



# 6G-NTN

## D3.10 (V)LEO SPACE SEGMENT

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<b>Abstract</b>	This document presents investigations and solutions regarding (V)LEO constellations to support the definition of the 6G-NTN system. This work is based on iterative trade-offs made during Tasks 3.1 and 3.3. It provides insights both in terms of capacity evaluation and the relevance of solutions, including aspects related to deployment (launchers) as well as operating effort (gateways).
<b>Keywords</b>	NTN Constellation, Constellation Optimisation, Constellation Capacity, gateways, Launchers.

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## EXECUTIVE SUMMARY

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This deliverable provides design and analysis of the (V) LEO space segment to support reflection on future 6G-NTN. It is devoted particularly to LEO and VLEO constellations. MEO, GEO and HAPS elements are not considered in this activity and are presented in [6].

An optimized constellation in terms of minimum number of satellites has been defined to provide global coverage [1]. Analysis and data for an initial assessment of the constellation parameters have been provided. It will allow to estimate the effort that could represent the deployment of these constellations.

A model has been developed to calculate the optimum configuration of the constellation to provide full coverage based on a range of parameters such as altitude, minimum user elevation and number of satellites visible (see document 3.9 of Task 3.3 [6]). A reference constellation has been defined with the following parameters:

- Minimum of 1 satellite visible at any time
- Minimum of 10s overlap between satellites
- Global coverage
- Minimum user elevation of 45°
- 600 km altitude

Moreover, an alternative constellation at VLEO altitude has been proposed by relaxing the first constraint of minimizing the number of satellites to gain in FSL and the parameters of such constellation have also been provided as follows:

- Minimum of 1 satellite visible at any time
- Minimum of 10s overlap between satellites
- Global coverage
- Minimum user elevation of 35°
- 350 km altitude

These two constellations offer an overview of potential configurations for 6G NTN, encompassing a broad spectrum of options. There is a trade-off balance between performance, payload complexity, and the number of satellites. These factors contribute significantly to assessing the overall cost of the constellation. Therefore, these two constellations have also been included in the analysis.

Moreover, within the scope of this study, two types of constellation architectures (Architecture 1 (conventional) and Architecture 2 (distributed)) have been explored in two ways: a conventional approach involving only one type of satellite (service satellites), and a second approach based on two types of satellites (service and feeder satellites). (See [1] & [6]).

The two constellations, each associated with one of the two architectures, will enable the analysis of sizing parameters and the evaluation of the relative effort required for one compared to the other.

Under these assumptions, the minimum number of service satellites (those that connect to the user) is 1269 (27 planes of 47 satellites, not considering spares). In the case of a distributed architecture (where a second layer of 'feeder' satellites provide some of the processing and connect the service satellites to each other and to ground stations), a further 336 satellites (14

planes of 24 satellites) are needed, assuming each feeder satellite serves 4 service satellites. It is assumed that these feeder satellites ‘co-orbit’ (at the same altitude and inclination) with the service satellites, as this simplifies the network.

For the VLEO constellation the number of services satellites is 1760 (32 planes of 55 satellites) and the feeder satellite constellation is composed of 448 satellites (16 planes of 28 satellites).

At this time, the coverage objectives of the C- and Q/V-Band constellations are the same. Therefore, the two constellations are assumed to be similar in terms of altitude and configuration. This allows a common architecture between the two constellations and simplifies management of coverage/ground cells. At this stage, multiple options remain open, and the choice of constellations depends on several interrelated factors. Generally, if no initial constraints are explicitly defined (such as at least altitude or coverage), the possibilities stay wide open. The trade-offs primarily focus on minimizing the number of satellites while ensuring acceptable performance levels, considering payload complexity and key link budget parameters (e.g., free space loss and scan losses), as outlined in Task 3.3 [6].

Since the requirements for each constellation still need to be refined, more detailed capacity sizing will be conducted as a continuation of this project, which remains at an initial stage of reflection.

Thus, sizing of the constellation capacity is relatively preliminary at this stage – so far, the sizing has been performed based on the minimum number of satellites as described above, and an initial estimate of the payload’s performance based on maximizing the power [ see task 3.3 [6]]

Another important point to mention is that work has been carried out to develop a traffic model based on population density. This effort helps clarify certain aspects of the actual demand and will contribute to defining target requirements for the next phase of investigations.

Finally, for future NTN, a concept of scalability has been included in the design to address uncertainties regarding future demand [6].

That is why the constellation definitions include the ability to be adjusted, for example, through partial updates or densification of certain elements. The performance of a system depends not only on the capabilities of individual nodes but also on the links established via OISL and ISL connections, as well as additional components that can be integrated to enhance performance. Therefore, the objective of this work is to simplify these components while maintaining sufficient flexibility to better adapt to uncertain demand. This approach aligns with the framework defined by this study, and more specifically with that outlined in Task 3.3 [6].

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## ABBREVIATIONS

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<b>AIT</b>	Assembly Integration and Tests
<b>FoV</b>	Field of View
<b>GEO</b>	Geostationary Earth Orbit
<b>GNSS</b>	Global Navigation Satellite System
<b>HAP(S)</b>	High Altitude Pseudo-Satellite/High Altitude Platform
<b>LEO</b>	Low Earth Orbit
<b>MEO</b>	Medium Earth Orbit
<b>NTN</b>	Non-Terrestrial Network
<b>OISL</b>	Optical Inter-Satellite Link
<b>RAAN</b>	Right Ascension of the Ascending Node
<b>RTT</b>	Round Trip Time
<b>TN</b>	Terrestrial Network
<b>UDT</b>	Urban Density Threshold
<b>UE</b>	User Equipment
<b>VLEO</b>	Very Low Earth Orbit

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## 1 INTRODUCTION

---

This deliverable focuses on the design of the (V)LEO space segment of the 6G NTN, based on the architecture(s) described as part of [1]. This includes the configuration of the constellation as well as an initial sizing of the satellites. With the constellation and payload defined, the capacity of the constellation and the service that can be delivered to users on the ground can be estimated. Once the constellation sizing, satellite sizing, and capacity models have been developed, the space segment configuration can be optimised based on the use cases and orientations defined in [2]-[3], [5] and [6].

Moreover, this work will allow to have a view on overall parameters such as coverage constellation size and interlinks characteristics, launcher/deployment evaluations. These data will serve as inputs for conducting analyses in other tasks. This Task focus on the main (V) LEO portion of the space segment – the design of potential GEO, MEO or HAPS parts of the system are not subject of this task.

The parameters of the payload (capacity, size, mass and power) are inputs from [6] completed by estimating the parameters of the satellite platform. The sizing of the constellation and the payload is an iterative process to converge on an optimal level of performance based on trade-offs in interaction with Task 3.3 [6]. The aim of this study is not to define a unique solution, but rather to identify avenues of analysis for the future 6G NTN. Since there are many uncertainties about what the 6G NTN will actually be, particularly regarding altitude and coverage constraints, assumptions will be made and all possibilities will remain open in order to explore every option. Thus, it is not intended to present a definition of constellations optimised to deliver a specific service/capacity, but rather to give an indication/guidelines or orientations of the services/capacities that can be delivered by the NTN. The objective is to contribute to the reflection on the future network and to identify the work areas in order to ultimately prepare for the deployment of 6G NTN.

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## 2 CONSTELLATION SIZING

---

The aim of the constellation sizing activity is to determine the minimum number of service satellites required to provide the global coverage. The term of global coverage is defined essentially by “UE connectable anywhere on the earth surface”. Naturally it point toward a quasi-polar constellation to ensure a “global coverage”. Nevertheless, alternative constellations could be possible by relaxing the term of global coverage and focusing on regions where the density of population is significant [See Appendix 13.2 & 13.3] so that a percentage of coverage goal could be defined.

For simplicity, it is assumed that the constellation consists of a single shell of satellites all with the same orbital inclination and altitude. This activity only defines the minimum number of satellites required to provide full coverage – it does not yet take into account more detailed trade-offs such as the number of satellites vs the size to achieve a certain capacity, or launch/deployment strategies. These parameters could only be completed after the definition of the constellations and by iterations. Nevertheless, they have been implicitly taken into account through preliminary analyses and reflections (assumptions on the dimensions of the coverage) as well as heritage. Once models for the constellation capacity have been developed, the constellation sizing can be revisited and the number of satellites increased to respond to the capacity need if necessary.

### 2.1 SIZING MODEL INPUTS

Coverage is defined according to the following parameters:

- Minimum User Elevation: to limit the required off-nadir angle/field of view (FoV) of the satellite, a minimum user elevation is imposed. Low user elevations may also result in obstruction of signal if the user is in hilly or built-up areas. For a given altitude, the minimum user elevation also restricts the variation in slant range (the distance between the user and the satellite). This (along with the altitude of the satellite) determines the size of the satellite footprint/FoV (the area covered by a single satellite).
- Minimum Number of Visible Satellites: this is the minimum number of satellites that must be visible to a user at any one time. To provide full coverage, this needs to be 1. However, it may be that more than 1 satellite needs to be visible at any one time (such as is the case of GNSS satellites), hence this is set as a variable input to the constellation sizing model.
- Minimum Overlap Duration: when a user is passed from one satellite to another, there may need to be a minimum duration where the user is connected to both satellites simultaneously to ensure a proper handover – this duration determines how much overlap there needs to be between satellite footprints.
  - In reality this overlap should take into account the cell size (as the fixed cells on ground would necessitate the whole cell to be handed over), however in this initial analysis the overlap is calculated ‘per user’.
- Inclination, or Maximum User Latitude: the inclination of the satellites determines the maximum latitude that the constellation can cover.

### 2.2 METHODOLOGY

Coverage is defined utilising the “streets of coverage” method. Figure 2-1Figure 2-1 shows how a street of coverage is defined for a single plane of satellites, with and without a minimum overlap duration. The black dots represent the satellites (or the sub-satellite point on ground),

the black dotted arrow indicates the satellite ground track, and the blue circles represent the satellite FoV, defined as the area where the elevation of the satellite relative to the user is above a defined minimum angle. The blue dotted lines denote the region where a user will always be in view of at least one satellite. However, a user right at the edge of this region (on the blue dotted line) will have no period where both satellites are simultaneously visible to allow an overlap. For a given overlap duration, the required overlap distance of the two satellite FoVs is this duration divided by the ground speed of the satellites. The ground speed of the satellites will be approximately  $7\text{kms}^{-1}$ , so for an example overlap duration of 10s, the required overlap is 70km in the direction of satellite motion. Therefore, the street of coverage where the minimum overlap duration is met is narrower – this is shown in red.

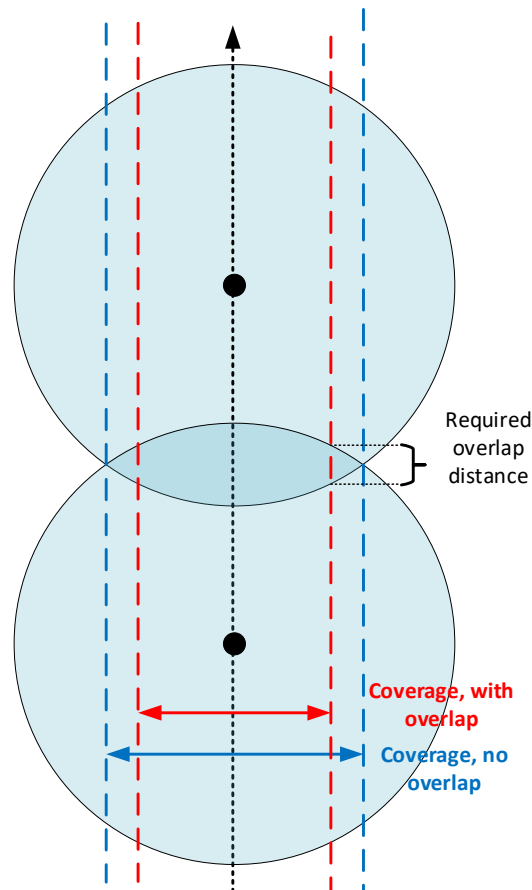


FIGURE 2-1 "STREET" OF COVERAGE FOR A SINGLE PLANE OF SATELLITES, WITH AND WITHOUT A MINIMUM OVERLAP DURATION

To provide full coverage, multiple planes of satellites are required. Figure 2-2 shows how this can be achieved with the satellites orbiting in alternating directions (left) and in the same direction (right). When the planes are orbiting in alternating directions, they need to be spaced such that their individual streets of coverage are touching. However, if all planes orbit in the same direction, the positions of the satellites remain fixed relative to each other<sup>1</sup>, therefore the satellite planes can be more widely spaced, requiring fewer satellites for coverage.

<sup>1</sup> This is not strictly true as the distance between the planes decreases as latitude increases, but this only serves to increase the overlap between FoVs.

Having the planes orbiting in alternating directions also has the disadvantage that it only works for a constellation in a  $90^\circ$  inclination orbit – if the constellation has any other inclination, the ascending and descending planes will be ‘tilted’ (as seen from the ground) in opposite directions, and therefore the streets of coverage will not align and there will be gaps. It would be possible for the ascending and descending planes to have ‘opposite’ inclinations (for example, one plane has an inclination of  $90^\circ - 20^\circ = 70^\circ$  and the other has  $90^\circ + 20^\circ = 110^\circ$ ) - this would allow the streets of coverage to align. However, as the planes have different inclinations, the Right Ascension of the Ascending Nodes (RAANs) of the planes will drift in opposite directions, again creating gaps in coverage.

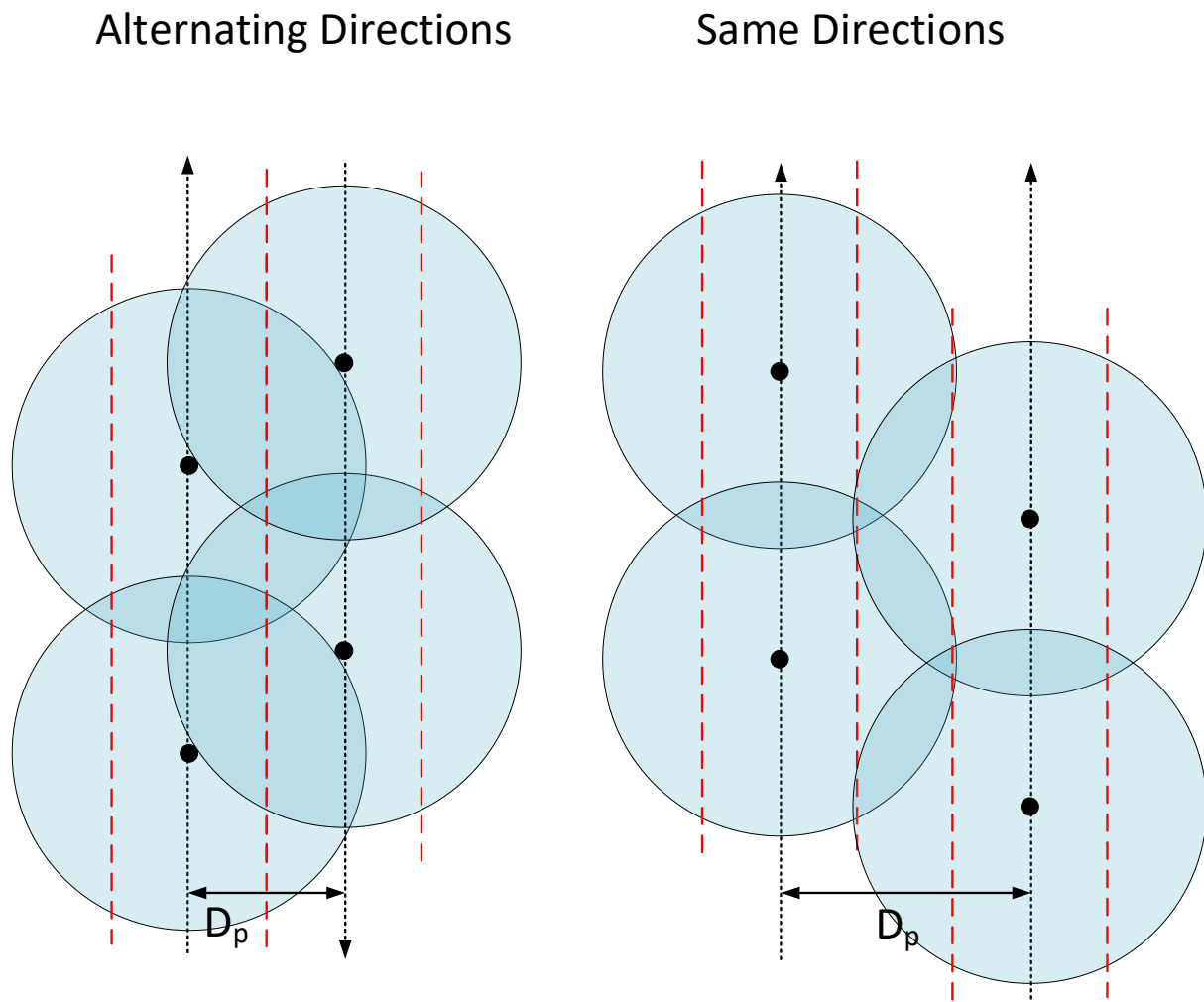


FIGURE 2-2 OVERLAP REQUIRED TO PROVIDE FULL COVERAGE, FOR SATELLITE PLANES ORBITING IN ALTERNATING DIRECTIONS (LEFT) AND IN THE SAME DIRECTION (RIGHT).  $D_p$  IS THE DISTANCE BETWEEN ADJACENT PLANES

Figure 2-3 shows the arrangement of satellites, depending on whether simultaneous visibility of 1 or 2 satellites is required, as well as

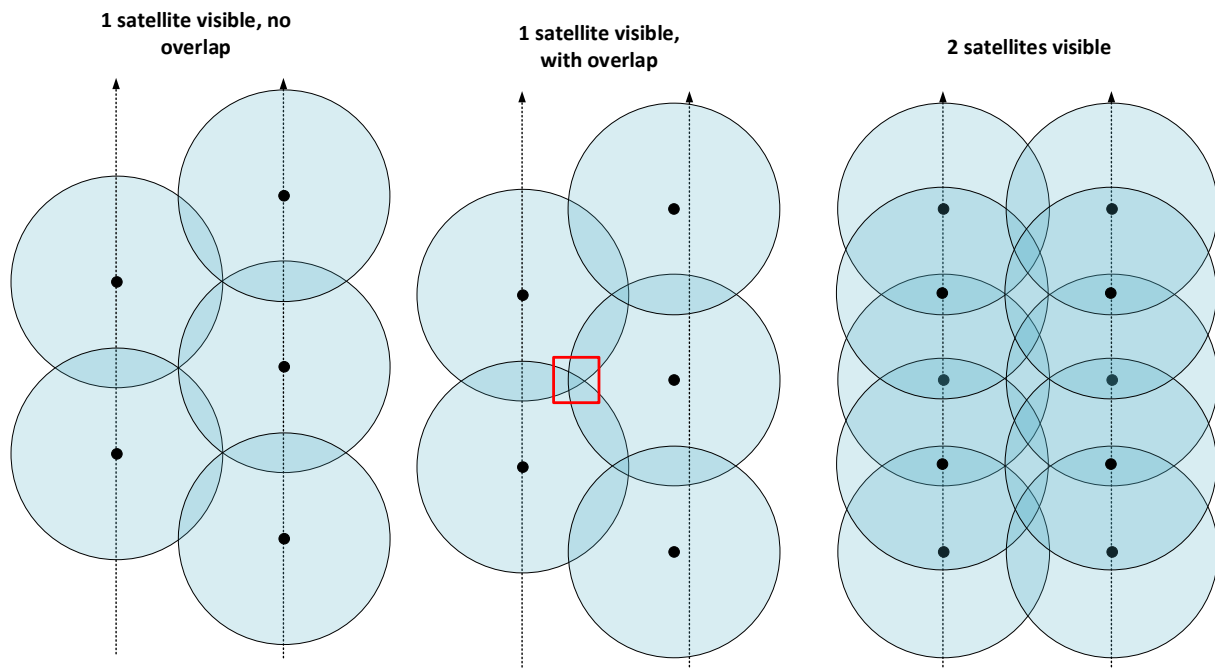


FIGURE 2-3 OVERLAP REQUIRED TO PROVIDE FULL COVERAGE WITH 1 SATELLITE VISIBLE (LEFT), 1 SATELLITE VISIBLE WITH MINIMUM OVERLAP DURATION (MIDDLE), 2 SATELLITES VISIBLE (RIGHT)

## 2.3 OUTPUTS

For the inputs defined above, the optimal constellation configuration (minimum number of satellites) required to provide the defined coverage is determined. The optimal constellation is computed for a range of altitudes between 250 km to 900 km (see trade-off [6] of Task 3.3).

## 2.4 FEEDER LAYER

As discussed in D3.7 [Error! Bookmark not defined.], a second feeder layer is proposed – each feeder satellite is connected a number of service satellites by an Optical Inter-Satellite Link (OISL), and provides a connection to feeder stations on ground, and to other feeder satellites via OISLs.

If the feeder layer was to operate at a higher altitude compared to the service layer, differences in orbital velocity and other perturbations (such as RAAN precession) will mean that the relative positions of the feeder and service satellites will drift over time. This will require periodic switchovers of service satellites between feeders (requiring extra OISLs), and greater distances for the feeder-service OISLs. In order to relax this constraint and for the first analysis the feeder layer will occupy the same orbit (inclination and altitude) as the service layer, which will allow one feeder to always serve the same service satellites, reducing the need for switchovers and reducing the OISL distances.

There are several different ways the feeder layer can be arranged relative to the service layer. Figure 2-4 and Figure 2-5 show some possible configurations for varying number of service satellites. The different configurations will have implications for the OISL in terms of the inter-satellite distance, required angles, and how much these change over an orbit. For example, in the configuration shown on the right in Figure 2-5, the two OISLs to the service satellites ahead and behind the feeder satellite will have a constant distance and orientation, whereas the ones

to satellites either side will vary over the orbit. This is especially true at the poles where the satellites on either side will swap sides.

