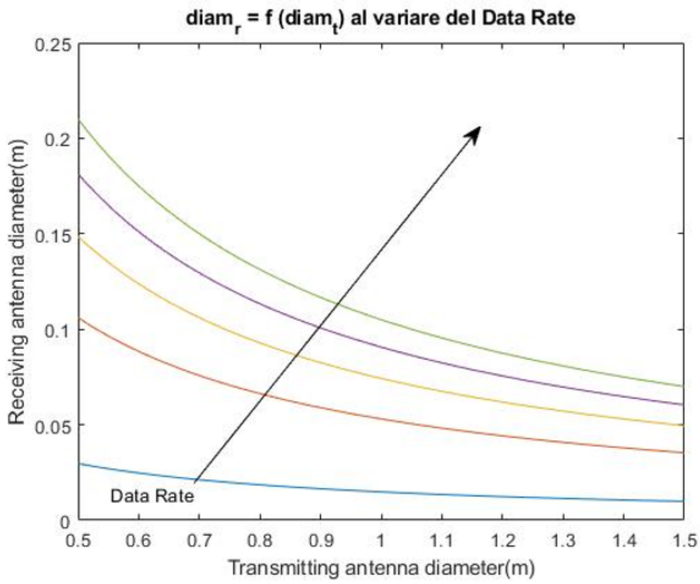

Fig. 3.14 Data Rate influence uplink

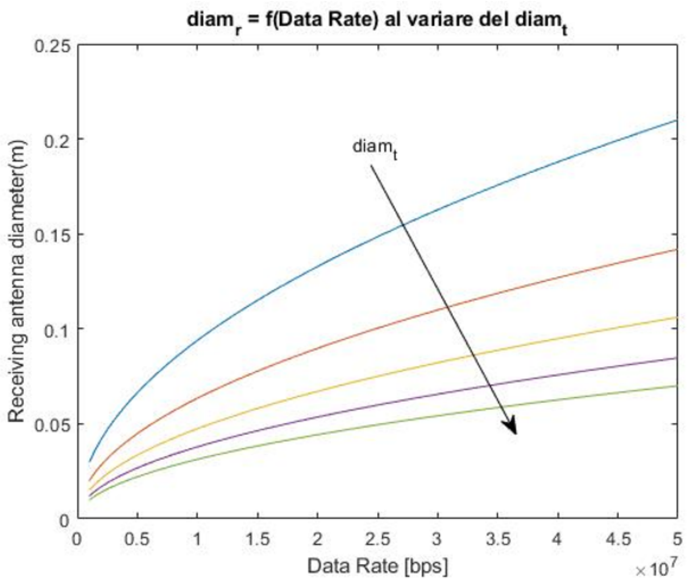

Fig. 3.15 diam t influence uplink

3.3.3 Conclusions

The analyzes were carried out keeping within a certain range the size of the antenna on board (dictated by the objective to use micro / nano sats), a range of Data Rate has been set and the output is related to the on ground transportable antenna size.
It is noted that in download against a transmitting antenna that varies from 10cm to 50 cm in diameter a ground antenna is required whose diameter reaches about 1.8m, these values are also calculated as the required Data Rate changes which has a maximum of 50Mbps.
The same output is obtained for the uplink analysis which, in the face of a receiving antenna that reaches 20cm in diameter, the transportable ground antenna varies between 50cm and 1.5m. (the Data Rate was set equal to the downlink).For analysis all the antennas, for simplicity, were supposed parabolics.

Chapter 4

Multi Objective Optimisation

The design of a satellites constellation is a process that includes several factors: number of planes, number of satellites per plane, altitude, inclination and right ascension of ascending node. Being able to find the optimal value of these design parameters is a challenge whose objective is to guarantee the continuous coverage of the region of interest.
In constellation design, coverage is normally a key parameter because it is a fundamental element of performance [10]. According to Wertz, "Earth coverage is not a Gaussian parameter and statistical data can give very misleading results" [10]. From this perspective, it was decided to also minimize the review time, in order to give more thickness to the results and not to fall into evaluation errors.
Keeping a low cost is another challenge to be faced in the constellation design. For this analysis we refer to the main cost in terms of the total mass of the constellation, being mass and cost strongly linked.

4.1 Genetic Algorithms

In the last two decades genetic algorithm have been employed for satellite constellation design optimisation. The GAs are used to find the optimal solutions of problems that are not well defined or difficult to model like discontinuous set, non linear functions, stochastic or even with undefined variables [15]. Also they are used to find the solution for problems that are difficult to solve with traditional optimisation algorithms. In the following, a comparison between the classical algorithms and the genetic ones is given.

Classical Algorithm:

- Generates a single point at each iteration. The sequence of points approaches an optimal solution.
- Selects the next point in the sequence by a deterministic computation.

Genetic Algorithm:

- Generates a population of points at each iteration. The best point in the population approaches an optimal solution.
- Selects the next population by computation which uses random number generators [11].

Genetic algorithms are not the only optimization method used for the study of satellite constellations but represent a valid solution for processing the large amount of data involved in this work and approaching optimal solutions.

It is important to understand the fundamentals of genetic algorithms to be able to apply in the best way to the purposes of this thesis. The Genetic Algorithms (GAs) are stochastic optimization techniques based on the genetic evolution processes of biological organisms. Figure 4.1 shows the logical process to which a genetic algorithm refers.

The mechanisms that govern their evolution are, essentially, two: natural selection and reproduction. Owing to natural selection, the individuals more adapted to the environment have more probabilities to survive and reproduce. Reproduction allows recombination of the genetic patrimony of the parents into their descendants who, in this way, take advantage of the peculiar characteristics of both the parents. Apart from these two mechanisms a third one, mutation, is acting from time to time. Mutation avoids existence of populations too much uniforms through the accidental change of part of the genetic patrimony. Moreover, mutation contributes to achieve a high degree of variety in a population.

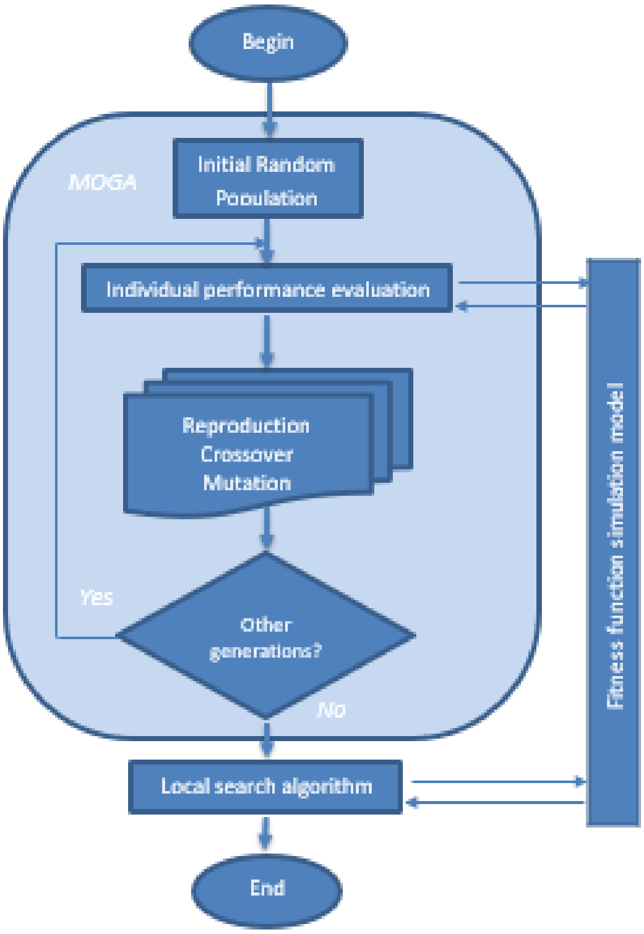

Fig. 4.1 Genetic Algorithm Flow Chart

In analogy with the biological process, there are several terms that are involved in the use of genetic algorithms. The following describes what refer to using these terms. Starting from the heart of the algorithm, the term *fitness function* refers to the function to be optimized. Also known as the objective function. It is possible to write the fitness function as a file or explicit function and pass it as a function handle input argument to the main genetic algorithm function [11].

An *individual* is any point to which you can apply the fitness function. Each individual could be a solution to the problem. The numeric value of the fitness function for an individual is its score. An individual is sometimes referred to as a *chromosome* which is represented by a vector of different *genes*. Each gene is one vector entry each one associated to a value of a problem variable [11]. Each individual based on their ability to adapt to the environment has a certain probability of survival. This probability influences the composition of the population of the next generation. The fitness function is also useful for calculating this skill, or the degree of adaptation of each individual to the environment. An evaluation of each gene belonging to an individual is made.

A *population* is a set of design points at the current iteration, in other words is an array of individuals. At each iteration, the genetic algorithm performs a series of computations on the current population to produce a new population. Each successive population is called a new *generation* [11].

Elite children are the individuals in the current generation with the best fitness values. These individuals automatically survive to the next generation.

Fig. 4.2 Elite Child

A genetic algorithm tries to improve the average value of the fitness function from generation to generation using the followings three genetic operators:

- *Selection*: the individuals, called parents, are selected according to their values of fitness function. A greater probability of reproduction is associated to the individuals of higher value and this allows, consequently, a greater probability of transmission of their proper genetic patrimony to the following generations. The individuals of the next generation are called children.

- *Crossover*: the individuals are selected in pairs to generate new individuals that exchange part of the parents genetic patrimony. The algorithm creates crossover children by combining pairs of parents in the current population. At each coordinate of the child vector, the default crossover function randomly selects an entry, or gene, at the same coordinate from one of the two parents and assigns it to the child. Usually crossover function creates the child as a random weighted average of the parents [11].

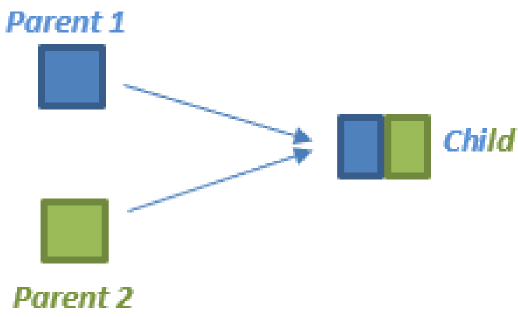

Fig. 4.3 Crossover

- *Mutation*: every gene of the chromosome of the new population can suffer an accidental mutation with a certain probability. The algorithm creates mutation children by randomly changing the genes of individual parents. By default, the algorithm adds a random vector from a Gaussian distribution to the parent. For bounded or linearly constrained problems, the child remains feasible [11].

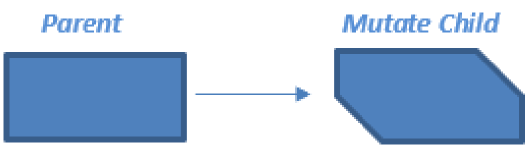

Fig. 4.4 Mutation

Diversity refers to the average distance between individuals in a population. A population has high diversity if the average distance is large; otherwise it has low diversity. Diversity is essential to the genetic algorithm because it enables the algorithm to search a larger region of the space [11]. In the following figure, the population on the left has high diversity, while the population on the right has low diversity.

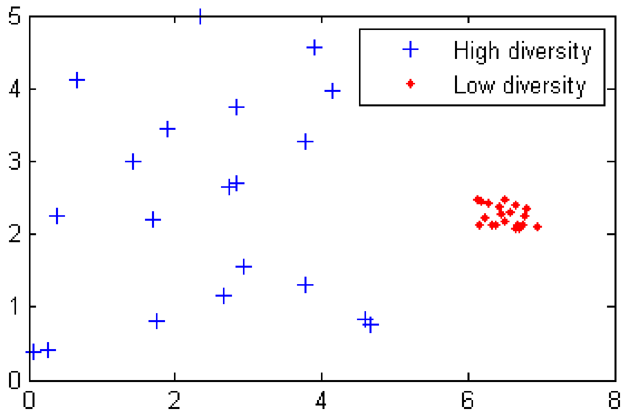

Fig. 4.5 Diversity

4.2 STK-MATLAB Interface

The STK/MATLAB Interface serves as a communication bridge between the analytical and visualization engines of STK and the flexible MATLAB workspace

The STK Programming Interface offers a wide variety of options to automate and customize STK and to integrate its technology into other applications, extending STK and the STK Engine. Additional options let you extend STK using plugins, interface to STK externally through COM and scripting interfaces, and develop custom applications.

