Optical downlink study for Low Earth Orbit satellite

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Author
Alessandro Luigi ARESTA
Aerospace Engineering student at Politecnico di Torino and ISAE-Supaero

Company supervisors
Julien L’HERMITTE
ADS Mission Chain Engineer

Sylvain POULENARD
ADS Optical Communications Engineer

Academic advisors
Paolo MAGGIORE
Professor at Politecnico di Torino

David MIMOUN
Professor at ISAE-Supaero

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ABSTRACT

Currently, the high increase of space systems capacity requires investigating a new generation of satellites capable of assuring a high data rate in the link between satellite and ground. In particular, in the Earth Observation domain, Optical Communications are being studied to ensure high throughput communication systems for the download of images taken by the satellite: they will play an important role in the near future as they offer potential advantages over microwaves. However, the impact of clouds delays its implementation for the time being. These atmospheric events vary as a function of the ground station location. Hence, this report describes a research study with a system engineering point of view on the feasibility of optical links. Employing the clouds databases provided by geostationary satellites and in-situ detectors, it aims at designing the network of ground stations and satellite features, which permit the complete download of Earth images acquired by the satellite during its period in orbit. Such a study is a step forward compared to the state of the art, which only considers cloud condition data from GEO imagery satellites. The comparison has been performed considering a 1-month simulation, due to the in-situ data unavailability: further studies will accomplish a 1-year (or more) simulation.

It is shown that link availability due to Cloud Mask derived from geostationary imagery has the 85% probability to correspond to an Optical Depth (averaged in space and time) smaller than 0.7, a preselected threshold that defines the OD cloud blockage. In the same way, it is discovered that CMa cloud blockage might be pessimistic: 40% of the CMa cloud blockage time corresponds to an Optical Depth (averaged in space and time) that is smaller than 0.7.

This study also has helped the IRT-Reuniwatt to improve their algorithm of cloud detection, showing special scene when the instrument seems not to work as expected: OD is set to zero, but the CMa states the presence of clouds.

Moreover, an end-to-end simulator of data downloaded has been implemented in order to process the feasibility of optical links. It permits the analysis of the mean downloaded data volume and the evolution of the satellite on-board memory along the entire simulation as functions of the minimum elevation and the Concepts of Operations (Adaptive FEC rate, $FEC = 1/2$, $FEC = 2/3$ and $FEC = 4/5$): this process permits to verify that all the images acquired by the satellite are transferred to the ground stations and to size the required satellite memory. This simulation has been carried on for 7 days, due to the SI data unavailability: further studies will accomplish a 1-year (or more) simulation.

The simulation that considers only one Optical Ground Station (Toulouse) states the uselessness of an adaptive FEC rate when the minimum elevation is greater than 20°: the added complexity does not permit to have a great difference in downloaded data volume with respect to the case of FEC equal to 4/5.

The results of a second simulation show the necessity of a network of optical ground stations and the use of a satellite on-board configuration that consists of at least 2 lasers: they are essential to satisfy the constraints imposed by all the minimum elevations and the Concepts of Operations.

The variation in downloaded data considering SI and SAFNWC data is also proven: SI data, thanks to their greater precision, permit to obtain a bigger quantity of transferred images. This information will encourage the use of SI detectors for many other stations.

All these results validate the functioning of the implemented simulator algorithm, but they should be reviewed and confirmed by additional simulations.
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Living far away from home is an instructive but difficult experience: this is why you will always have a place in my heart.
INTRODUCTION

Nowadays, thanks to the increasingly technological development, the need of data provided by a satellite is an important field of growth: as time goes on, a greater amount of data is required in order to satisfy the clients’ demands. In this area of interest, satellite communications fulfill a major role. Radio-frequencies are the most common choice, even if they are limited by their transmission capacity. As a consequence, optical link represents the main opportunity to overcome the RF limits and perform a faster yet reliable link between the satellites and the stations.

Unfortunately, optical links are characterized by several problems, most notably the clouds impact: in contrast with RF communications systems, clouds and atmospheric disturbances could easily impede data transmission. In this context, the necessity of mission planning is evident: data transmission should be realized in safety. A mission planning consists of all the actions that the in-orbit satellite must fulfill: they could be generated at the ground and, then, sent to the satellite or they could be produced automatically by the satellite.

Up to now, a lot of studies have been carried on about the useful exploitation of optical link: they study its potential capacity and the instrument required to perform such a link. On the other hand, because of the randomness of weather conditions, only few of them analyse the feasibility of an optical link and the methods required to solve its weaknesses: the design of a suitable mission planning is the most challenging phase of an Earth Observation mission that adopts optical links.

Therefore, the aim of this study is to give a system engineering point of view on the chances that optical links have to be employed in future Earth Observation missions. Thanks to the many tables and plots, the reader will be able to judge the impact of clouds and the necessity of using more than one ground station. The use of in-situ and geostationary imagery represents a step forward with respect to previous studies and a milestone for future developments: the choice to use in-situ clouds detector is justified by the necessity to gain more precise information about weather condition at a given time instant. In fact, the spatial and temporal resolutions of the in-situ detector are considerably higher than the ones of geostationary imagery: this implies a greater amount of weather data and more accurate information. All this information is collected in the mission planning in order to simulate the images download: it allows to identify all the time instants in which the link could be performed or not during the satellite lifetime.

This report consists of six sections. Section I will give an introduction to Airbus Group and a generic Earth observation mission, while Section II will deal with the technical knowledge necessary to make the reader understand the successive sections; Section III will introduce the difference amongst cloud datasets supplied by the detector SkyInsight and geostationary satellites. Section IV will describe the algorithm implemented for the simulation of optical downlink and the results for different scenarios are evaluated in Section V. Finally, Section VI concludes the report with the summary of the results and future work. Furthermore, the Annex describes the algorithm implemented for further details.

Keywords: Free space optical communications, optical ground station, cloud.
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I. CONTEXT

A. AIRBUS GROUP

1. Airbus group

Airbus Group is one of the largest European industrial corporations. It is a world leader in the aerospace sector, with flagship aircraft such as the commercial airline range of Airbus (single-aisle A320 family and double-aisle 330, 350 and 380 families) as well as military products (A400M, A330-MRTT), helicopters and satellite families. Airbus Group employs around 140,000 people all over the globe, with revenues of around €65 billion.

The current privatization of public enterprises that has occurred along Europe has had an impact on the formation of Airbus Group as well: currently, around a 75% of the company’s shares are not owned by any state, while the remaining 25% is split between France (11%), Germany (11%) and Spain (4%).

It was born in 2000 as Astrium as a merger of Matra Marconi Space (France and United Kingdom) and the space divisions of Daimler Chrysler Aerospace (German). During this period, Astrium became the leading satellite company in Europe. Later, it was renamed EADS Astrium because of a restructuring of the company.

In 2013, EADS was renamed Airbus Group. It currently operates in more than 170 locations worldwide. It is split into three business divisions (See Figure 1): (1) the first division called Airbus, which is the world’s largest manufacturer of commercial aircraft, (2) the second division is one of the world’s largest helicopter suppliers, namely Airbus Helicopters, (3) and the last division, called Airbus Defence and Space, which is responsible for defence and aerospace products and services in the space industry. This last division was formed in January 2014 after the merger of EADS Astrium, Airbus Military and Cassidian.

![Figure 1 - Airbus Group division](image)

Airbus DS is Europe’s No. 1 Defence and Space Company and it has a total capability in all fields of space design, engineering and manufacturing (See Figure 2)

Satellite systems are used for telecommunications, earth observation, navigation and science. Payloads, services and ground segments are also commercialized. In its joint venture with Safran, Airbus-Safran launchers manufactured the Ariane series of launchers.

In addition, Airbus Defence and Space participates in the joint-venture Airbus OneWeb satellites, in charge of manufacturing the more than 600 satellites that OneWeb will operate in a constellation to provide full Internet coverage everywhere on Earth.
2. My location

My internship took place in a department englobed inside the Engineering and Space Systems branches, which cover the full range of civil and defence space systems.

My thesis project has been developed in two departments (Mission Chain and Telecommunications Satellites Systems), based in the Palays site in Toulouse, the first site in engineering activities related to satellites, including conception, development, assembly, integration and test and validation of the final products.
A. Mission Chain Department

This department is mainly dedicated to ground segment activities, mainly for Earth Observation missions, but it also has an R&D section. This department counts up about 70 engineers, specialist in different activities such as software development and validation.

Overall, the scope of work in the department is divided in two areas:

- delivery of mission chains to Earth Observation Programs (specification, design, development and validation of SW) and project support (engineering, training…);

B. Telecommunications Satellites Systems

Within Airbus DS, The Telecommunications Satellites Systems Department studies civil and defence space systems as well as satellite based services in civil bands of frequencies, including space capacity, satellite communication engineering expertise, anchoring and backhauling services.

My internship was in the optical communication division, which is responsible for researching free space optical communications between space and ground.

I was granted virtually full autonomy, and the fact that none of my work was derived from previous Airbus proprietary tools or software meant that I was truly starting something from scratch, consequently I had large creative freedom. The direction of the project throughout these months was regularly accorded by my tutors and me during our meetings. I also had occasional support from other members of the department who had larger expertise on particular areas of a broad spectrum, from telecommunications to orbital mechanics or Earth Observation Missions. I also had sporadic meetings outside the department for discussing topics related to my project with the relevant experts.
B. EARTH OBSERVATION MISSION

1. Earth observation Mission

An Earth observation mission consists of the acquisition of data on a specified area, when needed by a customer. Satellite mission planning and scheduling are among the most challenging fields in the space mission analysis: detection, observation, data memorisation and download are different aspects that should be taken into account. A typical Earth Observation mission is described in Figure 4. Obviously, this figure could be extended to the use not only of a single satellite but of satellites constellations: in this case, a different mission planning is required.

A typical Earth Observation mission is characterized by a Sun-Synchronous orbit, with a repeat cycle that allows to accomplish the entire Earth coverage [2]. The payload consists of observations instruments (optical instrument, RF, radar, etc.) and a mass memory aimed at storing data before the download [2]. On-board elements essential to satisfy the mission requirements are:

- Power subsystem: it consists of solar panels and batteries. It is designed after all mission requirements are defined and it depends on the Attitude and Orbit Control System [2].
- Communications subsystem: it permits the data download and the reception of the costumer’s request [2];
- Attitude and Orbit Control subsystem: a satellite could be agile or non-agile, depending on the degree of freedom that it has. In an agile configuration, the acquisition and the download rely on the satellite capacity of turning itself in order to take the greatest amount of images [2].

![Figure 4 - Illustration of a typical Earth Observation mission](image-url)
As represented in Figure 4, the users give their requests to a mission centre, whose aim is to compute the mission plan and transmit it to the satellite. As a consequence, the satellite knows all the actions that it will perform to satisfy the user’s requests. Afterwards, the images are sent to the image centre, whose aim is to validate the images and give the final products to the users.

![Automatic planning system](image)

Figure 5 - Illustration of the automatic planning system [2]

As one can deduce, the most difficult part of the mission is the mission plan redaction: at the beginning of Earth Observation missions, it was done by hand by experts; then, with the development of computers, this process has become an automatic process [2]. Computers receive as inputs all the requests, the quality and priority evaluation criteria, the models of satellite observation requirements and of satellite capabilities (see Figure 5) [2]. All these elements impose a lot of constraints that could not be evaluated at the same time: for this reason, the Earth Observation mission is based on multi-criteria constrained optimisation model. For example, this automatic process should deal with the uncertainty due to clouds, the arrival of new user’s requests, different types of images quality, etc. There are many studies explaining different mission planning algorithms: the reader can find more information about them in [2].

Nowadays, engineers are trying to adapt the mission planning to the following features:

- the presence of constellation of satellites, which are equipped with different instruments and characterized by different orbits [2];
- the necessity to update the plan with regards to the arrival of new urgent requests [2];
- the necessity to obtain a completely autonomous on-board management, giving “intelligence” to the satellite: the satellite should deal with possible failures, detect clouds, take into account its actual state (memory, energy, etc.), analyse data in order to delete the low quality images [2].
2. Transmission system to download data

The communication link between space and Earth has for long been a critical part of the mission. The data acquired by a satellite can be transmitted to the ground stations in different ways, depending on the instruments available and the mission specifications. In particular, the transmission could occur with a direct link between the satellite and the ground station or with the use of relay satellites. The relay satellite is necessary when the considered satellite in orbit cannot pass along its information, since it lacks a clear view of the ground station. The main advantage of relay satellite is the possibility of transferring data even when the contact time is very short. Regarding the instruments that could be on board, the transmission could take place using radiofrequencies or using optical link.

a) Operational system

In this section, the already operating systems are discussed.

(1) Radio-frequency

The radio-frequencies communication is the main method of transmitting data from the satellite to a ground station: it permits the data exchange with a low signal attenuation caused by weather conditions. The main bands in satellite communications are listed in Table 1.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Frequency range [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band</td>
<td>2 - 4</td>
</tr>
<tr>
<td>X-band</td>
<td>8 - 12</td>
</tr>
<tr>
<td>Ka-band</td>
<td>20 - 30</td>
</tr>
</tbody>
</table>

Table 1 - Frequency range of typical and future satellites communication bands

Historically, the X band has been a military band, but its use is also spreading for other uses (commercial uses, telecommunications, etc.). It is very useful thanks to its features, like interference and rain resilience, data rate and remote coverage. In particular, the X-band communication is characterized by data rates (between 300 and 1200 Mbps) which are much higher than those achieved with UHF.

There are already several examples of space programs that have employed X band:

- the Voyager mission to Jupiter, Saturn and beyond;
- the Galileo Jupiter orbiter;
- the New Horizons mission to Pluto and the Kuiper belt;
- the Curiosity rover;
- the Cassini-Huygens Saturn orbiter.

In particular, Airbus Defence and Space has developed a constellation of satellites, called SPOT6 and SPOT7, in order to furnish high resolution data: in fact, their imagery resolution is 1.5 m and daily pass over each ground site is achieved. Moreover, they are also characterized by a great agility, which allows the satellites to obtain a great Earth coverage. These two satellites are equipped with X-band.
The Perusat is another example of Airbus Defence and Space satellite for Earth observation. It was required by the Peruvian government. Its imagery resolution is 0.7 m and the data transmission is also effectuated with X-band.

(2) European data relay satellite

The European Data Relay System (EDRS) aims at providing quasi real time access to Earth observation data by low earth orbiting spacecrafts using laser communication links and Ka-band. EDRS satellites receive information by other satellites by means of optical links and transfer data to ground using Ka-band.

Currently, there are five EDRS compatible Laser Communication Terminals (LCT) in orbit: three of them on Earth observation spacecrafts (Sentinel 1A, Sentinel 2A, Sentinel 1B) and two geostationary systems on Alphasat and Eutelsat 9B.

b) Future systems

In this section, the attention will be focused on the future perspective regarding the transmission systems.

(1) Radio-frequency

The main future advancement in the field of radio-frequencies transmission is given by the use of the Ka-band, even if X-band is going to be surely used too. In fact, the Mars Mission ExoMars will use the X-band communication to study the structure of Mars and to make precise measurements of the planet dynamics.

The Ka-band is being studied because, compared to S-band, it is characterized by transmission data rates that are hundreds of times faster [3]. It is also characterized by a more directive beam, which means that its energy is more condensed, having a wider frequency range. All these features imply that the Ka-band has a greater capacity with respect to other RFs and it could furnish less expensive services.

On the other hand, operating in Ka-band needs hardware and software to be developed and it is also more susceptible to rain attenuation. For this reason, it is now considered the future transmission method for space communications [3].

Ka band is actually used in the Inmarsat I-5 system and it will be used in the Iridium Next satellite series, as well as the James Webb Space Telescope [3].

Moreover, nowadays, the use of the Q/V band is considered a promising aspect in the telecommunication field: this is due to the fact that these bands are characterized by a frequency greater than 40 GHz.

(2) Optical downlink

The research on optical communication for Earth-to-Space link started at the end of the 1970s. The first experience came into reality in 1992 when the deep space Galileo probe on its way to Jupiter and at 6 million km from the Earth received the first optical uplink from the Table Mountain Facility in California [4]. Only three years after, the first bi-directional optical link was performed from the Japanese geostationary (GEO) satellite ETS-VI and the ground [5]. Six years after, in 2001, the first bi-directional inter-satellite optical link between a Low Earth Orbit (LEO) satellite and a GEO was performed in Europe [6]. Since that time, optical demonstrations have taken place in the entire technologically advanced region including but not limited to USA, Europe, Japan, Russia, and China.
Figure 6 and Table 2 show an extract of the main Earth-to-Space optical link demonstrations and they reveal the evolution of the tendencies for the essential technical trade-offs such as optical wavelengths, acquisition strategy and optical waveform. It results that, apart from some military experiments, 0.8µm was proved to be the preferred optical wavelength prior to 2006, because of the equipment availability (optical source and detector). Nowadays, new criteria as eye safety constraints, scalability, cost constraints, and data rate rising are essential for the wavelength choice and makes the paradigm changing. As a consequence, 1.55µm became the favourite wavelength for Earth to Space communication. With the exception of some European tentative of coherent detection at 1.06µm [7], direct detection with intensity modulation and beacon assisted acquisition strategy are the skeleton of all the demonstrations. The data rate records between Earth and Space is 50Mbps for the uplink and 622Mbps for the downlink. The last corresponds in fact to the downlink from a spacecraft orbiting around the Moon in 2013. Recently, the field demonstration rate has strongly increased and seems to bring ground-to-space optical communication to robust and affordable operational system. The proof being the publication of several roadmaps in this direction as well as the creation of the Consultative Committee for Space Data Systems in charge of the creation of an optical communication standard for Space applications.

In the following description, only few of the actual and future optical transmission systems are described in order to give to the reader an insight of the technology developed so far and their growth margin.

- OPALS (Optical PAyload for Lasercomm Science) is a system developed by JPL in order to demonstrate optical communications technology. This was accomplished by transferring a video from hardware on board the ISS towards various ground receivers with a data rate up to 50Mbps;
- SOTA (Small Optical TrAnsponder - Figure 7) has been developed as micro-satellites technology in order to demonstrate optical link feasibility in the field of the Space Optical Communication Research Advanced Technology Satellite (SOCRATES). It is characterized by 1 Gbps downlink data rate [8];
Figure 6 - Trends of space laser communications [9]

Figure 7 - Small Optical TrAnsponder (2014) [8]
### Past optical link demonstrations between ground and space

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
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<td>Japan</td>
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<td>Deep space</td>
<td>ISS-ground</td>
<td>LEO-ground</td>
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<td>LUCE</td>
<td>LLCD</td>
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<td>OICETS</td>
<td>LADEE</td>
<td>ISS</td>
<td>ALOS-2</td>
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<td>Up&amp;Dw</td>
<td>Up&amp;Dw</td>
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<td>300 000</td>
<td>700</td>
<td>2640</td>
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<td>40.15</td>
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<td>NA</td>
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<tr>
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<td>NA</td>
<td>26.12</td>
<td>10</td>
<td>NA</td>
<td>5</td>
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<td>1550</td>
<td>847</td>
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<tr>
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<td>1550</td>
<td>815</td>
<td>1550</td>
<td>1550</td>
<td>1550</td>
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<tr>
<td>Com. Data rate dw. [Mbps]</td>
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<td>50</td>
<td>622</td>
<td>50</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Com. Data rate up. [Mbps]</td>
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<td>2</td>
<td>20</td>
<td></td>
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<tr>
<td>Waveform uplink</td>
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<td>Intensity modulation</td>
<td>2-PPM</td>
<td>4-PPM</td>
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<td>NRZ-OOK</td>
<td>16-PPM</td>
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<td>Direct</td>
<td>Direct</td>
<td>Direct</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Past optical link demonstrations between ground and space
• OSIRIS (Optical Space Infrared Downlink system - Figure 8) is the system developed by DLR’s Institute of Communications and Navigation. It has been designed for earth downlinks from LEO satellites characterized by a weight up to 100 kg: this class of satellites uses generally the S-band with a limited data rate of 100 Mbps. OSIRIS was born with the intention of permitting the data transmission with a data rate comprised in the range of 200 Mbps and 10 Gbps. Unfortunately, until now, because of the necessity of additional tracking sensor, the data rate is increased up to 1 Gbps. In the next development step, OSIRISv3 will be equipped with a coarse pointing assemble (CPA) to point the transmission laser independently from the satellite attitude control and the data rate will be increased to 10 Gbps;

![OSIRISv2 for the BiROS satellite](image)

Figure 8 - OSIRISv2 for the BiROS satellite [10]

• OPTEL-µ is the system designed by RUAG Space under ESA contract and it comprises both space and ground segment (bi-directional link) [11]. It is characterized by 2.5 Gbps downlink rate: this data rate is permitted by the presence of two optical channels that could be used simultaneously [11]. This instrument works in two main different ways (See Figure 9):
  o “Eye-in-the-Sky” case: data are immediately downloaded after being collected by the satellite [11];
  o Complementary to radio-frequency: OPTEL-µ provides an additional transmission of data when the downlink demand volume is between 5 and 20 Tbits per day [11].

In the future, this system will be probably equipped with a third optical channel in order to provide redundancy and increase the downlink capacity [11];
The Tracking and Data Relay Satellite System (TDRSS) will include Laser Communications in the Next Generation Relay System. This system will exploit two optical channels (2.5 Gbps) for the download and up to 3 RF return channels from the ground station [13].

Moreover, Airbus Defence and Space is developing a constellation of four satellites, called Pléiades Neo with the purpose of civil and military Earth Observation. These satellites are expected to be sent in orbit between 2020 and 2022. This ensemble will be an improvement with respect to the previous one: the satellites imagery resolution will be 30 cm (instead of 70 cm) and it will assure two daily passes over each ground site considered (instead of just one). Images taken by the satellites will be sent to Earth ground stations in a particular way: they will be transferred to EDRS using an optical link and then sent to ground station with Ka-Band.