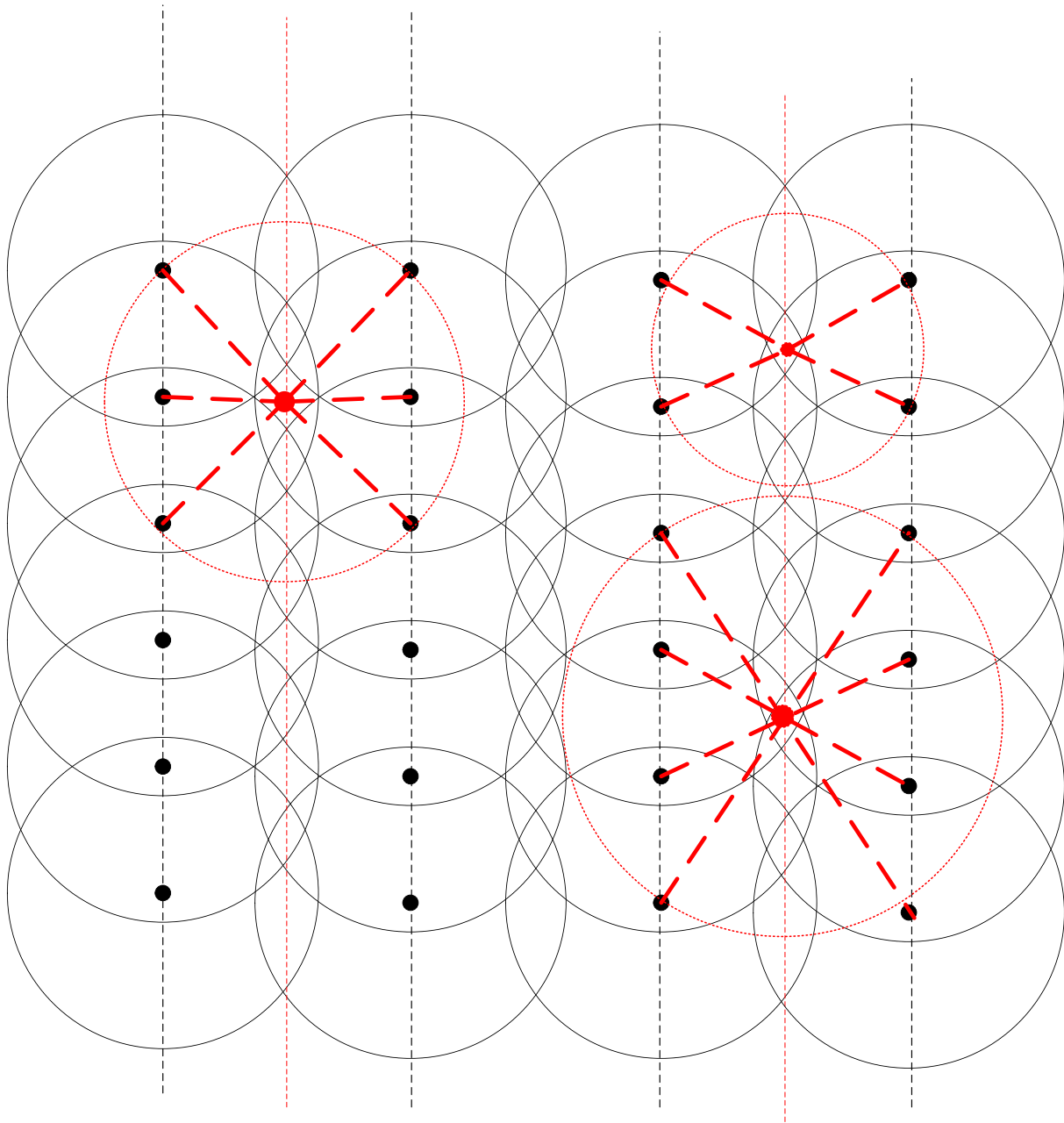


FIGURE 2-4 POSSIBLE CONFIGURATIONS OF FEEDER-SERVICE OISLS, FOR 4, 6, AND 8 SERVICE SATELLITES PER FEEDER, FOR SERVICE CONSTELLATIONS WITH AN EVEN NUMBER OF MINIMUM VISIBLE SATELLITES. FEEDER SATELLITES IN RED, SERVICE SATELLITES IN BLACK

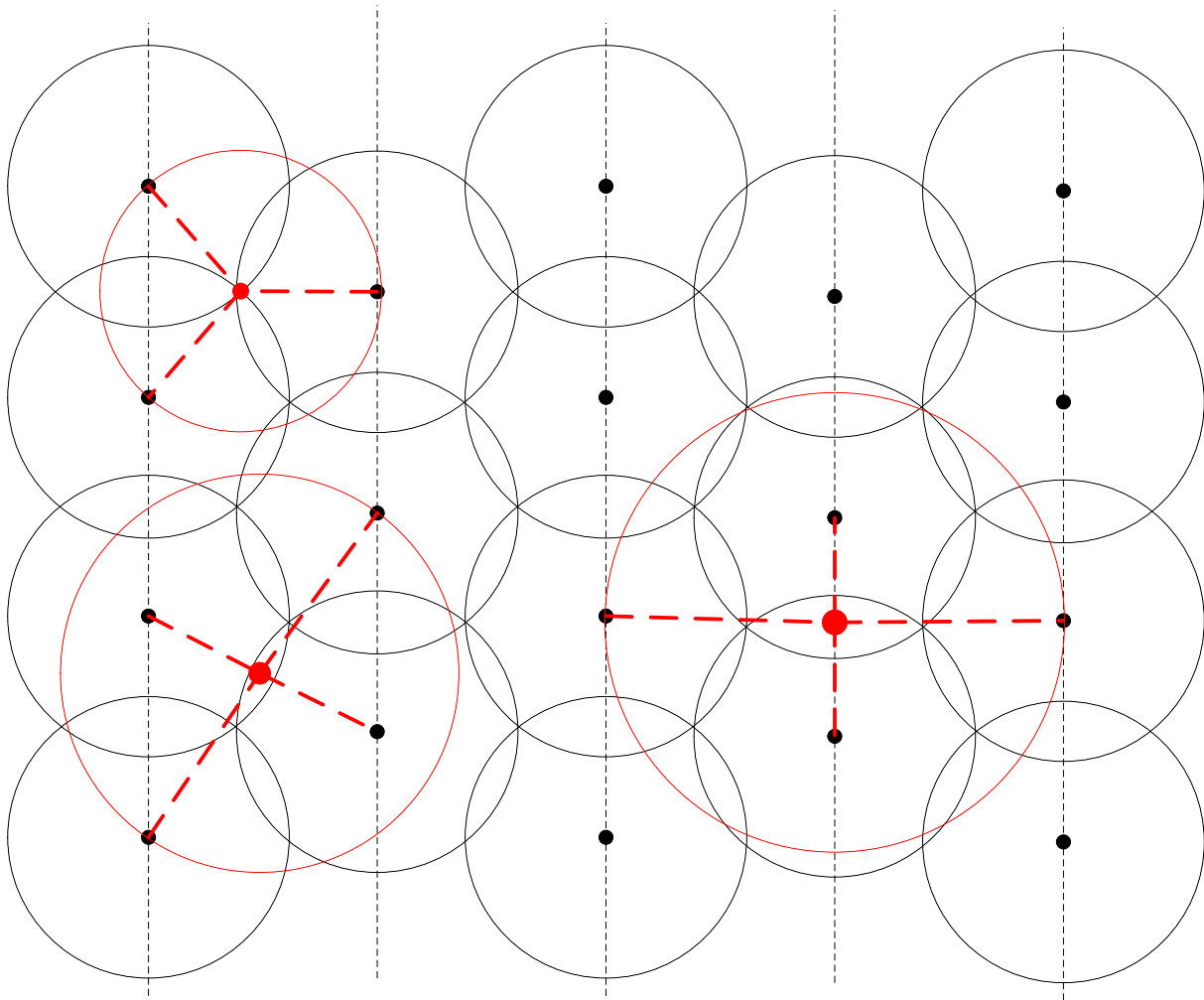


FIGURE 2-5 POSSIBLE CONFIGURATIONS OF FEEDER-SERVICE OISLS, FOR 3 AND 4 SERVICE SATELLITES PER FEEDER, FOR SERVICE CONSTELLATIONS WITH AN ODD NUMBER OF MINIMUM VISIBLE SATELLITES. FEEDER SATELLITES IN RED, SERVICE SATELLITES IN BLACK

Depending on the configuration of the service satellites, there are also different configurations for how the feeder satellites are positioned.

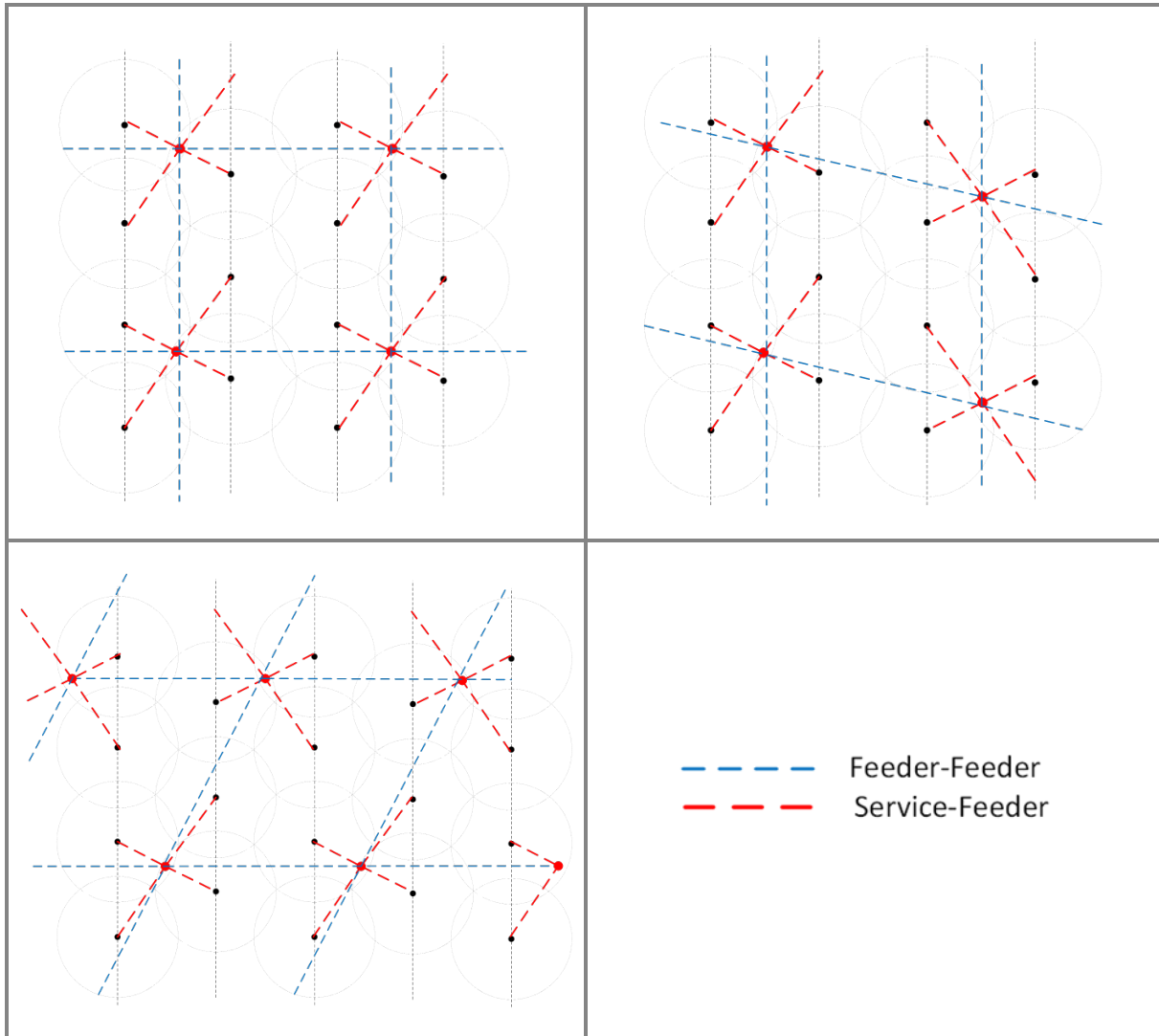


Figure 2-6 gives some examples of how the feeder satellites and feeder-feeder OISLs can be configured relative to the service satellites, in this case where each feeder is connected to 4 service satellites, and a minimum of 1 service satellite is visible to users.

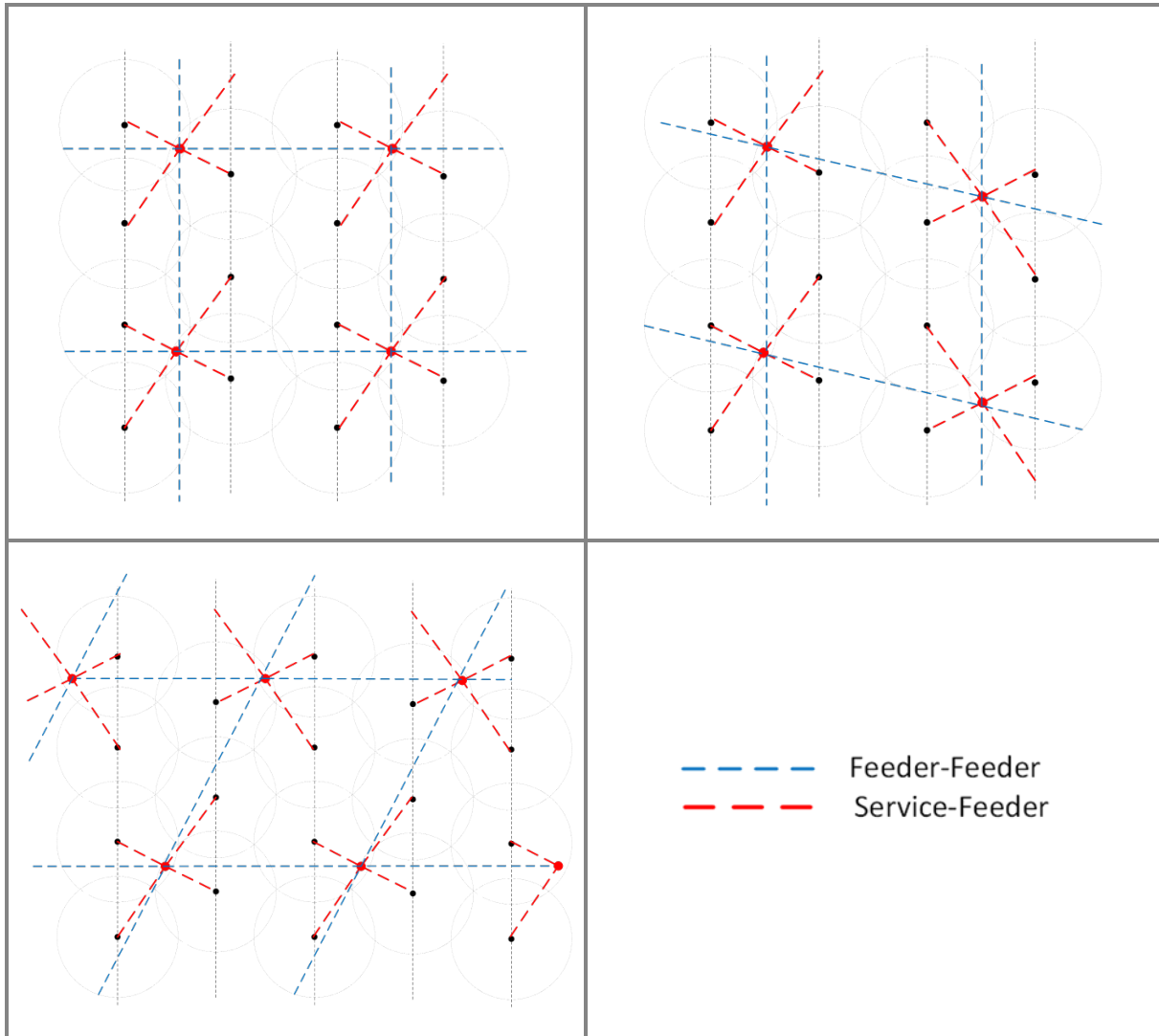


FIGURE 2-6 SOME POSSIBLE CONFIGURATIONS OF THE FEEDER CONSTELLATION, ASSUMING EACH FEEDER SATELLITE SERVES 4 SERVICE SATELLITES, AND 1 A MINIMUM OF 1 SERVICE SATELLITE VISIBLE TO THE USER

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## 3 IMPACT OF ALTITUDE

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The altitude of the constellation has a significant impact on the number of required satellites, as well as other parameters such as the RTT (Round Trip Time) of a signal and the Doppler shift – these impacts are discussed in this section. Currently, this analysis excludes the impact on the payload, such as the required antenna gain, required radiated power etc.

### 3.1 NUMBER OF SATELLITES

The primary output of the sizing model is the number of satellites required to provide the defined coverage. Figure 3-1 shows the optimal number of satellites to provide the defined coverage against altitude. In this example, the coverage is defined as a minimum of 1 satellite visible with a minimum 10s overlap between satellites, near polar orbit to ensure complete global coverage and a minimum user elevation of 45°. This shows as expected, fewer satellites are required at higher altitudes as each satellite can cover a larger area of the Earth. The graph of numbers of planes and number of satellites per plane is “jagged” because the sizing model requires that satellites and planes are equally spaced and does not allow for non-integer numbers, sometimes causing “jumps” in the calculation numbers. As stated in Section 2, this only accounts for the satellites that provide coverage to UEs, the feeder satellites are not included.

While lower altitudes require more satellites to provide the same coverage compared to higher altitudes, the reduced slant range between the satellite and the UE means that higher data rates/capacities can be achieved, or lower powers (and therefore smaller/cheaper satellites) can be used. The lower altitude and increased number of satellites also reduces the separation between the satellites, thereby also improving the data rate or reducing the size and/or power required by the OISLs. Finally, as satellites at lower altitudes each cover a smaller portion of the surface of the Earth, they can either be smaller than their higher altitude counterparts while delivering the same capacity, or deliver a higher capacity.

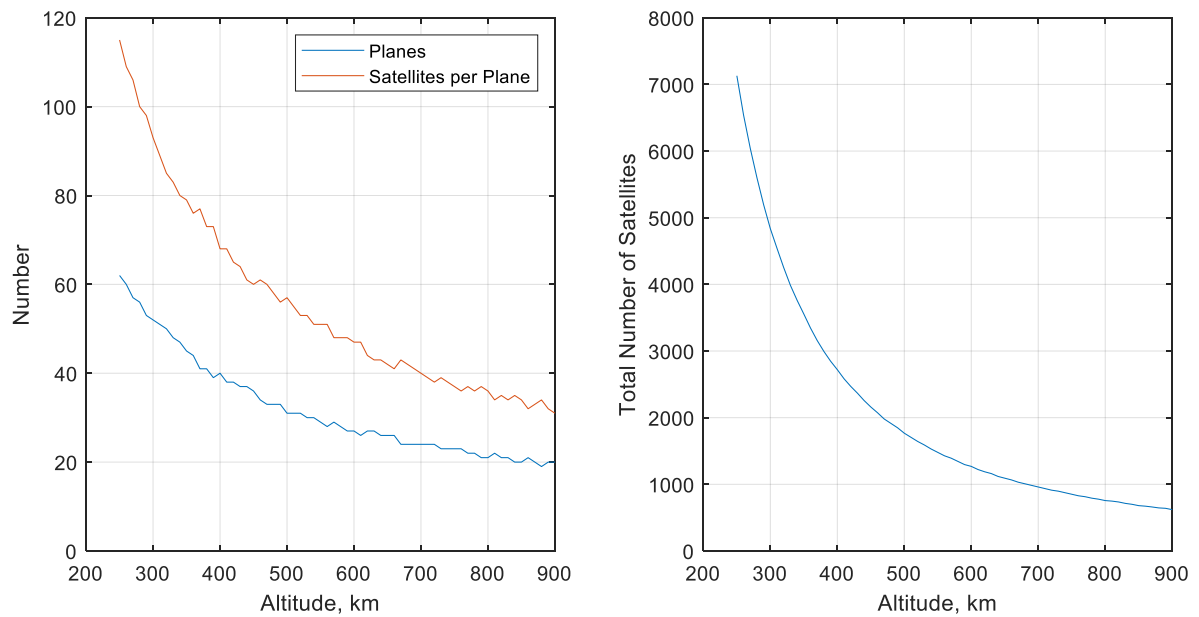


FIGURE 3-1: OPTIMAL NUMBER OF PLANES AND SATELLITES PER PLANE (LEFT) AND TOTAL NUMBER OF SATELLITES (RIGHT) FOR A NEAR-POLAR ORBIT, MINIMUM OF 1 SATELLITE VISIBLE WITH MINIMUM 10 SECOND OVERLAP, MINIMUM USER ELVATION OF 45°

The optimal number of satellites varies depending on the other input parameters. Figure 3-2 shows how the total number of satellites varies with user elevations between 30° and 50° - lower user elevations reduce the number of satellites required (as the FoV of each satellite increases), but increases the maximum slant range between the user and satellite, and increases the off-nadir angle the satellite needs to support.