In this thesis, a constellation design tool is created using MATLAB and STK. To create a constellation design tool, MATLAB is used to execute all the commands needed to operate STK in this scenario. Satellite Tool Kit, often referred to by its initials STK, is a physics-based software package from Analytical Graphics, Inc. that allows engineers and scientists to perform complex analysis (model, analyze, and visualize) of land, sea, air, and space assets, and share results in one integrated solution. At the core of STK is a geometry engine that is

designed to determine the time-dynamic position and attitude of assets, determining dynamic spatial relationships among all of the objects under consideration including the quality of those relationships or accesses given a number of complex, simultaneous constraining conditions. In other words, users can create objects such as satellites and constellations, as well as propagate specific orbits through time. Once the orbits and constellations are defined, the program allows users to quantify the performance using several different measurements. When a specific figure of mission effectiveness or geometric condition is met, MATLAB can automatically begin additional functions. MATLAB users can take advantage of STK's 2D and 3D visualization to view MATLAB data. Visualizing this data provides an intuitive understanding of it and allows you to view the effects of the data within a mission.
The documentation in STK's programming help lists specific STK operations in alphabetical order. This allows the user to search certain commands. The documentation illustrates basic examples of the code, but without prior knowledge of the format, it is difficult to debug the program.

4.3 Case Study Implementation

The first step is to modeling the problem by rewriting it so as to consider it as the input fitness function of the genetic algorithm. Therefore the FF must contain within it all the characteristics of the mission scenario within which the design variables contained DV will changes. The algorithm evaluates a different solution in different scenarios every time until it returns those that are closer to the optimum

4.3.1 Design Vector

All the variables present in the DV have a range of variability delimited by lowers and uppers boundaries. This range determines the search pool from which the algorithm pulls to find the optimal solution.In this analysis in DV it is composed of 5 elements.

$$\boldsymbol{x} = [h, i, RAAN, NP, NSP]$$

The first three variables inside the DV are orbital parameters:

h: is the altitude at which the satellites are placed in orbit. Assuming circular orbits you get the radius of the orbit (or semi-major axis) adding the Earth radius.The lower limit of the altitude was placed at 350 Km. Below, the friction with the upper layers of the atmosphere would soon slow down and precipitate the constellation. To validate this constraint a lifetime analysis was carried out with the lifetime tool of STK, which confirmed a minimum lifetime of one year above this altitude. The upper limit of the altitude has been placed at 700 km above the Earth surface, to avoid that excessive transmission power is required.However, this altitude is not very different from that of operational constellations such as IRIDIUM.

i: is the inclination of the orbital planes. The lower limit is 25 ° due to the minimum latitude to which the ROI has been delimited. The upper limit is also due to the ROI, whose maximum latitude is 75 °. By varying inclination within this range, the constellation ground track covers the whole latitude excursion.

RAAN: the longitude of ascending node, varies between 0° and 359°.

The last two DV variables are used to evaluate the "constellation mass" in terms of number of satellites.

NP: the number of planes varies between one and ten. The limit above the number of planes is fixed arbitrarily, following a research on papers that deal with the regional coverage.

NSP: The number of satellites per plane is also chosen arbitrarily, with the intent of modify it following the first results of the analyzes. Given their quantity, the satellites are then equispaced throughout the orbit.

Since circular orbits are supposed, the remaining orbital parameters are fixed (eccentricity = 0), or have no sense (argument of perigee ν) nor influence on design (mean anomaly M).
To make the populations evaluated by the GA consist only of integers, the DVstep is used. This vector has the length of DV and each element represents the stepsize of the variation range of each design variable.

$$DV\_step = [5, 11, 18, 10, 20]$$

h is divided in 5 steps of 50 km, ***i*** is splitted in 11 steps of 5 degrees and ***RAAN*** is separated in 18 steps of 20 degrees. Obviously NP and NSP are added one by one, wanting to minimize them.

$$h = 250 + x(1) * h\_step\_size$$

$$i = 20 + x(2) * inclination\_step\_size$$

$$RAAN = 0 + x(3) * RAAN\_step\_size$$

$$number\_of\_planes = x(4)$$

$$number\_of\_satellitesperplane = x(5)$$

4.3.2 STK Scenario

A scenario in STK is an instance of an analytical or operational task that you are modeling with STK. The mission scenario with the basic features has been previously modeled in STK and is recalled every time a new individual is evaluated, adding all the parameters and characteristics that are the subject of optimization.
First of all, the scenario analysis period is defined, it define the epoch and start and stop times that apply throughout the scenario. In order not to excessively increase the computational cost, the constellation is propagated for a single day. This approximation is based on the previous analysis of the lifetime tool. Over this period of time, continuous space and time

coverage is required.

The second step is to insert the objects that populate the scenario. These objects, as we will see, respect a hierarchy. For the purpose of this thesis the coverage definition is used. The

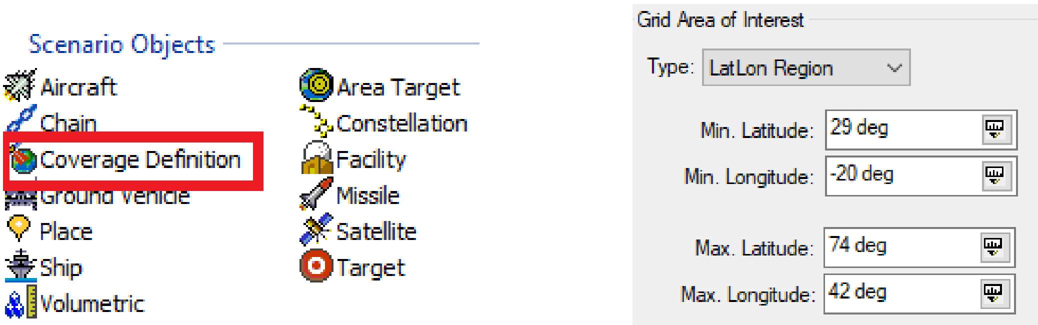

Fig. 4.7 Grid Area of Interest

Coverage Definition object defines a coverage areas for analysis. For analysis grid basic properties are setted, it is defined a grid area of interest, type: LatLon Region, providing in input the limits of latitude and longitude of the area. The Lat/Lon point granularity chosen is 1 deg, it affects the accuracy of the analysis and the computational cost, based on the number of points in the ROI.

At the end of the setting the ROI is displayed in the 3D graphic window as in the following figure.

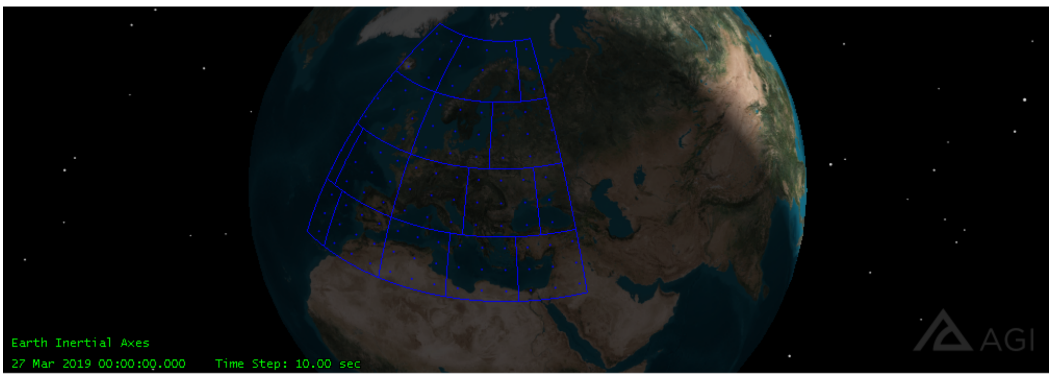

Fig. 4.8 ROI boundaries in 3D graphic window

Some objects can contain other objects subordinate to them, such as a sensor on a satellite or FOM on a coverege definition. In STK, objects that contain other objects are called parents, and the objects within them are called children.

The Coverage FOM object enables you to analyze coverage in various directions over time, using several attitude-dependent figures of merit. First FOM type selected for coverage analysis is *Coverage Time*.

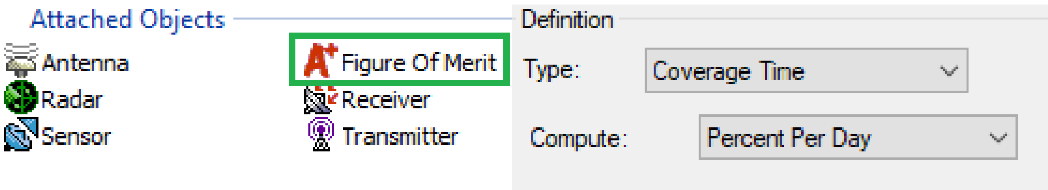

Fig. 4.9 Coverage Time Settings

Coverage Time measures the amount of time during which grid points are covered. Because Coverage Time does not have a dynamic definition, no time-dependent information is computed. For this reason the compute options specialized for Coverage Time is *Percent Per Day*, that is the percentage of time per day during which a point is covered. The computation provides the average percentage coverage value on each grid point. The goal is to achieve the 100% of coverage in each point.

Second FOM type selected for coverage analysis is *Revisit Time*. With this FOM the intervals during which coverage is not provided (“the gaps”) are measured. The dynamic definition of Revisit Time computes the duration of the current gap in coverage for each grid point. If a grid point is accessible at the current time, the gap duration is computed as zero.

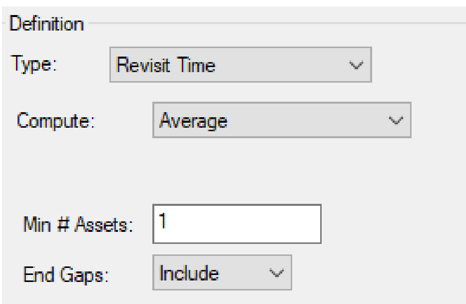

Fig. 4.10 Revisit Time Settings

The compute option chosen for Revisit Time is the *Average* of the durations of all the gaps in coverage over the entire coverage interval. If there are N number of gaps, then the average is:

$$AverageRevisitTime = \frac{\sum_{i=0}^{N} GapDuration_i}{N}$$

Min # Assets: this field is used to specify the minimum number of simultaneous Assets that are required for Coverage.

End Gaps: this field is set to *Include* to have gaps at the ends of the analysis interval included in the revisit time computations.

The other features of the scenario will be provided and described in the fitness function implementation.

4.3.3 Fitness Function Implementation

This section explains how the fitness function was written in MATLAB environment, going into the details of the functions used and how they model the problem.

4.3.3.1 Instance of STK

Working with the STK Object Model, the first thing to check is whether an open STK application already exists with the previously defined scenario. The function that allows what has just been said is *actxGetRunningServer*, it gets a reference to a running instance of the OLE Automation server and eeturns a handle to the default interface of the server. If the server specified is not currently running or if the server object is not registered, then the function returns an error. In this case the fitness function use *actxserver* to launch a new instance of STK11 and grab it. At the end of this statement, scenario is loaded, desired units of measurement are set and the scenario is ready to host the constellation.

4.3.3.2 Seed Satellite and Sensor

The next step is to set the orbital parameters of the seed satellite. This satellite will be used later to generate the constellation. In this scenario, the Earth is the central body around which the constellation orbits, the ICRF reference system is applied, in order to use the six classical orbital parameters to describe the orbit of the seed satellite. Inertial systems do not rotate in conjunction with the Earth, though they may rotate with respect to each other [3]:

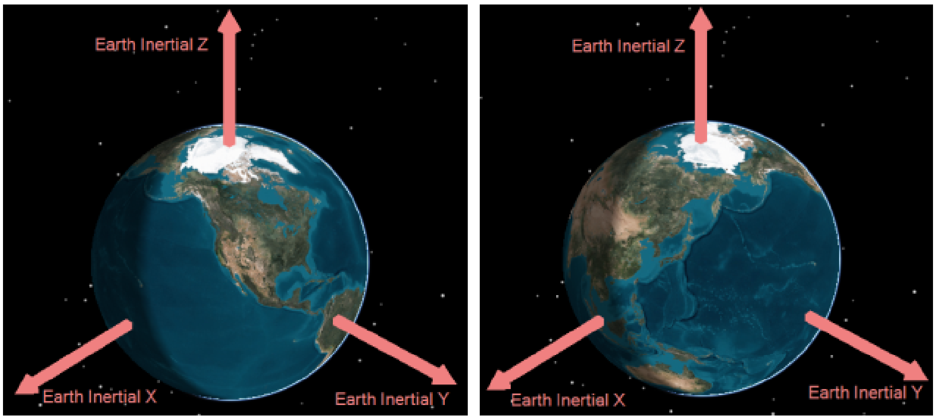

Fig. 4.11 Inertial Reference Frame [3]

Thus, from an observer on Earth's surface, fixed frames will look stationary while inertial frames will appear to rotate [3]. The fitness function receives in input from the permutation function the five elements of the DV. The first three (altitude, inclination and RAAN) are the orbital parameters to be optimized, while the other three parameters (eccentricity, argument of perigee and mean anomaly) are fixed, as circular orbits are supposed.