3. The perspective for optical communication system

As discussed in the previous section, several technologies of radio-frequencies communication have improved over time, but radio-frequencies will reach their limit because the demand for more data capacity continues to increase. For example, an X-band system is typically limited to 2Tbits per orbit.

Laser communications are revolutionary because they offer a much larger bandwidth, a smaller size, lower energy demand. Indeed, the very low optical communication signal wavelength in comparison with RF influences the signal received at the station. In fact, usually:

- the gain increases inversely proportional to the square of the wavelength;
- the free space losses decrease proportionally to the square of the wavelength.

Moreover, optical signals have a much narrower beamwidth than RF signals: that means that an on-board laser could not interfere with another laser.
Figure 10 - Advantages of implementing Free Space Optical Communications (FSOC) for space systems [1]

On the other hand, an optical communication system is characterized by large losses in presence of clouds and atmospheric turbulence. In fact, at the typical wavelengths in the Near Infrared (mainly 1064 nm and 1550 nm), clouds block the optical link.

a) The optical communication specificity: acquisition and tracking

Laser communications implies very narrow beam (~10µrad), which requires the setting of an accurate pointing, acquisition and tracking (PAT) system prior to the communication phase.

Figure 11 shows the different steps of the PAT process. The master terminal and the partner terminal correspond, respectively, to the emitter station and the receiver. The first phase is the pointing, which is done by the blind pointing of the transmission laser towards a priori direction of the receiver. The acquisition starts when the receiver detects the beacon signal and estimates its direction. The same process in the opposite direction is performed to correct the master terminal direction. The final phase is the tracking in which both terminals track with submicroradian accuracy the signal to be compatible with an error free transmission. Once the PAT phase has been successfully completed, the communication phase can start.

This is only an example of PAT: there could be other different ways to perform it.
Figure 11 - Pointing, acquisition and tracking process in Free Space Optical Communications [1]

b) Illustration of an optical forward feeder link

Figure 12 shows the different blocks of an optical transmission from Internet to the final user. Regarding the forward link, the information is tackled at the OGS by the gateway MODEM to satisfy the DVB-S2 standard. The resulting signal is provided to the optical transmission sub-system, amplified and sent to the satellite. At the satellite, the signal carried by the optical feeder is detected and converted to electrical before transmission to the End-users. For the return link, the radiofrequency signal for the end user is embedded on the optical feeder downlink.

Figure 12 - Block diagram for optical communications [1]
Given that a general optical communication system has been presented, the main topic of this study will be based only on the downlink phase.

4. The perspective for optical downlink system

The downlink represents the transmission of information from a space station or satellite to an Earth station. [14] describes an Airbus study in which it is stated the necessity of geographically spread optical ground stations in order to reach a defined link availability. Here, it has been showed the essential point of performing handovers between the stations, which are based on cloud forecasts done by a prediction system at each ground station.

Figure 13 shows this handover mechanism: in this case, each station is equipped with a weather prediction system. In general, a station without such a system should be able to use the cloud data provided by geostationary weather satellites.

![Figure 13 - Handover mechanism among the stations in the OGS network][15]

Thanks to the considerations made in the previous sections, it is possible to better understand the requirements needed for the successful implementation of the optical downlink system. First of all, an efficient ground network is required in order to face the possibility of an unavailable station: in this way, 100% link availability could be reached. This implies that the satellite should be supplied with a protocol which allows to understand if the image has been downloaded or not. To do so, usually the ground station furnishes an Automatic Repeat Request (ARQ) to specify the positive image reception. So, in this case, a cloud model is a very important part...
when selecting the optical ground station: if the traditional RF sites are used, it is possible to encounter non-optimal weather conditions. In this study, two cloud models will be used:

- the one from geostationary satellite passive imagery;
- the one from in-situ weather conditions measured by a ground instrument.

Therefore, these cloud models should provide two important guidelines to establish if the link with a ground station is feasible or not: in particular, the cloud presence probability should be analysed.

The network should also be designed in order to take into account the seasonal variations and minimize them: this issue has not been analysed yet, but it will be taken into account in future studies.

The choice of the OGS is also related to the cost and the following parameters should be considered:

- the distance between OGSs: the terrestrial fiber is very expensive, so the distance between stations is limited;
- the reusability of the station: for example a station at the pole could not be used for both the LEO and GEO scenarios;
- the available infrastructures.

In addition to the design of the OGS network, there are other system requirements that should be taken into account:

- the orbit to be chosen: the orbit and its Keplerian parameters influence the data download. For example, a sun-synchronous orbit implies a different field of view compared to the one for an orbit with different inclination;
- the downlink data rate: data rates comprised between 1 and 10 Gbps could be reached with single-wavelength communication systems and a low cost transmission chain. If a higher data rate is required, the system should be equipped with multi-wavelength communication systems or more complex transmission chain that imply a growth in system complexity;
- the Data Volume that should be achieved for each orbit;
- the lowest elevation angle: the data transmission starts when the satellite passes over the station with an elevation angle greater than the lowest admissible one;
- the maximum data latency: the image is gathered into the satellite memory for a precise period of time. This parameter is an important characteristics for the OGS network design;
- the mass memory bus rate: it is the speed of the information when passing in the on-board system. This feature should be compared to the download data rate: if the download data rate is greater than the mass memory bus rate, the overall system could be improved;
- the mass memory: the memory available on board has a limited capacity. The satellite should be able to download the information in the memory before reaching its saturation;
- the link availability;
- the link planning lead-time: it represents the amount of time that elapses between the beginning and the end of the data transmission. A shorter lead-time increases the complexity of the mission planning;
- the number of on-board laser terminals;
- the maximum number of ground station in the network.
In this thesis, the attention will be focused, in particular, on few of these system requirements:

- the cloud presence probability;
- the orbit;
- the downlink data rate;
- the data volume;
- the mass memory;
- the number of on-board laser terminals.

In conclusion, optical data download systems could be feasible and studies which recently have been done show that the transmission performed by optical downlink systems could be an alternative to the RFs use: this is possible if the on-board system is equipped with a large memory in order to compensate for the momentary unattainable ground station and with a protocol enabling the handover among stations.
C. MY MISSION

The main objective of this thesis is to design a space-to-Earth optical communication system for better optical downlink availability. This implies the necessity of planning the download of all the data acquired by a considered satellite during its period in orbit.

In this work, the interesting part is the system approach. The design of the optical link download is based on various mission planning considerations and hypothesis:

- the cloud presence probability;
- the orbit;
- the downlink data rate;
- the data volume;
- the mass memory;
- the number of on-board laser terminals.

In the first place, this study will focus the attention on the data download over a ground station only, then on the data download considering the presence of a ground stations network. In both these cases, the clouds attenuation plays an important role: the availability of the space optical system depends on the cloud probability. In order to consider the cloud attenuation, the data provided by GEO weather satellites will be considered as an important source of information.

At the beginning, Toulouse will be the single station considered: since it permits to define the amount of downloaded data, taking into account the weather in-situ measurement provided by an instrument called SkyInsight placed on a building in the Airbus and Defence site.

This study is divided into two work-packages (WP):

- the main goal of the first WP is the study of the data provided by the weather satellite (Section II.C.2) and SkyInsight (Section II.C.1). The comparison between these two kinds of data could give important information regarding the efficiency of the cloud detection. In addition, this comparison could allow to extrapolate the cloud condition over a station which is not equipped with a SkyInsight detector. It could be noted that the data comparison performed in this study is the first European comparative study in the space telecommunication field: its results will be used for further researches in order to improve the way cloud conditions should be treated in the design of optical links;

- the second WP has the goal of planning the download of data over the stations, taking into account the weather conditions and the results of the comparison obtained in the first WP. This WP is the result of a simulation which consists of orbit, acquisition and download capacities hypothesis. This mission planning could lead to the analysis of the optical ground stations network and the satellite on-board configuration (i.e. mass memory, number of lasers, etc.)

Now that the objectives of the internship have been presented, the next section aims at describing all the information necessary to better understand the methods used and the results obtained, i.e. SkyInsight characteristics, SAFNWC codes, etc.
II. TECHNICAL BACKGROUND

In this section, all the knowledge used over this study is presented.

A. ELEMENTS OF ORBITAL MECHANICS

1. ECEF reference frame

The Earth Centered Earth Fixed reference frame represents the principal reference frame used in the Earth Observation mission design. Its origin position is fixed on the Earth center of mass. The Z-axis is the line that connects the two Earth poles and its direction is oriented towards the North direction. The X and Y-axis lie on the equator plane: the X direction is given by the interception of the equator plane with the plane containing the Greenwich meridian (also called Prime meridian) and the Y direction is oriented in order to obtain a frame which respects the right-hand rule. This reference frame could be observed in Figure 15.

![Figure 15 - ECEF reference frame](image)

Thanks to its definition, it can be noticed that it is a rotating reference frame whose angular velocity is that of the Earth.

A point defined by its latitude $\lambda$, longitude $\phi$ and distance from the Earth center $r$, could be described in the ECEF reference frame using Equation 1.
\[
\begin{align*}
  x &= r \times \cos \varphi \times \cos \lambda \\
  y &= r \times \sin \varphi \times \cos \lambda \\
  z &= r \times \sin \lambda 
\end{align*}
\]

Equation 1 - ECEF coordinates from latitude, longitude and distance from the Earth center

2. Orbital parameters

The orbital mechanics is the discipline which studies the motion of a space object during its period in orbit. An orbit could be elliptical, parabolic and hyperbolic. In this study, only LEO orbits have been considered: as a consequence, the following description is referred only to elliptical orbits, which are the orbits used around the Earth.

The movement of an object is well determined by the knowledge of six important parameters, i.e. its position coordinates and its velocity components. In orbital mechanics, the six parameters used describe the orbit and the position of the satellite in orbit. These parameters are called Keplerian elements (see Figure 16):

- the orbit semimajor axis, \( a \);
- the eccentricity, \( e \);
- the inclination, \( i \): it is the angle between the orbit plane and the equatorial plane. It individuates prograde orbits (\( i > 0 \)) and retrograde orbits (\( i < 0 \));
- the right ascension of the ascending node, \( \Omega \): it is the angle in the orbital plane measured from the vernal equinox (one of the intersections of the ecliptic plane and the equatorial plane) to the ascending node (one of the intersections of equatorial plane and the orbit plane);
- the argument of perigee, \( \omega \): it is the angle in the orbital plane measured from the ascending node to the perigee;
- the true anomaly, \( \nu \): it is the angle in the orbital plane measured from the perigee to the satellite position.

Because of the difficulty in computing the true anomaly, another parameter is usually used: it is the mean anomaly \( M \), which represents the angular distance from de perigee to satellite position, if it moved in a circular orbit with constant angular speed \( n \) and with the same orbital period \( T \) of an elliptical orbit. It is possible to evaluate this parameter with Equation 3.

\[
n = \frac{2\pi}{T}
\]

Equation 2 - Angular speed on a circular orbit

\[
M = n(t - \tau)
\]

Equation 3 - Mean anomaly definition formula
Another important parameter that is usually employed is the eccentric anomaly $E$, which is the angle between the perigee and the projection of the satellite position on a circular orbit (see Figure 17).

The mean anomaly and eccentric anomaly are related by the Kepler’s equation (Equation 4).

$$M = E - e \times \sin E$$

Equation 4 - Kepler’s equation

**Figure 16 - Keplerian orbital parameters for elliptical orbits around the Earth [16]**

**Figure 17 - Illustration of the eccentric anomaly [17]**
Finally, another parameter is the specific energy, which is the satellite energy in orbit and it is composed by the kinetic energy and the potential energy. It is described by the Vis Viva relation, shown in Equation 5.

\[
\varepsilon = \frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}
\]

Equation 5 - Vis Viva equation

3. Orbital perturbations

Keplerian orbits are an approximation of real orbits: an object in orbit is affected by some perturbations that the Keplerian movement description does not take into account. The main external phenomena are:

- atmospheric drag;
- solar radiation pressure;
- third body interactions;
- non-spherical mass distribution.

In this study, which is characterized by a system engineering approach, only the Earth oblateness is considered as a perturbative effect. In order to deal with it, the Earth potential \( U \) at the point \((r, \lambda, \varphi)\) could be expanded in series: in Equation 6, \( \lambda \) is the point latitude, \( \varphi \) is point longitude, \( P_{nm} \) are the Legendre polynomials [18].

\[
U(r, \lambda, \varphi) = \sum_{n=0}^{\infty} \left( \frac{r}{R_{Earth}} \right)^{n+1} J_n P_{n0} (\cos \lambda)
+ \sum_{n=1}^{\infty} \sum_{m=1}^{n} \left( \frac{r}{R_{Earth}} \right)^{n+1} \left[ C_{nm} \cos (m\varphi) + S_{nm} \sin (m\varphi) P_{nm} (\cos \lambda) \right]
\]

Equation 6 - Geopotential expansion in series

It could be observed that the term \( n = 0 \) represents the potential due to the symmetric spherical mass distribution.

It has been demonstrated that the term \( J_2 \) is dominant with respect to the other terms characterized by \( n \geq 1 \): this parameter describes the mass distribution of the Earth equatorial plane. As a consequence, it is associated to Earth oblateness.

This oblateness effect causes the orbit rotation. In particular, it produces a rate of change in the ascending node, the mean anomaly and the argument of perigee [18]. This could be explained considering the angular momentum: a satellite in orbit has an angular momentum which is perpendicular to the orbit itself; whether the satellite position is further north than the equator or further south of the equator, it is affected by a gravitational attraction due to the greater mass distribution at the equator. As a consequence, the angular momentum starts to rotate (precess) around the Earth’s pole [18]. On the other hand, the gravitational forces are conservative forces, so that the energy, the semimajor axis and the eccentricity remain unchanged [18].
In general the described potential $U$ could be seen as the sum of the gravitational potential and a perturbative potential $R$ (Equation 7). Thanks to this composition, the Lagrange’s planetary equations could be derived: they represent the variation of the orbital parameters with time. These equations are presented in Table 3 [18].

$$U = -\frac{\mu}{r} + R$$

Equation 7 - Total potential formulation

<table>
<thead>
<tr>
<th>Orbital elements</th>
<th>Orbital elements variation formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$\frac{da}{dt} = \frac{2}{na} \left( \frac{\partial R}{\partial M} \right)$</td>
</tr>
<tr>
<td>$e$</td>
<td>$\frac{de}{dt} = \frac{(1 - e^2)^{\frac{1}{2}}}{na^2 e} \left{ \left( (1 - e^2)^{\frac{1}{2}} \left( \frac{\partial R}{\partial M} \right) - \left( \frac{\partial R}{\partial \omega} \right) \right) \right}$</td>
</tr>
<tr>
<td>$i$</td>
<td>$\frac{di}{dt} = \frac{1}{na^2 (1 - e^2)^{\frac{1}{2}} \sin(i)} \left{ \cos i \left( \frac{\partial R}{\partial \omega} \right) - \left( \frac{\partial R}{\partial \Omega} \right) \right}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$\frac{d\omega}{dt} = \frac{1}{na^2} \left{ -\cos i \frac{1}{(1 - e^2)^{\frac{1}{2}} \sin(i)} \left( \frac{\partial R}{\partial i} \right) + \frac{(1 - e^2)^{\frac{1}{2}}}{e} \left( \frac{\partial R}{\partial \omega} \right) \right}$</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$\frac{d\Omega}{dt} = \frac{1}{na^2 (1 - e^2)^{\frac{1}{2}} \sin(i)} \left( \frac{\partial R}{\partial i} \right)$</td>
</tr>
<tr>
<td>$M$</td>
<td>$\frac{dM}{dt} = n - \frac{1 - e^2}{na^2 e} \left( \frac{\partial R}{\partial e} \right) - \frac{2}{na} \left( \frac{\partial R}{\partial a} \right)$</td>
</tr>
</tbody>
</table>

Table 3 - Lagrange’s planetary equations [18]

4. Sun Synchronous Orbit

The Sun Synchronous Orbit is a particular orbit characterized by a fixed orbit plane with respect to the Sun (see Figure 18). As a consequence, a defined satellite passes over any point on the Earth surface at the same solar time. This feature is guaranteed by the Earth oblateness: the orbit plane is set with an inclination that allows the Earth oblateness to precess the orbital plane with a precise rate. This rate is precisely $1^\circ$/day [18].

Starting from the Lagrange’s planetary equations for the right ascension of the ascending node, it could be found that the SSO condition is described analytically by Equation 8: this allows to find the necessary inclination of a SSO ($i \cong 98^\circ$) [18].
\[ \omega_2 = \frac{d\Omega}{dt} = -\frac{3}{2} n \left( \frac{R_{\text{Earth}}}{\alpha (1-e^2)} \right)^2 I_2 \cos i = \frac{360^\circ}{365.25 \text{ days}} \]

Equation 8 - SSO condition

Figure 18 - Illustration of a SSO [19]

a) Dual-Axis Spiral

The dual-axis spiral is a geometrical shape: it represents the set of points \( P \) equidistant from a fixed axis \( S \), called secondary axis, which rotates with a fixed distance around another axis \( C \), called primary axis [18].

This spiral is very used in mission design and analysis, in order to trace the satellite ground track and the satellite relative motion [18].

From geometrical considerations, the formulation of the spiral coordinates is given by Equation 9, where \( \rho_1 \) is the angular distance between the two axis, \( \rho_2 \) is the angular distance between the secondary axis and the set of points rotating around it, \( \phi_1 \) is the azimuth angle around the primary axis and \( \phi_2 \) is the azimuth angle around the secondary axis [18]. For further details, the reader is invited to check [18].
\[ \lambda = \frac{\pi}{2} - \cos (\rho_1 \times \cos \rho_2 + \sin \rho_1 \times \sin \rho_2 \times \cos \phi_2) \]

\[ \varphi = (\phi_1 + \Delta \varphi) \]

\[ \Delta \varphi = \cos \left( - \frac{\cos \rho_2 - \cos \rho_1 \times \sin \lambda}{\sin \rho_1 \times \cos \lambda} \right) \]

Equation 9 - Dual-axis spiral equations

Figure 19 - Illustration of the dual-axis spiral [18]
B. OPTICAL DOWNLINK

1. Link budget

The link budget is the budget accounting for all of the gains and losses in the transmission chain: from the transmitter, throughout the atmosphere (free space, absorption, etc.) to the receiver. It also considers all the losses in the transmission chain, i.e. in cables. This budget permits to study how the optical signal is affected by the degradation during the transmission and which the critical parameters are.

Equation 10 presents the injected optical power for the downlink, while all the factors are well described in Table 4.

\[
P_{\text{rdw}} = P_{\text{booster}} T_{\text{Tx}} G_{\text{Tx}} L_{\text{FS}} L_{\text{ad}} L_{\text{scin}} L_{\text{c}} T_{\text{rx}} L_{\text{inj}} G_{\text{r}}
\]

**Equation 10 - Injected optical power in the downlink**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{booster}} )</td>
<td>Optical power booster amplifier</td>
</tr>
<tr>
<td>( T_{\text{Tx}} )</td>
<td>Optical transmission loss in emission</td>
</tr>
<tr>
<td>( G_{\text{Tx}} )</td>
<td>Emitter gain including pointing error and obscuration loss</td>
</tr>
<tr>
<td>( L_{\text{FS}} )</td>
<td>Free space loss</td>
</tr>
<tr>
<td>( L_{\text{ad}} )</td>
<td>Absorption and scattering loss</td>
</tr>
<tr>
<td>( L_{\text{scin}} )</td>
<td>Scintillation loss</td>
</tr>
<tr>
<td>( L_{\text{c}} )</td>
<td>Cloud loss</td>
</tr>
<tr>
<td>( G_{\text{r}} )</td>
<td>Receiver gain including obscuration loss</td>
</tr>
<tr>
<td>( T_{\text{rx}} )</td>
<td>Optical transmission loss in reception</td>
</tr>
<tr>
<td>( L_{\text{inj}} )</td>
<td>Fibre injection loss</td>
</tr>
<tr>
<td>( P_{\text{rdw}} )</td>
<td>Received optical power</td>
</tr>
</tbody>
</table>

**Table 4 - Parameter definition of the gains and losses in the downlink**

In this study all these factors have been considered, taking into account hypothesis and values that have been found during other studies based on optical link transmission.

- **Optical power booster amplifier** \( P_{\text{booster}} \)
  It represents the power coming from the optical amplifier on board;

- **Optical transmission loss in emission** \( T_{\text{Tx}} \)
  This is the loss in the on board optical transmission system: it contains the losses due to the WFE (wave-front error), transmission, defocus and Struss/occultation;
• Emitter gain including pointing error and obscuration loss $G_{T_x}$

It is the gain that describes how well the instrument converts input power into the output power produced by the emitter. Considering the pointing error $\theta$, the transmitter diameter $D_{T_x}$ and the Bessel function of the first kind $J_1(x)$, it is possible to compute the emitter gain with the following formulas:

$$x = \frac{\pi D_{T_x}}{\lambda \sin \theta}; \quad L_{dep} = \left(\frac{2J_1(x)}{x}\right)^2$$

**Equation 11 - Pointing error losses**

$$G_{T_{max}} = \left(\frac{\pi D_{T_x}}{\lambda}\right)^2$$

**Equation 12 - Maximum emitter gain**

$$G_{T_x} = 10 \log_{10}(G_{T_{max}}L_{dep})$$

**Equation 13 - Emitter gain formula**

• Free space loss

It represents the attenuation of the signal emitted before reaching the receiver: it is the loss due to the distance between the source and the target. This loss could be calculated as **Equation 14** shows, where $d$ is the distance covered by the signal and $\lambda$ is the wavelength;

$$L_{FS} = 20 \log_{10}\left(\frac{4\pi d}{\lambda}\right)$$

**Equation 14 - Free space loss computation formula**

• Absorption and scattering loss

The absorption phenomenon occurs when the light that passes through the atmosphere transmits part of its energy to the particles.