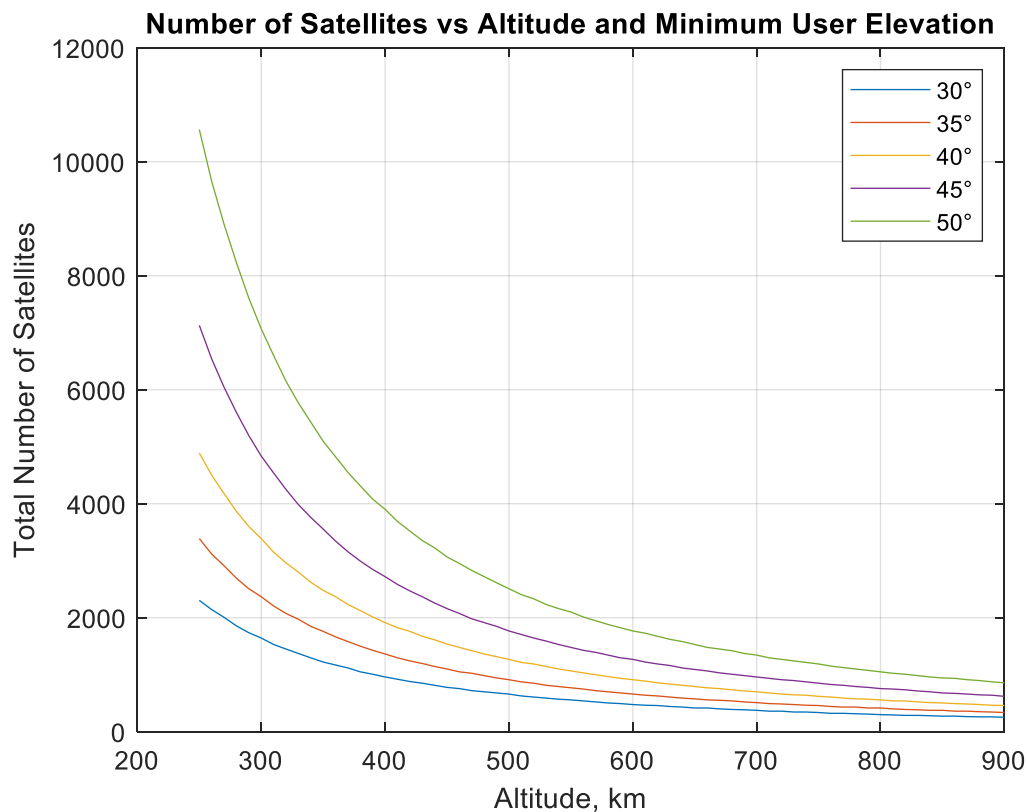


FIGURE 3-2 TOTAL NUMBER OF SATELLITES FOR A NEAR-POLAR ORBIT, MINIMUM OF 1 SATELLITE VISIBLE WITH MINIMUM 10 SECOND OVERLAP, FOR VARIOUS MINIMUM USER ELEVATIONS

### 3.2 DOPPLER SHIFT

Figure 3-3 shows the worst-case magnitude of relative Doppler shift (or Doppler shift fraction) that a user would experience, as a function of altitude, for a minimum elevation of 45°. The worst case occurs for a user at the very edge of the satellite FoV, who is directly on the satellite ground track. For example, at a constellation altitude of 600km, the worst-case relative Doppler shift is  $1.63 \times 10^{-5}$ , so for a nominal frequency of 4GHz, the user will experience a Doppler shift of  $\pm 65$ kHz. Over the full altitude range, at 250km the worst-case Doppler shift would be  $\pm 70$ kHz and at 900km would be 61 kHz. Whilst the Doppler shift is worst at the lowest altitudes compared to the highest. Nevertheless, for each specific case the compatibility with the UE tracking shall be compatible and should be taken into account in the final analysis.

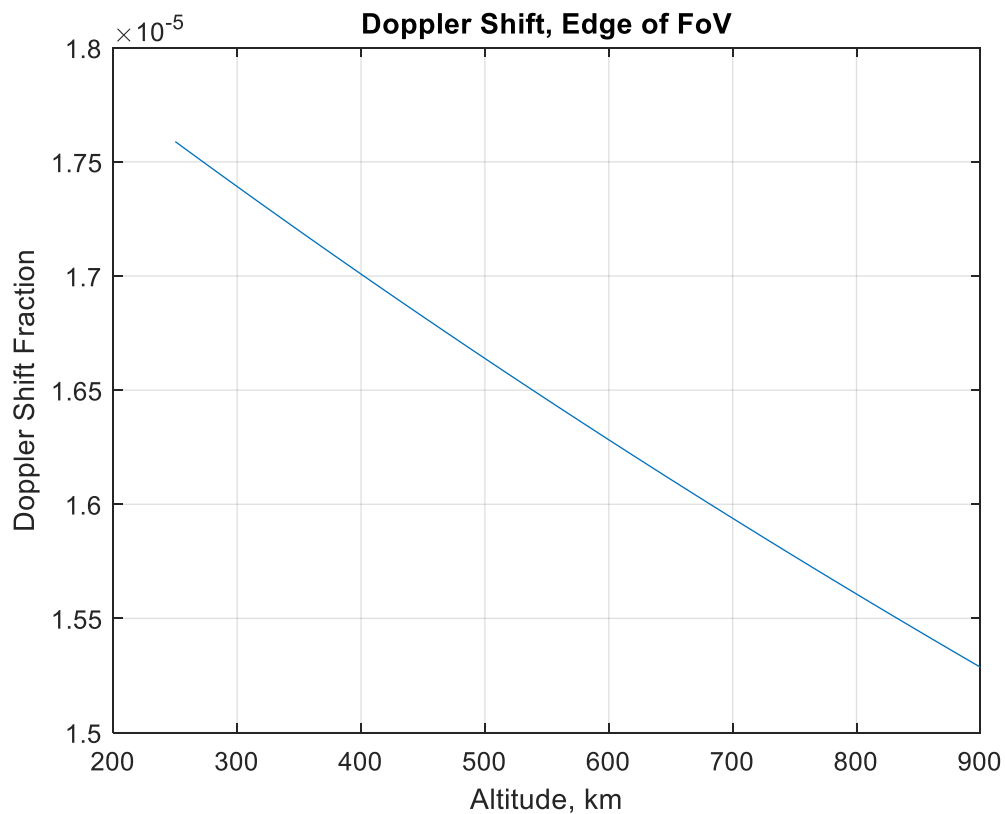


FIGURE 3-3 RELATIVE DOPPLER SHIFT EXPERIENCED BY A USER AT THE EDGE OF THE SATELLITE FOV (WHICH IS THE WORST CASE), FOR A MINIMUM USER ELEVATION OF 45°, FOR A RANGE OF SATELLITE ALTITUDES

Figure 3-4 shows the worst-case differential relative Doppler shift (the biggest difference in Doppler shift experienced by users within the same cell), for a range of cell diameters. Here, the worst-case differential shift is experienced in the cell directly beneath the satellite. For an altitude of 600km and a cell size of 45km, at 4GHz the differential Doppler shift over the cell would be 7.6kHz.

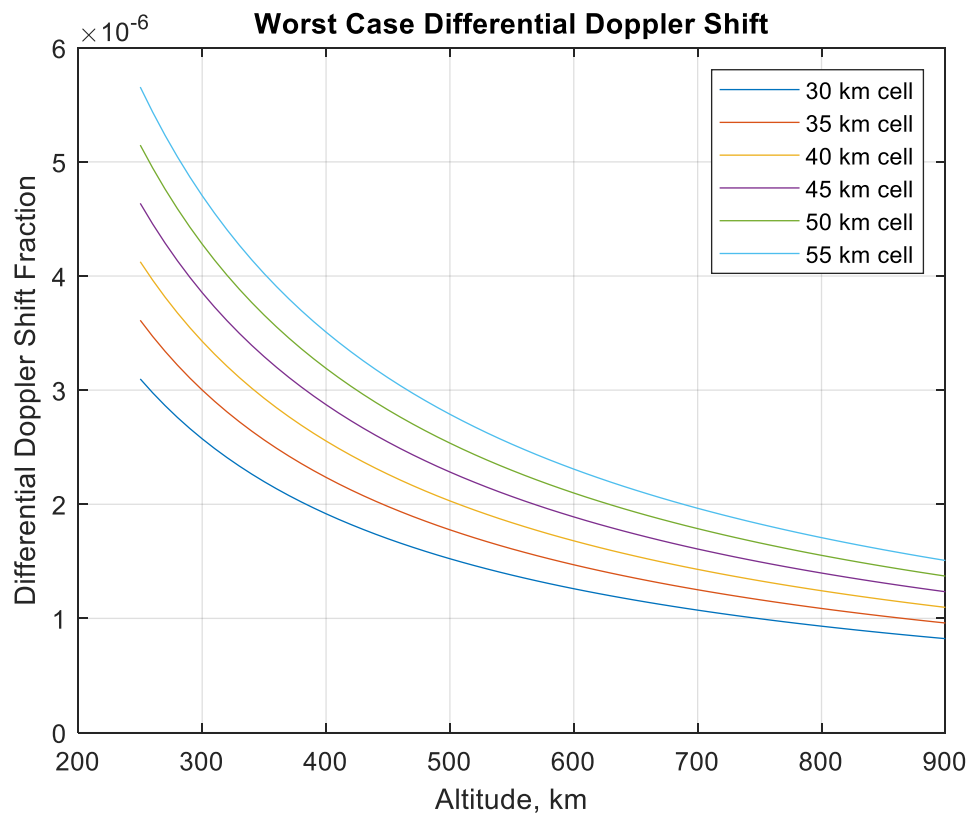


FIGURE 3-4 WORST CASE RELATIVE DIFFERENTIAL DOPPLER SHIFT EXPERIENCED ACROSS ONE CELL/BEAM, FOR DIFFERENT ALTITUDES AND CELL SIZES.

### 3.3 ROUND TRIP TIME (RTT)

The round trip time (RTT) is calculated as the time taken for a signal to travel from a UE to a target specified and back. Any delays incurred due to processing on the satellite(s) and feeder station are neglected, therefore the computed RTT is simply proportional to the distance the signal has to travel. Several cases are presented below, calculated between a UE and a target satellite or feeder station. The distance the signal travels varies depending on where the UE, feeder station and satellite(s) are relative to each other (for example, whether the UE is directly below the satellite or closed to the edge of the satellite FoV), so best and worst case values for RTT are presented.

RTT can give some indication of latency a user will experience, however the actual latency will depend on where the signal needs to be routed, and therefore will require a more detailed analysis. The RTT values calculated below only consider at most the signal routing from the UE to a feeder station via a single feeder satellite – in reality the signal may be routed through several feeder satellites before reaching the feeder station, and will need to travel further from the feeder station to the required destination/server and back, which will increase the RTT further. More nodes in the chain will also increase the additional processing time required, which is not accounted for here.

#### 3.3.1 UE -> Service Satellite

Figure 3-5 shows the best (UE directly below the satellite) and worst (UE at the edge of the satellite FoV) RTT computed vs altitude, for a signal between a UE and the satellite it is

connected to. There is an approximate linear relationship between the RTT and altitude. Here the edge of the FoV is defined by a minimum elevation for the UE of 45°.

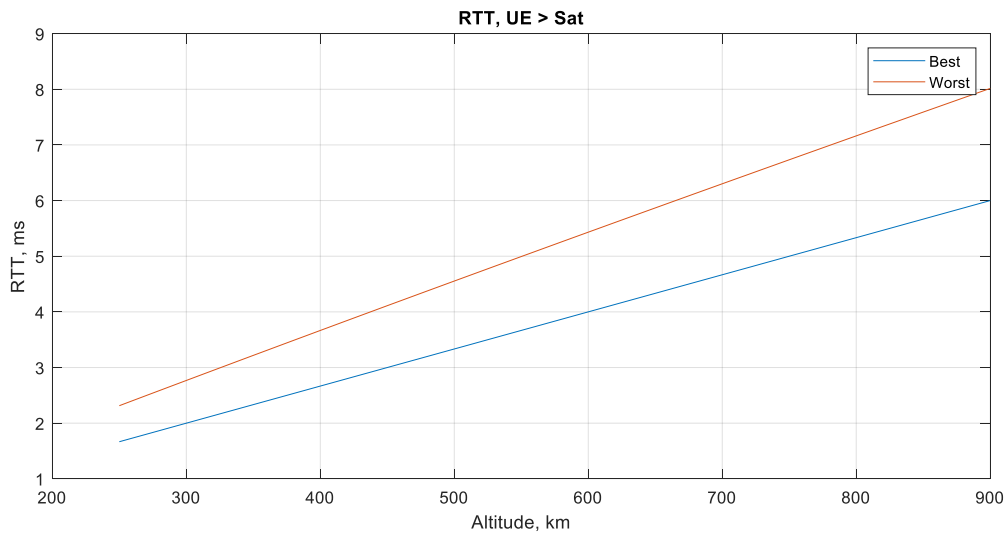


FIGURE 3-5 RTT FOR A USER TO SATELLITE VS ALTITUDE. BEST – UE DIRECTLY BELOW THE SATELLITE, WORST – UE AT EDGE OF FOV

### 3.3.2 UE -> Service Satellite -> Feeder Station (Gateways)

The RTT between a UE to a ground feeder station via 1 satellite has also been computed and is shown in Figure 3-6. Here the best case is when UE and feeder station are directly below the satellite, and the worst case is when the UE and feeder stations are at the edge of the satellite FoV. The FoV for the UE is again defined as a minimum elevation of 45°, and for the feeder station it is defined by a minimum elevation of 10° (as assumed in 3GPP).

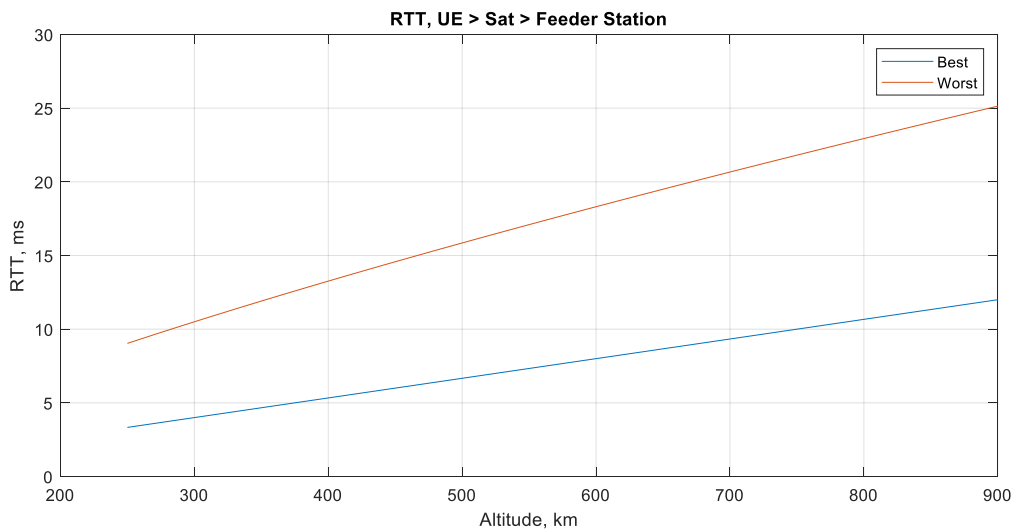


FIGURE 3-6 RTT FOR A USER TO FEEDER STATION VIA 1 SATELLITE VS ALTITUDE. BEST – UE AND FEEDER STATION DIRECTLY BELOW THE SATELLITE, WORST – UE AND FEEDER STATION AT EDGE OF FOV

### 3.3.3 UE -> Service Satellite -> Feeder Satellite ->Feeder Station (Gateway)

In a double layer constellation, users will connect to a service satellite, which will communicate with the feeder station via a separate feeder satellite. Figure 3-7 shows the best- and worst-case RTT for a user communicating with a feeder station via a service satellite and 1 feeder satellite. The best- and worst-case UE and feeder station positions relative to the satellites are the same as discussed above. Also, for the best case the service-feeder satellite distance is at a minimum (over the poles) and for the worst case the separation is at the maximum (over the equator). The variation in distance between the service and feeder satellites can be seen in more detail in Section 5.3. Here it is assumed that each feeder satellite serves 4 service satellites, and they are arranged as shown in Figure 5-3.

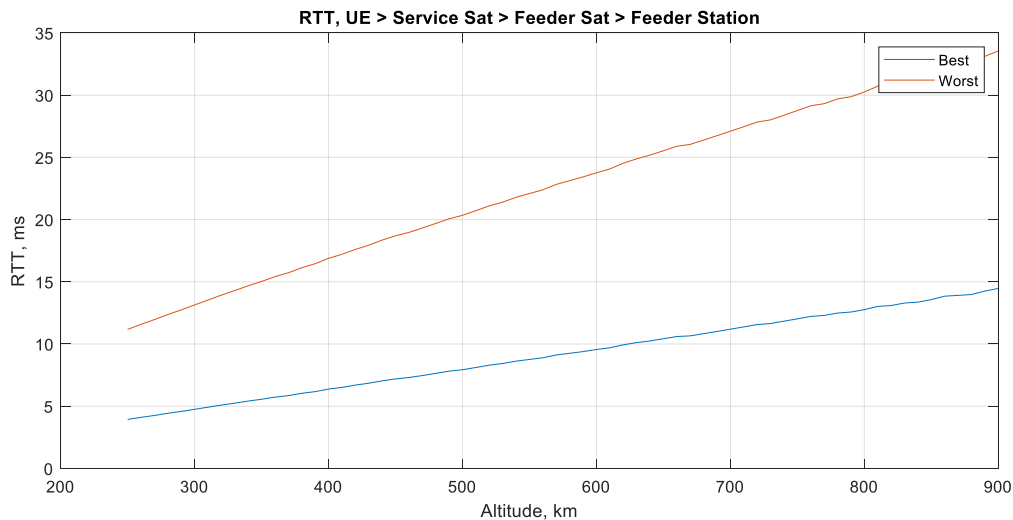


FIGURE 3-7 RTT FOR A USER TO FEEDER STATION VIA 2 SATELLITES (SERVICE SATELLITE AND FEEDER SATELLITE) VS ALTITUDE. BEST – UE AND FEEDER STATION DIRECTLY BELOW THE SATELLITES AND THE SERVICE/FEEDER SATELLITES AT THEIR MINIMUM SEPARATION, WORST – UE AND FEEDER STATION AT EDGE OF FOV AND THE SERVICE/FEEDER SATELLITES AT THEIR MAXIMUM SEPARATION

### 3.3.4 RTT Variation

The RTT will vary for a user depending on where the user is relative to the satellite. The worst case RTT variation is plotted in Figure 3-8. Here the worst case RTT variation is the difference computed for three different cases:

1. Handover: the difference in RTT (between the user and whatever the source/destination is of their data) when being handed over from one satellite to another. Here it is assumed that the difference in distance travelled by the signal is the same as the distance between the two satellites the user is handed over between.
2. Satellite FoV: the biggest difference in RTT users connected to the same satellite will experience – the two extremes are the for a user at the edge of the FoV and a user directly below the satellite.
3. Beam: the biggest difference in RTT users within the same beam will experience. Here the worst case occurs between a user at the nearest edge of the beam to the satellite and a user at the furthest edge of the beam, for a beam at the extreme edge of the satellite FoV. Here a beam/cell diameter of 45km is assumed. This is also known as differential RTT.

Figure 3-9 demonstrates how the different RTT cases are defined and calculated.

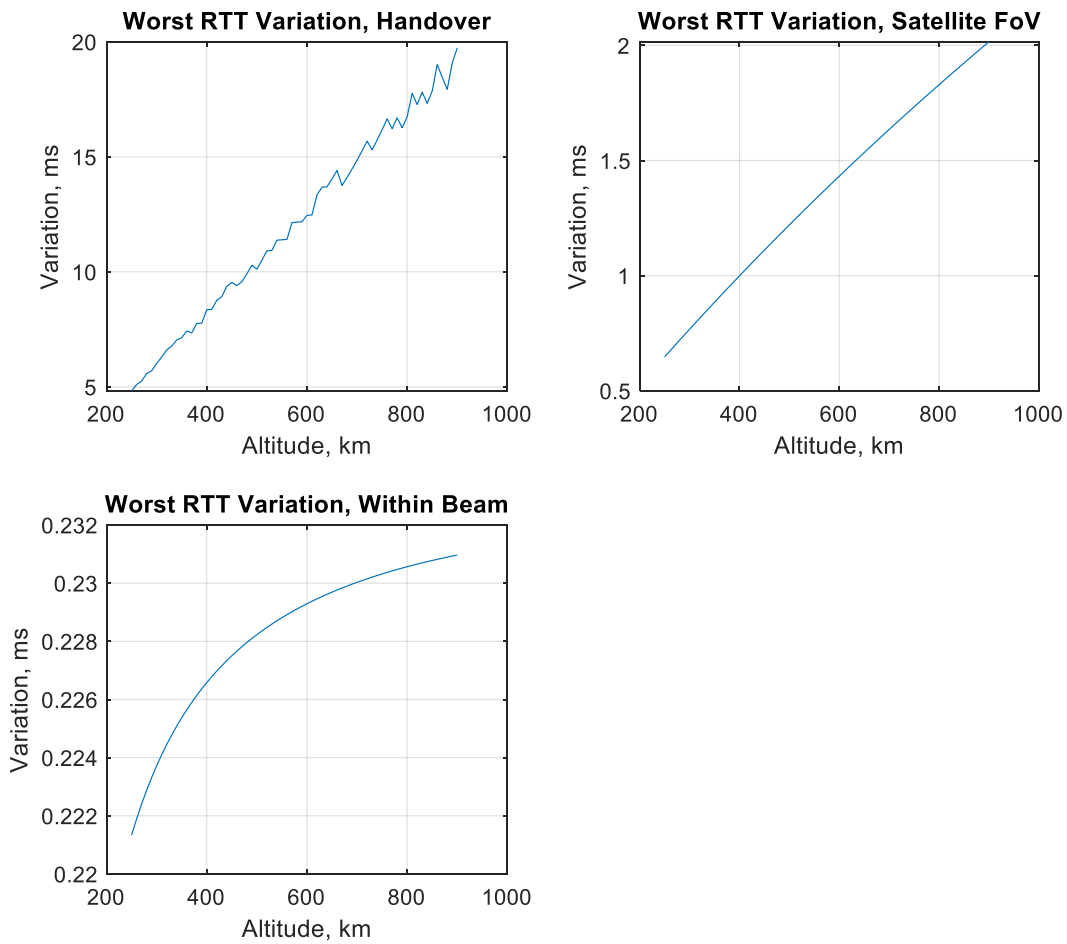


FIGURE 3-8 WORST CASE RTT VARIATION VS ALTITUDE, MINIMUM OF 1 SATELLITE VISIBLE WITH MINIMUM 10 SECOND OVERLAP, MINIMUM USER ELEVATION OF 45°.