The set orbits propagator is HPOP, it uses numerical integration of the differential equations of motions to generate ephemeris. Several different force modeling effects can be included in the analysis, including a full gravitational field model, third-body gravity, atmospheric drag and solar radiation pressure. For simplicity, the standard models supplied by STK are used in this work.

The satellite to communicate, transmitting and receiving the signal needs an antenna. The on board satellite antenna is modeled with a half-power beam width sensor. This sensor is defined by a frequency and diameter, the elected values are respectively 10 GHz (operating in X band) and 10 cm^2 (using COTS components).

4.3.3.3 Walker Constellation

There are various ways of defining a satellite constellation, but this work uses Walker constellations because in this constellation, all the satellites are equally distributed on similar and phased orbital planes, moreover all the satellites in the constellation have the same size. Walker constellations are usually classified using a shorthand notation:

$$\boldsymbol{i : t / p / f}$$

where $\boldsymbol{i}$ is the inclination of the orbital planes, $\boldsymbol{t}$ is the total number of satellites in the constellation, $\boldsymbol{p}$ is the number of planes and $\boldsymbol{f}$ is an inter-plane phasing designation.
The Walker type used in the optimisation tool is *Custom*, that allows for explicit input of the span over which ascending nodes should be distributed and allows for the explicit specification of inter-plane phasing in terms of a true anomaly offset.
The last two elements of the DV are number of planes and number of satellite per plane, each one to optimise. In each iteration, the fitness function calculates:

$$Inter-PlaneTrueAnomalyIncrement = \frac{360°}{NSP}$$

$$RAAN\_Increment = \frac{360°}{NP}$$

When a Walker constellation is created, the original seed satellite is duplicated as part of the constellation. The new satellites are considered as children of the seed. Each child has the same base name as the seed satellite plus two numbers: the first number identifies the plane in which the satellite resides and the second identifies the satellite's position in the plane.

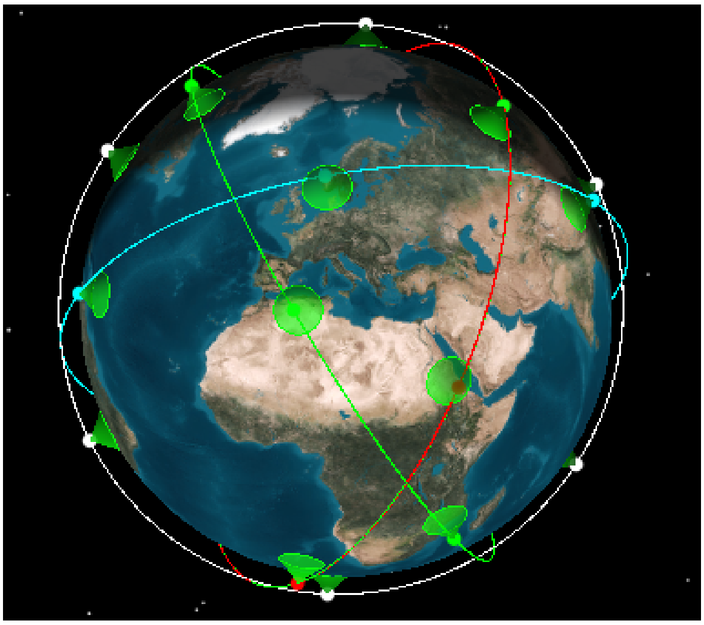

Fig. 4.12 Custom Walker Constellation

4.3.3.4 Coverage and FOM

The fitness function is written in order to recall the Coverage object previously defined in the base scenario. The grid resolution is defined inside the coverage object, this parameter defines the subdivision of the ROI into small squares centered in a point. Greater grid resolution corresponds to denser points, smaller squares and better quality of coverage analysis. On the other hand, a thick mesh means evaluating the coverage of many more points, with consequent increase in computation time. In this analysis, since the calculation times are already high, a point granularity of 1 deg has been set. Once the results are obtained from the algorithm, for the subsequent displaying in STK the point granularity is fixed at 0.5 deg. The next step is to assign the assets to the coverage object against which the coverage should be calculated. Two analyzes are performed, in the first all the constellation satellites are assigned and a geometric type coverage is evaluated. The second analysis assigns all the sensors connected to each satellite, evaluating the coverage given by their footprint.

The FOMs are those referred to in paragraph 4.3.2, the fitness function takes the coverage and revisit time values point by point and sorts them within a matrix, making the subsequent processing easier.

4.3.3.5 Metrics

Metrics are used to guide a search for optimal or near optimal individuals in a search space of possible solutions. The first that is used is the complementary of the coverage. this solution is algorithm friendly because the algorithm works in the optic to minimize this parameter, which is minimal when the coverage is maximum. The second metric is the revisit time in minutes, as already mentioned to obtain continuous coverage we want the revisit time to be zero. Finally, the overall mass of the constellation is used as the third metric. Optimizing the constellation means obtaining the maximum performance with the least number of satellites and this objective is pursued with the use of this metric. As reference mass, 20 kg were taken per single satellite. A good use of the metrics allows to obtain a more homogeneous and full of solutions Pareto front.

4.4 Multi-objective Genetic Algorithm

Much of the engineering design community is using multi-objective trade space exploration techniques, whereby a large set of design alternatives are generated based on multiple decision criteria, or objectives, and explored to make a choice. More specifically, a trade space is the collection of the input or design variable space X and the output or decision metric space Y denoted Z = [X | Y], where each element of Z corresponds to a candidate design [12].
Searching for the optimal constellation using a systematic approach is the main objective for this work. This search process uses the genetic algorithm as the search method because the fitness function is implicit and is highly dependent on a several variables.

4.4.1 gamultiobj Algorithm

This subsection describes how the *gamultiobj* function is used to achieve the goal of this work. The gamultiobj purpose is to create a set of points on the Pareto front. All these points give a set of solutions from which it will be necessary to choose the one that best reflects the previously set requirements. gamultiobj uses a controlled, elitist genetic algorithm (a variant of NSGA-II). An elitist GA always favors individuals with better fitness value (rank). A controlled elitist GA also favors individuals that can help increase the diversity of the population even if they have a lower fitness value.

4.4.1.1 Input Arguments

As a classic function of the MATLAB environment, *gamultiobj* requires a series of inputs to be able to work.

The first input given is **FitnessFcn**, that is the function to optimise described in section 4.3.3, specified as a function handle: FitnessFcn = @(x) Constellation_Coverage_Mission(x). FitnessFcn usually requires a real row vector of doubles *x* (the DV that contains the problem variables) of length *nvars* and returns a real vector of objective function values. Later when the use of vectorize will be described the size of these vectors will be different and the reason will be explained.

The second input is **nvars**: the number of design variables (or in other words the length of DV), specified as a positive integer. Like it has been said before, the solver passes row vectors of length nvars to fun.

If they are expected by the problem, linear equalities, linear inequalities and non linear constraints can also be assigned. For this analysis they are not expected and therefore the syntax requires to insert empty square brackets.

Other inputs are lower boundaries (**lb**) and upper boundaries **ub**. These boundaries are specified as a real vectors of length **nvars**. They impose the lower and upper limits within

which the elements of the DV can vary. As cleared up in section 4.3.1, these intervals are divided into steps so that the algorithm works with individuals formed only by integers having a predefined distance (step size) from each other.
The last input given to *gamultiobj* are the Optimization (**options**). This input is extremely important for the correct performance of *gamultiobj*, then subsequently a specific section will be dedicated to describe in detail which options are chosen and what effect they have on the algorithm.

4.4.1.2 Output Arguments

The first two output arguments returned by gamultiobj are **X**, and **FVAL**. X represents the points on the pareto front, is a matrix *m* by *nvars* where *m* is the umber of point on the Pareto, then each point on the Pareto is represented by one matrix rows. FVAL is a *m* by *nf* matrix, where like before *m* is the umber of point on the Pareto, while *nf* is the number of fitness functions. In the case study the fitness function is unique so *nf* represents in the number of metrics defined within the fitness, that is three. Each row of FVAL represents the function values at one Pareto point in X.
A third output argument, **exitFlag**, tells the reason why *gamultiobj* stopped. Return an integer that can be 1, 0, -1, -2, -5, which indicates respectively:

- Geometric average of the relative change in value of the spread is getting smaller over the generations,
- Maximum number of generations exceeded,
- Optimization terminated by an output function or plot function,
- No feasible point found,
- Time limit exceeded.

A fourth argument, **Output**, contains information about the performance of the solver. Information are returned as a structure with eight fields: *problemtype* in this thesis unconstrained, *rngstate* stete of random number generator, *generations* total number of generations, *funccount* number of function evaluations, *message* that is the *gamultiobj* exit message, *averagedistance* is the standard deviation of the norm of the difference between Pareto front members and their mean, *spread* a measure of the movement of the points on the Pareto front between the final two iterations and finally *maxconstraint* that is maximum constraint violation at the final Pareto set.
Function *gamultiobj* can also return a fifth argument, **Population**, a *n* by *nvars* matrix (where *n* is the number of members of the population), that contains the population when *gamultiobj* terminated. Finally a sixth argument, **Score**, that contains in a *n* by *nf* matrix the function values of all objectives for POPULATION when *gamultiobj* terminated.

4.4.2 Options

There are different ways to specify options for the genetic algorithm. In this implementation *gamultiobj* is called at command line, so *options* are created using the function *optimoptions*.

4.4.2.1 Population Options

The population options allow you to specify the parameters that the population of the genetic algorithm uses. Only the options used for this work are described below, but in reality there is a wide range of options to use to customize the algorithm based on the type of problem.
Population Type, specifies the type of input to the fitness function, wich can be: Double Vector, Bit String or custom. Using the latter type, they are also provided customs Creation function, Crossover function and Mutation function.
Population size, specifies how many individuals there are in each generation. With a large population size, the genetic algorithm searches the solution space more thoroughly, thereby

reducing the chance that the algorithm returns a local minimum that is not a global minimum. However, a large population size also causes the algorithm to run more slowly. The optimal population size is a hard problem and a general rule can not be applied to every type of problem or function to be evaluated [16]. Some works cite an optimal population size that is 10 times the DV, for this work a Population size was used which is 25 times the DV or 125. This dimension clearly requires longer computation time but should achieve a high rate of diversity.

Creation function (CreationFcn) specifies the function that creates the initial population for gamultiobj. Input arguments to the function are Population size and DV, the function returns Pop, the initial population for the genetic algorithm.

Initial population, the Initial Population Matrix specifies an initial population for the genetic algorithm. The first step in the functioning of a GA is, then,the generation of an initial population. Each member of his population encodes a possible solution to a problem [16]. After Producing the initial population, each individual is analyse and assigned a fitness value according to the fitness function.

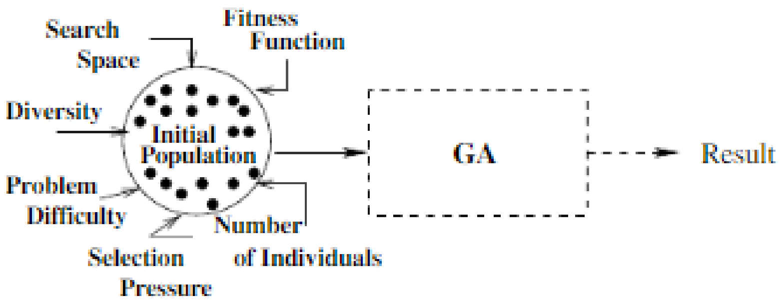

Fig. 4.13 Initial population influence factor [16]

Figure 4.12 reveals some factors that would weight the initial population or that should be evaluated when an initial population is generated stochastically: the search space, the fitness function, the diversity, the problem difficulty, the selection pressure, and the number of individuals. Some authors have suggested that diversity could be good in terms of performance of the algorithm, and diversity has been used not only to generate the initial population but also as a way to guide the algorithm to avoid premature convergence [16].