On the other hand, scattering losses are caused by the interaction of light with particles that do not absorb energy but transmit it in other directions. This loss could be calculated as **Equation 15** shows, where $E$ is the elevation angle and $T_{ad}$ represents the transmittance when the satellite is at the station zenith and the wavelength is $\lambda = 1.55\mu m$;

$$L_{ad} = 10 \log_{10} e^{\frac{\ln(T_{ad})}{\sin E}}$$

**Equation 15 - Absorption and scattering loss computation formula**
- **Scintillation loss**
  The scintillation losses represent the loss that a change in the refractive index involves. As a consequence, there are mainly due to the fluctuations created by the atmospheric turbulence;

- **Cloud loss**
  Clouds are the main source of loss in the optical link budget. There are different types of clouds (see Figure 20) and each one is characterized by different features, i.e. optical depth. Table 5 shows that losses resulting by clouds can vary from 0.1dB up to 2300dB. Considering higher altitudes, cirrus clouds attenuation is less than 6.8dB. Therefore, all types of clouds, except cirrus, occlude the signal completely and interrupt the communication;

![Figure 20 - Classification of clouds by Meteo France [1]](image)
### Types of clouds

<table>
<thead>
<tr>
<th>Types of clouds</th>
<th>Base altitude [km]</th>
<th>Thickness [km]</th>
<th>$\alpha_{ext}$ [m-1]</th>
<th>Horizontal extension [km]</th>
<th>Attenuation@~1μm [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cirrus</td>
<td>6 - 10</td>
<td>0.2 - 3</td>
<td>$10^4$</td>
<td>$10^2 - 10^3$</td>
<td>0.1 – 2</td>
</tr>
<tr>
<td>Cirro-cumulus</td>
<td>6 - 9</td>
<td>0.2 - 1</td>
<td>$2.10^4$</td>
<td>$10 - 10^2$</td>
<td>0.3 – 1.4</td>
</tr>
<tr>
<td>Cirro-stratus</td>
<td>5 – 9</td>
<td>0.5 - 5</td>
<td>$2x10^4$</td>
<td>$10^2 - 10^3$</td>
<td>0.7 – 6.8</td>
</tr>
<tr>
<td>Alto-Cumulus</td>
<td>2 – 6</td>
<td>0.1 – 0.8</td>
<td>$1.7x10^2$</td>
<td>$10 - 10^2$</td>
<td>12 – 92</td>
</tr>
<tr>
<td>Alto-Stratus</td>
<td>3 – 6</td>
<td>0.5 – 3</td>
<td>$1.1x10^{-1}$</td>
<td>$10^2 - 10^3$</td>
<td>400 – 2300</td>
</tr>
<tr>
<td>Strato-Cum.</td>
<td>0.4 – 2</td>
<td>0.1 – 1</td>
<td>$4.7x10^2$</td>
<td>$10 - 10^3$</td>
<td>30 – 300</td>
</tr>
<tr>
<td>Stratus</td>
<td>0.1 – 0.7</td>
<td>0.1 – 1</td>
<td>$1x10^{-1}$</td>
<td>$10 - 10^3$</td>
<td>70 – 670</td>
</tr>
<tr>
<td>Nimbo-Stratus</td>
<td>0.1 – 1</td>
<td>1 – 10</td>
<td>$1.3x10^{-1}$</td>
<td>$10^2 - 10^3$</td>
<td>&gt; 800</td>
</tr>
<tr>
<td>Cumulus</td>
<td>0.8 – 2</td>
<td>0.3 – 5</td>
<td>$2.2x10^{-2}$</td>
<td>1 – 10</td>
<td>40 – 700</td>
</tr>
<tr>
<td>Cumulonimbus</td>
<td>0.4 – 1.5</td>
<td>0.5 – 12</td>
<td>$4.4x10^{-2}$</td>
<td>5 – 50</td>
<td>&gt; 150</td>
</tr>
</tbody>
</table>

Table 5 - Comparison of cloud types [1]

- **Receiver gain including obscuration loss**
  
  It is the gain that describes how well the instrument converts input power into the output power produced by the receiver. If $D_{Rx}$ is the receiver diameter, this gain could be calculated as **Equation 16** shows;

  \[
  G_{Rx} = 10 \log_{10} \left( \frac{\pi D_{Rx}^2}{\lambda} \right)
  \]

  **Equation 16 - Receiver gain formula**

- **Optical transmission loss in reception**

  This is the loss in the ground optical system: it contains the losses due to the apportionment RFE/ATS, transmission, Struss/occultation;

- **Fibre injection loss**

  The injection losses imply a variation of the signal amplitude at the input to the fiber. The fiber injection losses depend on the atmospheric turbulence strength and the size of the receiving telescope. **Figure 21** illustrates two possible cases at the fiber input. First case presents low injection losses because the optical power is focused in the core of the fiber and by the absence of high power in side lobes. The other case, the power is more widely distributed over the fibre. Thus, there are more difficulties to inject the optical signal to the fiber.
Received optical power (ROP)

It represents the power coming from the optical receiver at the ground.

In this study, these factors will be considered as constants, except for the free space loss, the absorption and scattering loss and the cloud loss.

The free space loss is a function of the distance $d$ between the satellite and the ground station considered (see Equation 14): the larger is the distance, the bigger is the loss (see Figure 22).

![Figure 21 - Illustration of possible fibre input cases [1]](image)

![Figure 22 - Free space loss evolution](image)
The absorption and scattering loss is a function of the elevation angle $E$: for an OGS, it is the angle between the OGS horizontal plane and the satellite (see Figure 23). Figure 24 shows that the attenuation decreases with the elevation angle: low angular elevation implies an increasing atmospheric thickness in the line of sight (LOS).

**Figure 23** - Illustration of the important reference angles: elevation, zenith and azimuth angles [20]

**Figure 24** - Absorption and scattering loss evolution
Finally, the cloud loss is another factor whose variations should be taken into account: the cloud conditions are clearly a function of time.

2. From link budget to useful data rate

As it is described in the previous section, the link budget enables the computation of the received optical power as the result of the downlink. Thanks to this information, it is possible to calculate the useful data rate (UDR), starting from the theoretical data rate, called Optical Channel Rate (OCR).

In Section 1.B.2, recent and future optical technologies have been described: the developed downlink systems are able to transmit the data with a rate of 10 Gbps. This value is only theoretical because the overall transmission data rate is a function of the receiver considered.

- Avalanche Photodiode (APD) receiver
  It is a receiver that takes advantage of the photoelectric effect in order to transform light in electrical energy: a photon arriving at the receiver leads to the generation of a current of electrons (avalanche effect).
  For optical application, only the InGaAs receiver can be found on the market (see Figure 25).

![Figure 25 - Example of APD (Priceton Lightwave’s PLA-8XX) – low complexity receiver [21]](image)

- Erbium Doped Fiber Amplifier (EDFA) receiver
  This receiver uses an EDFA to amplify an optical signal. This process is well described in Figure 26.
  When a signal arrives at the receiver, it is sent in a doped fiber with another pumped signal: this pumped laser excites the doped fiber ions that will lose energy by stimulated emission of photons at the signal wavelength. The signal results amplified.
  Unfortunately, this system presents a problem due to the introduction of optical noise: the electrons could decay by spontaneous emission of photons: these emitted photons could enter into the fiber: they come into contact with other ions and, as a matter of the fact, they are amplified. So the spontaneous emission is amplified just as the original signal.
  In order to solve this problem, an optical bandpass filter is used, so that the noise is removed (see Figure 27).
In this study, the APD receiver will be considered. This receiver has been studied in the mission TMI (Telemeasure information). In this case, some important index should be defined:

- **FEC** – Forward Error Correction: it is the transmission efficiency $R$. It is used to compute the Useful Data Rate from the Optical Channel Rate (OCR), using **Equation 17**;

\[
UDR = R \times OCR
\]

**Equation 17 - Useful Data Rate computation**

- **FER** – Frame Error Rate: it is the ration between the data received with errors and the total data received. A very high FER implies a low quality transmission;
- **MI** – Mutual Information: it represents the statistical correlation between the receiver signal and the emitted one.

For this receiver, four CONOPS (Concepts of Operations) have been defined as followed:
• **CONOPS 1 - Adaptive FEC rate:** the transmission efficiency changes based on the MI
  - for $MI < 0.63$, the FER would be too high that the data transmission cannot be performed ($R = 0$);
  - for $0.63 < MI < 0.76$, the transmission efficiency $R = 1/2$;
  - for $0.76 < MI < 0.85$, the transmission efficiency $R = 2/3$;
  - for $MI > 0.85$, the transmission efficiency $R = 4/5$;

• **CONOPS 2 - $R = 1/2$:** whenever the transmission could occur, its efficiency $R$ is 1/2
  - for $MI < 0.63$, the FER would be too high that the data transmission cannot be carried out ($R = 0$);
  - for $MI > 0.63$, the transmission efficiency is always $R = 1/2$;

• **CONOPS 3 - $R = 2/3$:** whenever the transmission could occur, its efficiency $R$ is 2/3
  - for $MI < 0.76$, the FER would be too high that the data transmission cannot be realized ($R = 0$);
  - for $MI > 0.76$, the transmission efficiency is always $R = 2/3$;

• **CONOPS 4 - $R = 4/5$:** whenever the transmission could occur, its efficiency $R$ is 4/5
  - for $MI < 0.85$, the FER would be too high that the data transmission cannot be realized ($R = 0$);
  - for $MI > 0.85$, the transmission efficiency is always $R = 4/5$;

**Figure 28** shows graphically the evolution of the FEC rate as a function of the received optical power.

**Table 6** shows the final results for all the cases: given a CONOPS and the ROP, the Useful Data Rate is defined.
Figure 28 - Evolution of the FEC as a function of the ROP

<table>
<thead>
<tr>
<th>CONOPS</th>
<th>ROP</th>
<th>Useful Data Rate (UDR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONOPS1: Adaptive FEC rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ROP &lt; -33 dB</td>
<td>UDR = 0 Gbps</td>
</tr>
<tr>
<td></td>
<td>-33 dB &lt; ROP &lt; -31.9 dB</td>
<td>UDR = 10/2 Gbps = 5 Gbps</td>
</tr>
<tr>
<td></td>
<td>-31.9 dB &lt; ROP &lt; -31 dB</td>
<td>UDR = 10*2/3 Gbps = 6.67 Gbps</td>
</tr>
<tr>
<td></td>
<td>ROP &gt; -31 dB</td>
<td>UDR = 10*4/5 Gbps = 8 Gbps</td>
</tr>
<tr>
<td>CONOPS 2: FEC rate = 1/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ROP &lt; -33 dB</td>
<td>UDR = 0 Gbps</td>
</tr>
<tr>
<td></td>
<td>ROP &gt; -33 dB</td>
<td>UDR = 10/2 Gbps = 5 Gbps</td>
</tr>
<tr>
<td>CONOPS 3: FEC rate = 2/3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ROP &lt; -31.9 dB</td>
<td>UDR = 0 Gbps</td>
</tr>
<tr>
<td></td>
<td>ROP &gt; -31.9 dB</td>
<td>UDR = 10*2/3 Gbps = 6.67 Gbps</td>
</tr>
<tr>
<td>CONOPS 4: FEC rate = 4/5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ROP &lt; -31 dB</td>
<td>UDR = 0 Gbps</td>
</tr>
<tr>
<td></td>
<td>ROP &gt; -31 dB</td>
<td>UDR = 10*4/5 Gbps = 8 Gbps</td>
</tr>
</tbody>
</table>

Table 6 - Illustration of the Useful Data Rate values for all the CONOPS
C. CLOUDS IMAGERY FOR OPTICAL LINK SIMULATION

1. SkyInsight imagery

Satellite imagery provides weather conditions data across the entire globe. The supplied information depends on the satellite orbit: in fact, spatial and temporal resolutions vary from LEO and GEO orbits. Geostationary satellites produced data characterized by a low spatial resolution in a continuous way, while LEO satellites furnish weather data few times in a day but they are characterized by a higher spatial resolution [22].

For the abovementioned reasons, a ground-based cloud monitoring system should be placed at the ground site: in fact, it can perform greater spatial and temporal resolutions.

The SkyInsight is a detector placed on a building in Airbus Defence and Space in Toulouse, whose aim is to provide weather condition over the site. Its data have been provided in order to reach the goal of this study, thanks to a contract between IRT-Saint Exupery and Airbus.

a) Sensor

The SkyInsight detector is based on the instrument SIONS-T, which is the French acronym for a ground-based thermal infrared imager used for cloud detection (see Figure 30). It is an instrument developed by IRT-Reuniwatt and it is composed by:

- a LWIR (Long Wave InfraRed) camera, whose image resolution is 640x480 and its spectral band varies from 8 to 13 µm. This camera provides useful data during both day and night time: this is due to the fact that it does not rely on the detection of the sun light reflected or scattered by the atmosphere, but it directly detect the clouds emission. As a matter of the fact, performances do not rely on the clouds illumination by the sun and, then, the day time has no influence on the imagery results. Data could be obtained by continuous night and day observation [23]. Figure 29 shows that the contrast between clear sky and clouds is better displayed in the infrared image. Moreover, the visible image presents not only a sun flare, but also light zones and shadows. Those are not seen in the infrared image because sun radiations do not belong to thermal infrared, while clouds are characterized by a great emission in this spectrum;
- a hemispherical mirror, that provides a 180° field of view. The resolution of the field of view is about 0.35° per pixel [23];
- humidity and temperature sensors [23];
- an embedded computer for the data processing [23];

Figure 29 - Infrared (on the left) and visible (on the right) images [23]
b) Algorithm principle

The main results of the SkyInsight imagery system is the Optical Depth (OD). The algorithm is briefly outlined in Figure 31 [24].

Basically, it is based on the inversion of a radiative transfer model. The model chosen is libRadtran, a model which permits to reproduce the radiation emitted by the atmosphere layers giving as inputs the atmosphere physical state and chemical composition, which are information coming from the European Center for Medium Range-Weather Forecasts (ECMWF). This inversion is based on a lookup-table (LUT) approach [23] [24].

At the beginning, the radiance coming from a clear atmosphere is compared to the global one and their difference is called residual radiance, which is the radiance given by clouds only. Then, with the inversion of the radiative transfer model, it is possible to estimate the cloud presence and the optical depth for each image pixel [23] [24]. This estimation takes into account the difference between thin and thick clouds, which give different values of radiance, as shown in Figure 32. It is also important not to confuse thin cloud radiance with clear sky radiance [23] [24].

The algorithm used to find the clear sky radiance is an empirical method.
Figure 31 - SkyInsight data processing algorithm [24]

Figure 32 - Spectral irradiance for clear sky, thin cloud and thick cloud in the LWIR spectral band [23]
c) Optical depth mask

The optical depth is a dimensionless number that describes the amount of light that passes through a material, i.e. the atmosphere. A bigger optical depth implies that the light could not pass through the material. This number could be calculated with the following formulas (Equation 18), where \( I_0 \) is the incident power, \( I \) is the transmitted power and \( T \) is the material transmittance.

\[
I = I_0 e^{-\tau} \\
\tau = -\ln(T)
\]

Equation 18 – Beer-Lambert formula

SkyInsight provides an optical depth mask every 30 seconds. The loss due to the cloud presence can be computed with Equation 19.

\[
L_{cloud} = 10 \log_{10} (e^{-OD})
\]

Equation 19 – Cloud loss formula from OD value
2. SEVIRI

The MSG satellite is equipped with an optical imaging radiometer, called Spinning Enhanced Visible and Infrared Imager (SEVIRI). This instrument has been created by European industry with a strong participation of Astrium SAS in Toulouse.

a) Sensor

SEVIRI is a scanning radiometer characterized by an aperture of 50 cm: it provides data in four Visible and Near-InfraRed (VNIR) channels and eight InfraRed (IR) channels [25].

It continuously points the Earth taking images in the previously mentioned 12 spectral channels with a repeat cycle of 15 minutes [25]. A bi-dimensional scan method is used to accomplish the entire Earth imaging: a rapid scan (line scan) operates from east to west, exploiting the satellite rotation around its vertical spin axis. A mechanical element allows the mirror rotation in order to perform a South-North scan, which is slower than the first one. The scanning mechanism is described in Figure 34 [25].

This instrument depicts a remarkable improvement with respect to Meteosat radiometer. It is characterized by:

- an increased spatial resolution (3km compared to 5km for the Meteosat radiometer);
- an increased temporal sampling (15 minutes compared to the 30 minutes of Meteosat radiometer);
- increased number of spectral channels (12 channels compared to the 3 channels of Meteosat radiometer): this improvement allows a more accurate cloud analysis.

![Figure 34 - SEVIRI scanning principle [25]](image-url)
Algorithm principle

Software which uses MSG/SEVIRI has been developed by the Satellite Application Facility for NoWCasting and very short range forecasting (SAFNWC), a specialized centre within EUMETSAT [26]. The Centre de Météorologie Spatiale (CMS) of Météo-France is in charge of production of the cloud mask (CMa) and cloud type (CT) software modules implemented in the SAFNWC/MSG software package [26].

The algorithm that permits to obtain these two masks is based on a multispectral thresholding technique applied to each pixel of the image: the thresholds used are obtained from data of previous studies and they depend on the illumination, the viewing geometry, the geographical location and the data describing the water vapour content and a coarse vertical structure of the atmosphere [26]. At the end of this process, pixels characterized by reflectances and brightness temperatures very similar to the thresholds are reported as of low confidence [26].

c) CMa and CT masks outputs

The Cloud Mask identifies cloud free and cloud filled areas. On the other hand, the Cloud Type depicts the clouds nature by categorizing all the clouds previously detected by the Cloud Mask [26]. The outputs coming from the CMa and CT software are described in Table 7 and Table 8.

<table>
<thead>
<tr>
<th>Cloud mask value</th>
<th>Cloud mask data</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Non-processed</td>
<td>Containing no data or corrupted data</td>
</tr>
<tr>
<td>1</td>
<td>Cloud-free</td>
<td>No contamination by snow/ice covered surface, no contamination by clouds; contamination by thin dust/volcanic clouds not checked</td>
</tr>
<tr>
<td>2</td>
<td>Cloud-contaminated</td>
<td>Partly cloudy or semitransparent. It may also include dust clouds or volcanic plumes</td>
</tr>
<tr>
<td>3</td>
<td>Cloud filled</td>
<td>Opaque clouds completely filling the FOV. May also include thick dust clouds or volcanic plumes</td>
</tr>
<tr>
<td>4</td>
<td>Snow/Ice contaminated</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Undefined</td>
<td>Data has been processed but not classified due to known separability problems</td>
</tr>
</tbody>
</table>

Table 7 - CMa outputs description [26]
<table>
<thead>
<tr>
<th>Cloud type value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Non-processed (containing no data or corrupted data)</td>
</tr>
<tr>
<td>1</td>
<td>Cloud free land</td>
</tr>
<tr>
<td>2</td>
<td>Cloud free sea</td>
</tr>
<tr>
<td>3</td>
<td>Land contaminated by snow</td>
</tr>
<tr>
<td>4</td>
<td>Sea contaminated by snow/ice</td>
</tr>
<tr>
<td>5</td>
<td>Very low and stratiform cloud</td>
</tr>
<tr>
<td>6</td>
<td>Very low and cumuliform cloud</td>
</tr>
<tr>
<td>7</td>
<td>Low and stratiform cloud</td>
</tr>
<tr>
<td>8</td>
<td>Low and cumuliform cloud</td>
</tr>
<tr>
<td>9</td>
<td>Medium and stratiform cloud</td>
</tr>
<tr>
<td>10</td>
<td>Medium and cumuliform cloud</td>
</tr>
<tr>
<td>11</td>
<td>High opaque and stratiform cloud</td>
</tr>
<tr>
<td>12</td>
<td>High opaque and cumuliform cloud</td>
</tr>
<tr>
<td>13</td>
<td>Very high opaque and stratiform cloud</td>
</tr>
<tr>
<td>14</td>
<td>Very high opaque and cumuliform cloud</td>
</tr>
<tr>
<td>15</td>
<td>High semi-transparent thin cloud</td>
</tr>
<tr>
<td>16</td>
<td>High semi-transparent fairly thick cloud</td>
</tr>
<tr>
<td>17</td>
<td>High semi-transparent thick cloud</td>
</tr>
<tr>
<td>18</td>
<td>Semitranparent above low or medium cloud</td>
</tr>
<tr>
<td>19</td>
<td>Fractional cloud (sub-pixel water cloud)</td>
</tr>
<tr>
<td>20</td>
<td>Undefined (undefined by CMa)</td>
</tr>
</tbody>
</table>

Table 8 - CT outputs description [26]

d) Discussion on parallax effect

The weather information captured by the satellite depends on its position in relation to the OGS location.

The parallax is the distance between the considered OGS and the pixel on the line-of-sight between the OGS itself and the satellite. As one can infer from Equation 20, the parallax gets higher when the cloud altitude increases and when the satellite elevation decreases.
This effect is described in Figure 35: on the left, a typical situation is described, while the worst case is presented on the right. The latter is characterized by a cloud altitude of 10km and the satellite elevation is 10°: in this case, the parallax is approximately 55 km [27].

The data provided by the satellite ignore this cloud parallax: as a consequence, during the data processing, it should be necessarily taken into account. In fact, if another satellite is supposed to establish a communication connection with the same OGS but its position is different from the Meteosat position, the weather condition encountered along its line-of-sight will be probably different and another pixel is going to be selected [27].