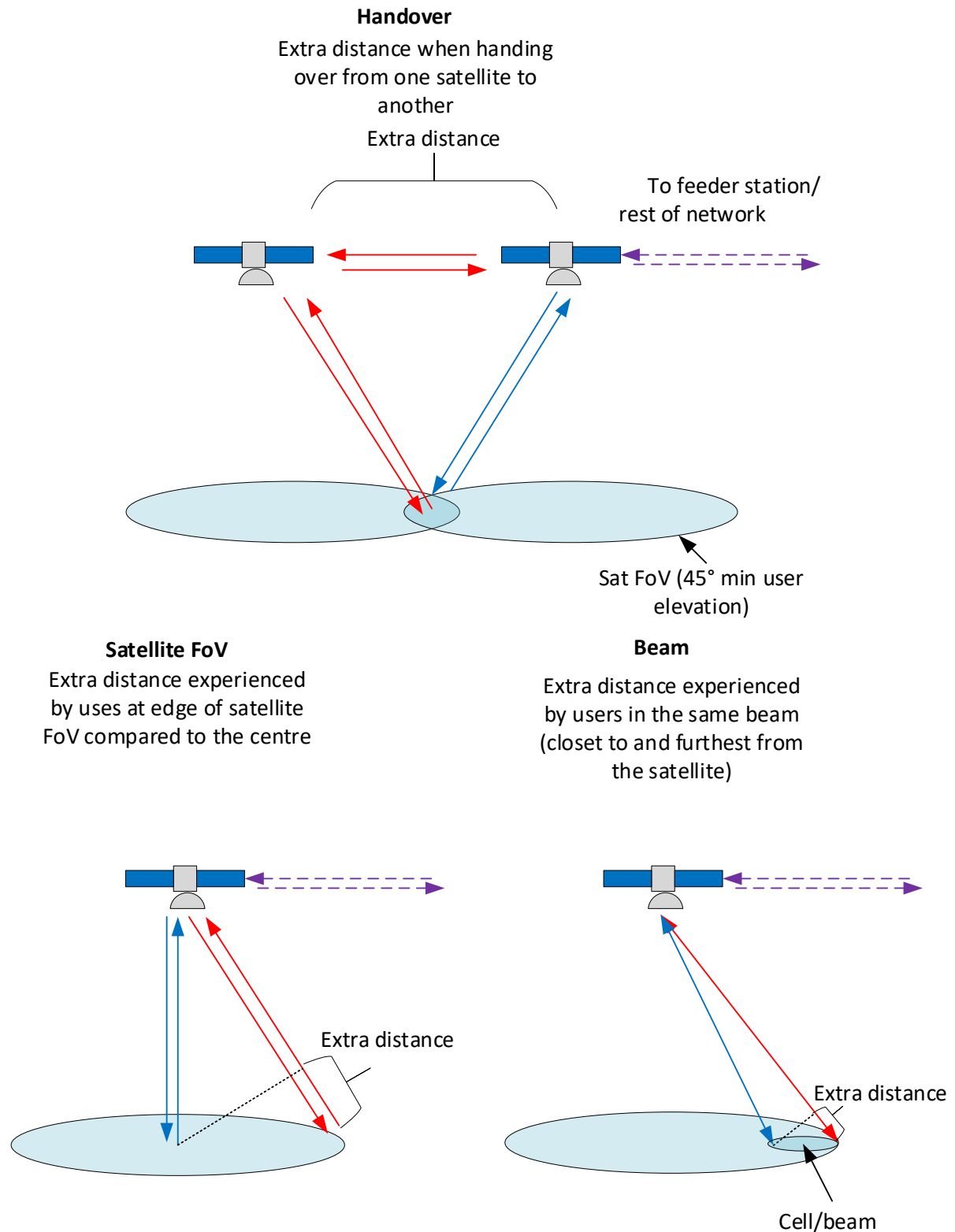


FIGURE 3-9 DIAGRAM OF HOW THE DIFFERENT RTT VALUES ARE COMPUTED FOR THE DIFFERENT CASES

### 3.4 IMPACT OF POINTING ERRORS

Error in the satellite pointing (or pointing knowledge) will result in errors in the position of the beams/cells on the ground. Figure 3-10 shows the error on ground (in km) depending on the satellite altitude and the user elevation angle, for a satellite pointing error of  $0.1^\circ$ . At 600km directly below the satellite the ground error would be 1km, and at an elevation angle of  $45^\circ$  ground error would be 2km. The error on ground is approximately proportional to the pointing error. For a given pointing error, lower altitudes result in a smaller error on ground.

The  $0.1^\circ$  pointing error is assumed based on existing telecoms platforms. Much greater accuracy is possible if needed – Earth observation satellites generally have pointing errors 1 or 2 orders of magnitude smaller, with position errors on ground measured in tens of m. As the beams are steerable, there will also be pointing errors in the pointing of the beam itself (due to thermal-mechanical distortion etc) that will need to be taken into account as well as the platform pointing errors.

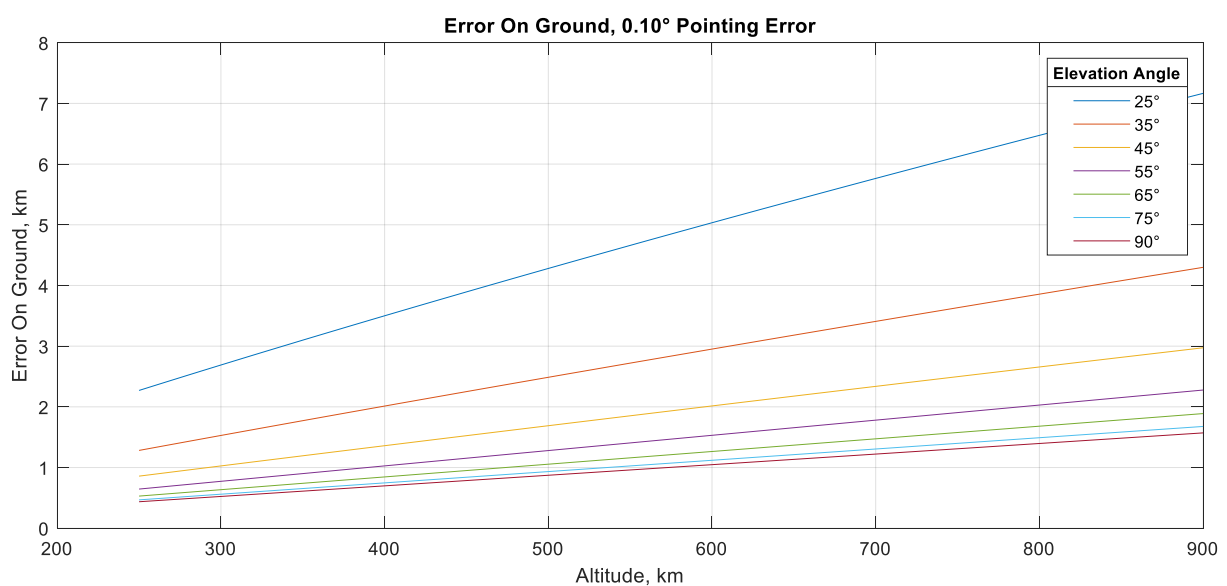


FIGURE 3-10 ERROR ON GROUND DUE TO SATELLITE POINTING ERROR OF  $0.1^\circ$

A pointing error on a satellite can lead to ground position deviations of several kilometers, resulting in performance losses, the need for constant updates, and potentially costly corrective measures. To minimize these errors, technologies such as star trackers, RF sensors, existing GNSS positioning systems, and thermal management devices are employed. Additionally, lower altitudes reduce positioning errors but involve higher satellite speeds and greater thermal variations. Therefore, it is essential to select cell sizes adapted to the available positioning capabilities, which requires an uncertainty budget assessment.

### 3.5 CONCLUSION

This chapter analyzes the impact of satellite altitude on the number of satellites, Doppler shift, Doppler rate, latency, and pointing errors. All these factors influence the overall system performance. This analysis provides guidelines for defining future constellations and contributes to the set of parameters considered so far.

## 4 CONSTELLATION INVESTIGATIONS

The work conducted in this deliverable in relation with [1] and [6], provide a comprehensive analysis of the trade-off between system design and satellite payloads, the initial trade-off was based on limiting the unit cost of each satellite (as a simplification) as well as restricting the total number of satellites, in order to control the overall system cost. To further refine this trade-off and to complete the study, additional investigations were carried out and alternative solutions have been studied in [6] with the aim of improving the performance of the initially defined solution. More specifically, the VLEO case (case B) was considered, along with an enhanced version of the initial LEO (case C). The first case relies on the assumption of a significantly reduced launch cost, while the second case (Case C) assumes very limited cost evolution of components [6]. These cases will be evaluated at the end in [1] in term of cost effort.

The constellation solutions resulting from these trade-offs are summarized below:

### For C Band :

- 3 CASES estimated → Case A B C (dimensioned for min EL 45)
  - **A** LEO 600 km 1056 RE ( reference performances)
  - **B** VLEO 350 km 1536 RE (improved performances)
  - **C** LEO 600 km 2048 RE (improved / could ensure smaller up to  $EL_{\min} 30^\circ$ )
  - For each case, three architectures 1, 2 & 2' are proposed :
  - 1 constellation ( service + feeder)
  - 2 : 1 constellation (service) & 1 constellation feeder
  - 2' (\*) : 1 constellation (service simplified) & 1 constellation feeder

(\*) The architecture 2' is an alternative to 2 defined in where the service satellite is limited to the minimum of equipment (see [6]).

### For Q/V Band:

- 1 CASE estimated → Case A ( dimensioned for min EL 45)
  - A LEO 600 km 7 DRA antenna of 512 RE in Tx and 7 DRA of 512 RE in Rx( reference performances)
  - For this case, two configurations (architectures 1, 2)
  - 1 constellation ( service + feeder)
  - 2 : 1 constellation (service) & 1 constellation feeder

REM: The architecture 2' is not envisaged in Q/V band, simplify the satellite is not considered pertinent due to the reduced footprint and volume of the satellites.

Thus, in summary, four constellations need to be defined:

- Constellation Service+ feeder or service at 600 km (reference constellation)
- Constellation feeder at 600 km
- Constellation service + feeder or Service at 350 km
- Constellation feeder at 350 km

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## 5 LEO REFERENCE CONSTELLATION (600 KM): SERVICE OR SERVICE + FEEDER & FEEDER CONSTELLATION

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To allow a more detailed model of the payload, link budgets, and constellation to be developed, a reference constellation has been defined to allow a consistent baseline to be assessed across all the work packages and tasks.

The reference constellation has been defined based on the following coverage parameters:

- Minimum of 1 satellite visible at any time
- Minimum of 10s overlap between satellites
- Global coverage

Based on the trade-off in D3.9 [6], the following parameters have been chosen:

- Minimum user elevation of 45°
- Near-polar orbit (~87°) to give global coverage
  - The slight deviation from a true polar constellation avoids having all orbital planes intersecting at one point over each of the poles

Issued from trade-off [6] an initial reference altitude of 600km has been chosen.

In the case of a distributed architecture, the feeder layer has been defined such that

- Each feeder satellite connected to 4 service satellites.
- Each feeder satellite is connected to 4 other feeder satellites

This results in the following constellation configuration:

- 1269 service satellites
  - 27 planes of 47 satellites

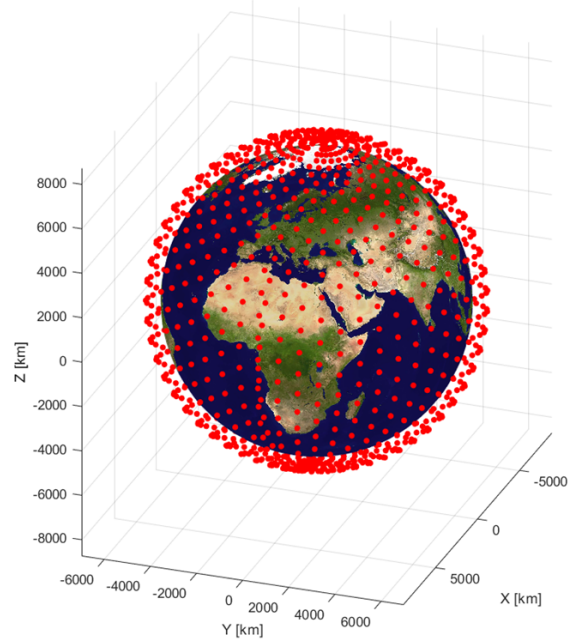


FIGURE 5-1 CONSTELLATION SERVICE+FEEDER OR SERVICE

- 336 feeder satellites
  - 14 planes of 24 satellites.

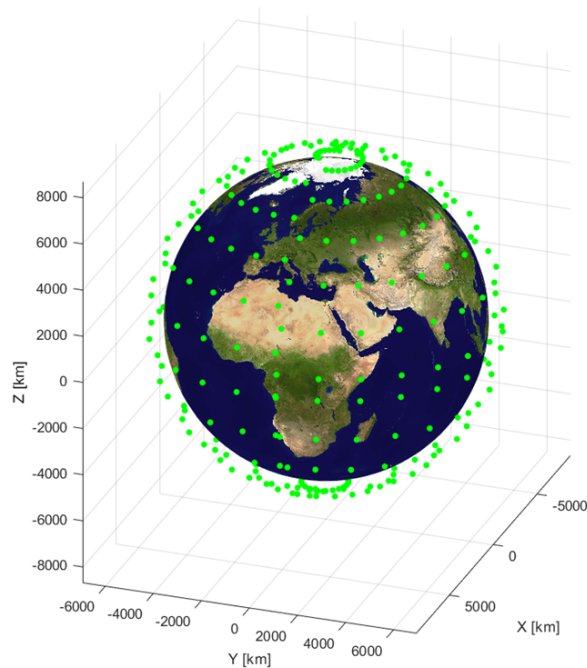


FIGURE 5-2 CONSTELLATION FEEDER

This configuration is shown in Figure 5-3. Here the service satellites and their orbits are shown in red, and the feeder satellites are green. The magenta lines show the service-feeder OISLs and the cyan lines are the feeder-feeder OISLs.

Nominally, each feeder satellite serves 4 service satellites – 2 adjacent satellites in 2 adjacent planes. However, as there are an odd number of satellites in each plane, there is a feeder satellite in each feeder plane that serves only the 1 remaining satellite in each service plane, and as there are an odd number of service planes, 1 plane of feeder satellites only serves this 1 plane. This overlap in feeder satellite coverage results in more feeder satellites required than might be expected (336 compared to  $1269/4 \approx 317$ ).

In this configuration, a feeder satellite plane is in between each pair of service satellite planes.

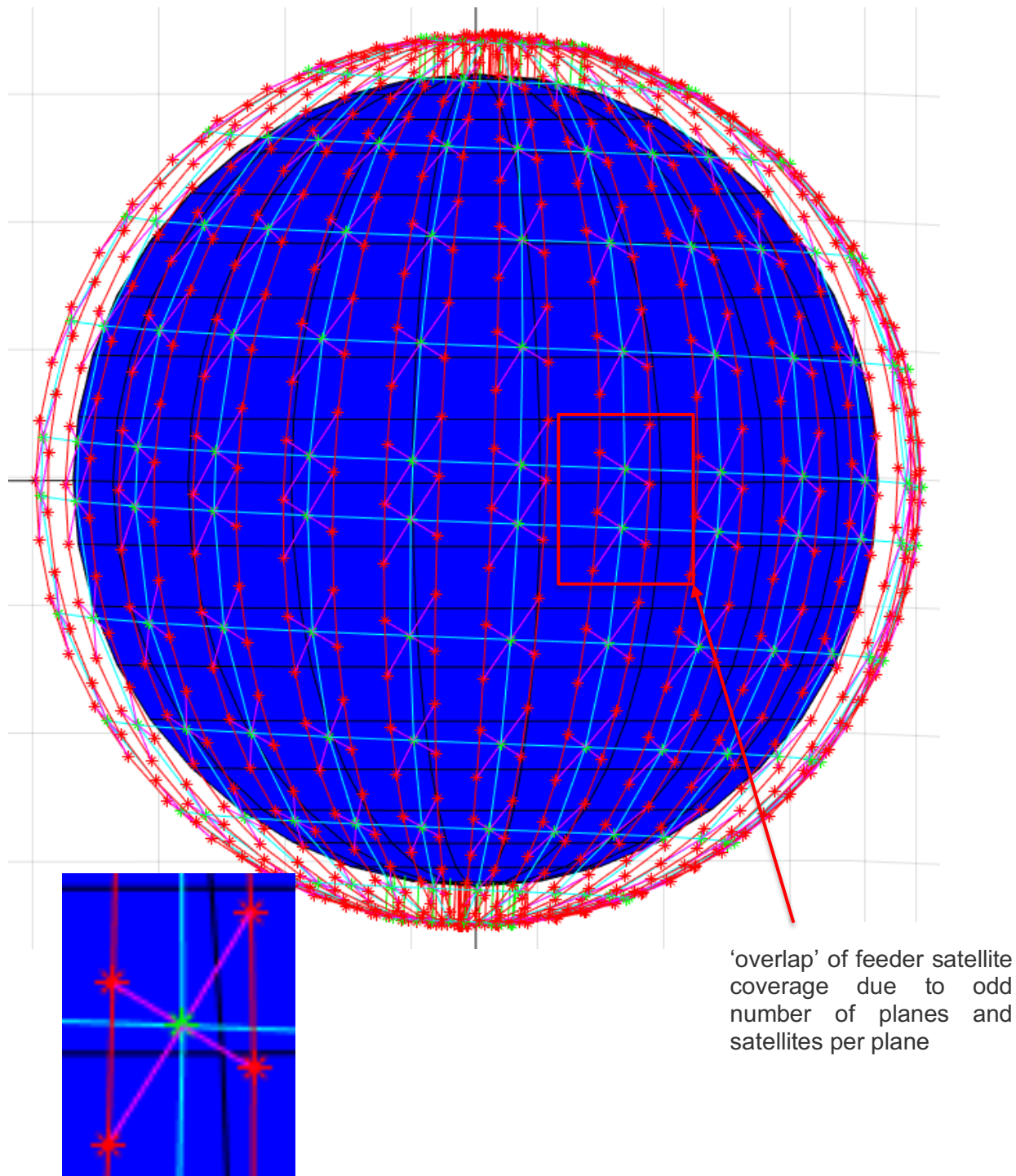


FIGURE 5-3 OVERVIEW OF REFERENCE CONSTELLATION. SERVICE SATELLITES SHOWN IN RED, FEEDER SATELLITES IN GREEN, SERVICE-FEEDER OISLS IN MAGNETA AND FEEDER-FEEDER OISLS IN CYAN

## 5.1 COVERAGE

Figure 5-4 shows the FoV of each service satellite in the reference constellation. The overlaps (here shown at 0° and 180° longitude) are where the ascending and descending planes meet – as these orbits in opposite directions they need to overlap more to provide the required coverage.

At higher latitudes, the satellite FoVs overlap more. Figure 5-5 shows how the un-overlapped area varies with latitude, in terms of area and approximate number of cells (assuming cells are 45km hexagons). Above latitudes of ~65°, there are always at least 2 satellites visible to a user on ground.

Figure 5-6 shows the minimum, maximum and average number of satellites visible to a user on ground, depending on their latitude. This demonstrates that the minimum of 1 satellite visible is always achieved.

Figure 5-7 shows a histogram of the number of cells [6] supported by each satellite, assuming each cell is connected only to the nearest satellite. This does not account for cells that are being handed over between satellites and would therefore require simultaneous connection to two satellites.