4.4.2.2 Multiobjective Options

These options specify parameters representative of the multiobjective genetic algorithm, the following parameters can be defined:
Pareto Fraction sets a number between 0 and 1 that specifies the fraction of the population (or individuals) on the best Pareto frontier to be kept during the optimization [11]. For example, consider a population of size 200. In the present case, having set a Pareto Fraction of 0.30, a population of size 125 is considered. After the genetic operation, we will have 125 * 0.30 = 38 individuals on the Pareto front, with grade 1. All others 87 individuals are dominated, with a grade higher than 1.
Crossover Fraction specifies the fraction of each population, other than elite children, that are made up of crossover children. A crossover fraction of 1 means that all children other than elite individuals are crossover children, while a crossover fraction of 0 means that all children are mutation children [11]. This analysis includes a crossover fraction of 0.85, while the remaining 35 percent of children undergo a random mutation through a custom mutation function.

4.4.2.3 Stopping Criteria Options

Stopping criteria determine what causes the algorithm to terminate, the following parameters are set:
Generations,specifies the maximum number of iterations for the genetic algorithm to perform. This value have a strong impact in the execution time of the algorithm. A very low number of generations has been set for initial analysis, useful for understanding the functioning of the algorithm. Subsequently, the algorithm was performed with 30 generations. This

value, given the complexity of the fitness function, is the result of a trade off between the precision of the minimum to be found and the calculation time. With a population of 125 individuals, a design vector pool of approximately 200,000 different combinations and 30 generations, the analysis ran for around 3 days.

Function tolerance, which intervenes if the geometric average of the relative change in the spread of the Pareto solutions over Stall generations is less than Function tolerance, and the final spread is smaller than the average spread over the last Stall generations, then the algorithm stops. The geometric average coefficient is 0,5 [11]. The spread is a degree of the changing of the Pareto front. Considering that we are optimizing the coverage percentage, the revisit time in minutes and the total mass of the constellation in kilograms, this parameter is set to 1. So if the algorithm improves the performance of the constellation with values lower than one percent of coverage , 1 minute of revisit time and 1 kg of mass, therefore it stops working.

4.4.2.4 Vectorize and Parallel Options

As often said, a heavy limitation in the use of genetic algorithms is the high calculation time, often due to the complexity of the fitness function. With the advent of more powerful computing devices, it is possible to adopt different strategies (vectorization an parallel pooling) that reduce this time.

The **parallel** options allow MATLAB to run the algorithm on different workers (in local). The number of workers depends on the computing power of the machine on which one operates. In this way each worker evaluates fitness function parallel to others, but each with a different individual. This has increased the calculation speed, but it has also created problems. In fact different solutions have different evaluation times, this creates a conflict between workers who require different variables at different times. These conflicts cause the unexpected algorithm stop at any time. For this reason, after several attempts it was decided to adopt other methods to increase the computation speed.

Usually if you **vectorize** the objective function, the direct search runs faster. This implies your function evaluate all the points in a poll or search pattern at once, with one function call, without having to loop through the points one at a time. A vectorized objective function accepts a matrix as input and generates a vector of function values, where each function value corresponds to one row or column of the input matrix. In this work the initial point x0 is a row vector of size nvars, the objective function takes each row of the matrix as a point in the pattern and returns a column vector of size m, as represented in Fig 1.13:

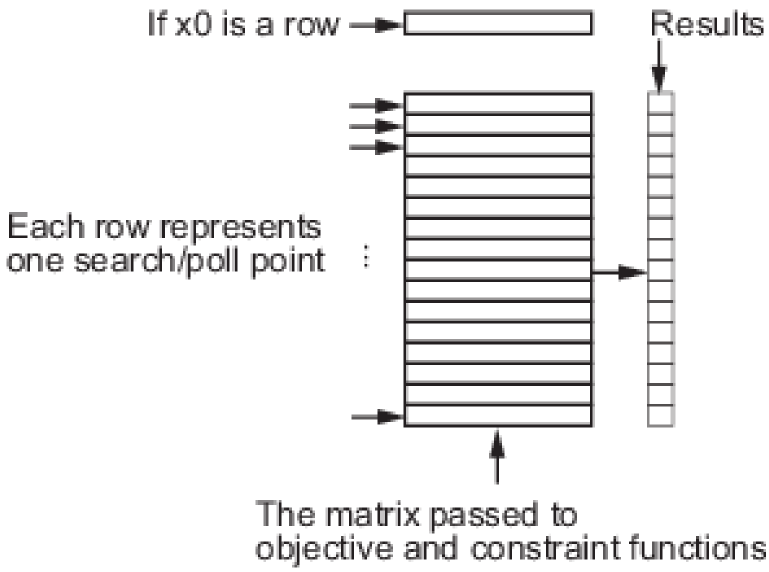

Fig. 4.14 Structure of Vectorized Functions [16]

for *gamultiobj*, return a matrix, where each row contains the objective function values of the corresponding input matrix row.

Chapter 5

Simulations and Results

A target region, for this case Europe,as shown in figure 5.1 defined by maximum latitude of 74 deg, minimum latitude of 29 deg, maximum longitude of 42 deg and minimum longitude of minus 20 deg is used as input of the coverage simulations. Given these boundaries, the region of interest is divided into 2790 grid points, on each one the coverage is computed.

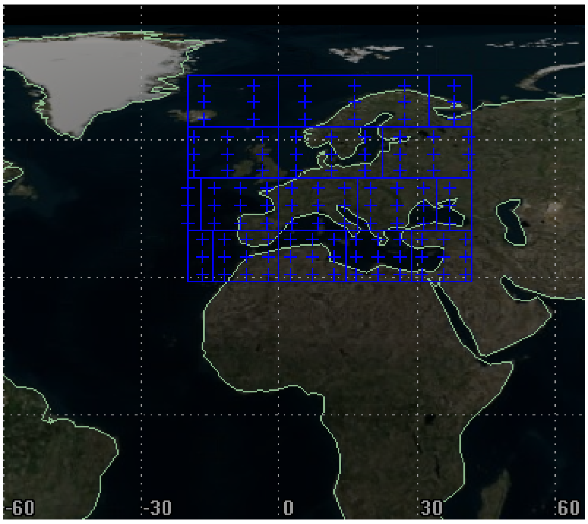

Fig. 5.1 Target region

In the following paragraphs the concepts explained in chapter 4 will be applied. Two analyzes will be shown highlighting the importance of parameters such as the number of individuals.

The results of these analyzes will be analyzed, focusing on the most significant solutions in terms of revisit time coverage and number of satellites.

5.1 First Case Study

A first analysis is performed keeping the population and generations low. This serves to make sure that the tool works correctly in a short computational time.

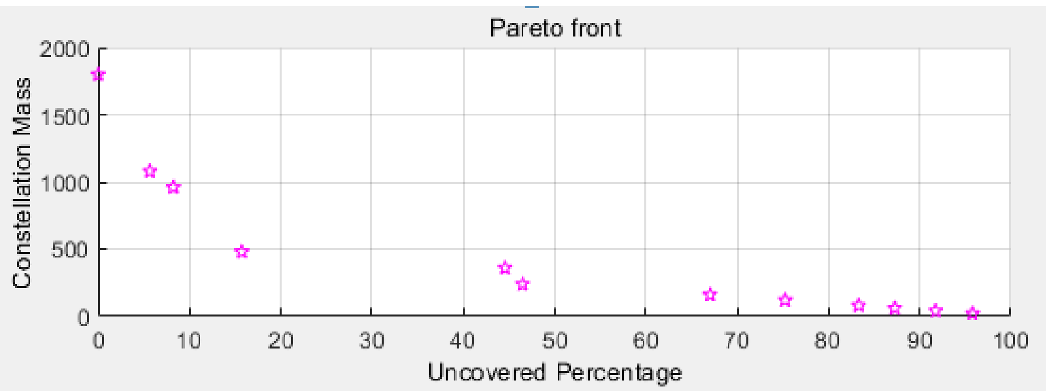

Fig. 5.2 Pareto Front with population size of 50 and 20 generations

Figure 5.2 shows the uncovered percentage of the region of interest in relation to the total mass of the constellation. The data presented refers to a population of 50 individuals and 20 generations. The latter strongly influence the number of solutions in the Pareto front. Having a sufficiently high number of generations and individuals per generations allows to have a more dense (meaning the number of solutions) Pareto front than the one shown in figure 5.2.

It is observed from Figure 5.2 the importance of having a sufficiently high number of generations and individuals per generation. These parameters allow to have a more dense (in the sense of solutions) Pareto Front than the one shown in figure 5.1.

Sol	100-%cov	Mass [kg]	RevTime [min]
1	44.6	360	18
2	0	1800	0
3	75.3	120	29
4	8.2	960	1
5	95.8	20	187
6	15.8	480	8
7	46.5	240	9
8	95.8	20	187
9	5.7	1080	1
10	91.7	40	105
11	87.2	60	67
12	67	160	19
13	83.3	80	48

Table 5.1 Analysis with population size of 50 and 20 generations

Table 5.1 shows the values of the three metrics used in the analysis: the uncovered area represented by 100% - %covered area, the total mass of the constellation considering satellites weighing 20 kg and finally the Revisit time. From the combination of these three metrics the thirteen solutions shown in the Pareto front are obtained.

	h [km]	inc [deg]	RAAN [deg]	NP	NSP
x1	450	55	200	9	2
x2	500	75	20	6	15
x3	450	55	160	3	2
x4	350	70	140	8	6
x5	450	65	320	1	1
x6	500	60	140	2	12
x7	500	55	140	2	6
x8	450	65	320	1	1
x9	350	55	140	9	6
x10	450	75	20	1	2
x11	450	75	320	3	1
x12	450	55	60	4	2
x13	450	75	200	2	2

Table 5.2 Pareto solutions with population size of 50 and 20 generations

Furthermore, table 5.2 shows the orbital parameters that the algorithm has selected as the best. Using these parameters we will then describe the orbit of the seed satellite that defines the whole constellation. Each type of constellation described by the solutions in table 5.2 has its metric values in the corresponding row in table 5.1. The solutions highlighted in green in tables 5.1 and 5.2 are the most advantageous. Solution 2 has better performing coverage and revisit time values. Solution 9 has less performing coverage and revisit time but has far fewer satellites and a lower operative altitude than solution 2. Only the best solution of this first analysis is displayed with STK graphic windows, in this case x2. This solution considers a constellation of 90 satellites equally placed on 6 orbital planes. The inclination is the same for all planes (75 degrees). The altitude is 500 km.

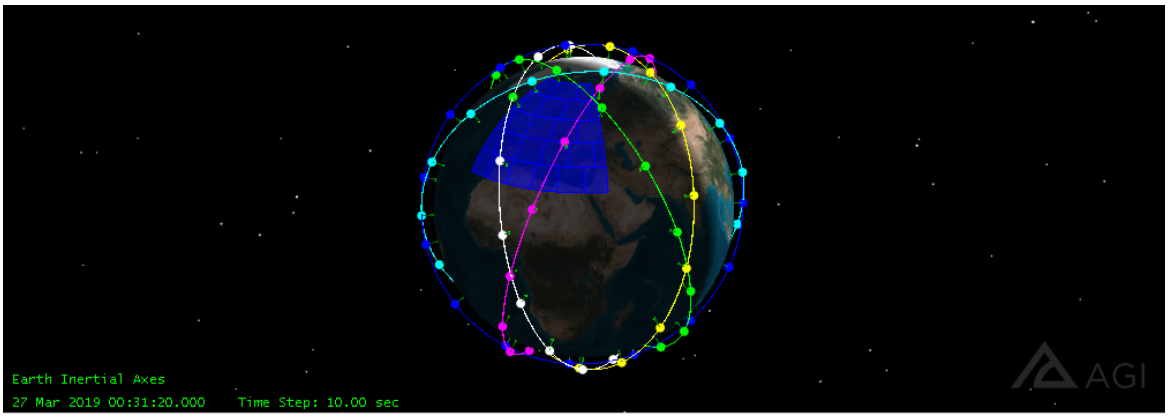

Fig. 5.3 Optimum constellation with population size of 50 and 20 generations

The 3D graphic representation in STK of solution number 2, parameterized by the values of row 2 in table 5.2, is shown in figure 5.3. The coverage values in the second row of table 5.1 define the coverage area, represented in blue in figure 5.3. Furthermore in figure 5.3 we observe the final arrangement of the satellites during their operational life.