![Figure 35 - Illustration of the parallax effect in a typical situation (on the left) and in the worst case (on the right) [27]](image)
### Table 9 - Parallax evolution with the cloud altitude

<table>
<thead>
<tr>
<th>$h_{\text{cloud}}$ [km]</th>
<th>$d_{\text{parallax}}$ [km]</th>
<th>pixel shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,22</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2,43</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>3,65</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>4,87</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>6,08</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>7,30</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>8,51</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>9,73</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>10,95</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>12,16</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>13,38</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>14,60</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>15,81</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>17,03</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>18,24</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>19,46</td>
<td>4</td>
</tr>
<tr>
<td>17</td>
<td>20,68</td>
<td>5</td>
</tr>
<tr>
<td>18</td>
<td>21,89</td>
<td>5</td>
</tr>
<tr>
<td>19</td>
<td>23,11</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>24,33</td>
<td>6</td>
</tr>
</tbody>
</table>
III. SKYINSIGHT & SAFNWC COMPARISON

SkyInsight will be used to estimate data downloaded over a site taking into account in-situ weather measurements. Such a study is a step forward compared to the state of the art, which considers cloud condition data from GEO imagery satellites.

Before proceeding with this analysis, it is in the interest of this study to compare SkyInsight data and GEO imagery data. The data provided by these two sources are completely different: SkyInsight detector allows the examination of the optical depth, while the GEO satellites provide the cloud mask and type. In other words, SI associates to each pixel a value of optical depth, while the GEO satellites associate to each pixel a value for CMa and CT.

The aim of this study is to find a correlation between the ODs and the CMAs and CTs. This relation has two purposes:

- to derive the distribution of OD for the cloud free pixel of the CMa and CT masks;
- to permit to understand possible SkyInsight algorithm improvements;
- to discuss the use of CMa and CTs masks for system dimensioning.

A. HYPOTHESIS AND INPUT DATA

Table 10 exhibits the input data which are necessary for the algorithm to work: it should extract all the data from the SI and SAFNWC database.

<table>
<thead>
<tr>
<th>Input data</th>
<th>Type of data</th>
<th>Name</th>
<th>Latitude [°]</th>
<th>Longitude [°]</th>
<th>Altitude [km]</th>
<th>Repeat cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>SkyInsight data</td>
<td>ODs</td>
<td>Toulouse</td>
<td>43.6</td>
<td>1.4</td>
<td>0</td>
<td>30 s</td>
</tr>
<tr>
<td>GEO Meteo satellite</td>
<td>CMAs and CTs</td>
<td>MSG+0000</td>
<td>0</td>
<td>0</td>
<td>36000</td>
<td>15 min</td>
</tr>
</tbody>
</table>

Table 10 - List of the input data and their features

In particular, the SEVIRI longitude and latitude grid is also provided (see Figure 36): every point of the grid contains the CMa and CT information. Thanks to the longitude and latitude grid, the SEVIRI spatial resolution grid could be computed: it portraits the distance between each point of the previous grid. If the variations of latitude and longitude between two consecutive points are depicted respectively with $\Delta \lambda$ and $\Delta \varphi$, the spatial resolution can be evaluated with Equation 21.

\[
\Delta \text{lat} = \Delta \lambda \times R_{\text{Earth}} \quad ; \quad \Delta \text{long} = \Delta \varphi \times R_{\text{Earth}}
\]

Equation 21 - Spatial resolution computation formulas: latitude resolution on the left, longitude resolution on the right
Obviously, $R_{Earth}$ is the Earth radius and its value should take into account the Earth shape: in fact, shows its dependency on the Earth eccentricity $e$ and latitude $\lambda$.

$$R_{Earth} = \frac{R_{equator}}{R_{pole}} \times (1 - e \times \cos^2 \lambda)^{3/2}$$

Equation 22 - Earth radius computation formula

It is important to note that this grid is not uniform, but the spatial resolution changes with the latitude and longitude considered. On the other hand, it is fixed in time and it does not change with the cloud altitude and elevation.

Moreover, in order to study the weather conditions in a precise area around the ground station, other information is required and the following hypothesis will be taken into account:

- the considered area elevation;
- the considered area azimuth;
- the cloud altitude.
B. ALGORITHM PRINCIPLE

The algorithm used to find the relation between the optical depth and the CMa/CT values is described in Figure 39. It consists of five consecutive steps:

1. SI spatial grid computation

The SkyInsight spatial resolution is the size of a pixel in the SkyInsight image. Differently from the SEVIRI spatial resolution, this grid does change with the cloud altitude and elevation. In fact, since the angular resolution $\theta$ of SEVIRI is constant, the pixel size depends on its distance to the OGS considered. Figure 37 shows well this variation, considering only the direction x:

- if the cloud altitude increases ($h_2 > h_1$), the spatial resolution increases ($\Delta x_2 > \Delta x_1$);
- if the cloud elevation decreases ($E_3 < E_1$), the spatial resolution increases ($\Delta x_3 > \Delta x_1$).

Finally, the SI spatial resolution is computed around the station.

It is possible to observe that a SI pixel is smaller than a SEVIRI pixel: each SEVIRI pixel contains more SI pixels. In particular, Table 11 highlights how this number of SI pixel changes when considering different SEVIRI pixel: as it will be described in Section II.C, it will vary based on the different elevation and altitude of the point considered. This table confirms also all the considerations done in Figure 37: when the cloud altitude increases or the elevation decreases, the SI spatial resolution rises and a less number of SI pixels are contained into the SEVIRI one. This will be seen also in Figure 41 and Figure 43.
2. Colocalisation at cloud height

Given the cloud altitude, elevation and azimuth, the colocalisation is the process which enables to identify the SEVIRI pixel and all the contained SI pixels with their ODs. It is the most complicated part in the algorithm and it is described in Section VII.A. This process will be validated in Section II.C.

3. Spatial averaging

The spatial averaging consists of computing the mean value of all the ODs contained into the SEVIRI pixel. Thanks to this averaging process, the value found \(< OD >\) will not be dependent from the spatial coordinates, but it will be related only to the temporal component.

This process is well described by Equation 23, where \(N\) is the number of SI pixels.

\[
< OD > (t) = \frac{\sum_{i=1}^{N} OD_i}{N}
\]

Equation 23 - Spatial averaging formula

4. SAFNWC data extraction

Employing the colocalisation process, the position of the SEVIRI pixel is settled. Given this position, the cloud mask and the cloud type associated to the pixel can be easily extracted from the satellite data, which constitute an input of the algorithm. Obviously, the found CMa and CT are also time dependent.

5. Time averaging

The time averaging process is the last step of the algorithm and it permits to find the comparison relation between the OD and the CMa and CT values. Remembering that SEVIRI and SI are characterized by different repeat cycles (15 minutes for SEVIRI and 30 seconds for SI), the average could not be implemented for all values of optical depth \(< OD >\). In fact, as shown in Figure 38, the number of spatially averaged optical depth is thirty times bigger than the number of CMa and CT values.

The time averaging process considers only the time instant when both CMa/CT and \(< OD >\) values are present. This means that only the black boxes in Figure 38 are taken into account.
Once that this temporal instant are selected, the algorithm computes the optical depth temporal average for each value of CMa/CT. For example, it starts searching the temporal instants whose CMa is equal to 1 (black boxes characterized by $CMa = 1$) and then evaluates the optical depth average. After that, the algorithm continues performing the same process for all the other values of CMa and CT.

**Equation 24** and **Equation 25** represent the analytical formulas used for this process: $n_{CMa = k}$ and $n_{CT = k}$ are respectively the numbers of time instants characterized by $CMa = k$ and $CT = k$.

\[
< OD >_{CMa=k} = \frac{\sum_{t_i=1}^{n_{CMa=k}} < OD > (t_i)}{n_{CMa=k}}
\]

\[
k = \{1,2,3,4\} \ ; \ t_i = \{t|CMa(t) = k\}
\]

**Equation 24** - Optical depth temporal averaging for every CMa value

\[
< OD >_{CT=k} = \frac{\sum_{t_i=1}^{n_{CT=k}} < OD > (t_i)}{n_{CT=k}}
\]

\[
k = \{1,2,3,4,...,20\} \ ; \ t_i = \{t|CT(t) = k\}
\]

**Equation 25** - Optical depth temporal averaging for every CT value

In addition, it is worth noticing that there are periods of time during which the SI detector does not work properly or it is not turned on: in this case, the OD values in the database are not considered during the averaging process.

![Figure 38 - Description of SI and SEVIRI repeat cycle](image-url)
C. VALIDATION PROCESS

A graphical validation has been performed for the first day, considering two kinds of validations:

- fixed elevation (40°) and variable azimuth ([0°, 40°, 80°, 120°, 160°, 200°, 240°, 280°, 320°, 360°]);
- fixed azimuth (0°) and variable elevation ([20°, 40°, 80°]);

Figure 40, Figure 41, Figure 42 and Figure 43 demonstrate that the algorithm has worked successfully. As a matter of the fact, a symmetric distribution of the SEVIRI grid could be seen in relation to the North-South direction: this is consistent with the SEVIRI latitude and longitude grid, which is more or less constant near the station.

Moreover, if the cloud altitude $H$ increases, the SI spatial resolution increases, while the SEVIRI grid is constant: the SEVIRI pixel should appear smaller for high altitudes. That could be easily seen considering Figure 40 and Figure 42 or Figure 41 and Figure 43.

The same reasoning may be done for an elevation variation: the SI spatial resolution increases when the considered elevation decreases. This implies that the SEVIRI pixel appears to be smaller for low elevations. This is straightforward in Figure 41 and Figure 42.

On the other hand, these figures emphasize a problem in the algorithm: the SEVIRI spatial grid is always centered on the station. This is not true in the reality and it is due to the fact that the algorithm finds $raw_{stat}$ and $column_{stat}$ (the indices of the station in the SEVIRI grid) in an approximated way (using the MATLAB® software).
function \textit{round}). Nevertheless, this error is completely negligible, since it causes a displacement error of maximum 2 km. In the following figures, $E$ stands for elevation, $H$ for altitude and $Az$ for azimuth.

![Graphical validation in the case of $E = 40^\circ$, $H = 5km$ and different azimuths. The SEVIRI pixels containing the red points are individuated with the red lines.](image1)

![Graphical validation in the case of $Az = 0^\circ$, $H = 5km$ and different elevations. The SEVIRI pixels containing the red points are individuated with the red lines.](image2)
Figure 42 - Graphical validation in the case of $E = 40^\circ$, $H = 20\, km$ and different azimuths. The SEVIRI pixels containing the red points are individuated with the red lines.

Figure 43 - Graphical validation in the case of $Az = 0^\circ$, $H = 20\, km$ and different elevations. The SEVIRI pixels containing the red points are individuated with the red lines.
D. RESULTS

The obtained results are presented for a 1-month simulation: in particular, September 2017 has been taken into account. This time period has been chosen as a trade-off between the statistical necessity to have a significant amount of data and the simulation computing time, which is very long. Moreover, the unavailability of 1-year SI weather data played an important role in performing a 1-month simulation.

As described in Section II.B, these results are presented for a precise point defined by the following parameters:

- the elevation angle of the considered point is $E = 80^\circ$. This elevation has been chosen to reach a compromise between its SEVIRI pixel size and the camera effects. In fact, a higher elevation implies a bigger SEVIRI pixel, but the case of elevation $E = 90^\circ$ would imply to consider the central pixel of the OD image, that is characterized by the shadow caused by the presence of the camera;
- the azimuth of the considered point is $Az = 182^\circ$, which is the azimuth towards the MSG+0000 satellite. This is just an assumption used to find the results, but the algorithm could work with any kind of azimuth direction;
- the clouds altitude is set to $H = 5km$. This value permits to obtain a SEVIRI pixel characterized by a large size.

The purpose of considering parameters which allow to consider a large SEVIRI pixel is that it would contain more OD information and the spatial averaging computed by the algorithm could be more accurate.

Two types of results are presented in this study: the time series and the relation between the ODs and CMa values.

![Comparison CMa & CT & ODs](image)

**Figure 44 - Time series in the case of $H = 5km$, $E = 80^\circ$ and time interval considered from 00:00 to 06:00 of the first day**
The time series, which represents the time evolution of the OD, CMa and CT, is shown in Figure 44, where one can observe the OD value at a defined time instant and its corresponding CMa/CT value. Specifically, when $CMa = 1$, very low OD is expected, while having $CMa = 2$ could give high and low values of OD: it depends on how big the cloudy part of the pixel is. On the other hand, $CMa \geq 3$ implies a higher optical depth.

Figure 44 shows accordance between SAFNWC and SI data: when the optical depth starts decreasing, CMa and CT tend to lower values. On the other hand, this correspondence between SAFNWC and SI data is not always respected, as two kinds of error can occur:

- the presence of time intervals in which the optical depth is greater than a threshold but $CMa = 1$. The threshold is classically set to 0.7, because a higher OD value implies cloud losses that are incompatible with optical link communications and SAFNWC algorithm shall be able to detect cloud with OD greater than 0.7. This condition is well represented by the red vertical line in the time series figures.

Figure 45 displays two intervals (second day - from 01:00 to 01:30 and from 02:00 to 02:15) in which SI data state the clouds presence, whilst SAFNWC data do not detect any cloud.

Figure 46 and Figure 47 shows the weather condition at 02:00 and 02:15: it seems that the SI detector worked properly, while SAFNWC data are not accurate.
Figure 46 - OD image from SI at 02:00 of the second day

Figure 47 - OD image from SI at 02:15 of the second day
Further information is provided by Figure 48, which exhibits the probability density function (PDF) of all the OD values that correspond to the case of $CMa = 1$. As a matter of fact, by definition, PDF is the representation of the likelihood of values that a defined variable can assume: in this case, the variable in question is the optical depth.

In conclusion, it can be noticed that this inaccurate situation occurs few times during the entire simulation period (30 days): Figure 48 displays that, when $CMa = 1$, the optical depth is more likely to assume low values, while high OD values are characterized by a low probability. The most common ODs are placed in the interval between 0 and 0.5, with a peak at about 0.1.

- the presence of time intervals in which $CMa \neq 1$ and ODs characterised by very low values. This situation is presented in Figure 49, where starting from 02:00 of the seventh day the optical depth assumes almost a zero value, while SAFNWC data detect the clouds presence. In this particular case, SI detector did not work properly. In fact, as Figure 50 shows, it seems that there is a lack in the OD values. This SI malfunctioning is to be searched in the SI detection algorithm described in Section II.C.1 and will be subject of further research studies.
Figure 49 - Time series in the case of $H = 5\text{km}$, $E = 80^\circ$ and time interval considered from 00:00 to 06:00 of the seventh day.

Figure 50 – OD image from SI at 03:00 of the seventh day.
All the considerations made so far enable to individuate the success/failure probability for the comparison between SI and SAFNWC data: in other words, this probability allows to point out the reliability of the results.

Two kinds of statistics are carried on: the non-detection probability and the false-alarm probability.

- The non-detection probability: it represents the probability to find $OD > 0.7$ when $CMa = 1$. To do so, the cumulative distribution function is taken into account: by definition, it is the probability of a variable to assume values lower than a defined value and it could be seen as the area below the PDF curve. In this case, OD is the variable and 0.7 is the considered value. The CFD has been plotted in Figure 51: this curve suddenly grows as a consequence of the presence of many low OD values. Moreover, in correspondence with a mean OD equal to 0.7, the figure shows an about 85% probability to find a value of $OD < 0.7$ when $CMa = 1$. As a matter of fact, the non-detection probability is about the 15%.

- The false-alarm probability: it represents the probability to find a low OD when $CMa \neq 1$. In this case, the CDF is well described in Figure 52. In this case, the curve grows more slowly than in the previous case and, in correspondence with a mean OD equal to 0.7, the figure shows a probability of about 40% to find a value of $OD < 0.7$ when $CMa \neq 1$. As a matter of fact, the false-alarm probability is about 40%.

In real life, this percentage is lower because $CMa = 2$ implies the presence of partially cloudy pixel: in order to obtain a more accurate value, a description of how much a pixel is filled by cloud should be conducted. This will be subject of further research studies.
Figure 52 - Cumulative distribution function for the OD values corresponding to $CMa \neq 1$, in the case of $H = 5km$ and $E = 80^\circ$

Figure 53 - Illustration of relation between the ODs and CMa values in the case of $H = 5km$ and $E = 80^\circ$
Finally, the algorithm leads to associate a mean value of optical depth to each CMa code. This link is described in Figure 53. One can note that, when $CMa = 1$, the mean OD value is about 0.55, which is lower than 0.7.
IV. OPTICAL DOWNLINK SIMULATION PROCESS

After having described the comparison between the geostationary satellite data and the SI data has been described, the data download planning could be dealt with. In this section, the algorithm which enables to simulate the downlink capacity will be described. This algorithm will be used in the following section to study different data download cases:

- Optical link capacity, considering Toulouse as the only station available and without taking into account the clouds impact,
- Optical link capacity, considering Toulouse as the only station available and taking into account the clouds impact;
- Optical link capacity, considering an OGS network. In this case, the clouds impact will be illustrated and compared to the case in which no clouds are present.

The simulation process consists of different steps:

A. INPUT DATA DEFINITION

At the beginning of the simulation process, it is necessary to insert three types of inputs: orbit, station and optical link features. All this information is described in Table 12.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>It represents the name of the orbit</td>
</tr>
<tr>
<td>Start</td>
<td>The user should enter the precise start date (i.e. dd/mm/yyyy)</td>
</tr>
<tr>
<td>End</td>
<td>The user should enter the precise start date (i.e. dd/mm/yyyy)</td>
</tr>
<tr>
<td>Minimum altitude $H_{\text{min}}$ [km]</td>
<td>It is the lowest altitude reached by the satellite. It will be important in the orbit analysis in order to find all the possible orbit possibilities</td>
</tr>
<tr>
<td>Maximum altitude $H_{\text{max}}$ [km]</td>
<td>It is the highest altitude reached by the satellite. It will be important in the orbit analysis in order to find all the possible orbit possibilities</td>
</tr>
<tr>
<td>Minimum repeat cycle $\text{MinCycle}$ [days]</td>
<td>It represents the minimum number of days necessary for the satellite to return in the same position</td>
</tr>
<tr>
<td>Maximum repeat cycle $\text{MaxCycle}$ [days]</td>
<td>It represents the maximum number of days necessary for the satellite to return in the same position</td>
</tr>
<tr>
<td>SSO</td>
<td>This parameter defines the orbit type. $SSO = 1$ defines a Sun Synchronous Orbit. If $SSO = 0$, the orbit is not a sun orbit</td>
</tr>
</tbody>
</table>
### Optical downlink study for Low Earth Orbit satellite

**Acquisition parameters**

- **Acquisition time step [s]**: It represents the time interval between two consecutive satellite image acquisitions.
- **Image size [Mbits]**: It represents the size of each acquired image.
- **Maximum daily acquisition capacity [Tbits]**: It represents the number of images that the satellite can acquire during a day.

**Station inputs**

- **Latitude [°]**: It is the station latitude.
- **Longitude [°]**: It is the station longitude.
- **Minimum elevation [°]**: It is the minimum elevation beyond which the satellite is allowed to transmit the data to the station.

**Optical link parameters**

- **Wavelength [µm]**: It defines the laser used.
- **Link budget margin [dB]**: It is a loss addition that will be used in the computation of the Link Budget.
- **Optical Channel Rate [Gbps]**: It represents the theoretical download rate (see Section II.B.2).
- **Transmitted power [dBm]**: See Section II.B.1.
- **Transmitter diameter [m]**: See Section II.B.1.
- **Pointing error [°]**: See Section II.B.1.
- **Optical transmission loss in emission [dB]**: See Section II.B.1.
- **Absorption and scattering loss [dB]**: See Section II.B.1.
- **Scattering loss [dB]**: See Section II.B.1.
- **Receiver diameter [m]**: See Section II.B.1.
- **Optical transmission loss in reception [dB]**: See Section II.B.1.
- **Injection loss [dB]**: See Section II.B.1.

| Table 12 - Simulation inputs list and features |
B. ORBIT ANALYSIS

The analysis consists in finding the orbit characterized by an altitude comprised between the minimum altitude and the maximum altitude and by a repeat cycle comprised between the minimum repeat cycle and the maximum repeat cycle: after a precise number of days, the satellites returns in the same location and then it will perform the same orbit. This is well described by Equation 26, where \( j \) is the number of orbits during the repeat period and \( k \) is the number of days of the repeat period. A ground observer could see that the path traced by the satellite is always the same [18].

\[
jT_{sat} = kT_{Earth}
\]

**Equation 26 - Repeating ground track formula**

\[
T_{sat} = 2\pi \sqrt{\frac{a^3}{\mu}}
\]

**Equation 27 - Third Kepler law**

This period of repetition is a function of the perturbative effects which affect the satellite in orbit. Given the previous considerations, the orbit should be a harmonic of the Earth rotation relative to the orbit plane [18]. As a consequence, it is important to take into account the orbit rotation caused by the Earth oblateness. This effect is a function of the altitude: so, in order to find the orbit altitude, an iterative process should be performed, as observable in Figure 54 [18]. This process is based on two different loops: an external loop for every value of \( k \) between the minimum and the maximum repeat cycles and an internal loop for every value of \( j \) between the minimum and maximum number of orbits in a period of \( k \) days. In particular, while the minimum and maximum repeat cycles are provided as inputs, the minimum and maximum number of orbits could be found by means of the minimum and maximum altitudes, which permit to compute the satellite period with Equation 27.

\[
\text{MinNbOrb} = k \times \frac{86400 \text{ s}}{T_{sat, min}}
\]

\[
\text{MaxNbOrb} = k \times \frac{86400 \text{ s}}{T_{sat, max}}
\]

**Equation 28 - Minimum and Maximum number of orbits for a period of \( k \) days**
The starting point is considering an initial altitude which does not include the oblateness effects: using Equation 26 and the third Kepler law (Equation 27), the initial altitude approximation can be computed with Equation 29 [18].

\[ H_0 = \frac{1}{\mu^3} \left( \frac{2\pi j}{T_{\text{Earth}} k} \right)^{-2/3} - R_{\text{Earth}} \]

Equation 29 - Initial approximation of the altitude, necessary for the iterative process

Afterwards, it is possible to calculate the Earth rotation rate \( \dot{L} \) and the effects of the oblateness on \( \dot{\Omega} \), \( \dot{\omega} \) and \( \dot{M} \). To do so, Equation 30, Equation 31, Equation 32 and Equation 33 are used, where \( k_2 \) is a parameter which depends on the Earth oblateness ( \( k_2 = 0.75/J_2 \mu^{1/2} R_{\text{Earth}}^2 \) ) [18].

\[ \dot{L} = 360^\circ/\text{day} \]

Equation 30 - Earth rotation rate formula

\[ \dot{\Omega} = -2k_2 a^{-7} \left( 1 - e^2 \right)^{-2} \cos i \]

Equation 31 – Rate of change of the ascending node
\[
\dot{\omega} = k_2 a^{-\frac{7}{2}} (1 - e^2)^{-\frac{3}{2}} (5 \cos^2 i - 1)
\]

Equation 32 – Rate of change of the perigee

\[
\dot{M} = k_2 a^{-\frac{7}{2}} (1 - e^2)^{-\frac{3}{2}} (3 \cos^2 i - 1)
\]

Equation 33 – Rate of change of the mean anomaly

After finding these rates of change, the iterative process continues by calculating the mean angular velocity, as described in Equation 34.

\[
n = \frac{j}{k} (L - \dot{\Omega}) - (\dot{\omega} + \dot{M})
\]

Equation 34 - Mean angular velocity formula

Finally, it is possible to update the initial altitude estimation through Equation 35.

\[
H = \frac{1}{\mu^2} n^{-2/3} - R_{Earth}
\]

Equation 35 - Update altitude formula

At the end of the loop, the output is a set of orbits characterized by their altitudes, repeat cycle and number of orbits per day. Thereupon, it is possible to compute the orbital period (Equation 4). In addition, if the parameter SSO is set to 1, the inclination of the orbit is estimated with the SSO condition (Equation 8).