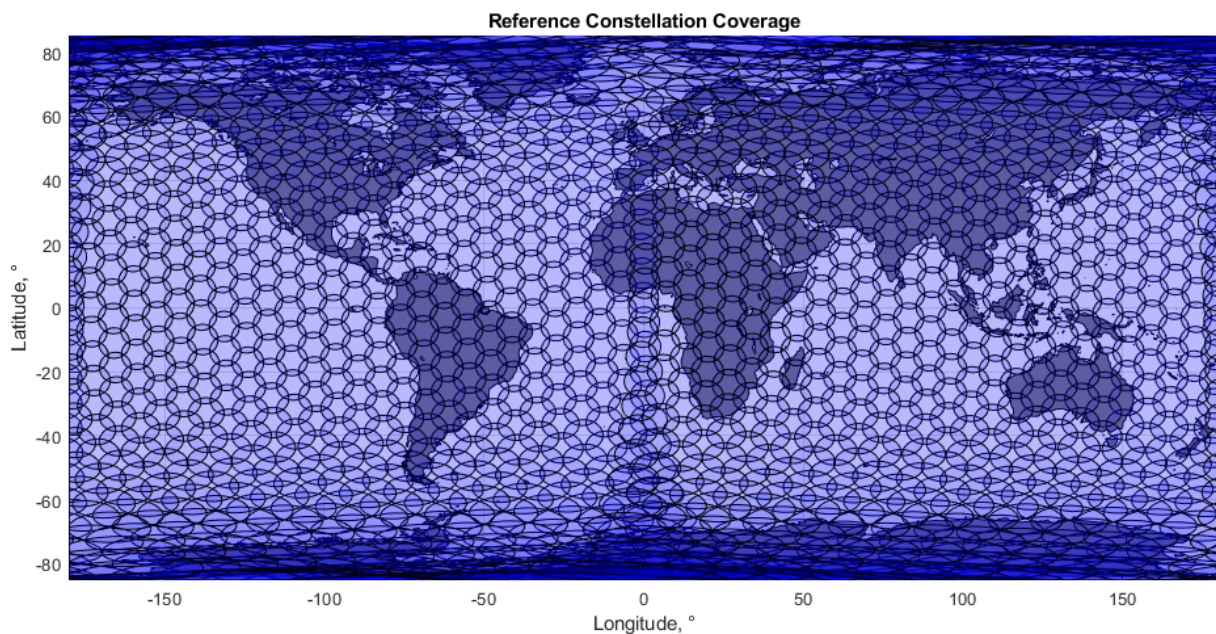


FIGURE 5-4 COVERAGE OF THE REFERNCE CONSTELLATION

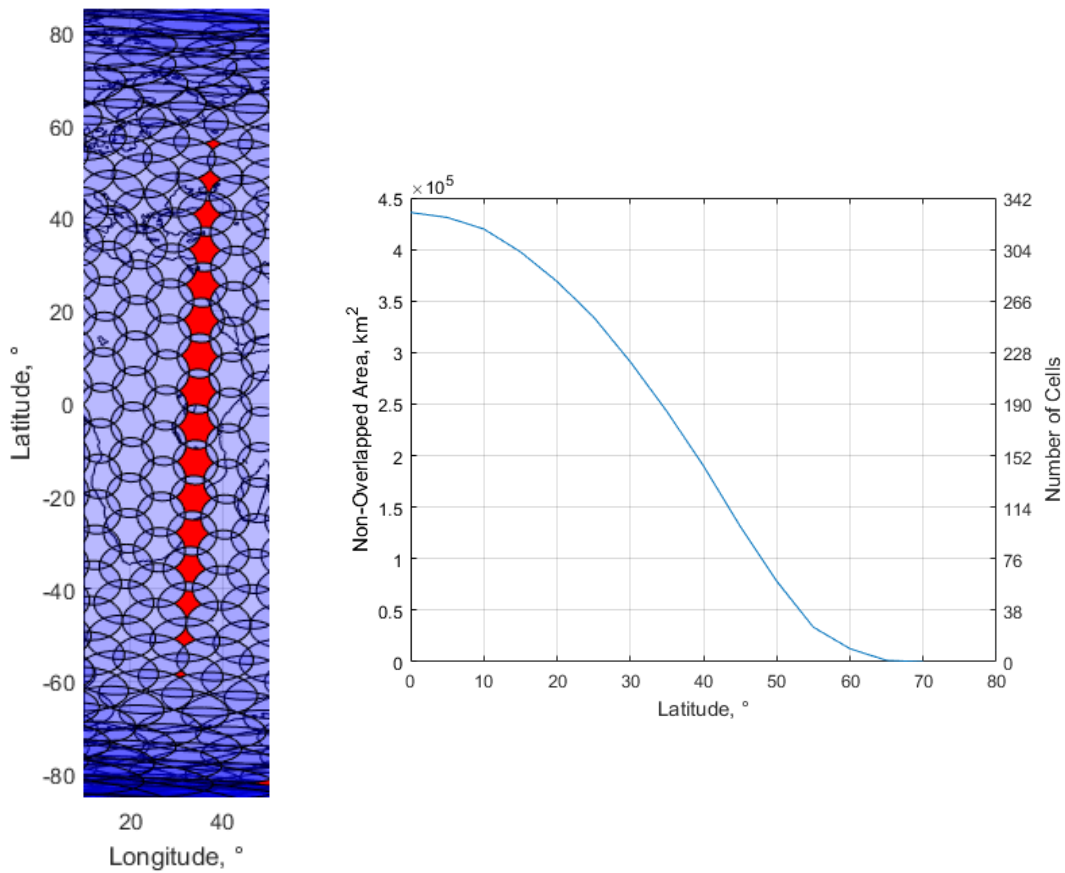


FIGURE 5-5 AREA OF SATELLITE FOV WITHOUT OVERLAP SHOWN (LEFT), AREA WIHTOUT OVERLAP IN KM<sup>2</sup> AND (APPROXIMATE) NUMBER OF CELLS, ASSUMING HEXAGONAL CELLS 45KM ACROSS.

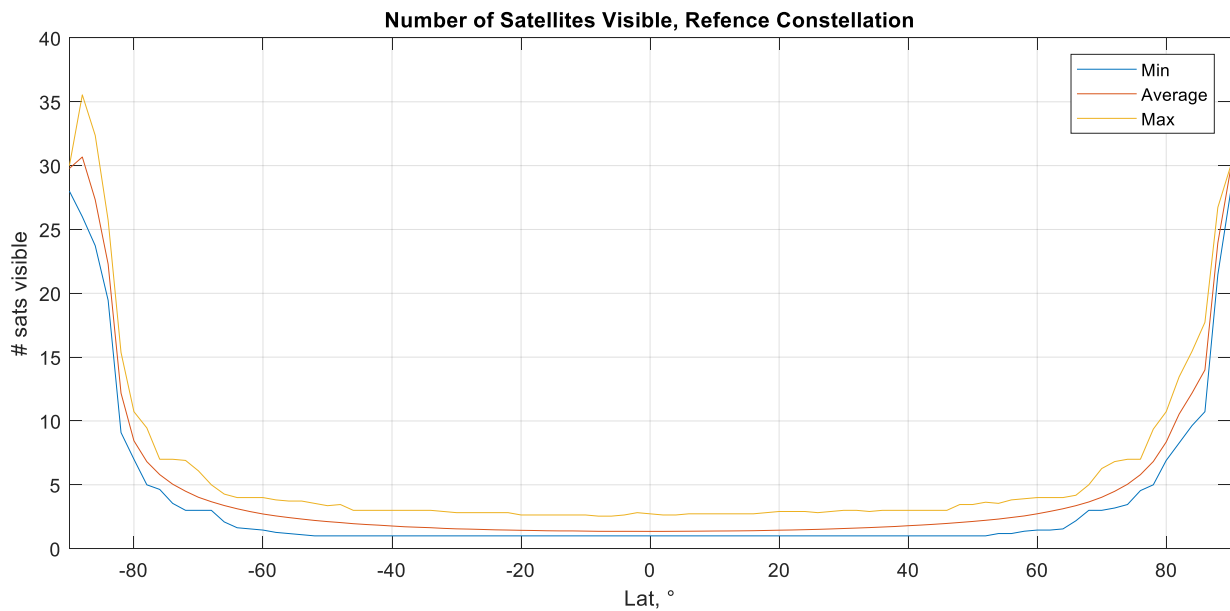


FIGURE 5-6 NUMBER OF SATELLITES VISIBLE (MINIMUM, AVERAGE AND MAXIMUM) VS LATITUDE, FOR THE REFERENCE CONSTELLATION

Remarks: As expected, the satellite overlap is significant in the Polar Regions and appears somewhat excessive compared to the population density in these areas. However, this drawback can be leveraged to optimize thermal control by temporarily deactivating a certain number of satellites during their passage near the poles (mute off RF power). Additionally, alternatives such as a hybrid constellation combining polar and inclined orbits could be considered [see appendix 13.2 & 13.3]. This optimization should be carried out once a distributed traffic model is established.

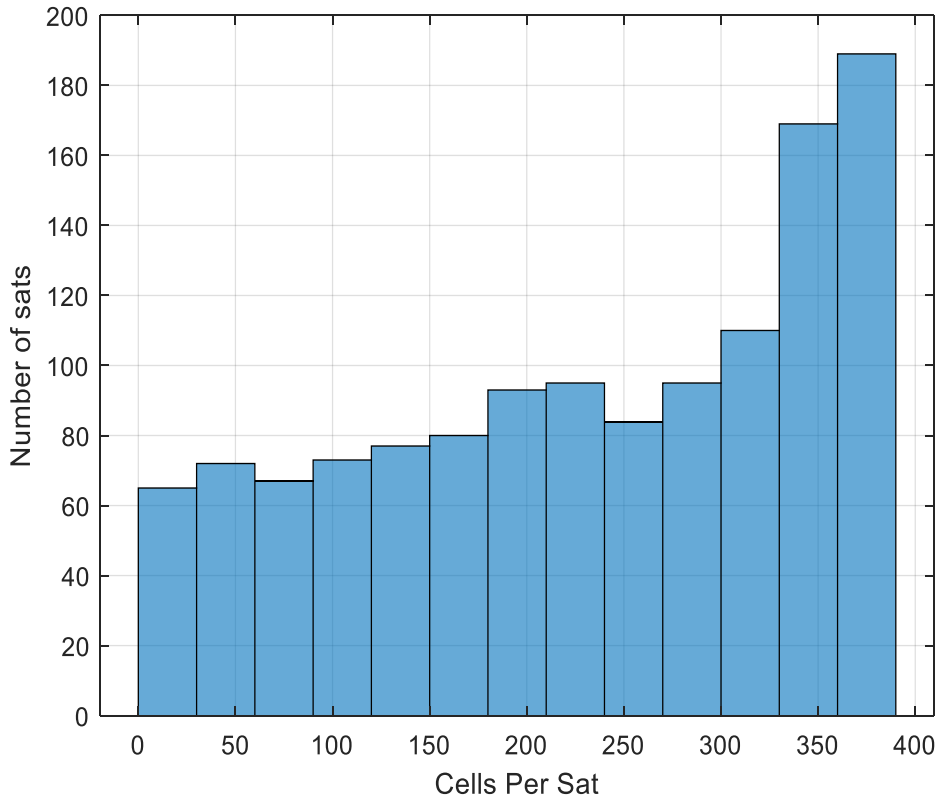


FIGURE 5-7 HISTOGRAM OF THE NUMBER OF CELLS SUPPORTED BY EACH SATELLITE FOR THE REFERENCE CONSTELLATION. THIS ASSUMES THAT EACH CELL IS SUPPORTED BY THE NEAREST SATELLITE ONLY – DUPLICATION OF CELL COVERAGE (WHERE A CELL WOULD NEED TO BE CONNECTED TO TWO SATELLITES SIMULTANEOUSLY) IS NOT ACCOUNTED FOR HERE.

## 5.2 DOPPLER SHIFT

Table 5-1 summarises the Doppler shift experienced for the reference constellation for a range of different frequencies. The maximum Doppler shift is experienced by a user on the satellite ground track when the satellite is at the minimum elevation. The maximum rate of change of Doppler shift is experienced when the satellite passes directly overhead. Appendix A gives these values for a range of altitudes, and also for a minimum elevation of 20°.

TABLE 5-1 DOPPLER SHIFT EXPERIENCED FOR THE REFERENCE CONSTELLATION (600KM ALTITUDE, 45° MINIMUM ELEVATION)

Frequency (GHz)	Max Doppler Shift(kHz)	Relative Doppler Shift	Max Doppler Shift Change (Hz/s)
3	48.9	0.0016%	871.0

4	65.2	0.0016%	1161.3
40	651.6	0.0016%	11612.9
50	814.5	0.0016%	14516.2

### 5.2.1 Variation over Satellite Footprint

The Doppler shift varies depending on where the user is relative to the satellite. This also means there will be a difference in Doppler shift across a single beam/cell. Figure 5-8 (left) shows the relative Doppler shift a user at the centre of each cell will experience. Note that here the relative Doppler shift is given as a decimal number rather than as a %, and that the satellite is moving in the +Y direction and is above the point 0° latitude 0° longitude. Here the greatest relative Doppler Shift is  $\pm 1.6 \times 10^{-5}$ , experienced when the satellite first enters/exits visibility, for a user directly on the satellite's ground track.

Figure 5-8 (right) shows the greatest difference between the relative Doppler shift experienced by users within a single cell. Here the greatest value is  $1.9 \times 10^{-6}$ , experienced in the cell directly below the satellite.

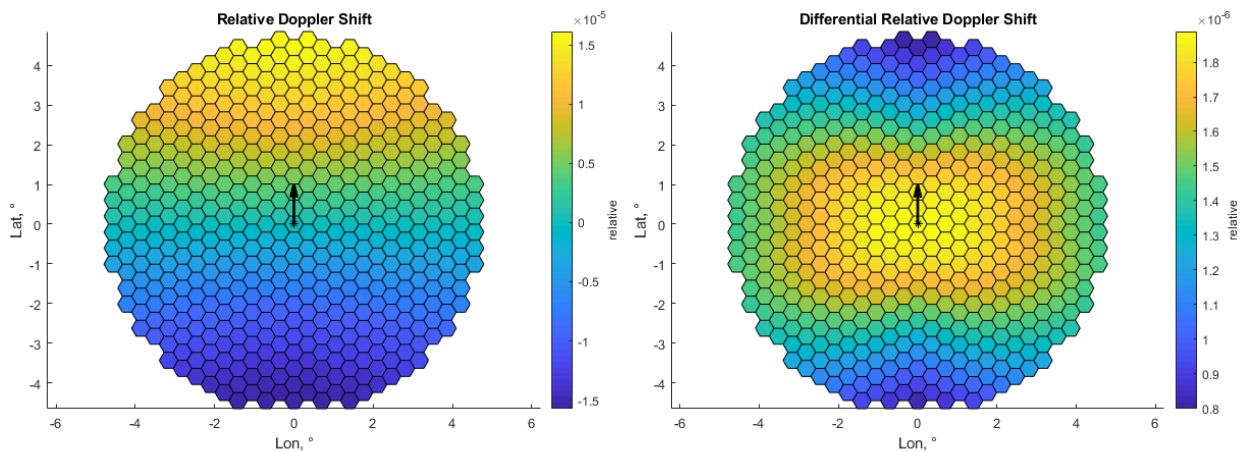


FIGURE 5-8 RELATIVE DOPPLER SHIFT VARIATION AND DIFFERENTIAL RELATIVE DOPPLER SHIFT ACROSS SATELLITE FOV

## 5.3 OISLS

As the relative positions of the satellites change over the orbit, the distance and orientation of the OISLS also needs to change. This section calculates the required distances, and the azimuth and elevation ranges and angular rates required to support the links. The sizing on the OISLS is discussed in D3.5 [Error! Bookmark not defined.], and the feasibility of these requirements will be assessed in the next phase.

### 5.3.1 Service-Feeder OISLS

Figure 5-9 shows the distance between the feeder and its 4 connected service satellites over one orbit – the distance varies between 700km and 800km for the two further service satellites, and between approximately 250km and 500km for the closer two. As the user's data needs to be transferred from the service to the feeder satellite and back, the RTT will vary depending

on the latitude of satellites. Figure 5-10 shows the total RTT for a user at the edge of a service satellite FoV, depending on latitude. Here RTT is calculated only considering time-of-flight of the signal – any delay due to processing on the satellites is not included. Here the RTT does not vary as significantly as the inter-satellite distance, as it is dominated by the distance between the user and the service satellite.

Figure 5-11 shows the required azimuth (relative to satellite velocity direction) and elevation angles and angular rates for the feeder-service OISLs on the feeder satellites. The elevation angles only vary by less than  $1^\circ$ , however the azimuth range is much greater, approximately  $\pm 50^\circ$ . The greatest angular rate of the OISLs is about  $0.1^\circ$  in azimuth. This occurs at the poles when the satellites swap sides relative to the feeder satellite.

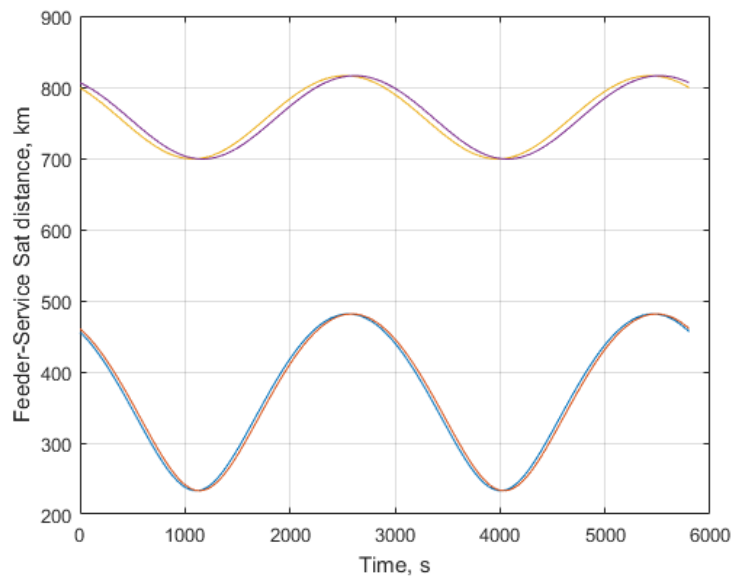


FIGURE 5-9 DISTANCE BETWEEN FEEDER AND SERVICE SATELLITES, OVER ONE ORBIT

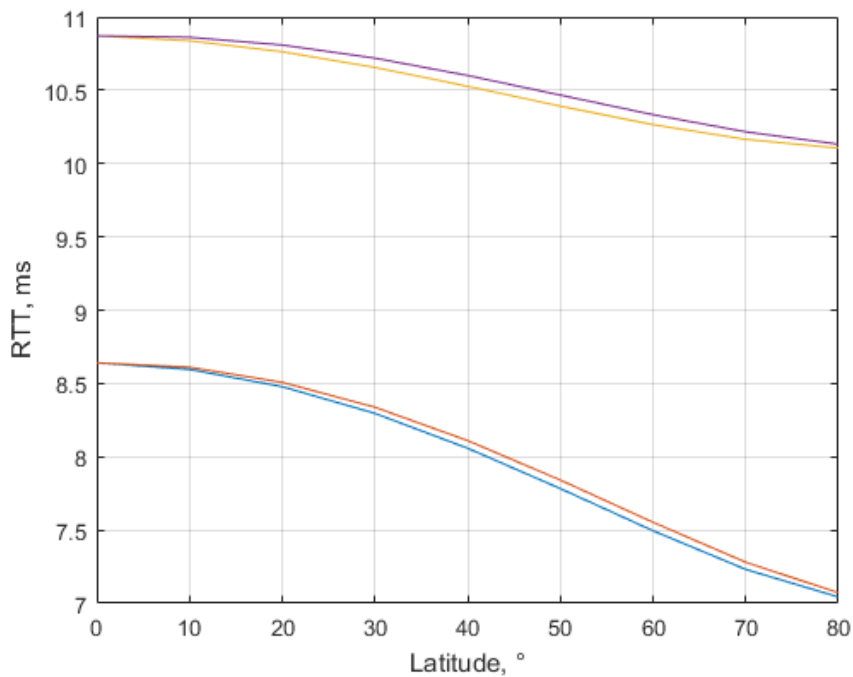


FIGURE 5-10 RTT (USER -> SERVICE SATELLITE -> FEEDER SATELLITE ->SERVICE SATELLITE ->USER) FOR A USER AT THE EDGE OF THE SERVICE SATELLITE FOV

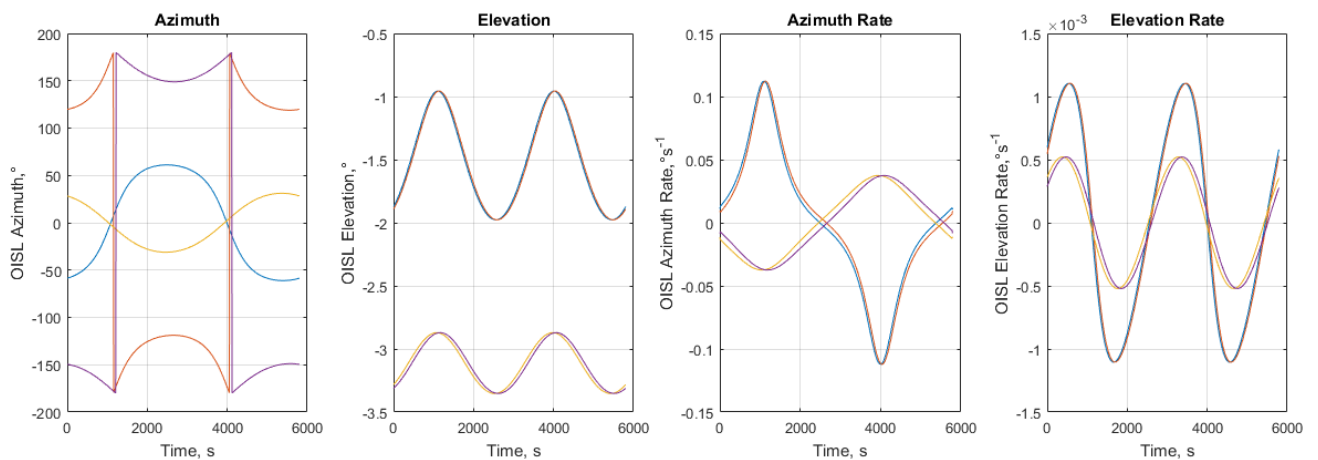


FIGURE 5-11 ANGLES AND ANGULAR RATES FOR FEEDER-SERVICE OISLS ON THE FEEDER SATELLITES

### 5.3.2 Feeder-Feeder OISLs

Figure 5-12 shows the variation in distance between a feeder satellite and the 4 other feeder satellites it is connected to. The 2 feeder satellites ahead and behind in the same plane remain at a fixed distance of 1850km, whereas the ones in adjacent planes vary significantly from approximately 1700km at the equator and 150km at the poles.

Figure 5-13 shows the angles and angular rates. Again, the ones to satellites in the same planes are stationary, whereas a very high azimuthal rate required when is when passing over the poles as the two satellites in adjacent planes swap sides. Here it may be necessary to

break the inter-plane OISL connections over the poles and reconnect them – intra-plane OISLs will remain connected.