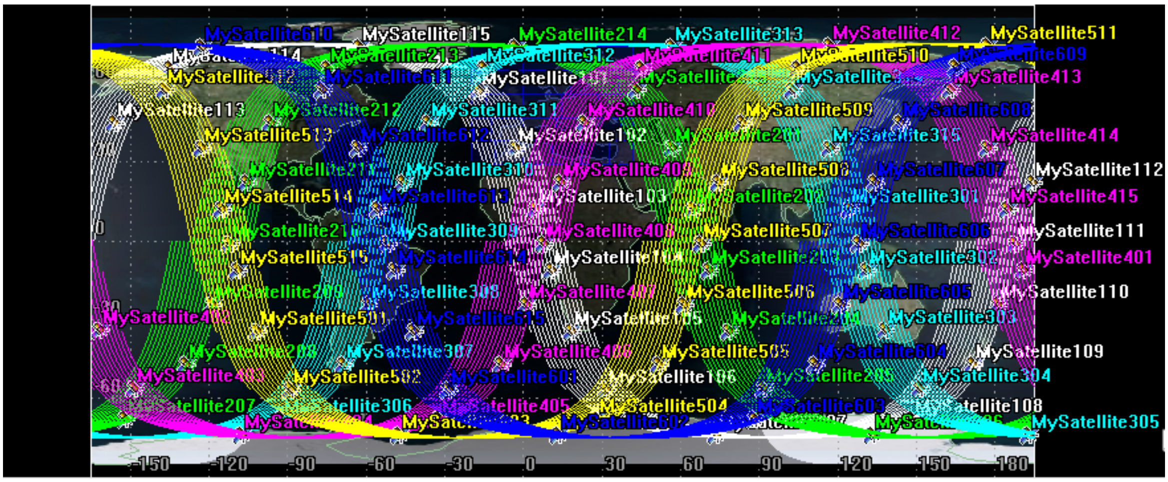

Fig. 5.4 Constellation Ground Track with population size of 50 and 20 generations

Figure 5.4 aims to show the constellation ground Track. Each color observed describes a different orbital plane and its evolution during the analysis time period.The orbital planes are the same as in figure 5.3, correlated by the same color. The ground track allows to visualize the position of each satellite at a specific time

5.2 Second Case Study

This second analysis is carried out using 30 generations and a population of 125 individuals. Compared to the first analysis these last two values have been increased with the aim of understanding how they affect the Pareto front. The total computation time was approximately three days with a *funccount* = 3876 times and optimization terminated because maximum number of generations is exceeded. The boundary conditions set for the simulation are listed below:

Altitude	350 - 650 km
Inclination	25° - 75°
RAAN	0° - 360°
NP	1 - 10
NSP	1 - 20

Below, in Table 5.3, there are the results obtained from the simulations. Solutions with low coverage and high revisit time are justified because algorithm tends to minimize the number of satellites. It should be remembered that as a metric the complementary to 100 percentage of the coverage has been placed. This choice is justified by the fact that the algorithm is able to find a minimum. It is possible to write an "algorithm friendly" fitness function. Although the algorithm has found a minimum, in reality it has found the maximum coverage.

Coverage [%]	*Rev. T [min]*	*# Sats*	*alt [km]*	*inc [deg]*	*RAAN [deg]*	*NP*	*NSP*
100	0	60	500	60	360	4	15
99.9	0.05	40	500	60	200	4	10
96.9	0.9	32	500	60	60	4	8
91	2	30	500	60	100	5	6
85.2	8	26	500	60	60	2	13
78.5	5.5	18	500	60	20	2	9
77	4.5	20	500	60	60	5	4
67	5	16	450	60	200	2	8
59	7	14	450	60	60	2	7
54	9.5	12	500	60	100	4	3
44	17.5	10	500	60	40	5	2
38	16.5	8	500	60	160	1	8
29	62.5	7	500	50	40	1	7
27.5	26	6	500	60	260	1	6
23	33.5	5	500	70	40	1	5
19	41	4	500	60	60	1	4
14	58	3	500	60	160	1	3
9	92	2	500	60	340	1	2
4	181	1	500	60	100	1	1

Table 5.3 Pareto points with relative fval

Figure 5.4 shows the pareto front in which the Objective 1 is the complement up to 100% of the coverage and the Objective 2 is the total mass of the constellation. Furthermore, the average spread of individuals is shown.

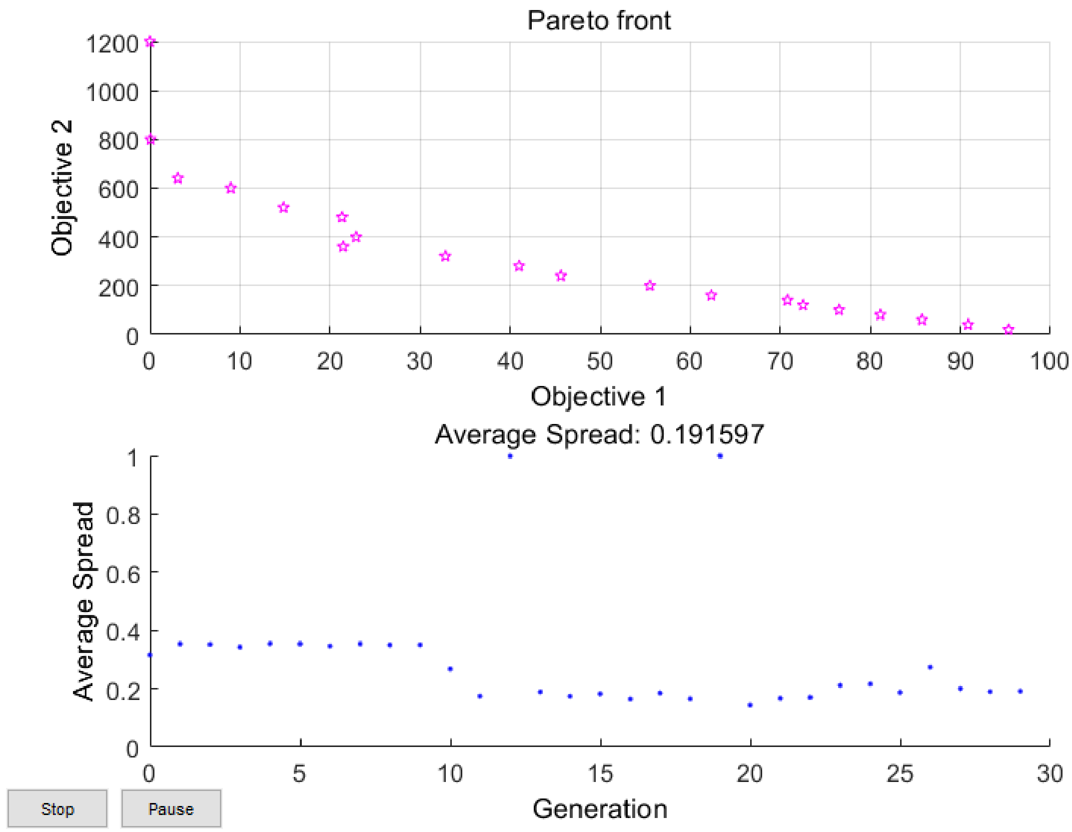

Fig. 5.5 Pareto front with popsize of 125 and 30 generations

From the Pareto front and from the data in table 5.3 different observations and comparisons can be made with the previous analysis. First of all, it is observed that by giving the algorithm a larger population and allowing a greater number of generations, it actually finds better solutions and this confirms that the tool works well. A small average spread measure indicates that the solutions on the Pareto front are evenly distributed over the generations. The highest average spread in the generations number 13 and 20, represents random mutations performed by the algorithm. The goal of these operations is to verify that the minimums found are global minima.

The first two rows of table 5.3, that is the first two solutions in the Pareto, show that with twenty satellites less and a considerable economic saving almost unchanged performances are obtained. These considerations are part of the trade off process.

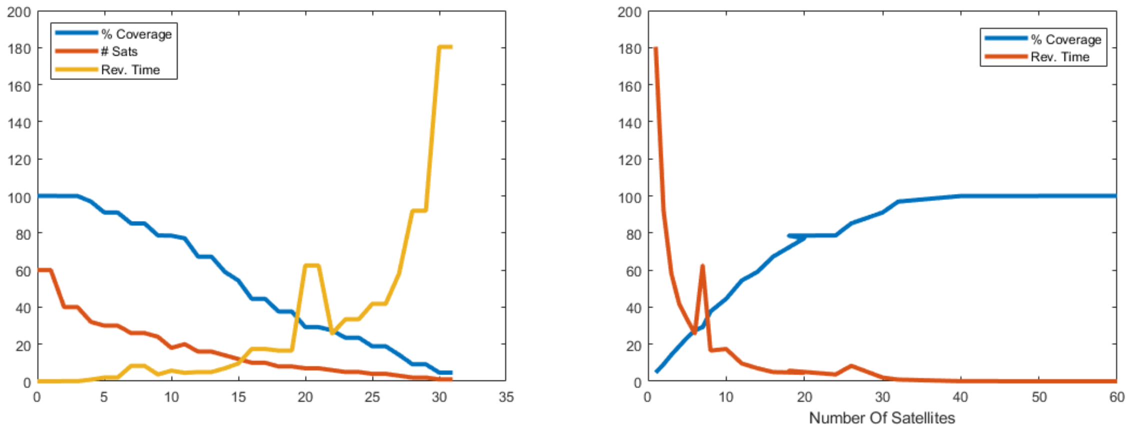

Fig. 5.6 Metrics trends

It should be noted that in figure 5.6 the axes do not have explicit units of measure. This is due to the different units of measurement that the plotted values have. The figure 5.6 on the left shows the trend of the metrics in the vector *fval* (the value of fitness function) after ordering them in ascending order. The figure on the right shows how the coverage percentage and revisit time vary with the mass of the constellation and therefore with the number of satellites. It should be noted that, apart from an isolated phenomenon, the two vary respectively in an inversely proportional manner and proportionally to the number of satellites. analysis. This information is shown in Figure 5.6, in the graph on the right, that shows over 30 satellites the performances do not have a substantial improvement, having already achieved excellent performance. From these considerations it is clear that if you want to save money, it is reasonable to accept a bit lower performance levels.

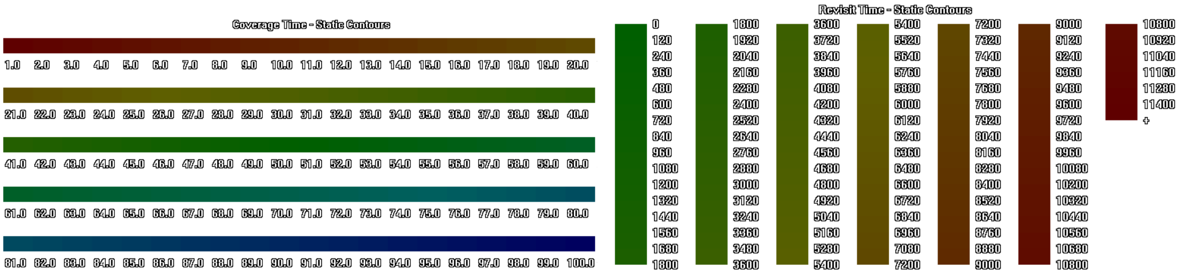

Fig. 5.7 Color Legend Coverage time (sx) and Rev.Time (dx)

Figure 5.7 shows the color scale used in the STK validation, to show the coverage and revisit time achieved on the region of interest. In figure 5.7 on the left the red represents a coverage of 0 percent. Gradually, at 2% steps, the color changes up to an intense blue at 100% coverage. On the right there is the color scale of revisit time variation. It starts with an intense green for a revisit time of zero, and then increases in steps of 100 seconds up to a revisit time of over 3 hours, represented in red. These color scales are very useful to give a visual impact information on the values reached by the metrics.