C. GROUND TRACK COMPUTATION

Computing the ground track implies the necessity to find the latitudes and longitudes corresponding to each satellite position during its time in orbit.

To do so, it is necessary to know the satellite angular velocity \( n \) in its plane and the angular velocity \( \omega_{f2} \) of the orbit plane due to the oblateness effect [18]. In particular, this second information allows the computation of the angular velocity \( \omega_R \) of the Earth with respect to the orbit plane: it can be calculated with Equation 36, where \( \omega_{day} \) is the Earth sidereal rotation rate [18].

\[
\omega_R = \omega_{f2} - \omega_{day} = \omega_{f2} - \frac{2\pi}{T_{Earth}}
\]

Equation 36 - Earth angular rate with respect to the orbit plane
Equation 37 allows the computation of the longitude of the orbit pole for each simulation time instant: in this equation, \( \varphi_{O_0} \) is the longitude of the orbit pole at \( t = 0 \) s [18].

\[
\varphi_O = \varphi_{O_0} + \omega_R t
\]

Equation 37 - Orbit pole longitude formula

On the other hand, since the orbit inclination is defined, the latitude of the orbit pole is fixed (see Equation 38) [18].

\[
\lambda_O = \frac{\pi}{2} - i
\]

Equation 38 - Orbit pole latitude formula

Thanks to the definition of satellite angular velocity, the angular distance \( \phi_s \) measured from the north along the ground track, can be found with Equation 39, where \( \phi_{s0} \) is the distance measured from the ascending node when \( t = 0 \) s [18].

\[
\frac{d\varphi}{dt} = \frac{2\pi}{T_{\text{sat}}} \quad \rightarrow \quad \phi_s = \frac{3\pi}{2} + \phi_{s0} + nt
\]

Equation 39 - Angular distance along the ground track

Finally, it is possible to adopt the dual-axis spiral equations in order to find the satellite longitudes and latitudes for every simulation time [18]. In this case, the primary axis is the axis that connects the Earth poles and the secondary axis is given by the axis of the orbit pole: this means that \( \rho_1 = i, \rho_2 = \frac{\pi}{2}, \phi_1 = \varphi_0 \) and \( \phi_2 = \phi_s \) [18]. This leads to a simplified formulation of the dual-axis spiral equations, which are presented in Equation 40 [18].

\[
\lambda = \frac{\pi}{2} - \cos(i \times \cos \phi_s) \\
\varphi = (\varphi_0 + \Delta\varphi) \\
\Delta\varphi = \cos(-\frac{\tan \lambda}{\tan i})
\]

Equation 40 - Longitude and latitude of the ground track for every time instant (dual-axis spiral equations)
D. FIND LANDS ON GROUND TRACK

The considered satellite, during its period in orbit, passes over lands and seas: this could be easily seen from the ground track obtained at the previous point. On the other hand, its aim is to take images of only Earth’s lands: there is no interest in taking images of the sea that could occupy part of the on-board memory.

In this study, among all the latitudes and longitudes found, only the ones corresponding to lands are considered: to do so, all the coasts on Earth have been traced with MATLAB® in order to separate lands by seas.

E. RESPECT THE SUN ZENITH ANGLE LIMIT CONDITION

Another constraint of observation is given by the Sun Zenith Angle (SZA), which is the angle comprised between the Sun direction and the station Zenith direction. This computation allows the satellite to take a picture only if there are good illumination conditions: in fact, in presence of a huge SZA, the Sun is near the horizon of the considered point. This means that the area is not well illuminated and an image of this area would be characterized by a poor quality.

In this study, the satellite is allowed to take images only when SZA<75°.

F. ACCESS COMPUTATION

As soon as the images have been acquired, it is necessary to download the data at the ground station in order to empty the on-board memory and allow the satellite to take more images. Basically, the satellite could transmit the information only during its period over the station: the access computation is the process that permits to find the time interval of link availability. In other words, the satellite transfers the data when its position is characterized by a defined elevation with respect to the station.

In order to compute the access start and stop times for each station, the process explained in Figure 55 has been adopted. This algorithm is based on the comparison between the real satellite elevation \( E_j \) calculated for every simulation time instant and the real minimum elevation \( E_{min} \).

The algorithm consists of an iterative process that takes into account all the stations concerned and all the simulation time instants. Given a station \( i \) and a time instant \( j \), one can estimate the local satellite elevation.

Firstly, the station and satellite coordinates are found in the ECEF reference frame (see Section II.A.1). They enable to find the distance unit vector \( \mathbf{d}_{sta-t} \) between the station and the satellite at the considered time: by definition, the scalar product between this vector and the unit vector \( \mathbf{U}_p \) perpendicular to the station gives the elevation of the satellite \( E_j \). In detail, the computation of \( \mathbf{U}_p \) is carried out with Equation 41.

\[
\mathbf{U}_p = \begin{bmatrix} \cos \varphi_{stat_i} \times \cos \lambda_{stat_i} ; \sin \varphi_{stat_i} \times \cos \lambda_{stat_i} ; \sin \lambda_{stat_i} \end{bmatrix}
\]

Equation 41 - Unit vector perpendicular to the station
On the other hand, the minimum elevation real $E_{\text{min}}$ is the result of the comparison between the $E_{\text{min}}$ imposed by the user (it is an input parameter) and $E_{\text{from nadir}}$, which is a minimum elevation computed taking into account only the geometrical constraints in the nadir maximum angle $\text{Nadir Max}$, satellite altitude $H_j$ and latitude $\lambda_j$. This last parameter can be calculated with Equation 42, where $\rho$ is the angular radius of the Earth (see Figure 56) and its computing formula is given by Equation 43. In this study, the maximum Nadir angle is set to 90° to have no constraint.

$$E_{\text{from nadir}} = \arccos\left(\frac{\sin(\text{Nadir Max})}{\sin \rho}\right)$$

Equation 42 - Minimum elevation derived from geometrical constraints

$$\sin \rho = \frac{R_{\text{Earth,stat}}}{R_{\text{Earth,eq}} + H_j}$$

Equation 43 - Earth angular radius formula
Finally, the comparison between these two values leads to individuate the most restrictive case for the data transmission and to find the real $E_{\text{min}}$:

- if $E_{\text{min}} > E_{\text{from nadir}}$ → the real $E_{\text{min}}$ will be set equal to $E_{\text{min}}$;
- if $E_{\text{min}} < E_{\text{from nadir}}$ → the real $E_{\text{min}}$ will be set equal to $E_{\text{from nadir}}$.

Once that $E_j$ and the real $E_{\text{min}}$ are available, it is possible to know if the satellite can send the information to the station and, as a consequence, to find the access start and stop times:

- if $E_j > \text{real } E_{\text{min}}$ → the satellite and the station can be linked;
- if $E_j < \text{real } E_{\text{min}}$ → the satellite and the station cannot be linked.

**G. ACQUISITION PROCESS**

Whenever the land and sun constraints presented in the previous points are respected and the satellite is not flying over one station, it takes images with a time step and size that are specified as inputs.

**H. DOWNLOAD PROCESS**

Whenever the satellite is over a station, a link can be performed. As discussed in Section I.B, this link availability is not only dependent on the geometric point of view, but it is related also to weather conditions. The download process is described in Figure 57: the downloaded data should be calculated for each station and pass over station.

In order to understand if it is feasible to transmit the information to the station, the Optical Depth along the distance between the satellite and the station should be evaluated. In Section II.C, two different databases have been described. Depending on the cloud database used, the OD computation process is different:
• If SI database is taken into account, the OD is directly available knowing the position of the satellite at that time instant. Unfortunately, the SI database presents some missing data: in this study, when such a problem is met, it is assumed that the link cannot be established (worst case);

• If SAFNWC database is considered, the CMa could be extracted knowing the position of the satellite at that time instant. In this case, as discussed in Section II.C.2, the data could not be available when a satellite passes over the station, because the SEVIRI temporal resolution (15 min) could be higher than the satellite transition time: to solve this issue, the nearest cloud mask in time is considered. Then, once that the CMa value is done, the corresponding OD is computed:
  o If CMa=1, the results in Section III let one find the corresponding OD: \( OD \approx 0.55 \).
  o In the other cases, the link cannot be performed: an OD of 530 is taken into account because it corresponds to the biggest transmission lost that it is possible to encounter (worst case) (see Table 5).

Subsequently, the Link Budget can be performed as discussed in Section II.B.1 and the Received Optical Power is obtained. This one is used to compute the contact duration and the Useful Data Rate as discussed in Section II.B.2: it depends on the chosen CONOPS.

Finally, the total volume of downloaded data can be calculated by the multiplication of the Useful Data Rate and the contact duration.
I. VOLUME EVOLUTION ANALYSIS

At the end, it is interesting to analyse the on board data volume evolution during the satellite time in orbit. It is very useful in order to optimise the number and position of the stations, the number of lasers and to define the satellite memory needed on board.
V. OPTICAL DOWNLINK SIMULATION RESULTS

In the following sections, the results of this algorithm are shown for different scenarios. They have been selected in order to analyse the difference in mission planning when the station is equipped with SI and when it is not and to visualise the impact of the OGS network. These scenarios are described in Table 13.

For all the scenarios, the same Concepts of Operations (CONOPS) described in Section II.B.2 are considered. Moreover, all the inputs necessary to perform the simulation are described in Table 14, Table 15 and Table 16. The simulation is carried on for seven days: this temporal interval has been chosen as a consequence of a trade-off between 7-days orbit repeat cycle, which permits to have a good Earth coverage, and relatively low simulation duration. On the other hand, this 7-days simulation implies the presence of precise weather conditions and the results could not be extended to other annual time periods. In conclusion, the simulation should be carried for at least one year of time, but, because of the unavailability of the SI weather data, it has not been performed in this study. To solve this problem, a simulation based on statistical analysis has been carried on at the end.

These inputs will not change for the different scenarios, so that the chosen orbit will be always the same.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sub-scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>The simulation is carried on considering only one ground station, which is Toulouse, and without taking into account the cloud impact</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>The simulation is carried on considering only one ground station, which is Toulouse, and taking into account the cloud impact given by SI and SEVIRI</td>
</tr>
<tr>
<td>2</td>
<td>a</td>
<td>The simulation is carried on considering an OGS network and without taking into account the cloud impact</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>The simulation is carried on considering an OGS network and the cloud impact given by SI and SEVIRI</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>The simulation is carried on considering an OGS network, the cloud impact given by SI and SEVIRI and an optimised number of lasers</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>The simulation is carried on considering an OGS network, the cloud impact given by average cloud conditions and an optimised number of lasers</td>
</tr>
</tbody>
</table>

Table 13 - Illustration of the scenarios considered in this study
<table>
<thead>
<tr>
<th>Orbit Name</th>
<th>‘SPOT’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>2017-09-01 00:00:00</td>
</tr>
<tr>
<td>End</td>
<td>2017-09-07 23:59:59</td>
</tr>
<tr>
<td>Minimum altitude [km]</td>
<td>690</td>
</tr>
<tr>
<td>Maximum altitude [km]</td>
<td>710</td>
</tr>
<tr>
<td>Minimum repeat cycle [days]</td>
<td>7</td>
</tr>
<tr>
<td>Maximum repeat cycle [days]</td>
<td>7</td>
</tr>
<tr>
<td>SSO</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 14 - Orbit inputs**

<table>
<thead>
<tr>
<th>Acquisition time step [s]</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image size [Gbits]</td>
<td>~4.5</td>
</tr>
<tr>
<td>Maximum daily acquisition capacity [Tbits]</td>
<td>~10</td>
</tr>
</tbody>
</table>

**Table 15 - Acquisition parameters**

<table>
<thead>
<tr>
<th>Wavelength [µm]</th>
<th>1.55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link budget margin [dB]</td>
<td>-3</td>
</tr>
<tr>
<td>Optical Channel Rate [Gbps]</td>
<td>10</td>
</tr>
<tr>
<td>Transmitted power [dBm]</td>
<td>Taken from [8]</td>
</tr>
<tr>
<td>Transmitter diameter [mm]</td>
<td>-</td>
</tr>
<tr>
<td>Pointing error [µrad]</td>
<td>-</td>
</tr>
<tr>
<td>Optical transmission loss in emission [dB]</td>
<td>-2.7</td>
</tr>
<tr>
<td>Transmittance when the satellite is at the station zenith</td>
<td>0.9</td>
</tr>
<tr>
<td>Scintillation loss [dB]</td>
<td>-3</td>
</tr>
<tr>
<td>Receiver diameter [mm]</td>
<td>600</td>
</tr>
<tr>
<td>Optical transmission loss in reception [dB]</td>
<td>-2.7</td>
</tr>
<tr>
<td>Injection loss [dB]</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

**Table 16 - Optical link parameters**
The simulation carried on with the input parameters expressed in this section leads to the orbit that is characterized by the following features:

- Altitude: \( H = 696.7 \text{ km} \);
- Inclination: \( i = 98.17^\circ \);
- Orbital period: \( T = 1.64 \text{ h} \);
- Number of orbits in a day: 14.6.

The considered orbit implies the ground track illustrated in Figure 58: it shows every Earth location over which the satellite passes. As a matter of fact, this orbit does not guarantee the total Earth coverage: this is due to the fact that the repeat cycle is very low (7 days). Normally, the repeat cycle of LEO satellite is about 26 days in order to allow the satellite to pass over every spot on Earth. In this study, the 7 days repeat cycle has been chosen in order to obtain a compromise between the Earth coverage and the simulation computation time. Obviously, this feature represents a significant limitation in the way the satellite observes the Earth: there are locations of which the satellite is not able to take any image.

![All illuminated ground tracks, start day243 - SPOT](image)

Figure 58 - Orbit ground track, starting from 01/09/2017 to 07/09/2017: the black orbit track corresponds to the over ground track where SZA < 75° is observed
A. SCENARIO 1: OPTICAL DOWNLINK CAPACITY – SINGLE SITE

The station considered is Toulouse (TLS): this choice lies on the fact that TLS is equipped with SI, so that the comparison between the downlink performed with SI and SAFNWC data could be carried on.

Table 17 shows the station inputs necessary for the algorithm to run.

<table>
<thead>
<tr>
<th>Station</th>
<th>Country</th>
<th>Latitude [°]</th>
<th>Longitude [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toulouse</td>
<td>France</td>
<td>43.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Table 17 - Station inputs

Figure 59 shows the number of minutes in a day, in which the link between the station and the satellite can be set up. This contact duration is a mean value, found by averaging all the contact time intervals present in a day. As it could be observed, the contact duration decreases when the minimum elevation angle increases: this is due to the fact that a lower minimum elevation involves that the satellite starts to transfer the data earlier and completes it later.

In this study, the maximum value of minimum elevation has been fixed to 40°: this is a reasonable value and it should not be exceeded. In fact, a greater value would imply contact duration lower than 4 minutes in a day.
1. No clouds impact

Figure 60 shows the data downloaded in a day and its evolution considering different minimum elevations. This is also a mean value, found by averaging the data downloaded for each satellite pass over the station in a day. As a consequence of what said before, the volume of data transferred decreases as the minimum elevation increases. In this figure, four evolutions can be analyzed, considering different CONOPS. It is obvious that, by definition, the Adaptive FEC rate allows a greater quantity of data to be downloaded, while FEC rate equal to $\frac{1}{2}$ represents the worst case: as a matter of the fact, the first one implies an higher useful data rate, as described in Section II.B.2.

Moreover, the blue and green curves tend to be overlapped with an increasing minimum elevation: in fact, when $E_{\min}$ increases, the ROP increase and the Adaptive FEC rate and the 4/5 FEC give the same useful data rate. This is exhibited in Figure 28.

![Mean downloaded data volume in a day](image.png)

**Figure 60 - Illustration of the volume of downloaded data as a function of the minimum elevation $E_{\min}$, for different CONOPS and without considering weather conditions**

Finally, Figure 61 shows the evolution of the on-board memory for all the different CONOPS. Obviously, the Adaptive FEC rate gives always the best configuration: it permits a greater quantity of data to be downloaded. On the other hand, it never allows the complete data transfer: the on-board memory grows and it would imply that some images could not be given to the client (there is never a time instant in which the on-board memory is empty).
Figure 61 - Evolution of on-board memory for different CONOPS and without considering weather conditions

In conclusion, considering the orbit obtained with the defined inputs, a single station in Toulouse is not enough to satisfy the user’s needs, even if the clouds impact has not been considered yet: it is expected that the clouds impact would also increase the curves growth rate.

Figure 61 has been obtained for $E_{\text{min}} = 10^\circ$: if a higher value of minimum elevation is considered, the on-board memory conditions would be even worse.

2. Clouds impact

Considering the clouds conditions over Toulouse, it is important to observe that the contact time expressed in Figure 59 does not change, because it represents the duration of a possible link between the satellite and the station: in other words, it is based only on geometrical constraints and it does not take into account the clouds impact. On the other hand, the clouds presence decreases so gravely the real contact duration that the data volume downloaded drops drastically: it could be seen in Figure 62, whose considerations on the curves evolutions are the same of those presented in Section V.A.1 for Figure 60. It could be pointed out that the data downloaded for every CONOPS are reduced of 60% with respect to the case of no clouds impact, visible in Figure 60.
Figure 62 - Illustration of the volume of downloaded data as a function of the minimum elevation $E_{\text{min}}$, for different CONOPS and considering weather conditions

Figure 63 - Evolution of on-board memory for different CONOPS and considering weather conditions
Obviously, the evolution of the on-board memory is affected by this clouds impact: the difference between Figure 61 and Figure 63 is remarkable: the clouds presence implies that the data which could not be downloaded by the OGS, should be gathered in the satellite memory, involving a greater growth rate of the curves. It should be noted that this plot has been obtained with the lowest value of minimum elevation $E_{min}$: the plots for the others $E_{min}$ values are not presented explicitly, but they clearly involve more deteriorated situations.

The clouds impact is displayed in Figure 64 and Figure 65: these curves are obtained for an Adaptive FEC rate. All the assumptions made so far are well confirmed by the shown evolutions. They lead also to an important conclusion on the difference between the SI and SEVIRI data: SI allows a greater amount of data to be downloaded. This is due to the fact that:

- SI gives a more precise definition of the weather conditions due to its smaller pixels, while SAFNWC Cloud Masks consists of only four values. In particular, only the condition of $CMa = 1$ allows the data transfer;
- SEVIRI time resolution is so high ($\approx 15$ min) that during a satellite pass over the station, no weather information are available and the optical link cannot be established.

These considerations will have a great impact in the following sections, when dealing with the optimisation of the ground stations site in OGS network.

Finally, it could be stated that a single station placed in Toulouse is not sufficient in order to download all the images taken by the satellite.
Satellite data volume evolution
OGS=TLS | Adap FEC Rate | $E_{\text{min}}=10^\circ$

Figure 65 - Evolution of on-board memory in the case of Adaptive FEC rate and considering different clouds conditions

B. SCENARIO 2: OPTICAL DOWNLINK CAPACITY – OGS NETWORK

In this section, the complete simulation of data download is described: in such a case, a ground station network has been considered accordingly to the study in [28]. In this previous work, it is presented the choice of the optical ground stations in relation to some optimization criteria:

- The current infrastructure of the station considered;
- The expected weather conditions;
- Latitude;
- Longitude.

In particular, the expected cloud conditions are inferred by the weather analysis over 30 years of time, in order to have a high realistic probability to find these conditions.