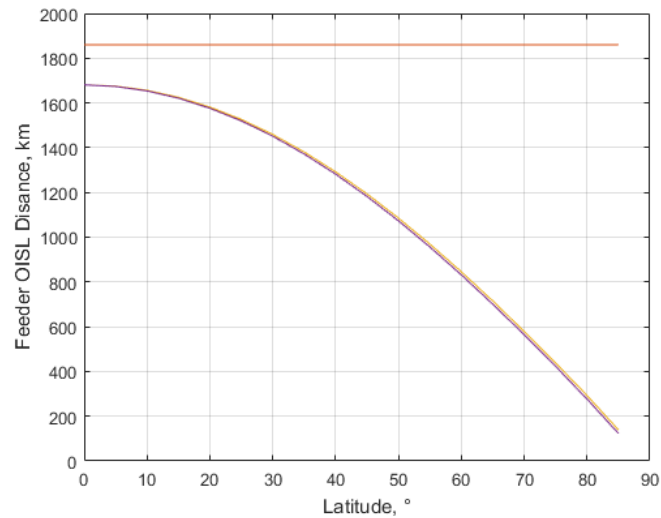


FIGURE 5-12 FEEDER-FEEDER SATELLITE DISTANCE, REFERENCE CONSTELLATION

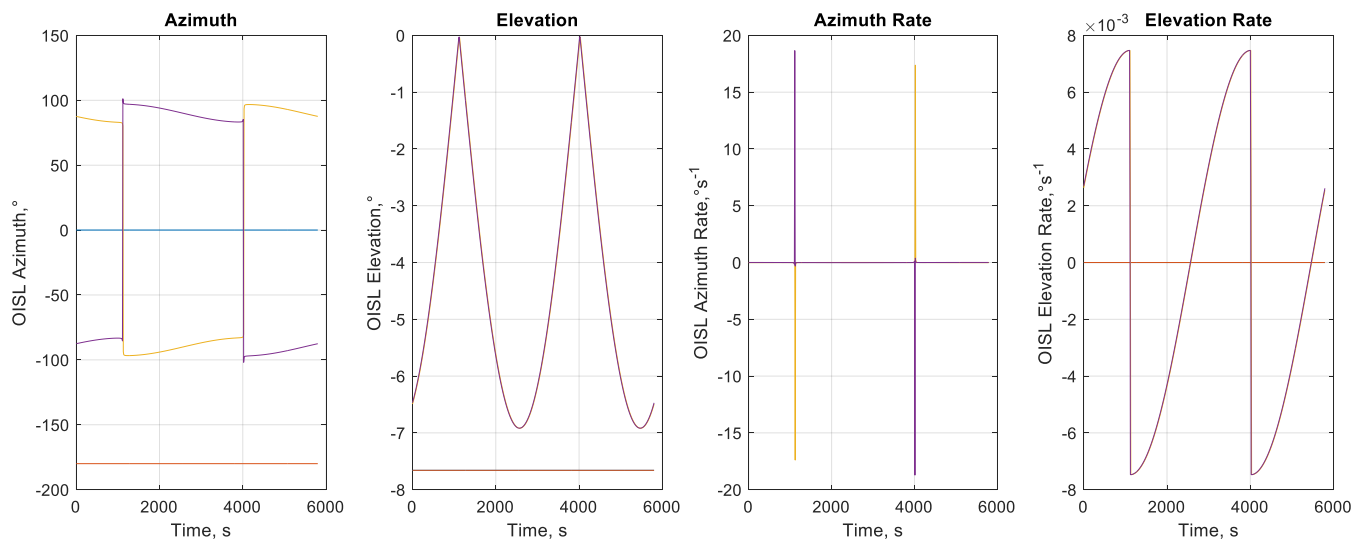


FIGURE 5-13 ANGLES AND ANGULAR RATES FOR FEEDER-FEEDER OISLS

## 5.4 ALTERNATIVE CONFIGURATIONS

Due to the potentially high azimuth rates described above, or the need to break and remake the inter-plane connections over the poles, alternative configurations of the feeder layer and the configuration of the feeder-feeder OISLs is possible, as discussed in Section 2.4 .

One possibility is to space the feeder satellites out between each of the service satellite planes – this results in twice as many feeder satellite planes, with half as many satellites in. This is shown in Figure 5-14. Also, rather than inter-plane OISLs connecting to satellites immediately to the side, the connections are two forwards and two behind. The inter-satellite distances and angles are shown in Figure 5-14 and Figure 5-15. Here the inter-satellite distances are greater compared to the baseline, but there is less variation, and the range of azimuth angles and the magnitude of the azimuth rate is significantly reduced.

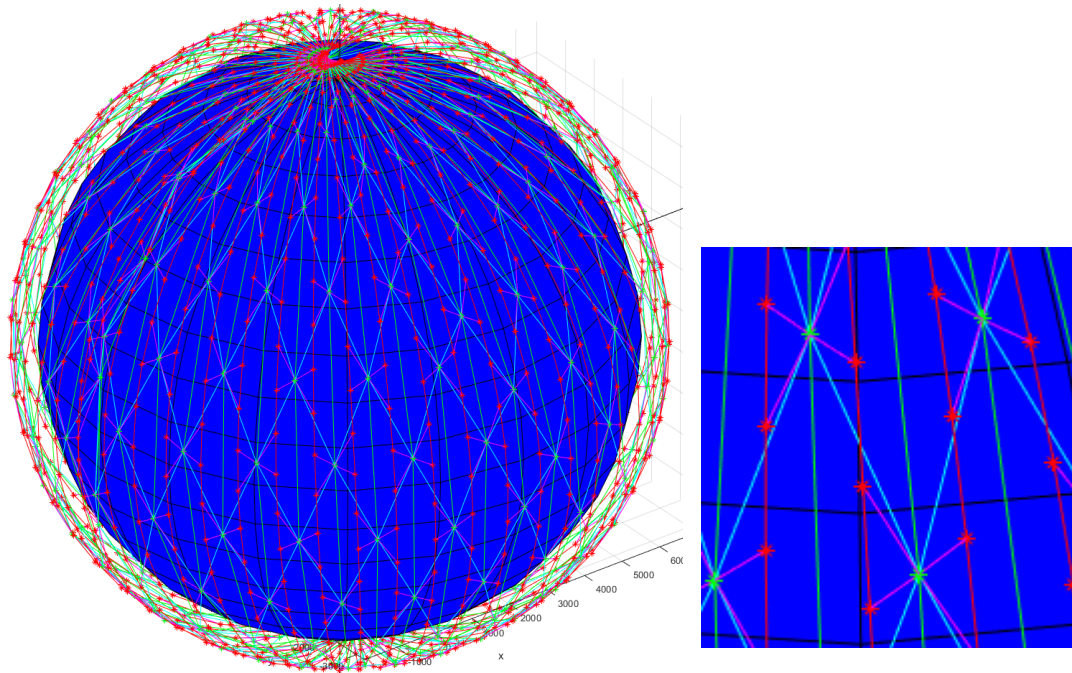


FIGURE 5-14 ALTERNATIVE CONFIGURATION OF THE FEEDER LAYER

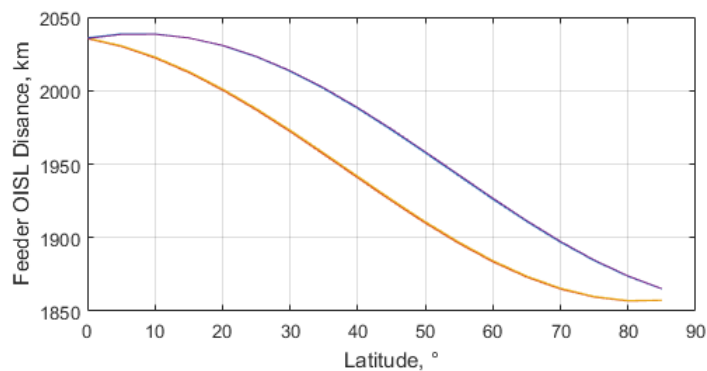


FIGURE 5-15 FEEDER-FEEDER OISL DISTANCES, FOR ALTERNATIVE FEEDER CONFIGURATION FOR THE REFERENCE CONSTELLATION

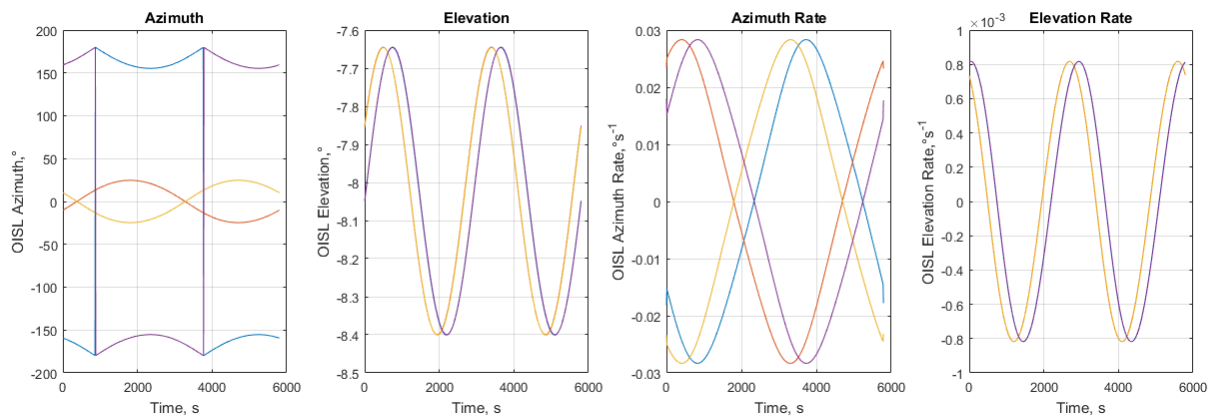


FIGURE 5-16 FEEDER-FEEDER OISL ANGLES AND RATES, , FOR ALTERNATIVE FEEDER CONFIGURATION FOR THE REFERENCE CONSTELLATION

## 5.5 REDUNDANCY

### 5.5.1 Service Satellite Failure

Loss of a service satellite will result in a gap in coverage for users – the only way redundancy can be provided in this case would be to ensure that at every point on the Earth there are always at least 2 satellites in view at any one time. This will increase the number of satellites to 2314 service satellites and 585 feeder satellites, giving a total 2899 satellites (assuming all other constellation parameters are kept the same).

In the reference constellation, the loss of 1 service satellite will result in a maximum area (at the equator) of approximately  $4.5 \times 10^5 \text{ km}^2$  without coverage, as shown in Figure 5-5. The greatest extent of this coverage gap is approximately 756km at the equator – the constellation moves over the surface of the Earth at a speed of approximately  $7 \text{ km s}^{-1}$ , meaning that this gap will pass over a user in a maximum time of 108s (ignoring any time taken to re-establish the connection once a functioning satellite comes into view).

This area decreases with latitude, reducing to 0 above latitudes of approximately  $\pm 65^\circ$ , where there is sufficient overlap from satellites in adjacent planes to ensure there are always at least 2 satellites in view at any one time.

### 5.5.2 Feeder Satellite Failure

Loss of a feeder satellite will result in a significantly larger area without coverage. The maximum duration of the coverage gap will be approximately 216s (double that of the loss of a service satellite) as each feeder satellite connects to 2 adjacent service satellites in an orbital plane.

Redundancy in the feeder layer could be realised by redistributing the affected service satellites to adjacent feeder satellites. An example of this is shown in Figure 5-17. Here the feeder satellites are shown in red, with the feeder-service OISLs shown as red dotted lines. The failed feeder satellite and feeder-service OISLs are shown in grey, and the potential redistributed feeder-service links are shown in purple – there are multiple ways the service satellites can be redistributed.

The highlighted OISL may cause problems as the angular separation between the two service satellites (as seen from the feeder satellite) could be very small and cause interference between the OISLs – this will need to be taken into account.

This scheme will result in greater OISL distances, resulting in either reduced data rates (likely acceptable for a temporary backup) or would require increased transmission power for the OISLs. This will also require spare OISLs on the feeder satellites to support these backup connections, and possibly extra OISLs on the service satellites if the backup feeder connections are in a position not reachable by the nominal OISLs.

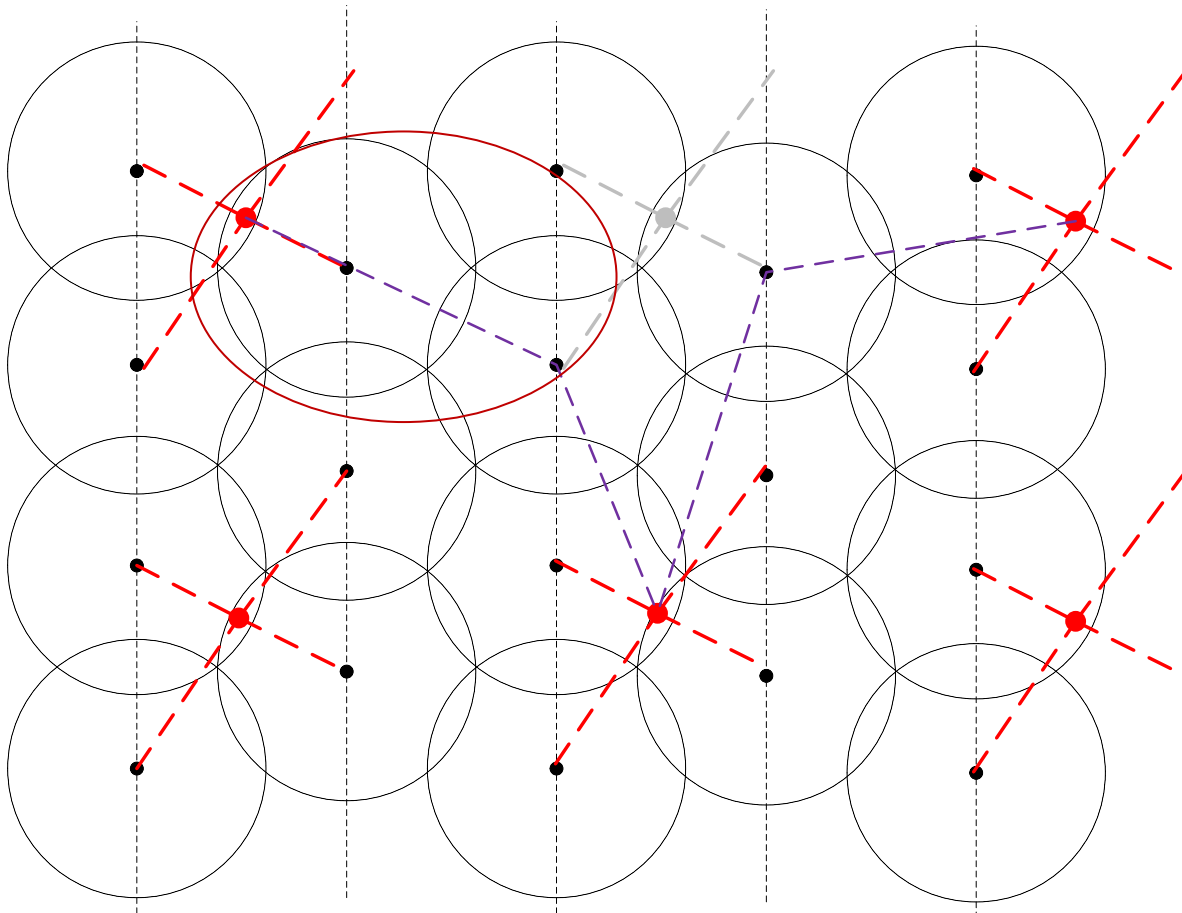


FIGURE 5-17 POSSIBLE REDUNDANCY SCHEME FOR FEEDER SATELLITES SHOWING SERVICE SATELLITES REDISTRIBUTED AMONG ADJACENT FEEDER SATELLITES.

### 5.5.3 Spare Satellites

It will be necessary to keep some spare satellites in orbit to rapidly replace any that fail. The required number of spares will depend on several factors, but it will likely be beneficial to keep at least one spare in every orbital plane (for both the service and feeder satellites), as plane changes require either a long time or a large amount of propellant.

The time taken to position a replacement satellite will depend on how far around the orbit the spare is from where the failed satellite is, and how much propellant is used to perform the relocation manoeuvre – quicker manoeuvres require more propellant.

In-depth analyses are necessary to accurately assess the impact in terms of mass and, consequently, cost. This requires setting a reliability objective and defining an associated strategy.



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## 6 VLEO CONSTELLATION (350 KM) (CASE B)

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This section analyzes a very low altitude solution, in connection with the investigations conducted in [6]. Initial trade-offs revealed that choosing a reduced altitude entails a significant number of satellites. Although the trade-off was based on the number of satellites, as mentioned in the § 4, relaxing this constraint would pave the way for large-scale constellations, notably thanks to the high-capacity launch vehicles currently under development. The objective is to provide a comprehensive overview of cost parameters, thereby enabling an evaluation based on extended criteria (complexity, performance gain, design simplicity, etc.) of costs compared to a LEO solution.

The constellation has been defined based on the following coverage parameters:

- Minimum of 1 satellite visible at any time
- Minimum of 10s overlap between satellites
- Global coverage

Based on the trade-off in Task 3.3 [6] the following technical parameters have been chosen:

- Minimum user elevation of 35°
  - Since we are at a low altitude, for a minimum elevation, each coverage area will consist of a smaller number of cells; therefore, it is necessary to adjust by lowering the minimum elevation at 35° instead of 45° used for LEO constellation at 600 km.
- Near-polar orbit (~87°) to achieve global coverage
  - The slight deviation from a true polar constellation avoids having all orbital planes intersecting at one point over each of the poles

The altitude of 350 km has been chosen for the study of VLEO configuration, it will allow to reduce the FSL considering a balance between number of satellite and number of cells on the coverage [6].

In the case of a distributed architecture, the feeder layer has been defined such that

- Each feeder satellite connected to 4 service satellites.
- Each feeder satellite is connected to 4 other feeder satellites

This results in the following constellation configuration:

Constellation Service satellites:

- 1760 service satellites
  - 32 planes of 55 satellites

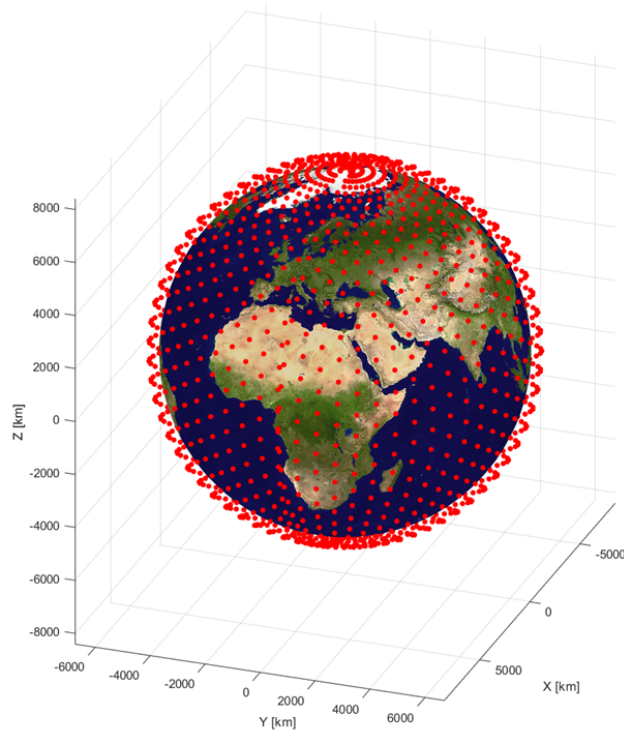


FIGURE 6-1 VLEO SERVICE SATELLITES CONSTELLATION

Constellation feeder satellites:

- 448 feeder satellites
  - 16 planes of 28 satellites.

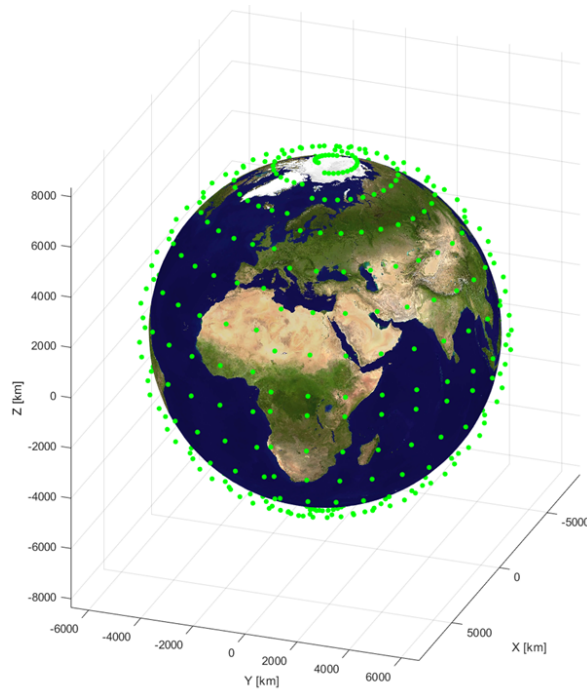


FIGURE 6-2 FEEDER SATELLITES CONSTELLATION

This configuration is shown in Figure 6-1. The service satellites and their orbits are shown in red, and the feeder satellites are green Figure 6-2. The magenta lines show the service-feeder OISLs and the cyan lines are the feeder-feeder OISLs.

As for the LEO constellation, each feeder satellite serves 4 service satellites ( i.e., 2 adjacent satellites in 2 adjacent planes). However, as there are an odd number of satellites in each plane, there is a feeder satellite in each feeder plane that serves only the 1 remaining satellite in each service plane, and as there are an odd number of service planes, 1 plane of feeder satellites only serves this 1 plane. This overlap in feeder satellite coverage results in more feeder satellites required than might be expected (i.e., 448 compared to  $1760/4 \approx 440$ ).

In this configuration, a feeder satellite plane is in between each pair of service satellite planes.

## 6.1 COVERAGE

Figure 6-3 shows the FoV of each service satellite in the reference constellation. The overlaps (here shown at  $0^\circ$  and  $180^\circ$  longitude) are where the ascending and descending planes meet – as these orbits in opposite directions they need to overlap more to provide the required coverage.

At higher latitudes, the satellite FoVs overlap more. Figure 6-4 shows how the un-overlapped area varies with latitude, in terms of area and approximate number of cells (assuming cells are 45km hexagons). Above latitudes of  $\sim 65^\circ$ , there are always at least 2 satellites visible to a user on ground.