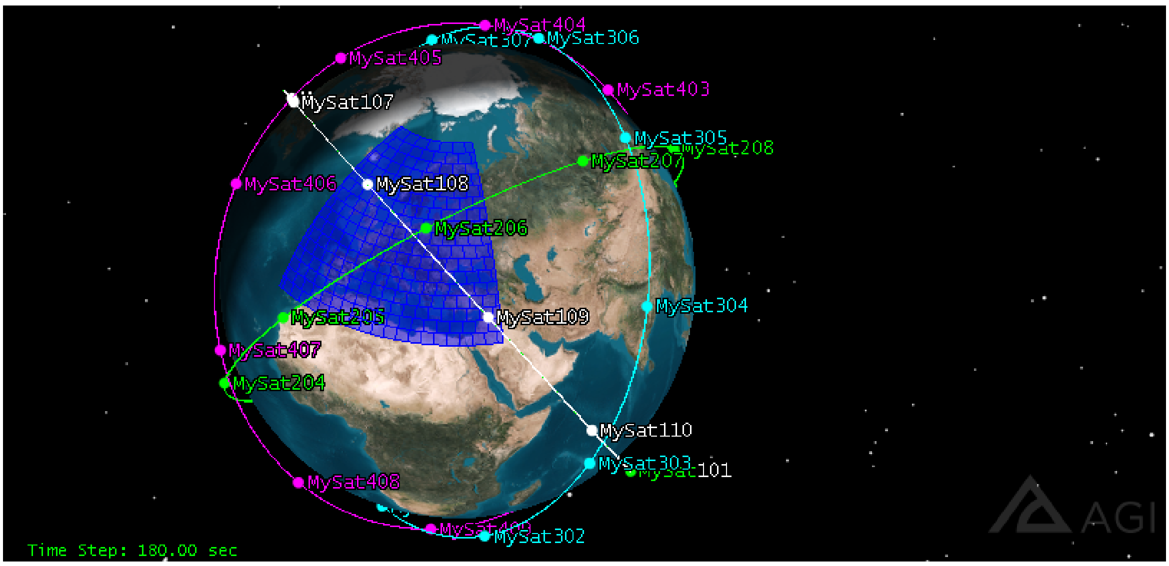

Fig. 5.8 Coverage Percentage Of The Second Analysis Constellation

Figures 5.8 and 5.9 show the best solution in the STK GUI (the second in Table 5.3). The first of the two figures shows the percentage of coverage achieved by a constellation of 40 satellites, arranged in 4 orbital planes at an altitude of 500 km and with an inclination of 60 degrees. Thanks to the color scale it is clear that the area is blue, which means that the coverage reaches values close to 100%. Figure 5.9 shows the revisit time value reached on the same area. Also in this case the green color immediately identifies a revisit time very close to zero.

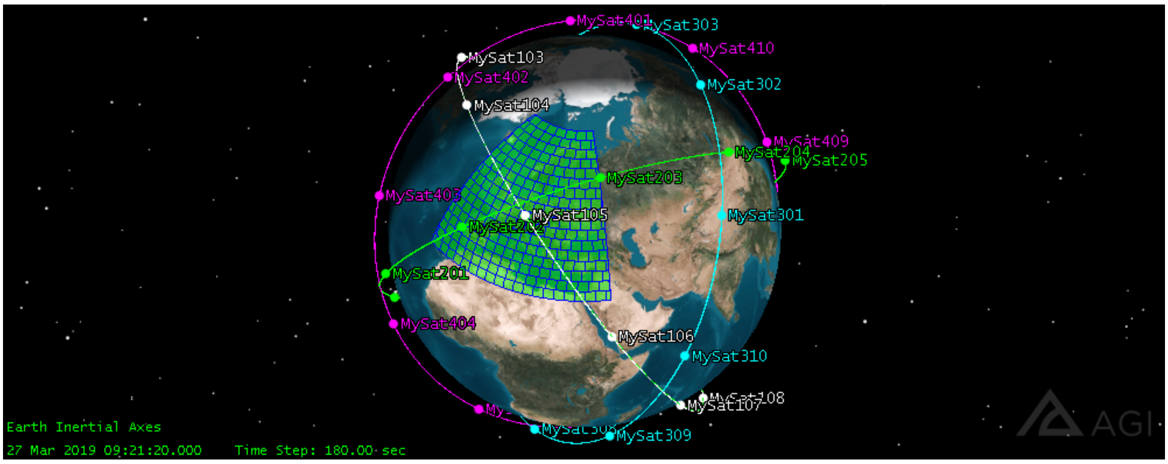

Fig. 5.9 Revisit Time Of The Second Analysis Constellation

In figure 5.10 the ground track of the constellation confirms that all satellites have the same inclination of 60 degrees. This inclination is sufficient to carry out access also to points in the region of interest at the higher latitudes. Also in this case, each orbital plane is represented by a color that distinguishes it from the others.

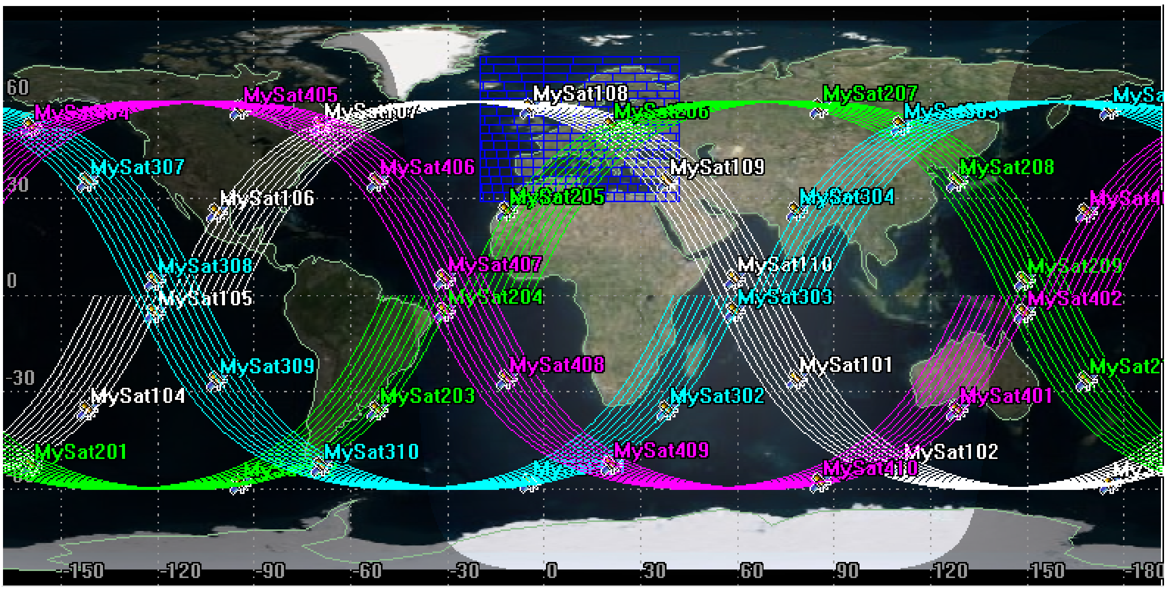

Fig. 5.10 Ground Track Of The Second Analysis Constellation

By placing a facility in a random point to model an end user, the table 5.4 shows the number of accesses and the total access times for each satellite to the facility. From the table it is observed that each satellite is on average 8 times in view of the facility. For each satellite the total time in which it is in contact with the facility is indicated. If you add up the total access times of each satellite, you would have a longer time than the 24 hrs. This means that often the facility sees more than one satellite at the same time.

Sat	Acc	Time [sec]	Sat	Acc	Time [sec]	Sat	Acc	Time [sec]	Sat	Acc	Time [sec]
Sat101	7	4493	Sat201	8	4501	Sat301	9	5128	Sat401	8	4682
Sat102	7	4504	Sat201	7	4480	Sat301	9	5106	Sat401	8	4705
Sat103	7	4502	Sat201	7	4497	Sat301	8	4607	Sat401	8	4661
Sat104	7	4489	Sat201	7	4501	Sat301	7	4497	Sat401	7	4456
Sat105	7	4462	Sat201	7	4494	Sat301	7	4507	Sat401	7	4487
Sat106	8	4659	Sat201	7	4474	Sat301	7	4505	Sat401	7	4504
Sat107	8	4715	Sat201	8	4592	Sat301	7	4491	Sat401	7	4508
Sat108	8	4709	Sat201	8	4698	Sat301	7	4463	Sat401	8	4639
Sat109	8	4631	Sat201	8	4719	Sat301	8	4633	Sat401	8	5037
Sat110	7	4469	Sat201	8	4682	Sat301	8	4698	Sat401	9	5025

Table 5.4 Number of Access and Tot.Time Duration for each Satellite

Figure 5.10 refers to the second case study, with a constellation of 40 satellites and shows how many satellites are simultaneously in view of the facility. The x axis represents the simulation time period that goes from 0:00 on 27 March to 0:00 on 28 March. The satellites are placed along the axis of the ordinates. Also in this case the coverage is defined in a geometric way, therefore based on the accesses. Each colored dash represents the time in which the satellite is in sight. By drawing a vertical line starting from the time of interest, it intersects all the satellites in sight at that moment.

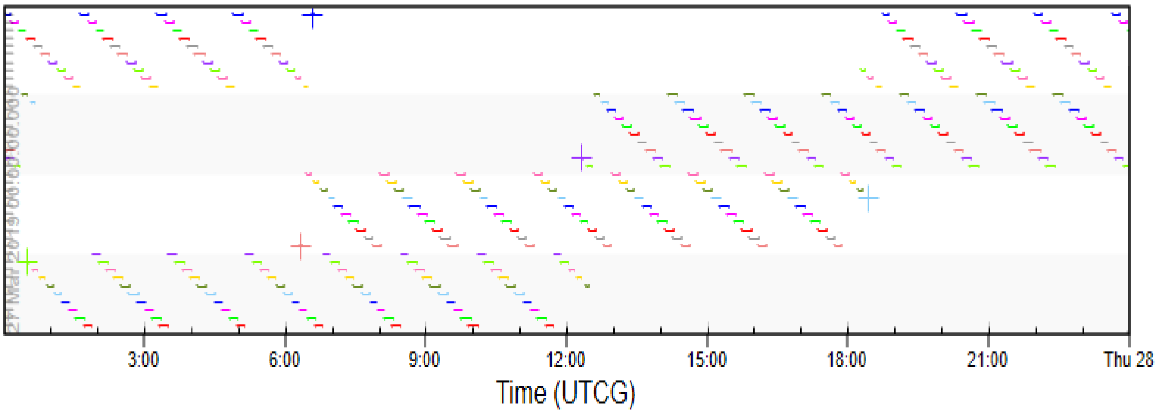

Fig. 5.11 Access to Facility

5.3 Third Case Study

The case study addressed in this section differs from the previous two due to the presence of sensors. In fact, in this case the coverage analysis is not carried out in a geometric manner but it is based on the sensors footprint. To give preliminary feedback on the coverage in terms of communication, the satellite on board antenna is modeled using a sensor with a half-beamwidth of 40 degrees. This value is taken as a reference of the 2x2 Endurosat patch array antenna supplied for cubesats [ENDUROSAT].

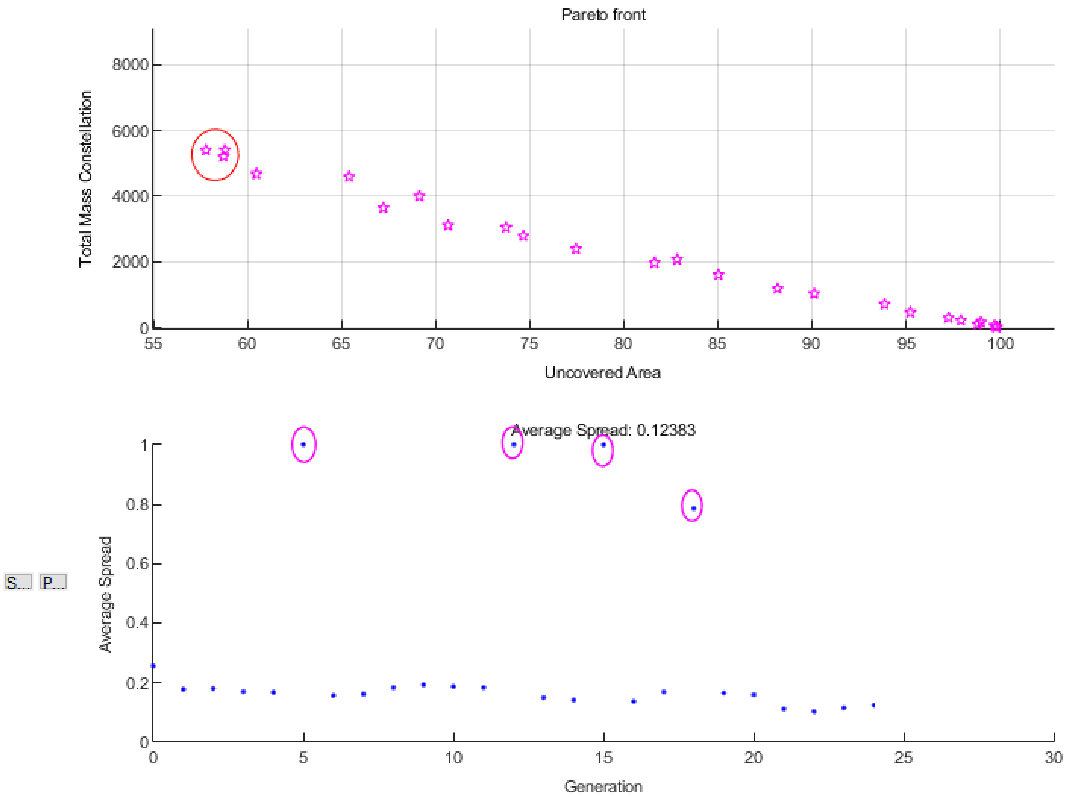

Fig. 5.12 Pareto Front of Sensors Case Study

The Pareto front in figure 5.12 shows the set of solutions obtained, considering an analysis of 30 generations and 125 individuals. The set of parameters and the respective ranges of variation in this case study are the same as in the previous case study. The results, highlighted in red in the upper graph of figure 5.12, relate to solutions with a total constellation mass of 5400 kg. From this value, having considered a mass per satellite of 20 kg, it is obtained that the constellation is composed of 270 satellites. These satellites are divided in 10 orbital planes, with 27 satellites for each one. Each satellite is at 500 km altitude and has an inclination of 65 degrees.