Finally, the OGS network is composed by the stations presented in Table 18. They are reported in Figure 66: it shows their position on the Earth and their field of view, which is the area around the station in which the link with the satellite can be set.
Table 18 - OGS network features

<table>
<thead>
<tr>
<th>Station</th>
<th>Country</th>
<th>Latitude [°]</th>
<th>Longitude [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toulouse</td>
<td>France</td>
<td>43.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Esrange</td>
<td>Sweden</td>
<td>67.9</td>
<td>21.1</td>
</tr>
<tr>
<td>Inuvik</td>
<td>Canada</td>
<td>68.4</td>
<td>-133.7</td>
</tr>
<tr>
<td>Santiago</td>
<td>Chile</td>
<td>-33.4</td>
<td>-70.7</td>
</tr>
<tr>
<td>WASC</td>
<td>Australia</td>
<td>-27.7</td>
<td>121.6</td>
</tr>
<tr>
<td>Hartebeesthoek</td>
<td>South Africa</td>
<td>-25.8</td>
<td>27.6</td>
</tr>
<tr>
<td>Tenerife</td>
<td>Spain</td>
<td>28.3</td>
<td>-16.6</td>
</tr>
</tbody>
</table>

Figure 66 - Illustration of the position of the stations in the considered OGS network and their field of view
1. No clouds impact

The algorithm described in Section IV enables to carry on two different analyses:

- the study of the evolution of data downloads with the minimum elevation, when CONOPS is fixed: Figure 67 and Figure 68 show the feasible volume of data downloaded for each station in the OGS network in the case of Adaptive FEC rate and no clouds. It could be observed that, for a lower value of $E_{\text{min}}$, this quantity of data is bigger and there are some images that are transferred with different data rates. When $E_{\text{min}}$ increases, the lowest data rates tend to disappear and all the images are sent to the station with the highest data rate;

- the study of the evolution of data downloads with the CONOPS, when the minimum elevation is fixed: this can be observed comparing Figure 67 and Figure 69. Obviously, in the case of FEC rate equal to $\frac{1}{2}$, there is only a data rate observed.

It is important to understand that these plots represent a mean value of downloaded data: they have been computed taking the average for each satellite pass over the station in a day. Moreover, they depict a feasible value: when the on-board memory is empty and the satellite is over a station, it does not send any image to the station.

For a better comprehension of the following analysis, only the case of Adaptive FEC rate and $E_{\text{min}} = 10^\circ$ is considered: this is the best case and, if it does not allow the entire data download, the other case cannot achieve it either.

![Mean data volume in a day](image)

Figure 67 - Volume downloaded for each station, in the case of Adaptive FEC rate, no clouds and $E_{\text{min}} = 10^\circ$
Mean data volume in a day
OGS network | Adap FEC Rate
$E_{\text{min}} = 40^\circ$ | SkyInsight=0000000 | SAFNWC=0000000

<table>
<thead>
<tr>
<th>Station</th>
<th>5 Gbit/s</th>
<th>6.67 Gbit/s</th>
<th>8 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esrange</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inuvik</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santiago</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WASC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harbourschook Toneriib</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 68 - Downloaded volume for each station, in the case of Adaptive FEC rate, no clouds and $E_{\text{min}} = 40^\circ$

Mean data volume in a day
OGS network | FEC rate = 1/2
$E_{\text{min}} = 10^\circ$ | SkyInsight=0000000 | SAFNWC=0000000

<table>
<thead>
<tr>
<th>Station</th>
<th>5 Gbit/s</th>
<th>6.67 Gbit/s</th>
<th>8 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Esrange</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inuvik</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santiago</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WASC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harbourschook Toneriib</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 69 - Downloaded volume for each station, in the case of FEC rate equal to $1/2$, no clouds and $E_{\text{min}} = 10^\circ$
2. Clouds impact

Taking into account the clouds impact, Figure 67 should be compared to Figure 70 and Figure 71. As it was stated in the previous sections, clouds determine a drastic decrease of possible downloaded data, in particular when only SAFNWC data are available. The main difference is stated for the optical stations placed in Inuvik and Esrange: since their position is characterized by high latitudes, a polar orbit permits more transitions over these stations with respect to equatorial sites. For this reason, if clouds impact is not considered, they imply the two greatest capacities of data downloading. On the other hand, their norther position involves a greater amount of clouds: Figure 70 and Figure 71 demonstrate that they are not used for all the simulation time.

In addition, comparing Figure 70 and Figure 71, it is possible to observe again the huge difference for the station in Toulouse, when using the SAFNWC and SI data.

Figure 72 describes the evolution of downloaded data when the minimum elevation increases: all the considerations made in the Section V.A.2 are always valid.

Finally, the satellite volume evolution in the case of $E_{\text{min}} = 10^\circ$ and Adaptive FEC rate is shown in Figure 73. It proves that:

- in case of no clouds impact, the considered OGS network performs the entire data download. During one day, the on-board memory is emptied more than once;
- in the case of clouds impact, the stations comprised in the OGS network do not allow the complete data download: the on-board memory is always increasing and a lot of required images cannot reach the users.

---

**Figure 70 - Downloaded volume for each station, in the case of Adaptive FEC rate, $E_{\text{min}} = 10^\circ$ and clouds impact governed by SAFNWC data**
Figure 71 - Downloaded volume for each station, in the case of Adaptive FEC rate, $E_{\text{min}} = 10^\circ$ and clouds impact governed by SI data for Toulouse and SAFNWC data for the other stations

Figure 72 - Illustration of the volume of downloaded data as a function of the minimum elevation $E_{\text{min}}$, in the case of Adaptive FEC rate and for different clouds conditions
In conclusion, the designed OGS network is not capable of performing all the users’ requests. In order to improve its download capacity, two methods may be realized:

- Adding other stations: this solution cannot be easily implemented. In fact, the selection of a ground station is very strict: it depends on its weather conditions, its actual infrastructure used for the link with the satellites and with other stations;
- Equipping the satellite payload with more than one laser: this solution does not involve a great additional complexity to the satellite equipment, but structural reasons impose a maximum number of lasers equal to four.

3. Multi-lasers configuration

In this study, the multi-lasers solution is dealt with: 2-lasers and 4-lasers configurations have been examined. The 2-lasers configuration involves always download problems, while the 4-lasers one permits to satisfy the users need. In fact, Figure 74 shows the satellite memory evolution for the simulation time, $E_{\text{min}} = 10^\circ$, different CONOPS, 4 lasers and considering the clouds impact. In any case, the memory is emptied almost each day. Moreover, after a time interval of a repeat cycle (7 days), all the data are downloaded and the satellite can start again its cycle.
Figure 74 - Evolution of on-board memory for different CONOPS, considering the clouds impact, the OGS network, $E_{\text{min}} = 10^\circ$ and four lasers

Figure 75 - Evolution of on-board memory for different CONOPS, considering the clouds impact, the OGS network, $E_{\text{min}} = 40^\circ$ and four lasers
Figure 75 shows the same evolution but considering $E_{\text{min}} = 40^\circ$: this is the worst case and, even in this case, the 4-lasers configuration performs correctly the complete data download.

Finally, Figure 74 and Figure 75 could be used in order to size the on-board memory, necessary to keep the images before transferring them. The memory should be characterized by a memory bigger than 7 Tbits.

This simulation has been performed in a time period of 7 days: this implies the use of very specific weather conditions. With these simulations, the algorithm has been validated and a first result has been obtained. On the other hand, all the considerations expressed in this Section should be verified with a longer simulation time. That simulation will be performed when the weather data will be available in the feature.

In order to get more precise results, a statistic analysis is required and the simulation time should be extended in order to consider seasonal weather variations. This subject is to be discussed in the following section.

4. Averaged weather conditions

This last section aims to solve the problem of 1-week simulation, extending the simulation time to more than a year: this has been performed considering the different clouds probabilities over each station. In particular, the attention is focused on the no-clouds probability $P$, which is the probability of having good weather conditions, so that the optical link between the satellite and the station could be feasible. This probability is well described in Table 19: its values have been picked up from an internal 6-years database. This database contains all the weather statistics resulting from the study of the cloud conditions for several consecutive years.

<table>
<thead>
<tr>
<th>Ground station</th>
<th>No-clouds probability $P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toulouse</td>
<td>39 %</td>
</tr>
<tr>
<td>Esrange</td>
<td>21 %</td>
</tr>
<tr>
<td>Inuvik</td>
<td>35 %</td>
</tr>
<tr>
<td>Santiago</td>
<td>53 %</td>
</tr>
<tr>
<td>WASC</td>
<td>68 %</td>
</tr>
<tr>
<td>Hartebeesthoek</td>
<td>67 %</td>
</tr>
<tr>
<td>Tenerife</td>
<td>78 %</td>
</tr>
</tbody>
</table>

Table 19 - Probability to find good weather conditions over each station

This no-clouds probability has been applied in the determination of the total downloaded data volume $DV_{\text{clouds}}$ in presence of the OGS network: it is found by multiplication of the data volume $DV_{\text{no clouds}}$, which has been described in Figure 67, with the no-clouds probability (see Equation 44).

$$DV_{\text{clouds}} = DV_{\text{no clouds}} \times P$$

Equation 44 - Data volume formula, considering an averaged clouds impact
A first result is obtained in Figure 76 and Figure 77: the two figures describe the downloaded data volume with different OGS networks. In particular, Figure 76 shows this data amount when the clouds impact is not considered, while Figure 77 takes into account the weather conditions. Clearly, the stations are integrated in the network accordingly to their data download capacity: for example, Inuvik is the first station considered in Figure 76 since it allows the greatest data transfer in the case of no clouds. Similarly, in Figure 77, the first station considered is Tenerife, because of its lowest cloud probability, while Inuvik is one of the last stations, being characterized by a high cloud probability, as described in Table 19.

It is important to observe that this process allows the determination of the necessary ground stations in the OGS network. In fact, the blue horizontal line defines the mean acquisition volume in a day: it is more or less 7.8 Tbits and it is different from the Maximum daily acquisition capacity defined in the inputs (~10 Tbits): this difference is due to the fact that the satellite takes no images when the download could be performed.

In order to download all the acquire data, the downloaded data columns, depicted in the images, should be higher than the horizontal line: in the case of no clouds, it could be stated that the ground station in Inuvik is enough to satisfy the mission requirements and the addition of one more station brings only to the oversizing of the OGS network.
Acquisition vs Download in a day

OGS network | Adap FEC Rate

$E_{\text{min}} = 10^\circ$

Figure 77 - Data download capacity for different OGS network, considering the clouds impact, $E_{\text{min}} = 10^\circ$ and Adaptive FEC rate

Acquisition vs Download in a day

OGS network | FEC rate = 1/2

$E_{\text{min}} = 40^\circ$

Figure 78 - Data download capacity for different OGS network, considering the clouds impact, $E_{\text{min}} = 40^\circ$ and FEC rate equal to 1/2
On the other hand, Figure 77 shows that Tenerife and WASC are the necessary stations when the clouds are present. This is what is required in the best case ($E_{\text{min}} = 10^\circ$ and Adaptive FEC rate): if the worst case is considered ($E_{\text{min}} = 40^\circ$ and FEC rate equal to $\frac{1}{2}$), all the 7 stations do not allow the complete data download, as noticeable from Figure 78. Moreover, the comparison between these two images shows that, when the minimum elevation increases, Inuvik and Esrange tend to increase their importance in the downlink capacity: this is due to their norther positions which allow more satellite transitions with respect to the other stations that are characterized by lower latitudes. In this case, even if the weather conditions on Inuvik are worse, the satellite could transfer data during a greater contact period. This phenomenon has can be observed also comparing Figure 67 to Figure 68.

The solution of this problem has already carried on in Section V.B.3: the number of lasers on-board is increased. Figure 79 and Figure 80 takes into account the 2-laser configuration:

- The best case implies the utilization of only one station (Tenerife);
- The worst case involves the employment of all the 7 station considered.

Finally, it is possible to observe that the results obtained in this section and those of the Section V.B.3 are quite different:

- while using the weather statistics, a 1-laser configuration is enough to allow the complete data download, considering $E_{\text{min}} = 10^\circ$ and the Adaptive FEC rate (see Figure 77), it was not sufficient when the real weather data were used in the previous section (see Figure 73);
- considering the worst case, the 7-day simulation shows the necessity to use a 4-lasers configuration, while the use of averaged weather conditions implies the need of a 2-lasers configuration

In conclusion, this implies that the simulation carried on with averaged weather conditions is just a starting point in order to define the stations to be considered. After that, a simulation, like the one done for 7 days, but with a simulated time of 1 year (or more), is required in order to update the number of station and design the number of lasers needed on-board.
Figure 79 - Data download capacity for different OGS network, considering the clouds impact, $E_{\text{min}} = 10^\circ$, Adaptive FEC rate and 2 lasers

Figure 80 - Data download capacity for different OGS network, considering the clouds impact, $E_{\text{min}} = 40^\circ$, FEC rate equal to $1/2$ and 2 lasers
VI. CONCLUSIONS AND FUTURE WORK

This document is the final outcome of a six-months internship dedicated to the planning of Earth Observation mission, focused on the utilisation of optical links.

This study has been conceived the aim to give a system engineering point of view on the feasibility of optical link communication system applied to Earth Observation missions. A simulation tool has been implemented in order to simulate the influence of many significant parameters:

- the cloud presence probability;
- the orbit;
- the downlink data rate;
- the data volume;
- the mass memory;
- the number of on-board laser terminals.

The results of this work show the feasibility of the use of optical links.

This analysis represents the first of a kind: the optical links have been simulated considering the clouds impact and, in particular, their feasibility is assured by the exploitation of geostationary weather data and in-situ data given by SI. The difference in these two datasets has been analysed and a correlation between them has been found. To do so, an algorithm has been developed and then validated. This comparison has been described and the results have been achieved for a 1-month simulation. They show the relation between each value of Cloud Mask and the corresponding OD. This relation is affected by some errors: it is demonstrated that link availability due to Cloud Mask has the 85% probability to correspond to an Optical Depth smaller than 0.7, in other words, it is characterized by 15% of non-detection error. In the same way, it is discovered that CMa cloud blockage might be pessimistic: 40% of the CMa cloud blockage time corresponds to an Optical Depth (averaged in space and time) that is smaller than 0.7 (false-alarm error).

In order to improve these results, the simulation is expected to be run for 1-year (or more) simulation, so that the seasonal variation could be taken into account. It has not been performed in this study because of the unavailability of SI data.

Moreover, this comparison helped the IRT-Reuniwatt to improve their algorithm of cloud detection, showing special scene when the instrument does not seem to work as expected: OD is set to zero, but the CMa states the presence of clouds.

After the comparison, the link feasibility has been obtained by an end-to-end simulator that has been implemented in order to define the data volume download at each station: to do so, the clouds impact and its implication in the data transfer have been taken into account. In particular, SAFNWC and SI data affect differently the optical link data download: SI detector, whose data are more accurate, allows the download of a greater quantity of images. This implies the necessity, for future studies, to equip other stations with this detector.

A first simulation has been carried on for the first week of September 2017: this time interval has been chosen in accordance with a 7-day orbit repeat cycle and because of the unavailability of data. It validates the simulator algorithm, but its results should be reviewed in further studies, considering a longer time period. To solve this problem, a second simulation takes into account weather statistics in order to obtain more general results.

Finally, the results outline the possibility to perform an optical link using the existing optical ground stations. In addition, the number of lasers needed on-board is related to the minimum elevation angle and the Concepts of
Operations: in particular, the configuration with 4 lasers is required in order to satisfy all the possible situations, even the worst case scenario \( E_{\text{min}} = 40^\circ \) and FEC equal to \( \frac{1}{2} \).

The next steps that should be considered in order to improve the simulation results are:

- the increase of orbit repeat cycle in order to achieve the total Earth coverage. This would imply the growth of the acquired data volume and transitions over each station;
- the increase of simulation time: in this study, a simulation of 7 days has been carried on, but, in order to obtain more realistic results, the simulation time can be expanded to 1-year (or more);
- the necessity to equip the ground stations with a SkyInsight detector;
- the utilisation of new ground stations that could permit to reduce the number of on-board lasers.

To conclude, my internship at Airbus DS in the Telecommunication System Division and Mission Chain has been an excellent experience because I was able to put into practice the knowledge of the satellite conception acquired during my years of study in Italy and France. The research on free space optical communications for future space systems gave me an idea of the steps and the complex phases to develop a big project. Furthermore, I had the opportunity to be a part of a work, requiring good planning and communication skills.
VII. ANNEXE

A. GEOMETRY FOR COLOCALISATION SKYINSIGHT AND SAFNWC CLOUD MASK

The colocalisation is the process which allows to identify the SEVIRI pixel and all the contained SI pixels with their ODs. In this section, the entire process and its formulas are described in detail.

This process consists of several steps whose inputs and outputs are listed in Table 20.

- **Find the station pixel coordinates**
  The SEVIRI spatial grid covers a latitude range of about [-70°; +70°] and a longitude range of about [-50°; +50°]. From the station latitude $\lambda_{stat}$ and longitude $\varphi_{stat}$, it is possible to obtain the pixel on the grid corresponding to the station considered. This pixel is identified by two coordinates $raw_{stat}$ and $column_{stat}$.
  This information is then used in an iterative time loop in order to extract data for every considered day. This first part of the algorithm is graphically described in Figure 81.
The following described steps are illustrated in Figure 82: these steps are carried on for each day.

- **Computation of the β angle**
  The β angle is the rotation angle between the SI grid reference frame and the SEVIRI grid reference frame: in other words, it represents the angle between the vertical direction in the SI image and the Earth Nod-South direction, as in Figure 83.
  Figure 83 shows also that SkyInsight image is not centred on the station.

- **Computation of the distance from the station**
  The fixed altitude \( H \), elevation \( E \) and azimuth \( A_z \) identify a precise point (see Figure 84). It is important to find analytically the horizontal distance between the station and the point itself.
  This distance \( d \) can be evaluated thanks to Equation 45.

\[
d = H \times \tan\left(\frac{\pi}{2} - E\right)
\]

**Equation 45 - Distance computation formula**
<table>
<thead>
<tr>
<th>Step name</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Find the station pixel coordinates</td>
<td>$\lambda_{stat}$ ; $\varphi_{stat}$</td>
<td>$raw_{stat}$ ; $column_{stat}$</td>
</tr>
<tr>
<td>Computation of the $\beta$ angle</td>
<td>None</td>
<td>$\beta$</td>
</tr>
<tr>
<td>Computation of the distance from the</td>
<td>$H$ ; $E$ ; $Az$</td>
<td>$d$ ; $d_x$ ; $d_y$</td>
</tr>
<tr>
<td>station</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Find SEVIRI pixel</td>
<td>$\beta$ ; $d$ ; $d_x$ ; $d_y$</td>
<td>SEVIRI pixel position</td>
</tr>
<tr>
<td>Computation of the distance from the</td>
<td>$E$ ; $Az$ ; $\beta$</td>
<td>SI pixel position</td>
</tr>
<tr>
<td>station in terms of SI pixels</td>
<td>SI spatial resolution</td>
<td></td>
</tr>
<tr>
<td>Find all the SI pixels inside the</td>
<td>SI pixel position;</td>
<td>Optical depths</td>
</tr>
<tr>
<td>SEVIRI pixel</td>
<td>SEVIRI pixel position</td>
<td></td>
</tr>
</tbody>
</table>

Table 20 - List of the algorithm steps with their inputs and outputs
Moreover, this distance could be split into two components \( d^2 = d_x^2 + d_y^2 \) in the SI reference frame. To do so, the angle \( \theta \) between the distance \( d \) and the horizontal direction needs to be found: it depends on the point position. Its formulas are described in Table 21. Then, the horizontal and vertical components are evaluated with Equation 46.

\[
\begin{align*}
d_x &= d \times \cos \theta \\
d_y &= d \times \sin \theta
\end{align*}
\]

Equation 46 - Projections of the distance on the SI reference frame

<table>
<thead>
<tr>
<th>Point position</th>
<th>Formula for computing ( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta + Az \leq 90^\circ )</td>
<td>( \theta = \frac{\pi}{2} - (\beta + Az) )</td>
</tr>
<tr>
<td>( 90^\circ &lt; \beta + Az \leq 180^\circ )</td>
<td>( \theta = -\left(\frac{\pi}{2} - (\beta + Az)\right) )</td>
</tr>
<tr>
<td>( 180^\circ &lt; \beta + Az \leq 180^\circ + \beta )</td>
<td>( \theta = \frac{3\pi}{2} - (\beta + Az) )</td>
</tr>
<tr>
<td>( 180^\circ + \beta &lt; \beta + Az \leq 270^\circ )</td>
<td>( \theta = \frac{3\pi}{2} - (\beta + Az) )</td>
</tr>
<tr>
<td>( 270^\circ &lt; \beta + Az \leq 360^\circ )</td>
<td>( \theta = -\left(\frac{3\pi}{2} - (\beta + Az)\right) )</td>
</tr>
<tr>
<td>( \beta + Az &gt; 360^\circ )</td>
<td>( \theta = \frac{5\pi}{2} - (\beta + Az) )</td>
</tr>
</tbody>
</table>

Table 21 - Formulas for computing the \( \theta \) angle
Find SEVIRI pixel

This part of the algorithm is based on some iterative process, which is necessary because the SEVIRI and SI spatial grids are not uniform.