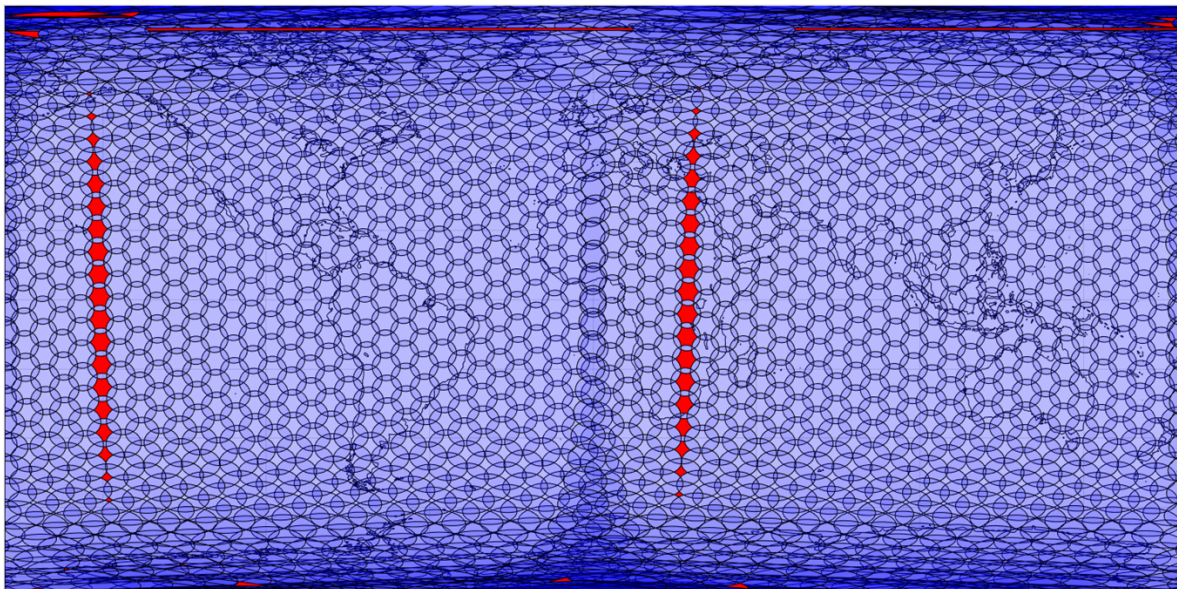


FIGURE 6-3 COVERAGE OF THE VLEO CONSTELLATION 350 KM

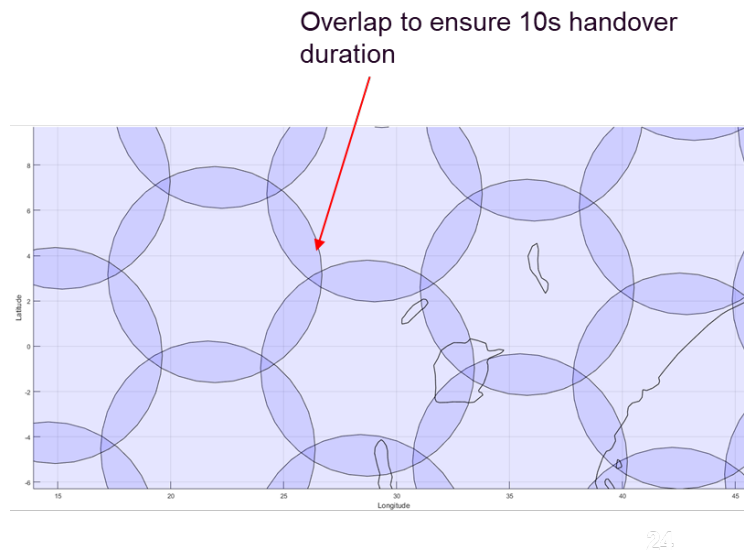


FIGURE 6-4 CELLS OVERLAP VLEO CONSTELLATION 350 KM

## 6.2 OISLS

As the relative positions of the satellites change over the orbit, the distance and orientation of the OISLs also needs to change. This section calculates the required distances, and the azimuth and elevation ranges and angular rates required to support the links. The sizing on the OISLs is discussed in D3.5 [**Error! Bookmark not defined.**] for C-LEO constellation, this work focus on defining the parameters that intervene in the OISL dimensioning and analysis on the feasibility of these requirements will be assessed in [1].

### 6.2.1 Service-Feeder OISLs

Figure 6-5 shows the distance between the feeder and its 4 connected service satellites over one orbit – the distance varies between 570 km and 870 km for the two further service satellites, and between approximately 200 km and 400 km for the closer two. As the user's data needs to be transferred from the service to the feeder satellite and back, the RTT will vary depending on the latitude of the satellites. Figure 5-10 shows the total RTT for a user at the edge of a service satellite FoV, depending on latitude. Here RTT is calculated only considering time-of-flight of the signal – any delay due to processing on the satellites is not included. Here the RTT does not vary as significantly as the inter-satellite distance, as it is dominated by the distance between the user and the service satellite.

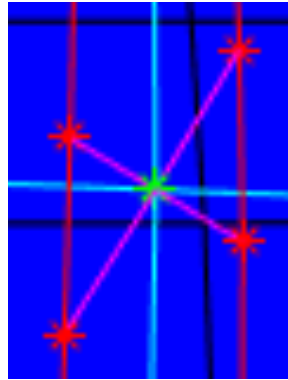


FIGURE 6-5 SERVICE SATELLITE O FEEDER SATELLITE CONECTION

Figure 6-6 shows the required azimuth (relative to satellite velocity direction) and elevation angles and angular rates for the feeder-service OISLs on the feeder satellites. The elevation angles only vary by less than  $1^\circ$ , however the azimuth range is much greater, approximately  $\pm 50^\circ$ . The greatest angular rate of the OISLs is about  $0.1^\circ$  in azimuth. This occurs at the poles when the satellites swap sides relative to the feeder satellite.

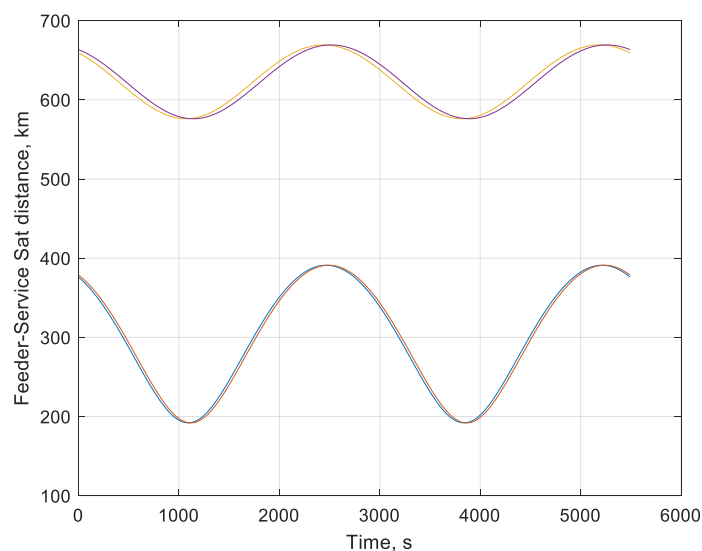


FIGURE 6-6 DISTANCE BETWEEN FEEDER AND SERVICE SATELLITES, OVER ONE ORBIT

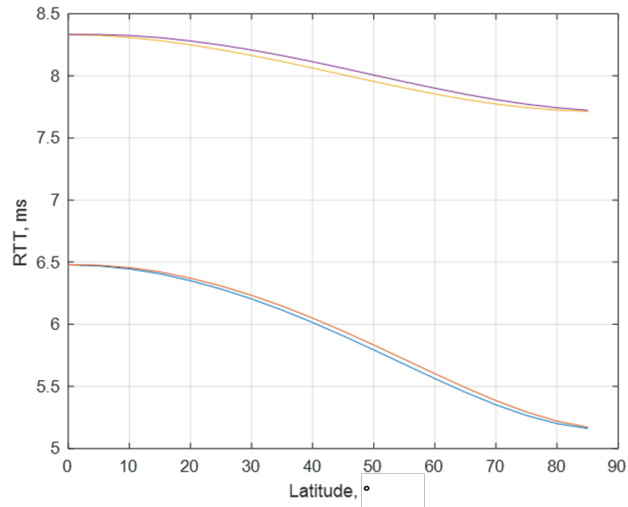


FIGURE 6-7 RTT (USER -> SERVICE SATELLITE -> FEEDER SATELLITE ->SERVICE SATELLITE ->USER) FOR A USER AT THE EDGE OF THE SERVICE SATELLITE FOV

As expected, the distances are shorter than in the case of altitude 600 Km. And the RTT slightly lower than in the case of LEO constellation at 600 km.

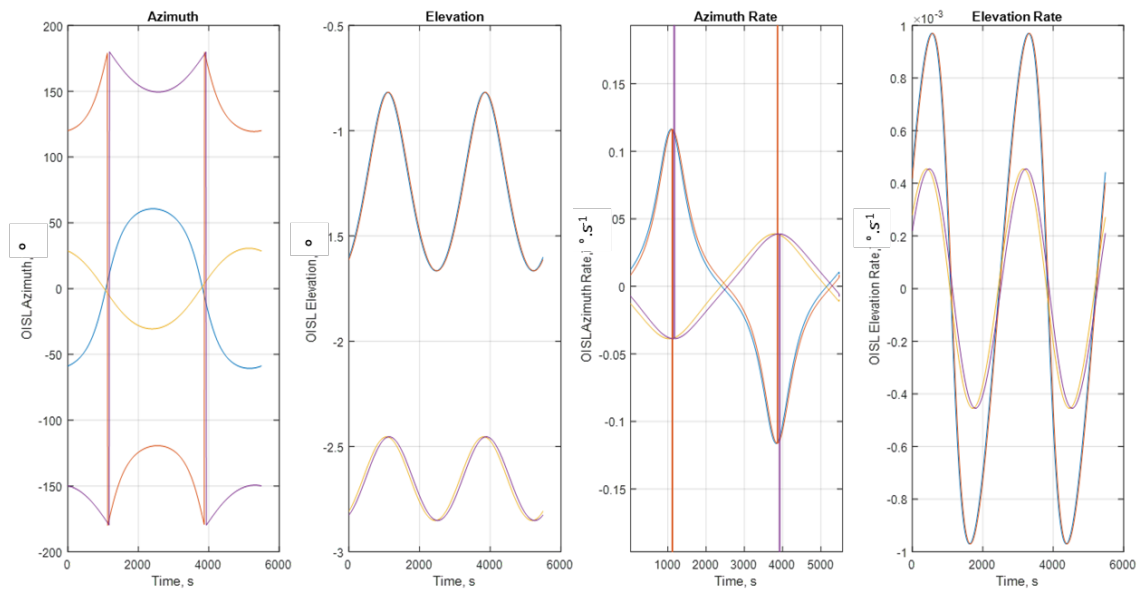


FIGURE 6-8 ANGLES AND ANGULAR RATES FOR FEEDER-SERVICE OISLS ON THE FEEDER SATELLITES

### 6.2.2 Feeder-Feeder OISLs

Figure 5-12 shows the variation in distance between a feeder satellite and the four other feeder satellites it is connected to. The two feeder satellites ahead and behind in the same plane

remain at a fixed distance of 1550 km, whereas the ones in adjacent planes vary significantly from approximately 1400km at the equator and 100km at the poles.

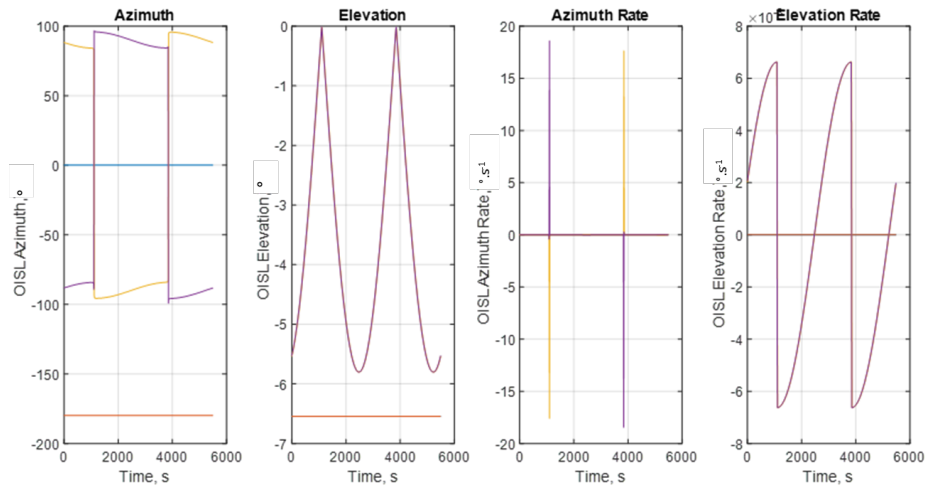


Figure 6-10Figure 5-13 shows the angles and angular rates. Again, the ones to satellites in the same planes are stationary, whereas a very high azimuthal rate is required when passing over the poles as the two satellites in adjacent planes swap sides. Here, it may be necessary to break the inter-plane OISL connections over the poles and reconnect them. That way, intra-plane OISLs will remain connected whatsoever.

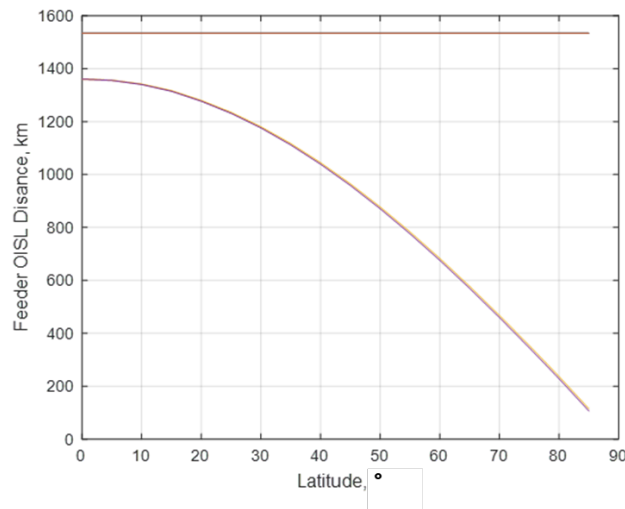


FIGURE 6-9 FEEDER-FEEDER SATELLITE DISTANCE, REFERENCE CONSTELLATION

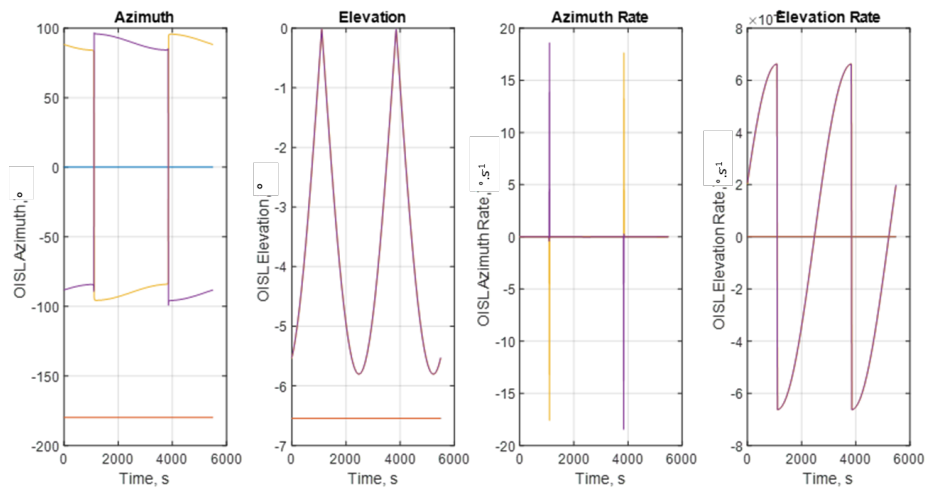


FIGURE 6-10 ANGLES AND ANGULAR RATES FOR FEEDER-FEEDER OISLS

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## 7 SATELLITE SIZING

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### 7.1 INTRODUCTION

The sizing of the satellites will be mostly driven by the size, mass and power consumption of the payload elements, as output from task 3.3 [6]]. Sizing will also take into account operation of the payload (how many beams are active and when), eclipses, the size and power consumption of the OISLs, and mission level considerations such as launch/deployment and orbit maintenance. The objective is to evaluate the impact of each architecture in term of global cost including deployment (number of launches) and in term of number of gateways needed. In Task 3.1 and synthesized in document [1]. The information related to this evaluation are presented in appendices 14, 15 and 16. The trade-off on the architecture are presented in the document of Task 3.3 [6].

The parameters of the payload elements will account for the RAN architecture split, i.e., what equipment is operated and what processing is performed on which satellite(s).

The expected outputs from task 3.3 [6] are as follows:

- Size and mass of the antennas for both the service and the feeder links, for both C and Q/V band.
- Size and mass of the payload processing electronics
  - These will vary depending on the RAN architecture split
- Power consumption of the payload
  - This will be a function of the data rate/number of active beams
- Efficiency of the RF elements of the antenna
  - To estimate power dissipation of the antenna

The number, size and power consumption of the OISLs will also need to be taken into account. The required information is

- The number on each satellite
- The size, mass and power of each OISL

As shown in D3.5 [**Error! Bookmark not defined.**], there is a multidimensional trade-off covering aperture size, power and distance. These factors will need to be taken into account, along with the expected data rate required, in order to size the OISLs and account for them in the satellite sizing.

There are expected to be overall 5 satellite configurations to size:

- C-band and Q/V-band satellites for the conventional architecture
- C-band, Q/V-band and Feeder satellites for the distributed architecture

The satellite budgets estimation will be done only for C-band, for the three architectures (architecture 1, 2 & 2') and the three cases (A,B,C) (a total of nine configurations defined in [6]) with their associated budget (mass, volume & power consumption).

For the Q/V band, the maturity of the technology does not yet allow for a realistic and reliable estimation; moreover, it will impose fewer constraints in terms of launcher requirements.

## 7.2 C-BAND (CASE B SATELLITE / VOLUME/POWER BUDGET)

	Architecture 1	Architecture 2	Architecture 2'
<b>USER SATELLITE</b>			
C-Band DRA	1	1	1
Ka band ISL to GEO (Ka)	1	0	0
Q/V band INL to HAPS	1	1	0
OISL	4	2	2
Q/V band Feeder	2	0	0
<b>FEEDER SATELLITE</b>			
OISL	N/A	4 to 8	4 to 8
Q/V band INL to HAPS	N/A	0	1
Q/V band Feeder	N/A	2	2
Ka band ISL to GEO (Ka)	N/A	1	1

FIGURE 7-1 CONTENTS OF EACH ARCHITECTURE (PAYLOAD ONLY)

The budget (mass, volume, power consumption) have been done in Task 3.3 [6]

### 7.2.1 CASE A : LEO CONSTELLATION 600 km, 1056 RE ( Reference)

- 600km altitude
- 45° min user elevation
- Near-polar inclination (~87°) in order to provide global coverage
- Minimum of 1 satellite always visible
- Minimum 10 s of overlap between 2 satellites for a user on ground to allow handover from one satellite to another
- Each feeder satellite nominally serves 4 service satellites in each of the C and Q/V constellations
- 1269 service satellites total (27 planes, 47 satellites per plane)

336 feeder satellites total (14 planes, 24 satellites per plane)

- **Architecture 1** : composed of one type of satellites
- **Architecture 2** : Composed of two types of satellites :
  - service satellites and feeder satellites ( linked by OISL)
- **Architecture 2'** : Composed of two types of satellites :
  - service satellites and feeder satellites ( linked by OISL)


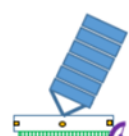


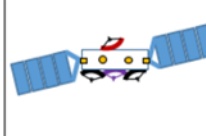
LEO SAT 600 Km 1056 RE				
<b>ARCHITECTURE 1</b>	Service Satellite		Contents	1269 satellites
Notes : Only one type of satellites	 (1)		(1) : OISL (4) C-BAND DRA (1) Q/V band feeder (2) Q/V band INL (1) Ka band ISL (1)	
<b>ARCHITECTURE 2</b>	Service Satellite	Feeder satellite	(1) : OISL (2) C-BAND DRA (1) Q/V band INL (1)  (2) : OISL (8) Q/V band Feeder (2) Ka Band ISL (1)	
Notes : 2 types of satellites 1 composing two constellations	 (1)	 (2)		1269 satellites
<b>ARCHITECTURE 2'</b>	Service Satellite	Feeder satellite	(1) : OISL (2) C-BAND DRA (1)  (2) : OISL (8) Q/V band Feeder (2) Q/V band INL (1) Ka Band ISL (1)	336 satellites
Notes : 2 types of satellites 1 composing two constellations	 (1)	 (2)		

FIGURE 7-2 CASE A : SYNTHESIS OF THE 3 ARCHITECTURES CONTENTS

## 7.2.2 CASE B : VLEO CONSTELLATION 350 km, 1536 RE (Alternative)

- Reference Definition (inputs):
  - 350km altitude
  - 35° min user elevation
  - Near-polar inclination (~87°) for global coverage
  - 1 satellite always visible
  - Minimum 10s handover between satellites
- Optimal Constellation Configuration (minimum number of satellites):
  - 1760 sats total
    - 32 planes, 55 sats per plane
  - **Architecture 1** : composed of one type of satellites.
  - **Architecture 2** : Composed of two types of satellites :
    - service satellites and feeder satellites (linked by OISL)
  - **Architecture 2'** : Composed of two types of satellites :
    - service satellites **simplified** and feeder satellites (linked by OISL)

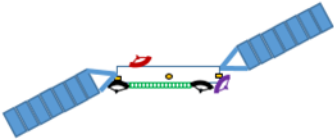
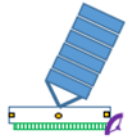
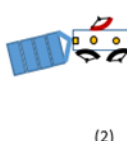
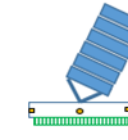

VLEO SAT 350 Km 1536 RE			
<b>ARCHITECTURE 1</b>	Service Satellite		Contents
Notes : Only one type of satellites	 <p>(1)</p>		(1) : OISL (4) C-BAND DRA (1) Q/V band feeder (2) Q/V band INL (1) Ka band ISL (1)
			<b>1760 satellites</b>
<b>ARCHITECTURE 2</b>	Service Satellite	Feeder satellite	
Notes : 2 types of satellites 1 composing two constellations	 <p>(1)</p>	 <p>(2)</p>	(1) : OISL (2) C-BAND DRA (1) Q/V band INL (1)  (2) : OISL (8) Q/V band Feeder (2) Ka Band ISL (1)
			<b>1760 satellites</b>
			<b>448 satellites</b>
<b>ARCHITECTURE 2'</b>	Service Satellite	Feeder satellite	
Notes : 2 types of satellites 1 composing two constellations	 <p>(1)</p>	 <p>(2)</p>	(1) : OISL (2) C-BAND DRA (1)  (2) : OISL (8) Q/V band Feeder (2) Q/V band INL (1) Ka Band ISL (1)
			<b>1760 satellites</b>
			<b>448 satellites</b>

FIGURE 7-3 CASE B : SYNTHESIS OF THE 3 ARCHITECTURE

### 7.2.3 CASE C : LEO CONSTELLATION 600 km, 2048 RE ( Enhanced solution)

- 600km altitude
- 45° min user elevation
- Near-polar inclination (~87°) in order to provide global coverage
- Minimum of 1 satellite always visible
- Minimum 10 s of overlap between 2 satellites for a user on ground to allow handover from one satellite to another
- Each feeder satellite nominally serves 4 service satellites in each of the C and Q/V constellations
- 1269 service satellites total (27 planes, 47 satellites per plane)

336 feeder satellites total (14 planes, 24 satellites per plane)

- **Architecture 1** : composed of one type of satellites
- **Architecture 2** : Composed of two types of satellites :
  - Service
- **Architecture 2'** : Composed of two types of satellites :
  - service satellites + feeder satellites (linked by OISL)

- e satellites + feeder satellites ( linked by OISL)

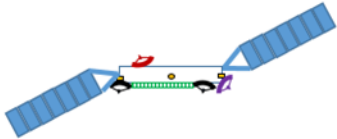
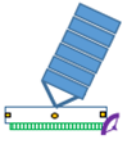



VLEO SAT 350 Km 1536 RE			
<b>ARCHITECTURE 1</b>	Service Satellite		Contents
Notes : Only one type of satellites	 <p>(1)</p>		(1) : OISL (4) C-BAND DRA (1) Q/V band feeder (2) Q/V band INL (1) Ka band ISL (1)
<b>ARCHITECTURE 2</b>	Service Satellite	Feeder satellite	
Notes : 2 types of satellites 1 composing two constellations	 <p>(1)</p>	 <p>(2)</p>	(1) : OISL (2) C-BAND DRA (1) Q/V band INL (1)  (2) : OISL (8) Q/V band Feeder (2) Ka Band ISL (1)
<b>ARCHITECTURE 2'</b>	Service Satellite	Feeder satellite	
Notes : 2 types of satellites 1 composing two constellations	 <p>(1)</p>	 <p>(2)</p>	(1) : OISL (2) C-BAND DRA (1)  (2) : OISL (8) Q/V band Feeder (2) Q/V band INL (1) Ka Band ISL (1)

FIGURE 7-4 CASE C : SYNTHESIS OF THE 3 ARCHITECTURES CONTAINS

Power, mass and volume budget for this case for the 3 architectures have been estimated in Task 3.3.