Of particular importance are the points highlighted in purple in the graph below in figure 5.12. They represent the times when the algorithm has found a local minimum. Each time it made a mutation to understand if the minimum was global.

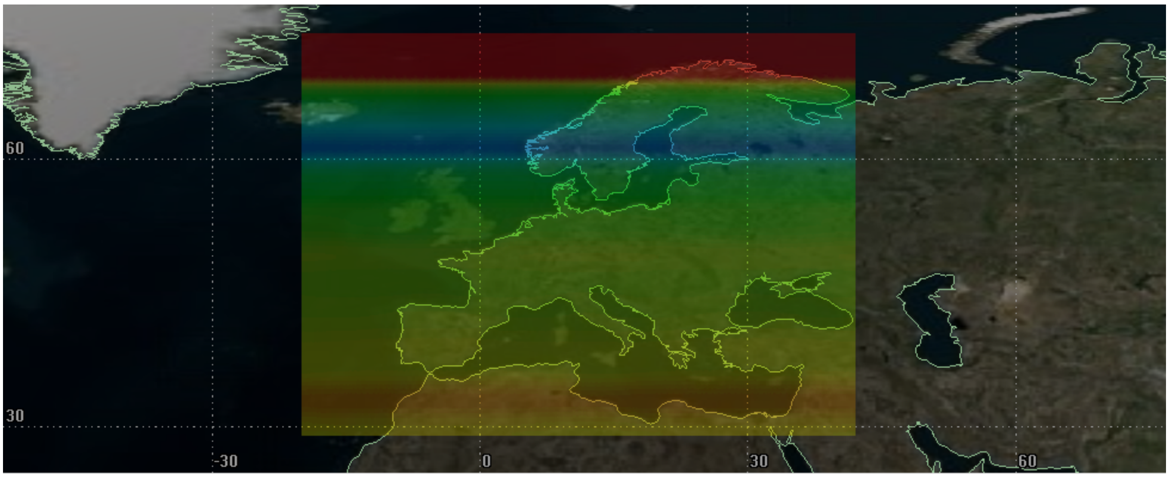

Fig. 5.13 Coverage Percentage of Sensors Case Study

Figure 5.13 shows the 2D graphic windows of STK, which shows the coverage percentage reached in the various areas of the region of interest. The colors shown in figure 5.13 refer to the color legend on the left in figure 5.7. It is noted that for latitudes above 70 degrees, unfortunately, the constellation does not provide coverage. For the latitudes of about 60 degrees the coverage provided is over 90 percent. The entire range of mid-latitudes (35 to 60 degrees) has a coverage value of between 25 and 40 percent. The coverage drops below 20 percent at latitudes below 35 degrees. Evaluating an average of the coverage on all the points of the region of interest, it is obtained about 40 percent of coverage given by the footprint of the sensors of all satellites.

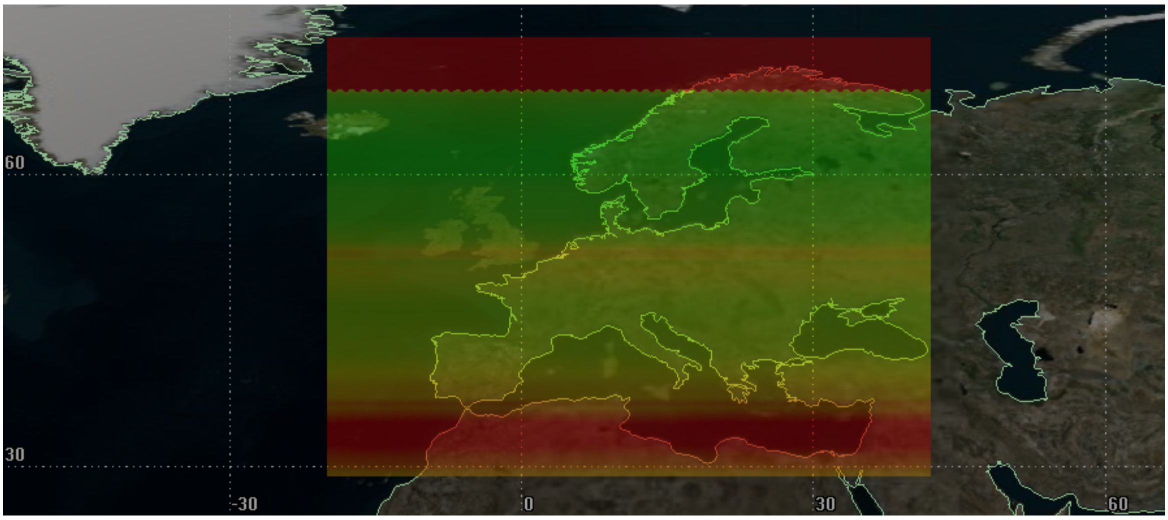

Fig. 5.14 Revisit Time of Sensors Case Study

Also for figure 5.14 the color scale shown for the revisit time in figure 5.7 is used. Figure 5.14 shows the revisit time values reached in the various areas of the region of interest. It is immediately observed that in confirmation of what shown in figure 5.13, the areas above 70 degrees of latitude have infinite revisit time, not being covered. The same goes for areas below 35 degrees latitude, revisit time varies between 5 and 10 minutes. In the range up to 53 degrees of latitude, the revisit time begins to fall. An average value in this area is 3 or 4 minutes. Exceeded 56 degrees and up to 59 degrees, the revisit time drops again to 1.5 minutes. The minimum revisit time provided by the constellation in analysis is given for latitudes between 59 and 65 degrees. In these areas the revisit time is less than one minute. Beyond these latitudes the revisit time starts to grow again.

By placing a facility, for example in Turin, it is possible to understand how many accesses there are and for how long it is covered. For the facility under examination, 312 accesses were counted with a total coverage time of 8 hours and 30 minutes. This temporal coverage is not continuous, but rather fragmented throughout the day.

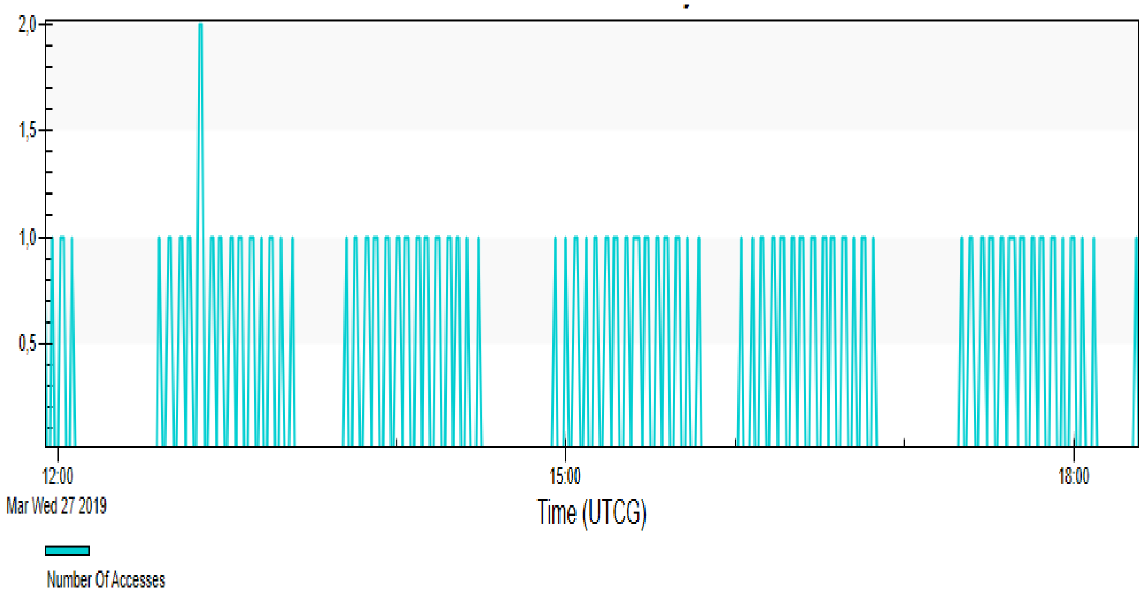

Fig. 5.15 Number of Accesses to Facility

Figure 5.15 shows the number of accesses to the example facility located in Turin. To facilitate the reading of the graph the accesses from 12 a.m to 18 p.m are shown, but the previous statements on the total number of accesses are based on a daily analysis. The white spaces in figure 5.15 represent the gaps, or the periods in which the facility is not covered.

Chapter 6

Conclusion

6.1 Summary of Results

The results of two simulations were presented and analyzed. The first simulation has shown how conceptually the algorithm works well. This means that the results obtained are validated by a subsequent analysis in STK implementing the solutions individually. He also highlighted the importance of having a huge number of individuals and a population suited to the problem, such as to have a Pareto front full of solutions. With the first analysis we also obtained a first geometry of the constellation that allows the geometric coverage. The first simulation also allowed to restrict the boundary conditions in such a way to refine the optimization and to estimate the processing time of the simulation. The second simulation showed that a constellation of 60 satellites is able to provide geometric coverage of the entire ROI. An important observation that should be made regards the possibility of having a much lighter constellation is by accepting a performance degradation of 0.5% in coverage and a couple of seconds in Revisit time. All this with much lower costs. An important phase is to decide how to deploy the constellation, whether to launch on multiple orbital planes or make them on a single plane but on different heights waiting for the natural phasing. The first one will be more expensive but allows the start of operations quickly, the second allows

a considerable economic saving, but only if natural waiting times are possible.
Regarding the communication system, the feasibility study has shown that with the use of COTS components in X-band it is difficult to obtain high performance from the communication system. One possible reason may be related to a higher on-board power requirement than currently assumed. Another possible cause may be the use of antennas too large compared to the standard size taken into consideration by the analysis. Another limitation can always be in terms of power and how it affects the constellation's operating altitude. In fact, both the algorithm and the feasibility study do not exceed an altitude of 500 km, beyond which there would be an improvement in terms of coverage.
The mission study carried out allows us to understand the potential of the mission and the possible scenarios involved, both in terms of work for the aerospace industry and in terms of support for the service used so far.The constellation proposed in the second analysis of chapter 5 provides a complete geometric coverage and can be used as a starting design.

6.2 Limitations of Algorithm

During the analyzes the main limit found regards the calculation times of the algorithm. As already mentioned, the FF itself has a calculation time that can reach up to 1 minute for the most massive constellations. This problem has been partially resolved by avoiding calling the STK GUI at each iteration and trying to streamline the FF in the less impacting elements of the result. In this regard, the techniques of paralellization and vectorization were used, favoring the latter. The limitation of the communication system feasibility study concerns the fact of not having a full knowledge of the ground segment. For this reason many approximations and assumptions have been made that more or less heavily influence the result.

6.3 Future Work

This thesis sets the milestone for the development of a very important project that requires the mutual contribution of many project areas. The most urgent point to be addressed is certainly a thorough dimensioning of the communication system, including the use of an ISL in the analysis in order to reduce the required satellites and latency times. At the end of this phase it would be useful and interesting to include the communication system in the FF. In this way the algorithm could provide results that are more strictly constrained than the communication requirements

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Appendix A

Orbit Determination

Coordinate Systems

Explaining coordinate systems is necessary to understand the motion of a satellite in orbit around the Earth. In this description the geocentric-equatorial system is used. Moreover it is necessary to establish the position of the origin, the orientation of the plane, the main direction and the direction of the Z-axis. Since the latter is perpendicular to the fundamental plane, it is useful to specify only its positive direction. The three axes must form a set of right-handed coordinate axes, appropriately choosing the Y-axis.