This process is described in the flowchart presented in Figure 85. It consists of the following consecutive steps:

- Consider the geometrical quarter in which the point considered is placed. Depending on the quarter, the geometrical formulas would be different (i.e. $Az < 90^\circ$, $90^\circ < Az < 180^\circ$, etc.);
- Initialise a distance which will be important in the next step: this initialised distance is the spatial resolution of the pixel near to the station in the direction of the point. There are two distances to be examined: the one in the North-South direction (latitude direction) and the one in the East-West direction (longitude direction). Depending on the point azimuth, Table 22, Table 23, Table 24 and Table 25 show the formulas to be adopted;

<table>
<thead>
<tr>
<th>$Az &lt; 90^\circ$</th>
<th>$Az &gt; 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direction</strong></td>
<td><strong>Distance initialisation</strong></td>
</tr>
<tr>
<td>North-South</td>
<td>$dist_{lat} = A_{lat}(raw_{stat} - 1, column_{stat})$</td>
</tr>
<tr>
<td>East-West</td>
<td>$dist_{long} = A_{long}(raw_{stat}, column_{stat})$</td>
</tr>
</tbody>
</table>

Table 22 - Distance initialisation formulas in the case $Az < 90^\circ$
\[
\begin{array}{|c|c|}
\hline
\text{Direction} & \text{Distance initialisation} \\
\hline
\text{North-South} & \text{\( \text{dist}_{\text{lat}} = \Delta_{\text{lat}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}}) \)} \\
\text{East-West} & \text{\( \text{dist}_{\text{long}} = \Delta_{\text{long}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}}) \)} \\
\hline
\end{array}
\]

Table 23 - Distance initialisation formulas in the case \(90^\circ < Az < 180^\circ\)

\[
\begin{array}{|c|c|}
\hline
\text{Direction} & \text{Distance initialisation} \\
\hline
\text{North-South} & \text{\( \text{dist}_{\text{lat}} = \Delta_{\text{lat}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}} - 1) \)} \\
\text{East-West} & \text{\( \text{dist}_{\text{long}} = \Delta_{\text{long}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}}) \)} \\
\hline
\end{array}
\]

Table 24 - Distance initialisation formulas in the case \(180^\circ < Az < 270^\circ\)

\[
\begin{array}{|c|c|}
\hline
\text{Direction} & \text{Distance initialisation} \\
\hline
\text{North-South} & \text{\( \text{dist}_{\text{lat}} = \Delta_{\text{lat}}(\text{raw}_{\text{stat}} - 1, \text{column}_{\text{stat}}) \)} \\
\text{East-West} & \text{\( \text{dist}_{\text{long}} = \Delta_{\text{long}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}} - 1) \)} \\
\hline
\end{array}
\]

Table 25 - Distance initialisation formulas in the case \(270^\circ < Az < 360^\circ\)

- A first iterative process has the purpose of finding the SEVIRI pixel which contains the considered point. It should update the distances in North-South and East-West direction, starting from the initialised one and adding the nearest SEVIRI spatial resolution (Process 1 and 2). The loop stops when this distance reaches a value greater than the point distance \(d\) (Condition 1 and 2). In this way, the indices \(\text{shift}_{\text{lat}}\) and \(\text{shift}_{\text{long}}\) describe the position (relative to the station) of the SEVIRI pixel vertex \(V_1\), which is the furthest one from the station (see Figure 86).

Table 26, Table 27, Table 28 and Table 29 show the detailed formulas used in this step for the different cases;
Figure 85 - Flowchart of the process used to find the SEVIRI pixel
Figure 86 - Illustration of the SEVIRI pixel vertices disposition
<table>
<thead>
<tr>
<th>Case</th>
<th>Direction</th>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta + Az \leq 90^\circ$</td>
<td>North-South</td>
<td>Condition 1</td>
<td>$d_y \times \cos(\beta) + d_x \times \sin(\beta) &gt; \text{dist}_{lat}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 1</td>
<td>(\text{dist}<em>{lat} = \text{dist}</em>{lat} + \Delta_{lat}(\text{raw}<em>{stat} - 1) - \text{shift}</em>{lat}, \text{column}<em>{stat} ); (\text{shift}</em>{lat} = \text{shift}_{lat} + 1)</td>
</tr>
<tr>
<td></td>
<td>East-West</td>
<td>Condition 2</td>
<td>$d_x \times \cos(\beta) - d_y \times \sin(\beta) &gt; \text{dist}_{long}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 2</td>
<td>(\text{dist}<em>{long} = \text{dist}</em>{long} + \Delta_{long}(\text{raw}<em>{stat}, \text{column}</em>{stat}) + \text{shift}<em>{long} ); (\text{shift}</em>{long} = \text{shift}_{long} + 1)</td>
</tr>
<tr>
<td></td>
<td>North-South</td>
<td>Condition 1</td>
<td>$-d_y \times \cos(\beta) + d_x \times \sin(\beta) &gt; \text{dist}_{lat}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 1</td>
<td>(\text{dist}<em>{lat} = \text{dist}</em>{lat} + \Delta_{lat}(\text{raw}<em>{stat} - 1) - \text{shift}</em>{lat}, \text{column}<em>{stat} ); (\text{shift}</em>{lat} = \text{shift}_{lat} + 1)</td>
</tr>
<tr>
<td></td>
<td>East-West</td>
<td>Condition 2</td>
<td>$d_x \times \cos(\beta) + d_y \times \sin(\beta) &gt; \text{dist}_{long}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 2</td>
<td>(\text{dist}<em>{long} = \text{dist}</em>{long} + \Delta_{long}(\text{raw}<em>{stat}, \text{column}</em>{stat}) + \text{shift}<em>{long} ); (\text{shift}</em>{long} = \text{shift}_{long} + 1)</td>
</tr>
</tbody>
</table>

Table 26 - $1^\circ$ iterative process formulas in the case of $Az < 90^\circ$
<table>
<thead>
<tr>
<th>Case</th>
<th>Direction</th>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>90° &lt; Az &lt; 180°</td>
<td>North-South</td>
<td>Condition 1</td>
<td>(-d_y \times \cos(\beta) + d_x \times \sin(\beta) &gt; \text{dist}_{\text{lat}})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 1</td>
<td>(\text{dist}<em>{\text{lat}} = \text{dist}</em>{\text{lat}} + \Delta_{\text{lat}}(\text{raw}<em>{\text{stat}}, \text{shift}</em>{\text{lat}}, \text{column}<em>{\text{stat}})); (\text{shift}</em>{\text{lat}} = \text{shift}_{\text{lat}} + 1)</td>
</tr>
<tr>
<td>90° &lt; (\beta + Az) &lt; 180°</td>
<td>East-West</td>
<td>Condition 2</td>
<td>(d_x \times \cos(\beta) + d_y \times \sin(\beta) &gt; \text{dist}_{\text{long}})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 2</td>
<td>(\text{dist}<em>{\text{long}} = \text{dist}</em>{\text{long}} + \Delta_{\text{long}}(\text{raw}<em>{\text{stat}}, \text{column}</em>{\text{stat}} + \text{shift}<em>{\text{long}})); (\text{shift}</em>{\text{long}} = \text{shift}_{\text{long}} + 1)</td>
</tr>
<tr>
<td>(\beta + Az) &gt; 180°</td>
<td>North-South</td>
<td>Condition 1</td>
<td>(-d_x \times \cos(\beta) + d_y \times \sin(\beta) &gt; \text{dist}_{\text{lat}})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 1</td>
<td>(\text{dist}<em>{\text{lat}} = \text{dist}</em>{\text{lat}} + \Delta_{\text{lat}}(\text{raw}<em>{\text{stat}}, \text{shift}</em>{\text{lat}}, \text{column}<em>{\text{stat}})); (\text{shift}</em>{\text{lat}} = \text{shift}_{\text{lat}} + 1)</td>
</tr>
<tr>
<td></td>
<td>East-West</td>
<td>Condition 2</td>
<td>(\text{dist}<em>{\text{long}} = \text{dist}</em>{\text{long}} + \Delta_{\text{long}}(\text{raw}<em>{\text{stat}}, \text{column}</em>{\text{stat}} + \text{shift}<em>{\text{long}})); (\text{shift}</em>{\text{long}} = \text{shift}_{\text{long}} + 1)</td>
</tr>
</tbody>
</table>

Table 27 - 1° iterative process formulas in the case of \(90° < Az < 180°\)
### Optical downlink study for Low Earth Orbit satellite

**Ref:** TESUT/2018/245/AA  
**Edition:** 1  
**Rév.:** 1  
**Date:** 29 October 2018  
**Page:** 118

<table>
<thead>
<tr>
<th>Case</th>
<th>Direction</th>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>180° &lt; Az &lt; 270°</td>
<td>North-South</td>
<td>Condition 1</td>
<td>( d_y \times \cos(\beta) + d_x \times \sin(\beta) &gt; \text{dist}_{\text{lat}} )</td>
</tr>
</tbody>
</table>
| | | Process 1 | \( \text{dist}_{\text{lat}} = \text{dist}_{\text{lat}} + \Delta_{\text{lat}}(\text{raw}_{\text{stat}}, \text{shift}_{\text{lat}}, \text{column}_{\text{stat}}); \)  
| | | | \( \text{shift}_{\text{lat}} = \text{shift}_{\text{lat}} + 1 \) |
| | East-West | Condition 2 | \( d_x \times \cos(\beta) - d_y \times \sin(\beta) > \text{dist}_{\text{long}} \) |
| | | Process 2 | \( \text{dist}_{\text{long}} = \text{dist}_{\text{long}} + \Delta_{\text{long}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}} - 1) \)  
| | | | \( \text{shift}_{\text{long}} = \text{shift}_{\text{long}} + 1 \) |
| 180° < β + Az < 270° | North-South | Condition 1 | \( -d_y \times \cos(\beta) + d_x \times \sin(\beta) > \text{dist}_{\text{lat}} \) |
| | | Process 1 | \( \text{dist}_{\text{lat}} = \text{dist}_{\text{lat}} + \Delta_{\text{lat}}(\text{raw}_{\text{stat}}, \text{shift}_{\text{lat}}, \text{column}_{\text{stat}}); \)  
| | | | \( \text{shift}_{\text{lat}} = \text{shift}_{\text{lat}} + 1 \) |
| | East-West | Condition 2 | \( d_x \times \cos(\beta) + d_y \times \sin(\beta) > \text{dist}_{\text{long}} \) |
| | | Process 2 | \( \text{dist}_{\text{long}} = \text{dist}_{\text{long}} + \Delta_{\text{long}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}} - 1) \)  
| | | | \( \text{shift}_{\text{long}} = \text{shift}_{\text{long}} + 1 \) |
| β + Az > 270° | North-South | Condition 1 | \( d_y \times \cos(\beta) + d_x \times \sin(\beta) > \text{dist}_{\text{lat}} \) |
| | | Process 1 | \( \text{dist}_{\text{lat}} = \text{dist}_{\text{lat}} + \Delta_{\text{lat}}(\text{raw}_{\text{stat}}, \text{shift}_{\text{lat}}, \text{column}_{\text{stat}}); \)  
| | | | \( \text{shift}_{\text{lat}} = \text{shift}_{\text{lat}} + 1 \) |
| | East-West | Condition 2 | \( d_x \times \cos(\beta) + d_y \times \sin(\beta) > \text{dist}_{\text{long}} \) |
| | | Process 2 | \( \text{dist}_{\text{long}} = \text{dist}_{\text{long}} + \Delta_{\text{long}}(\text{raw}_{\text{stat}}, \text{column}_{\text{stat}} - 1) \)  
| | | | \( \text{shift}_{\text{long}} = \text{shift}_{\text{long}} + 1 \) |

**Table 28 - 1° iterative process formulas in the case of 180° < Az < 270°**
<table>
<thead>
<tr>
<th>Case</th>
<th>Direction</th>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>270° &lt; Az &lt; 360°</td>
<td>North-South</td>
<td>Condition 1</td>
<td>(-d_y \times \cos(\beta) + d_x \times \sin(\beta) &gt; \text{dist}_{lat})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 1</td>
<td>(\text{dist}<em>{lat} = \text{dist}</em>{lat} + \Delta_{lat}(\text{raw}<em>{stat} - 1)) (\text{shift}</em>{lat} = \text{shift}_{lat} + 1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition 2</td>
<td>(d_x \times \cos(\beta) + d_y \times \sin(\beta) &gt; \text{dist}_{long})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 2</td>
<td>(\text{dist}<em>{long} = \text{dist}</em>{long} + \Delta_{long}(\text{raw}<em>{stat}, \text{column}</em>{stat} - 1)) (\text{shift}<em>{long} = \text{shift}</em>{long} + 1)</td>
</tr>
<tr>
<td>(\beta + Az) &gt; 360°</td>
<td>North-South</td>
<td>Condition 1</td>
<td>(-d_y \times \cos(\beta) + d_x \times \sin(\beta) &gt; \text{dist}_{lat})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 1</td>
<td>(\text{dist}<em>{lat} = \text{dist}</em>{lat} + \Delta_{lat}(\text{raw}<em>{stat} - 1)) (\text{shift}</em>{lat} = \text{shift}_{lat} + 1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condition 2</td>
<td>(d_x \times \cos(\beta) - d_y \times \sin(\beta) &gt; \text{dist}_{long})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process 2</td>
<td>(\text{dist}<em>{long} = \text{dist}</em>{long} + \Delta_{long}(\text{raw}<em>{stat}, \text{column}</em>{stat} - 1)) (\text{shift}<em>{long} = \text{shift}</em>{long} + 1)</td>
</tr>
</tbody>
</table>

Table 29 - 1° iterative process formulas in the case of 270° < Az < 360°
Find the azimuth angle of all the vertices of the SEVIRI pixel that contains the considered point. The used formulas are described in Table 30:

<table>
<thead>
<tr>
<th>Azimuth case</th>
<th>Vertices azimuth formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1 &lt; 90^\circ$</td>
<td>$A_{Z1} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}}}{\text{shift}</em>{\text{long}}}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z2} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}}}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z3} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z4} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td>$90^\circ &lt; A_1 &lt; 180^\circ$</td>
<td>$A_{Z1} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}}}{\text{shift}</em>{\text{long}}}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z2} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}}}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z3} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z4} = \frac{\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td>$180^\circ &lt; A_1 &lt; 270^\circ$</td>
<td>$A_{Z1} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}}}{\text{shift}</em>{\text{long}}}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z2} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}}}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z3} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z4} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td>$270^\circ &lt; A_1 &lt; 360^\circ$</td>
<td>$A_{Z1} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}}}{\text{shift}</em>{\text{long}}}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z2} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}}}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z3} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
<tr>
<td></td>
<td>$A_{Z4} = \frac{3\pi}{2} - \arctan\left(\frac{\text{shift}<em>{\text{lat}} - 1}{\text{shift}</em>{\text{long}} - 1}\right)$</td>
</tr>
</tbody>
</table>

Table 30 - Vertices azimuth formulas for different cases
Find the distances between the SEVIRI pixel vertices and the station. To do so, the formulas in Table 31 are adopted:

<table>
<thead>
<tr>
<th>Azimuth case</th>
<th>Vertices distance formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Az &lt; 90^\circ$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v1} = dist_{lat} \times \cos(Az_{v1}) + dist_{long} \times \sin(Az_{v1})$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v2} = \left( \text{dist}<em>{lat} - \Delta</em>{lat}(raw_{stat} - shift_{lat}, c_{stat} + shift_{long}) \right) \times \cos(Az_{v2}) + \text{dist}<em>{long} \times \sin(Az</em>{v2})$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v3} = \left( \text{dist}<em>{lat} - \Delta</em>{lat}(raw_{stat} - shift_{lat}, c_{stat} + shift_{long}) \right) \times \cos(Az_{v3}) + \left( \text{dist}<em>{long} - \Delta</em>{long}(raw_{stat} - shift_{lat} + 1, c_{stat} + shift_{long} - 1) \right) \times \sin(Az_{v3})$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v4} = \text{dist}<em>{lat} \times \cos(Az</em>{v4}) + \left( \text{dist}<em>{long} - \Delta</em>{long}(raw_{stat} - shift_{lat}, c_{stat} + shift_{long} - 1) \right) \times \sin(Az_{v4})$</td>
<td></td>
</tr>
<tr>
<td>$90^\circ &lt; Az &lt; 180^\circ$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v1} = dist_{lat} \times \sin(Az_{v1} - \frac{\pi}{2}) + dist_{long} \times \cos(Az_{v1} - \frac{\pi}{2})$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v2} = dist_{lat} \times \sin(Az_{v2} - \frac{\pi}{2})$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v3} = \left( \text{dist}<em>{lat} - \Delta</em>{lat}(raw_{stat} - shift_{lat} - 1, c_{stat} + shift_{long}) \right) \times \sin(Az_{v3} - \frac{\pi}{2}) + \left( \text{dist}<em>{long} - \Delta</em>{long}(raw_{stat} - shift_{lat} - 1, c_{stat} + shift_{long} - 1) \right) \times \cos(Az_{v3} - \frac{\pi}{2})$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v4} = \left( \text{dist}<em>{lat} - \Delta</em>{lat}(raw_{stat} - shift_{lat} - 1, c_{stat} + shift_{long}) \right) \times \sin(Az_{v4} - \frac{\pi}{2}) + \text{dist}<em>{long} \times \cos(Az</em>{v4} - \frac{\pi}{2})$</td>
<td></td>
</tr>
<tr>
<td>$180^\circ &lt; Az &lt; 270^\circ$</td>
<td></td>
</tr>
<tr>
<td>$dist_{v1} = dist_{lat} \times \sin(-Az_{v1} + \frac{3\pi}{2}) + dist_{long} \times \sin(-Az_{v1} + \frac{3\pi}{2})$</td>
<td></td>
</tr>
</tbody>
</table>

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\[
\begin{align*}
\text{dist}_v &= \left(\text{dist}_{\text{lat}} - \Delta_{\text{lat}}(\text{raw}_{\text{stat}} - \text{shift}_{\text{lat}} - 1, c_{\text{stat}} + \text{shift}_{\text{long}}) \right) \times \sin(-Az_v + \frac{3\pi}{2}) \\
&+ \text{dist}_{\text{long}} \times \cos(-Az_v + \frac{3\pi}{2})
\end{align*}
\]

\[
\begin{align*}
\text{dist}_v &= \left(\text{dist}_{\text{lat}} - \Delta_{\text{lat}}(\text{raw}_{\text{stat}} - \text{shift}_{\text{lat}} - 1, c_{\text{stat}} + \text{shift}_{\text{long}}) \right) \times \sin(-Az_v + \frac{3\pi}{2}) \\
&+ \left(\text{dist}_{\text{long}} - \Delta_{\text{long}}(\text{raw}_{\text{stat}} - \text{shift}_{\text{lat}}, c_{\text{stat}} + \text{shift}_{\text{long}}) \right) \times \cos(-Az_v + \frac{3\pi}{2})
\end{align*}
\]

\[
\begin{align*}
\text{dist}_v &= \text{dist}_{\text{lat}} \times \cos(-Az_v + 2\pi) \\
&+ \text{dist}_{\text{long}} \times \sin(-Az_v + 2\pi)
\end{align*}
\]

\[
\begin{align*}
\text{dist}_v &= \text{dist}_{\text{lat}} \times \cos(-Az_v + 2\pi) \\
&+ \left(\text{dist}_{\text{long}} - \Delta_{\text{long}}(\text{raw}_{\text{stat}} + \text{shift}_{\text{lat}}, c_{\text{stat}} + \text{shift}_{\text{long}}) \right) \times \cos(-Az_v + 2\pi) \\
&+ \left(\text{dist}_{\text{long}} - \Delta_{\text{long}}(\text{raw}_{\text{stat}} + \text{shift}_{\text{lat}}, c_{\text{stat}} + \text{shift}_{\text{long}}) \right) \times \sin(-Az_v + 2\pi)
\end{align*}
\]

\[
\begin{align*}
\text{dist}_v &= \text{dist}_{\text{lat}} - \Delta_{\text{lat}}(\text{raw}_{\text{stat}} + \text{shift}_{\text{lat}}, c_{\text{stat}} + \text{shift}_{\text{long}}) \\
&\times \cos(-Az_v + 2\pi) \\
&+ \text{dist}_{\text{long}} \times \sin(-Az_v + 2\pi)
\end{align*}
\]

Table 31 - Vertices distance computation formulas

\[270^\circ < Az < 360^\circ\]
A second iterative process is implemented in order to find the vertices coordinates into the SI reference frame. In this case, the algorithm updates the distance $d_{\text{comparison}}$ for all the vertices, starting from a 0 value and adding the SI spatial resolution (Process 3, 4, 5 and 6). The loop stops when this distance $d_{\text{comparison}}$ reaches a value greater than the considered vertex distance (Condition 3, 4, 5 and 6). In this way, the index $index_{V_n}$ could be used to find the position of the SEVIRI pixel vertex $V_n$ in the SI reference frame.

Table 32 shows the formulas used for the 2° iterative process:

<table>
<thead>
<tr>
<th>Vertex</th>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>Condition 3</td>
<td>$dist_{V_1} &gt; dist_{\text{comparison}}$</td>
</tr>
<tr>
<td></td>
<td>Process 3</td>
<td>$dist_{\text{comparison}}$ = $dist_{\text{comparison}}$ + $SI_{\text{spatial res}}(index_{V_1})$; $index_{V_1} = index_{V_1} + 1$</td>
</tr>
<tr>
<td>$V_2$</td>
<td>Condition 4</td>
<td>$dist_{V_2} &gt; dist_{\text{comparison}}$</td>
</tr>
<tr>
<td></td>
<td>Process 4</td>
<td>$dist_{\text{comparison}}$ = $dist_{\text{comparison}}$ + $SI_{\text{spatial res}}(index_{V_1})$; $index_{V_2} = index_{V_2} + 1$</td>
</tr>
<tr>
<td>$V_3$</td>
<td>Condition 5</td>
<td>$dist_{V_3} &gt; dist_{\text{comparison}}$</td>
</tr>
<tr>
<td></td>
<td>Process 5</td>
<td>$dist_{\text{comparison}}$ = $dist_{\text{comparison}}$ + $SI_{\text{spatial res}}(index_{V_1})$; $index_{V_3} = index_{V_3} + 1$</td>
</tr>
<tr>
<td>$V_4$</td>
<td>Condition 6</td>
<td>$dist_{V_4} &gt; dist_{\text{comparison}}$</td>
</tr>
<tr>
<td></td>
<td>Process 6</td>
<td>$dist_{\text{comparison}}$ = $dist_{\text{comparison}}$ + $SI_{\text{spatial res}}(index_{V_1})$; $index_{V_4} = index_{V_4} + 1$</td>
</tr>
</tbody>
</table>

Table 32 - 2° iterative process formulas

Find the precise SEVIRI pixel vertices in the SI reference frame. Table 33, Table 34, Table 35 and Table 36 present the adopted formulas. These formulas are basically a projection of $index_{V_n}$ in the horizontal and vertical axes of the SI reference frame.

$Az < 90°$
### Coordinates position formulas

**Table 33** - Set of formulas used to compute the SEVIRI pixel vertices in the SI reference frame in the case of $Az < 90^\circ$

<table>
<thead>
<tr>
<th>Vertex</th>
<th>Case</th>
<th>Coordinates position formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>$Az_{v1} + \beta \leq 90^\circ$</td>
<td>$\text{round} \left[ -\text{index}<em>{v1} \times \cos(Az</em>{v1} + \beta) ; -\text{index}<em>{v1} \times \sin(Az</em>{v1} + \beta) \right]$</td>
</tr>
<tr>
<td>$Az_{v1} + \beta &gt; 90^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v1} \times \cos(\pi - (Az</em>{v1} + \beta)) ; -\text{index}<em>{v1} \times \sin(\pi - (Az</em>{v1} + \beta)) \right]$</td>
<td></td>
</tr>
<tr>
<td>$V_2$</td>
<td>$Az_{v2} + \beta \leq 90^\circ$</td>
<td>$\text{round} \left[ -\text{index}<em>{v2} \times \cos(Az</em>{v2} + \beta) ; -\text{index}<em>{v2} \times \sin(Az</em>{v2} + \beta) \right]$</td>
</tr>
<tr>
<td>$Az_{v2} + \beta &gt; 90^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v2} \times \cos(\pi - (Az</em>{v2} + \beta)) ; -\text{index}<em>{v2} \times \sin(\pi - (Az</em>{v2} + \beta)) \right]$</td>
<td></td>
</tr>
<tr>
<td>$V_3$</td>
<td>$Az_{v3} + \beta \leq 90^\circ$</td>
<td>$\text{round} \left[ -\text{index}<em>{v3} \times \cos(Az</em>{v3} + \beta) ; -\text{index}<em>{v3} \times \sin(Az</em>{v3} + \beta) \right]$</td>
</tr>
<tr>
<td>$Az_{v3} + \beta &gt; 90^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v3} \times \cos(\pi - (Az</em>{v3} + \beta)) ; -\text{index}<em>{v3} \times \sin(\pi - (Az</em>{v3} + \beta)) \right]$</td>
<td></td>
</tr>
<tr>
<td>$V_4$</td>
<td></td>
<td>$\text{round} \left[ -\text{index}<em>{v4} \times \cos(Az</em>{v4} + \beta) ; -\text{index}<em>{v4} \times \sin(Az</em>{v4} + \beta) \right]$</td>
</tr>
</tbody>
</table>

### Coordinates position formulas

**Table 34** - Set of formulas used to compute the SEVIRI pixel vertices in the SI reference frame in the case of $90^\circ < Az < 180^\circ$

<table>
<thead>
<tr>
<th>Vertex</th>
<th>Case</th>
<th>Coordinates position formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>$Az_{v1} + \beta \leq 180^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v1} \times \cos(\pi - (Az</em>{v1} + \beta)) ; -\text{index}<em>{v1} \times \sin(\pi - (Az</em>{v1} + \beta)) \right]$</td>
</tr>
<tr>
<td>$Az_{v1} + \beta &gt; 180^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v1} \times \cos(\pi - (Az</em>{v1} + \beta)) ; \text{index}<em>{v1} \times \sin(-\pi + (Az</em>{v1} + \beta)) \right]$</td>
<td></td>
</tr>
<tr>
<td>$V_2$</td>
<td>$Az_{v2} + \beta \leq 180^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v2} \times \cos(\pi - (Az</em>{v2} + \beta)) ; -\text{index}<em>{v2} \times \sin(\pi - (Az</em>{v2} + \beta)) \right]$</td>
</tr>
<tr>
<td>$Az_{v2} + \beta &gt; 180^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v2} \times \cos(-\pi + (Az</em>{v2} + \beta)) ; \text{index}<em>{v2} \times \sin(-\pi + (Az</em>{v2} + \beta)) \right]$</td>
<td></td>
</tr>
<tr>
<td>$V_3$</td>
<td>$Az_{v3} + \beta \leq 180^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v3} \times \cos(\pi - (Az</em>{v3} + \beta)) ; -\text{index}<em>{v3} \times \sin(\pi - (Az</em>{v3} + \beta)) \right]$</td>
</tr>
<tr>
<td>$Az_{v3} + \beta &gt; 180^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{v3} \times \cos(-\pi + (Az</em>{v3} + \beta)) ; \text{index}<em>{v3} \times \sin(-\pi + (Az</em>{v3} + \beta)) \right]$</td>
<td></td>
</tr>
<tr>
<td>$V_4$</td>
<td></td>
<td>$\text{round} \left[ \text{index}<em>{v4} \times \cos(\pi - (Az</em>{v4} + \beta)) ; -\text{index}<em>{v4} \times \sin(\pi - (Az</em>{v4} + \beta)) \right]$</td>
</tr>
</tbody>
</table>
### Table 35 - Set of formulas used to compute the SEVIRI pixel vertices in the SI reference frame in the case of $180^\circ < Az < 270^\circ$

<table>
<thead>
<tr>
<th>Vertex</th>
<th>Case</th>
<th>Vertices coordinates position formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>$Az_{V1} + \beta \geq 270^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{V1} \times \sin \left( \frac{3\pi}{2} - (Az</em>{V1} + \beta) \right) ; \text{index}<em>{V1} \times \cos \left( \frac{3\pi}{2} - (Az</em>{V1} + \beta) \right) \right]$</td>
</tr>
<tr>
<td></td>
<td>$Az_{V1} + \beta &gt; 270^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{V1} \times \sin \left( -\frac{3\pi}{2} + (Az</em>{V1} + \beta) \right) ; \text{index}<em>{V1} \times \cos \left( -\frac{3\pi}{2} + (Az</em>{V1} + \beta) \right) \right]$</td>
</tr>
<tr>
<td>$V_2$</td>
<td>$Az_{V2} + \beta \geq 270^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{V2} \times \sin \left( \frac{3\pi}{2} - (Az</em>{V2} + \beta) \right) ; -\text{index}<em>{V2} \times \cos \left( \frac{3\pi}{2} - (Az</em>{V2} + \beta) \right) \right]$</td>
</tr>
<tr>
<td></td>
<td>$Az_{V2} + \beta &gt; 270^\circ$</td>
<td>$\text{round} \left[ -\text{index}<em>{V2} \times \sin \left( -\frac{3\pi}{2} + (Az</em>{V2} + \beta) \right) ; \text{index}<em>{V2} \times \cos \left( -\frac{3\pi}{2} + (Az</em>{V2} + \beta) \right) \right]$</td>
</tr>
<tr>
<td>$V_3$</td>
<td>$Az_{V3} + \beta \geq 270^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{V3} \times \sin \left( \frac{3\pi}{2} - (Az</em>{V3} + \beta) \right) ; \text{index}<em>{V3} \times \cos \left( \frac{3\pi}{2} - (Az</em>{V3} + \beta) \right) \right]$</td>
</tr>
<tr>
<td></td>
<td>$Az_{V3} + \beta &gt; 270^\circ$</td>
<td>$\text{round} \left[ -\text{index}<em>{V3} \times \sin \left( -\frac{3\pi}{2} + (Az</em>{V3} + \beta) \right) ; \text{index}<em>{V3} \times \cos \left( -\frac{3\pi}{2} + (Az</em>{V3} + \beta) \right) \right]$</td>
</tr>
<tr>
<td>$V_4$</td>
<td>$Az_{V4} + \beta \geq 270^\circ$</td>
<td>$\text{round} \left[ \text{index}<em>{V4} \times \sin \left( \frac{3\pi}{2} - (Az</em>{V4} + \beta) \right) ; \text{index}<em>{V4} \times \cos \left( \frac{3\pi}{2} - (Az</em>{V4} + \beta) \right) \right]$</td>
</tr>
</tbody>
</table>

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### 270° < Az < 360°

<table>
<thead>
<tr>
<th>Vertex</th>
<th>Case</th>
<th>Coordinates position formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>$Az_{V_1} + \beta \leq 360°$</td>
<td>$\text{round}[-\text{index}<em>{V_1} \times \cos(2\pi - (Az</em>{V_1} + \beta)); \text{index}<em>{V_1} \times \sin(2\pi - (Az</em>{V_1} + \beta))]$</td>
</tr>
<tr>
<td></td>
<td>$Az_{V_1} + \beta &gt; 360°$</td>
<td>$\text{round}[-\text{index}<em>{V_1} \times \cos(-2\pi + (Az</em>{V_1} + \beta)); \text{index}<em>{V_1} \times \cos(-2\pi + (Az</em>{V_1} + \beta))]$</td>
</tr>
<tr>
<td>$V_2$</td>
<td>$Az_{V_2} + \beta \leq 360°$</td>
<td>$\text{round}[-\text{index}<em>{V_2} \times \cos(2\pi - (Az</em>{V_2} + \beta)); \text{index}<em>{V_2} \times \sin(2\pi - (Az</em>{V_2} + \beta))]$</td>
</tr>
<tr>
<td></td>
<td>$Az_{V_2} + \beta &gt; 360°$</td>
<td>$\text{round}[-\text{index}<em>{V_2} \times \cos(-2\pi + (Az</em>{V_2} + \beta)); \text{index}<em>{V_2} \times \sin(-2\pi + (Az</em>{V_2} + \beta))]$</td>
</tr>
<tr>
<td>$V_3$</td>
<td>$Az_{V_3} + \beta \leq 360°$</td>
<td>$\text{round}[-\text{index}<em>{V_3} \times \cos(2\pi - (Az</em>{V_3} + \beta)); \text{index}<em>{V_3} \times \sin(2\pi - (Az</em>{V_3} + \beta))]$</td>
</tr>
<tr>
<td></td>
<td>$Az_{V_3} + \beta &gt; 360°$</td>
<td>$\text{round}[-\text{index}<em>{V_3} \times \cos(-2\pi + (Az</em>{V_3} + \beta)); \text{index}<em>{V_3} \times \sin(-2\pi + (Az</em>{V_3} + \beta))]$</td>
</tr>
<tr>
<td>$V_4$</td>
<td></td>
<td>$\text{round}[-\text{index}<em>{V_4} \times \cos(2\pi - (Az</em>{V_4} + \beta)); \text{index}<em>{V_4} \times \sin(2\pi - (Az</em>{V_4} + \beta))]$</td>
</tr>
</tbody>
</table>

Table 36: Set of formulas used to compute the SEVIRI pixel vertices in the SI reference frame in the case of 270° < Az < 360°

- Computation of the point distance from the station in terms of SI pixels

This process aims to find the number of pixels between the considered point and the station. It is described in the flowchart presented in Figure 87. It consists of the following consecutive steps:

- Consider the point direction. Depending on the direction, the geometrical formulas would be different (i.e. $Az + \beta < 90°$, $90° < Az + \beta < 180°$, etc.).
- An iterative process is necessary to find point position. The algorithm starts from the station coordinates and find all the pixels which are placed on the line that connect the station and the point. It stops when the point elevation is achieved and the coordinates ($r, c$) represents the row and column of the point in the SI matrix;
- The post-process permits to obtain the point coordinates ($shift_h$ and $shift_v$) in the SI reference frame (the station is the origin of the frame).

Table 37, Table 38, Table 39 and Table 40 describe in details all the employed formulas.
Figure 87 - Flowchart of the point distance computation process

### Table 37 - 3° iterative process computation formulas in the case of $Az + \beta < 90°$

<table>
<thead>
<tr>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 7</td>
<td>$E &lt; E_{matrix}(r, c)$</td>
</tr>
<tr>
<td>Process 7</td>
<td>$c = c - 1;$ $r = \text{round} \left{ \frac{1}{\text{abs}(\tan(Az + \beta))} \times \frac{c_{\text{stat}} + r_{\text{stat}}}{\text{abs}(\tan(Az + \beta))} \right}$</td>
</tr>
<tr>
<td>Post-process</td>
<td>$\text{shift}<em>h = c</em>{\text{stat}} - c$ $\text{shift}<em>v = r - r</em>{\text{stat}}$</td>
</tr>
</tbody>
</table>
### 90° < Az + β < 180°

<table>
<thead>
<tr>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 7</td>
<td>$E &lt; E_{matrix}(r,c)$</td>
</tr>
</tbody>
</table>
| Process 7           | $c = c - 1$; $\begin{align*} r &= \text{round}\left[\frac{1}{\text{abs}(\text{tan}(Az + \beta))} \times c + r_{stat} \\
&+ \frac{c_{stat} \times \text{abs}(\text{tan}(Az + \beta))}{\text{abs}(\text{tan}(Az + \beta))}\right]\end{align*}$ |
| Post-process        | $\text{shift}_h = c_{stat} - c$; $\text{shift}_v = r_{stat} - r$ |

Table 38 - 3° iterative process computation formulas in the case of 90° < Az + β < 180°

### 180° < Az + β < 270°

<table>
<thead>
<tr>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 7</td>
<td>$E &lt; E_{matrix}(r,c)$</td>
</tr>
</tbody>
</table>
| Process 7           | $c = c + 1$; $\begin{align*} r &= \text{round}\left[\frac{1}{\text{abs}(\text{tan}(Az + \beta))} \times c + r_{stat} \\
&+ \frac{c_{stat} \times \text{abs}(\text{tan}(Az + \beta))}{\text{abs}(\text{tan}(Az + \beta))}\right]\end{align*}$ |
| Post-process        | $\text{shift}_h = c - c_{stat}$; $\text{shift}_v = r_{stat} - r$ |

Table 39 - 3° iterative process computation formulas in the case of 180° < Az + β < 270°

### 270° < Az + β < 360°

<table>
<thead>
<tr>
<th>Flowchart statement</th>
<th>Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 7</td>
<td>$E &lt; E_{matrix}(r,c)$</td>
</tr>
</tbody>
</table>
| Process 7           | $c = c + 1$; $\begin{align*} r &= \text{round}\left[\frac{1}{\text{abs}(\text{tan}(Az + \beta))} \times c + r_{stat} \\
&+ \frac{c_{stat} \times \text{abs}(\text{tan}(Az + \beta))}{\text{abs}(\text{tan}(Az + \beta))}\right]\end{align*}$ |
| Post-process        | $\text{shift}_h = c - c_{stat}$; $\text{shift}_v = r - r_{stat}$ |

Table 40 - 3° iterative process computation formulas in the case of 270° < Az + β < 360°
- Find all the SI pixels inside the SEVIRI pixel

Once that the SEVIRI pixel is defined in the SI reference frame, the algorithm uses the vertices coordinates and the point coordinates found in the previous paragraph to find the ODs included in the SEVIRI pixel. To do so, it considers the entire rectangle that contains all the vertices. Figure 88 shows in blue the external rectangle taken into account: it contains all the information included in the SEVIRI pixel (red rectangle). This procedure is described analytically in Table 41, Table 42, Table 43 and Table 44.

Then, the information contained in the pixels outside the SEVIRI rectangle is deleted. It is done using the MATLAB® function inpolygon, which considers only the points inside the polygon defined by the four vertices.

Figure 88 - Illustration of the rectangle considered
### Case 1: $Az + \beta < 90^\circ$

<table>
<thead>
<tr>
<th>Case</th>
<th>Rectangle formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Az + \beta &lt; 90^\circ$</td>
<td>$OD(\max(r_{stat} + \text{shift } t_v - \text{index } up, 1): \min(r_{stat} + \text{shift } t_v + \text{index } down, 480), \max(c_{stat} - \text{shift } t_h - \text{index } left, 1) : \min(c_{stat} - \text{shift } t_h + \text{index } right, 640))$</td>
</tr>
</tbody>
</table>

### Table 41 - Rectangle computing formulas in the case of $Az + \beta < 90^\circ$

### Case 2: $90^\circ < Az + \beta < 180^\circ$

<table>
<thead>
<tr>
<th>Case</th>
<th>Rectangle formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$90^\circ &lt; Az + \beta &lt; 180^\circ$</td>
<td>$OD(\max(r_{stat} - \text{shift } t_v - \text{index } up, 1): \min(r_{stat} - \text{shift } t_v + \text{index } down, 480), \max(c_{stat} - \text{shift } t_h - \text{index } left, 1) : \min(c_{stat} - \text{shift } t_h + \text{index } right, 640))$</td>
</tr>
<tr>
<td>$Az + \beta &gt; 180^\circ$</td>
<td>$OD(\max(r_{stat} - \text{shift } t_v - \text{index } up, 1): \min(r_{stat} - \text{shift } t_v + \text{index } down, 480), \max(c_{stat} + \text{shift } t_h - \text{index } left, 1) : \min(c_{stat} + \text{shift } t_h + \text{index } right, 640))$</td>
</tr>
</tbody>
</table>

### Table 42 - Rectangle computing formulas in the case of $90^\circ < Az + \beta < 180^\circ$
### Table 43 - Rectangle computing formulas in the case of $180^\circ < Az + \beta < 270^\circ$

<table>
<thead>
<tr>
<th>Case</th>
<th>Rectangle formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$180^\circ &lt; Az + \beta &lt; 270^\circ$</td>
<td>$OD\left( \max\left( r_{stat} - \text{shift}<em>{tv} - \text{index}</em>{up}, 1 \right) \cdot \min\left( r_{stat} - \text{shift}<em>{tv} + \text{index}</em>{down}, 480 \right), \max\left( c_{stat} + \text{shift}<em>{th} - \text{index}</em>{left}, 1 \right) : \min\left( c_{stat} + \text{shift}<em>{th} + \text{index}</em>{right}, 640 \right) \right)$</td>
</tr>
</tbody>
</table>

### Table 44 - Rectangle computing formulas in the case of $270^\circ < Az + \beta < 360^\circ$

<table>
<thead>
<tr>
<th>Case</th>
<th>Rectangle formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$270^\circ &lt; Az + \beta &lt; 360^\circ$</td>
<td>$OD\left( \max\left( r_{stat} + \text{shift}<em>{tv} - \text{index}</em>{up}, 1 \right) \cdot \min\left( r_{stat} + \text{shift}<em>{tv} + \text{index}</em>{down}, 480 \right), \max\left( c_{stat} + \text{shift}<em>{th} - \text{index}</em>{left}, 1 \right) : \min\left( c_{stat} + \text{shift}<em>{th} + \text{index}</em>{right}, 640 \right) \right)$</td>
</tr>
</tbody>
</table>

Table 43 - Rectangle computing formulas in the case of $180^\circ < Az + \beta < 270^\circ$

Table 44 - Rectangle computing formulas in the case of $270^\circ < Az + \beta < 360^\circ$
### Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARQ</td>
<td>Automatic Repeat Request</td>
</tr>
<tr>
<td>bps</td>
<td>Bits per seconds</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CMa</td>
<td>Cloud Mask</td>
</tr>
<tr>
<td>CMS</td>
<td>Centre de Météorologie Spatiale</td>
</tr>
<tr>
<td>CONOPS</td>
<td>Concepts of Operations</td>
</tr>
<tr>
<td>CT</td>
<td>Cloud Type</td>
</tr>
<tr>
<td>E</td>
<td>Elevation angle</td>
</tr>
<tr>
<td>ECEF</td>
<td>Earth Centered Earth Fixed</td>
</tr>
<tr>
<td>ECMRWF</td>
<td>European Center for Medium Range-Weather Forecasts</td>
</tr>
<tr>
<td>EDRS</td>
<td>European Data Relay System</td>
</tr>
<tr>
<td>EO</td>
<td>Earth observation</td>
</tr>
<tr>
<td>EUMETSAT</td>
<td>European Organization for the Exploitation of Meteorological Satellites</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
</tr>
<tr>
<td>FER</td>
<td>Frame error rate</td>
</tr>
<tr>
<td>FSOC</td>
<td>Free space optical communications</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary</td>
</tr>
<tr>
<td>H</td>
<td>Altitude of satellite</td>
</tr>
<tr>
<td>IR</td>
<td>InfraRed</td>
</tr>
<tr>
<td>( L_c )</td>
<td>Cloud loss</td>
</tr>
<tr>
<td>LCT</td>
<td>Laser Communication Terminals</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth orbit</td>
</tr>
<tr>
<td>( L_{inj} )</td>
<td>Injection losses</td>
</tr>
<tr>
<td>LOS</td>
<td>Line Of Sight</td>
</tr>
<tr>
<td>( L_{scin} )</td>
<td>Scintillation losses</td>
</tr>
</tbody>
</table>
LWIR  Long Wave InfraRed
LUT   LookUp-Table
MI    Mutual information
MSG   Meteosat Second Generation
OCR   Optical Channel Rate
OD    Optical Depth
OGS   Optical ground station
OPALS Optical PAyload for Lasercomm Science
OSIRIS Optical Space Infrared Downlink system
PAT   Pointing, Acquisition and Tracking
PDF   Probability Density Function
r₀    Fried parameter
RF    Radio-frequency
ROP   Received optical power
SAFNWC Satellite Application Facility for NoW Casting and very short range forecasting
SEVIRI Spinning Enhanced Visible and Infrared Imager
SI    SkyInsight
SOTA  Small Optical TrAnsponder
SOCRATES Space Optical Communication Research Advanced Technology Satellite
SZA   Sun Zenith Angle
TMI   Telem easure information
TDRSS Tracking and Data Relay Satellite System
UDR   Use ful Data Rate
VNIR  Visible and Near-InfraRed
λ     Wavelength/ Latitude
φ     Longitude
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