The earth's center is the origin of the geocentric-equatorial system. In this coordinate system the fundamental plane is the equator and the positive points of the X-axis are oriented in the direction of the spring equinox. In this way the Z-axis points in the direction of the north pole. It is important to remember that XYZ system is not fixed to the earth and turnig with it.

In the Right Ascension-Declination System the fundamental plane is the "celestial equator". This plane is obtained as an extension of the terrestrial equatorial plane to a fictitious

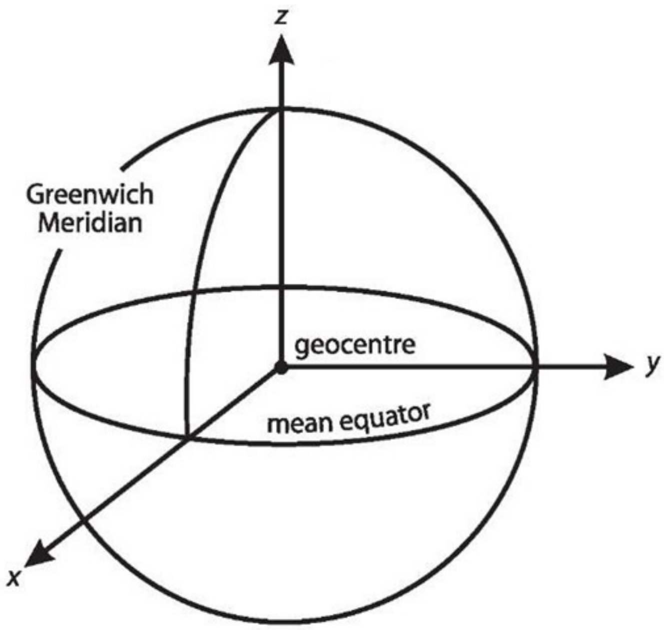

Fig. A.1 Geocentric-equatorial coordinate system

sphere of infinite radius called the "celestial sphere". The origin of the system may be anywhere, because any point may be considered the center of the infinite celestial sphere. The position of an object projected against the celestial sphere is described by two angles called right ascension and declination. As shown in the figure, the right ascension is measured eastward in the plane of the celestial equator from the vernal equinox direction. The declination is measured northward from the celestial equator to the line-of-sight.[17]

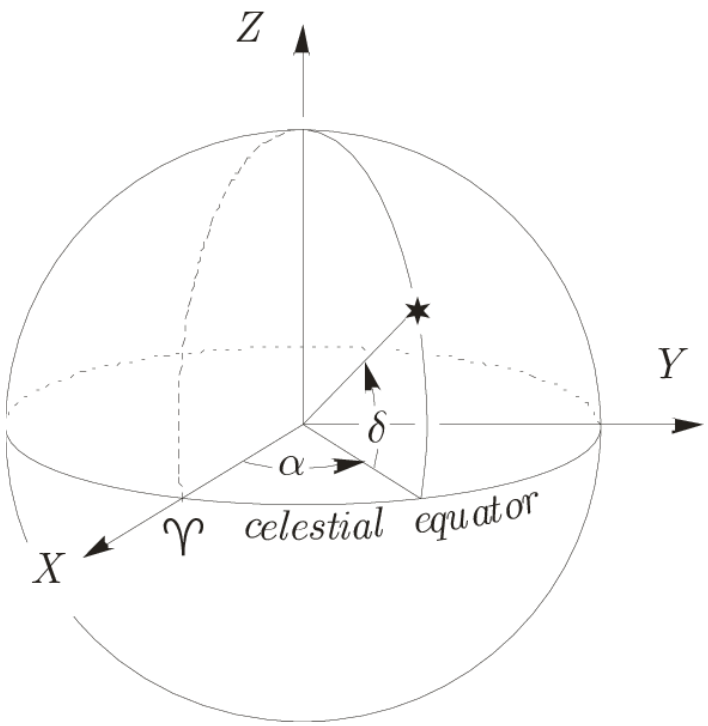

Fig. A.2 Right ascension-declination coordinate system

Anyway the Perifocal Coordinate System is the most convenient coordinate frame for describing the motion of a satellite. The X_ω axis points toward the peiapsis; the Y_ω axis is rotated 90°in the direction of orbital motion and lies in the orbital plane; the Z_ω axis along h completes the right- handed perifocal system. Unit vectors are called P,Q and W. [17]

Classical Orbital Elements

In order to describe the shape, size and orientation of an orbit, the orbital elements are needed. However, a sixth element is required to know the position of a satellite at a given time.

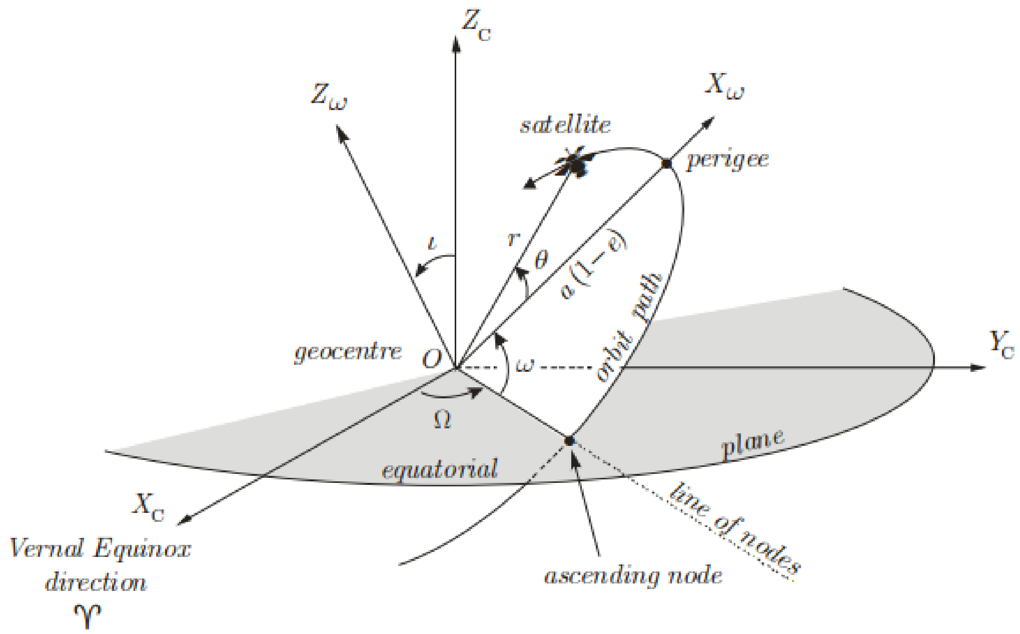

Fig. A.3 Perifocal coordinate system [6]

Looking at the figure, the six orbital elements turn out to be:

1. Ω, *longitude of the ascending node* - the angle, in the fundamental plane, between the **I** unit vector and the point where the satellite crosses through the fundamental plane in a northerly direction (ascending node) measured counterclockwise whn viewed from the north side of the fundamental plane.

2. ω, *argument of periapsis* - the angle, in the plane of the satellite's orbit, between the ascending node and the peiapsis point, measured in the direction of the satellite's motion.

3. T, *time of periapsis passage* - the time when the satellite was ai periapsis.

4. a, *semi-major axis* - a constant defining the size of the conic orbit.

5. e, *eccentricity* - a constant defining the shape of the conic orbit.

6. i, *inclination* - the angle between the **K** unit vector and the angular momentum vector, **h**. [17]

Sometimes instead of ω, Π is used. The latter is the angle between the periapsis direction and **I** in the orbital plane to periapsis.

If there is periapsis :

$$\Pi = \Omega + \omega$$

otherwise ω and Π are undefined.

T can be replaced with ν_0, u_0 or l_0. ν_0 is the angle between the periapsis direction and the position of the satellite at the "epoch" (t_0). u_0 is the angle between the ascending node and the radius vector to the satellite at time t_0.

If there is ascending node :

$$u_0 = \omega + \nu_0$$

otherwise ω and u_0 are undefined.

l_0 is the angle, in the orbital plane, between r_0 and **I**. The *true longitude at epoch* (l_0) is always defined because :

$$l_0 = \Omega + \omega + \nu_0 = \Pi + \nu_0 = \Omega + u_0$$

So if there isn't periapsis $l_0 = \Omega + u_0$, or if there isn't equatorial orbit $l_0 = \Pi + \nu_0$. In the case the orbit is both equatorial and circular, l_0 is the true angle between **I** and r_0.

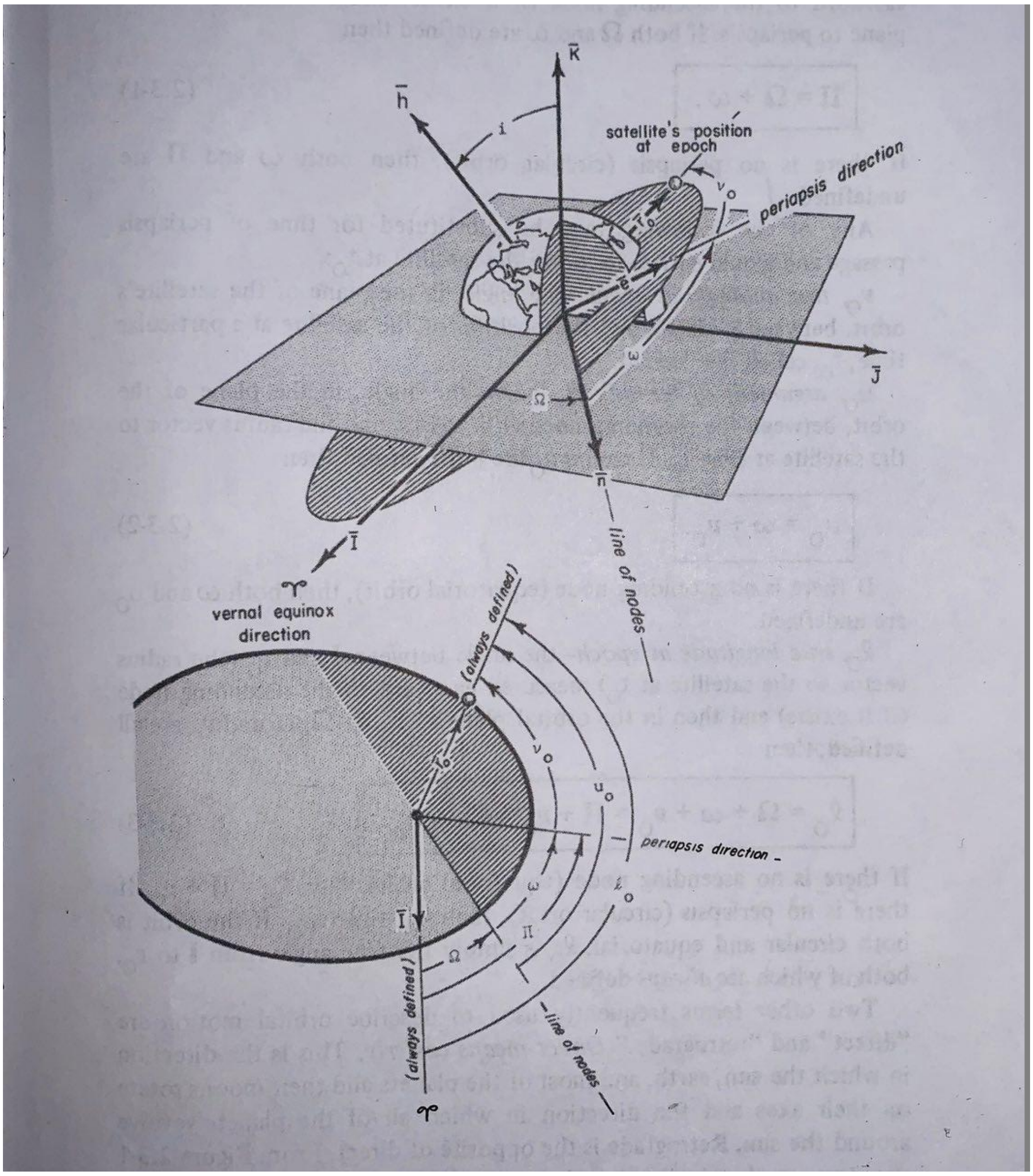

Fig. A.4 Orbital Elements