## 8 LAUNCHERS EVALUATION

### 8.1 INTRODUCTION

The objective of this chapter is to provide the elements that allow to evaluate the effort needed to deploy the constellations in C-Band. A somewhat tangible evaluation would nevertheless require thorough and meticulous work. In our case, the goal is to gather enough meaningful data to estimate and identify reliable trends. Based on the preliminary studies from Task 3.3, as well as estimates regarding the platforms (both heritage and potential improvements in the coming years) and launchers, comparisons have been made. The primary objective is to estimate the mass, volume, and power consumption of each satellite, then assess their accommodation within each type of launcher. Using the payload fairing dimensions and launch capacity, we then determine the number of launches needed. These results, combined with other parameters such as satellite cost and the number of required Gateways, will provide a clear understanding of what deploying each solution entails, as well as help evaluate the relevance of one architecture over another."

### 8.2 LAUNCHERS IDENTIFIED

The evaluation of launchers was carried out through an extensive analysis based on their availability and suitability for the missions. The table in above presents the most promising launchers identified among the list of available launchers for the deployment of C-Band constellation (Case A, Case B and Case C defined in Task 3.3 doc) according to the 3 versions of architecture 1,2 and 2'. The objectives is to give the elements to evaluate the overall cost parameters of each solution.

The primary selection criterion is the fairing dimension, ensuring it can allow to accommodate the C-band satellites.

Launch Vehicle	Mass to LEO (kg)	Altitude / Inclination	Fairing usable dimensions (m)		Availability
			Diameter	Height	
Falcon 9 - 6500	13280	600km x 97.8deg	4.5	12	Available
Ariane 64	14700	600km x 97.8deg	4.6	11.2	Available
Starship	100000	TBC	6	12	2028
New Glenn	23500	600km x 97.8deg	5.4	13.2	Available
Vulcan-6	20000	556km x 98.7deg	5.4	12	Available
Falcon 9 - 5500	11380	600km x 97.8deg	4.5	12	Available

FIGURE 8-1 LAUNCHERS SELECTED FOR THE EVALUATION

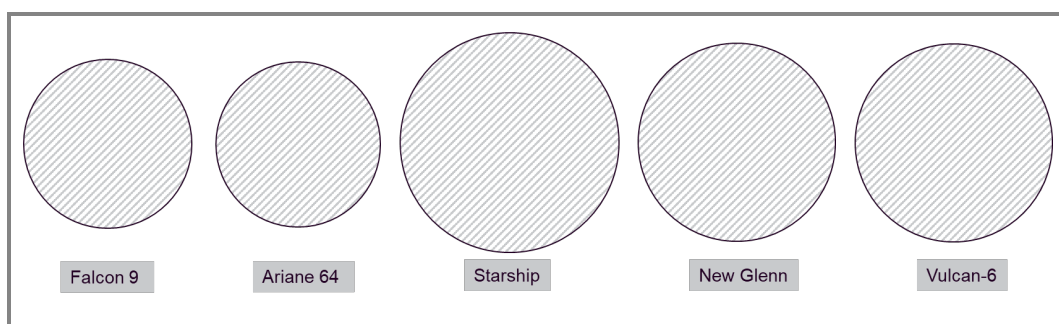


FIGURE 8-2 LAUNCHER FAIRINF FOOTPRINT

The Launchers selected correspond to potentially available or foreseen solutions in the near future and could be envisaged for respond to the LEO and VLEO mission in C-band at least a fairing diameter > 2 m.

For the C-band the 3 architectures described in TASK 3.3 and Task 3.1 are envisaged:

### 8.3 CONSTELLATION FOR ESTIMATIONS

The 3 constellations:

CASE A : LEO 600 km 1056 RE

CASE B : VLEO 350 km 1536 RE

CASE C : LEO 600 km 2048 RE

Have been taken to evaluate the effort in terms of launchers.

Figure 8-3 shows the contents of each satellite for each architecture of the 3 cases.

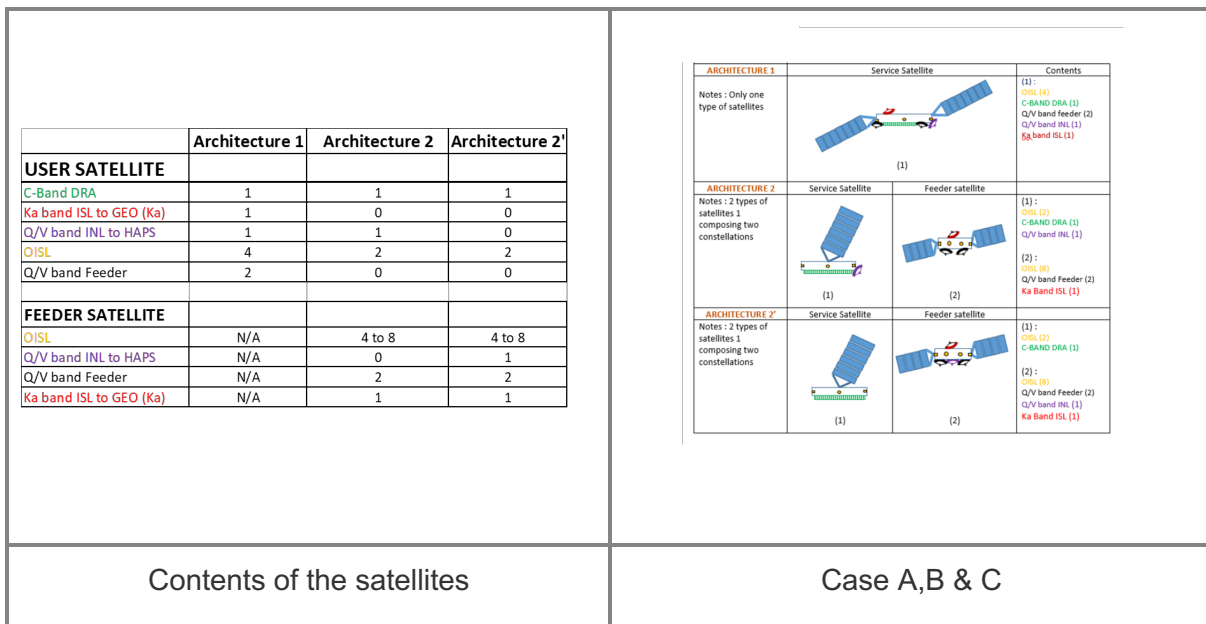


FIGURE 8-3 DESCRIPTION OF THE SATELLITE

The number of satellites are presented in the Figure 7-2, Figure 7-3 and Figure 7-4

### 8.4 SYNTHESIS OF REQUIRED LAUNCHERS

According to the volume, mass, power consumption defined in Task 3.3, the satellite accommodation have been estimated in appendix13.5 for the five launchers defined in 8.2.

The main tendency issued from the results show that:

- Due to the large footprint of the satellites, only large launchers have an interest in reducing the number of launches (New Glenn and Starship)
- Simplifying the satellites of a constellation into two types of satellites (architecture 2 or even architecture 2') allows to reduce significantly the number of launches.
- The mass remains the main limitation for smaller launchers (Ariane 64, Falcon 9 and Vulcan 6) in optimizing the number of satellites on a fairing, A progress has to be done to decrease the mass of the platform and the satellite. More precisely, the mass remains a limitation for Architectures 2 and 2' and volume a limitation for architecture 1.
- For Large Launchers the number of satellites is limited by the volume under fairing: this class of launcher is therefore interesting for Architecture 2 and 2'.

These tendencies shall be slightly adjusted according to some specificities of each launcher, Nevertheless, to deploy such constellations, two main tendencies could be pointed out:

- Ensure satellites have a low height (reduced number of components), hence favor Architectures 2 & 2', to be able to stack multiple satellites under the payload fairing. It is necessary to have the widest possible payload fairing diameters (i.e., use large launchers).
- The satellite surface area must be optimized to accommodate as many units as possible.
- Thus, satellite surface areas of diameter range from 2 to 3 meters. The goal is to choose a diameter that allows for the maximum number of satellites to be arranged per layer.

The table in Appendix 13.6 summarizes the three configurations and three cases the total launches needed. It appears that architecture 2 and 2' allow, regardless of the configurations, a reduction ranging from 10 to 20% in the number of launches. Certainly, in some cases, the reduction is greater than in others. Above all, it is meant to provide an idea of what this represents, and the estimates were made based on existing expertise (heritage) and the anticipated progress in this field.

Furthermore, these results should be considered in the overall cost evaluation effort for each architecture (see Appendix 14). The cost of each satellite has been assessed based on their complexity in design, manufacturing, and AIT, using Architecture 1 as the reference. Cost is an important factor in deploying these constellations, and a gain of 10% to 20% can also be expected.

Thus, in terms of launches and cost per satellite, a significant gain can be observed. Additionally, the operational costs must also be considered, that is, the number of gateways required for each constellation. As we saw in the chapter on gateways, having feeder constellations allows for a drastic reduction in the number of gateways needed. Furthermore, in terms of scalability, configurations 2 and 2' provide a much higher level of scalability and therefore greater flexibility.

Remark: for Q/V band constellation, the mass and the volume of the satellite is reduced and could be optimized. However, regarding the gains related to launches and complexity, the same conclusions can be drawn. In the case of the Q/V band, as detailed in the previous chapter 7.1, the volume and footprint are less restrictive, providing greater flexibility in terms of launcher selection and layout optimization.

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## 9 GATEWAYS

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### 9.1 INTRODUCTION

The objective of this chapter is to estimate the number of gateways required to support constellations operations. Several configurations are possible, according to constraints we impose: number of visible gateways and minimum elevation angle. Moreover, all the satellites have been connected together through OISL and could be used to reach a gateway. Nevertheless, it implies some latency constraints. Moreover, additional constraints may occur, notably regarding the capacity of the OISLs, which in some cases can constitute bottlenecks depending on the traffic to be handled through them. Different cases are studied in the following subsections.

For constellations in the C-band (CASE A and C), the coverage of the LEO satellites is ensured at 600 km with an elevation angle minimum of 45°. For the VLEO constellation in C-band at 350 km the field of view is ensured at minimum elevation angle of 35° (CASE B).

The study is based on station visibility optimization and has to be confirmed by additional capacities analysis for dimensioning the Gateways and was analyzed in [1].

- LEO altitude 600 km (coverage user  $E_{\min}=45^\circ$ )
  - Architecture 1
  - Architecture 2 or 2'
- VLEO altitude 350 km (coverage user  $E_{\min}=35^\circ$ )
  - Architecture 1

The precise objective is to determine the number of gateways required for each scenario to ensure a connection (visibility) with a maximum of satellites when possible.

For the Q/V band only one constellation has considered. This constellation is the baseline defined 600 km and the results in C-band is applicable as the number of satellite and the coverage are identical.

Thus, the main objective of this analysis is to quantify the advantage of Architecture 2 or 2' compared to Architecture 1. In other words, whether the introduction of feeder satellite has an interest in the context of the number of gateways to deploy.

## 9.2 SATELLITE GATEWAYS COVERAGE LEO CONSTELLATION 600 KM

### 9.2.1 Coverage view

In the two identified architectural cases, Figure 9-1 and Figure 9-2 show the coverage that each gateway must provide, either for Architecture 1 by the service satellite or for Architectures 2 and 2' by the feeder satellite.

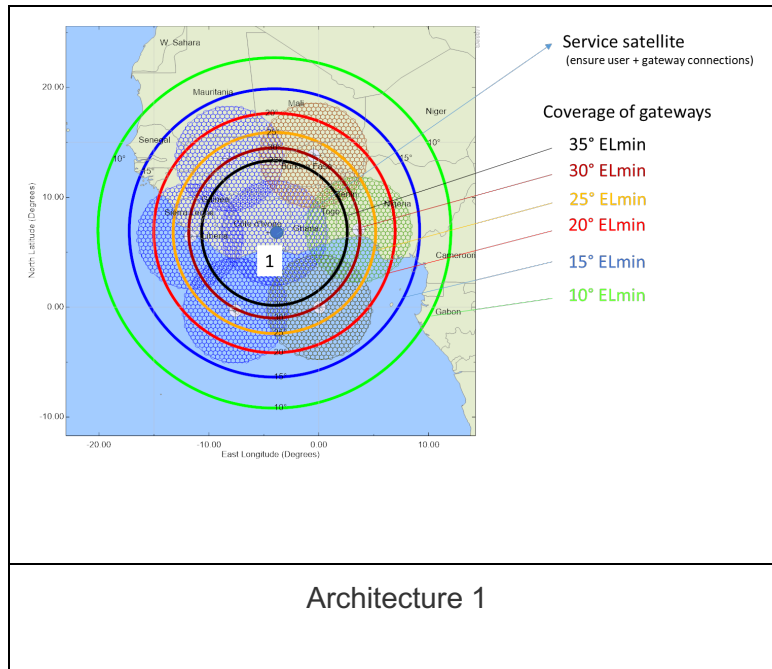


FIGURE 9-1 COVERAGE OF GATEWAYS (ARCHITECTURE 1)

For Architecture 1, the feeder coverage is on the service satellite and its coverage is centered on the center of each satellite. For Architecture 2, the feeder coverage is centered on the feeder satellite and is placed at the center of the four services satellites (see Figure 6-5) as shown in Figure 9-2 .

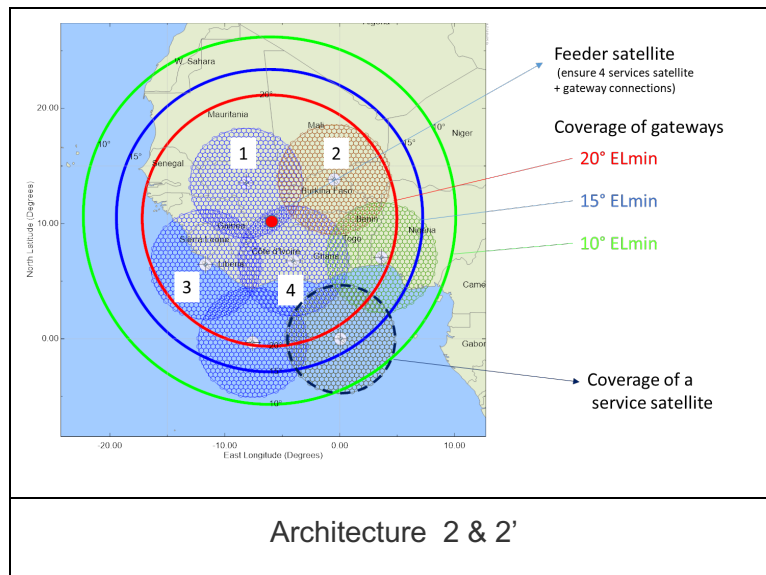


FIGURE 9-2 COVERAGE OF GATEWAYS (ARCHITECTURE 2)

For VLEO 350 km coverage, Appendix 15 gives the view of the coverage for the two types of architectures.

### 9.2.2 Architecture 1 (service satellite only)

Each service satellite must provide both the user link and the link to the gateways. A calculation was performed to estimate the number of gateways required based on the minimum elevation angle (see Figure 9-1 ), with the constraint of always having at least one or two satellites in view.

Figure 9-3 shows a view of satellites served directly by the gateways on the Earth's surface, corresponding to 746 out of 1269 satellites. To estimate the number of gateways required, satellites beyond latitudes of 70° are excluded, as these are areas with overlapping coverage and zones that do not require high capacity, considering that user density is low at these latitudes.

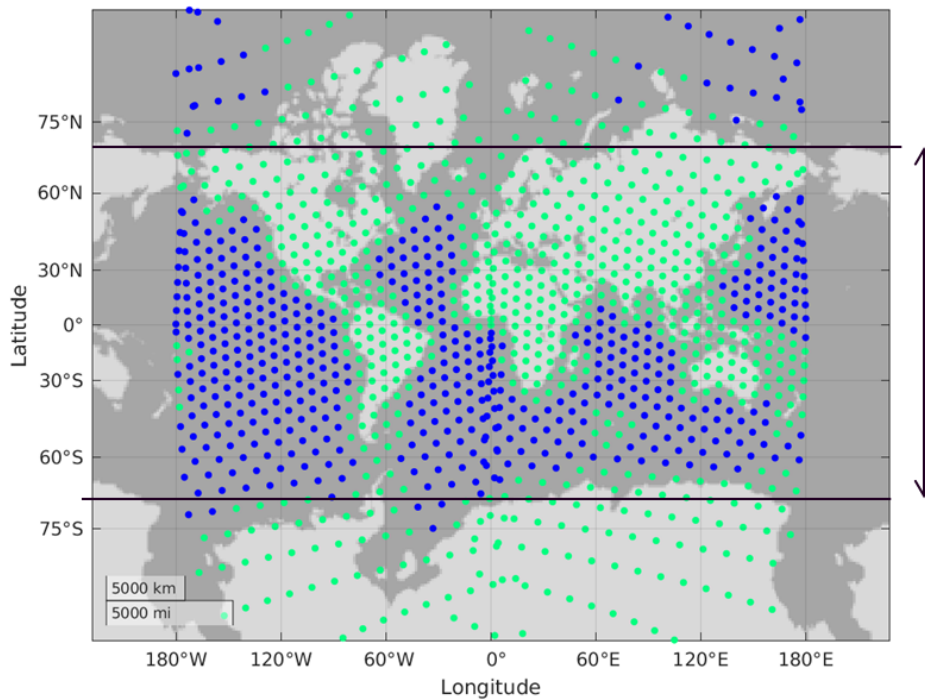


FIGURE 9-3 SATELLITE SERVED (●), SATELLITE OVER SEAS CONNECTION VIA OISL (●).

After this filtering (i.e., excluding latitudes above 70°), the number of gateways required to ensure one or two links to the gateways is presented in the table in Figure 9-4.

<b>n gw allocated = 1</b>	<b>elevation min</b>	<b>nGW</b>
	20	85
	25	103
	30	126
	35	146
<b>n gw allocated = 2</b>	<b>elevation min</b>	<b>nGW</b>
	20	159
	25	185
	30	225
	35	259

FIGURE 9-4 NUMBER OF GATEWAYS NEEDED

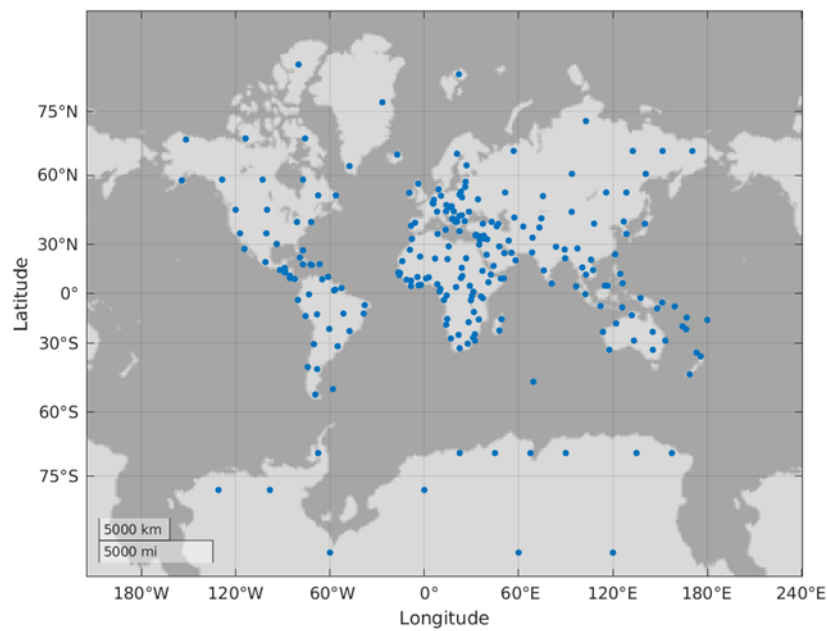


FIGURE 9-5 POSSIBLE GATEWAYS LOCATION (238 GW FOR 30° EL ANGLE AT LEAST ONE PER COUNTRY)

The view of possible gateways locations in the case of 35° ELmin angle are presented in Figure 9-5.

For architecture 2, the computations were carried out in the same way as for Architecture 1.

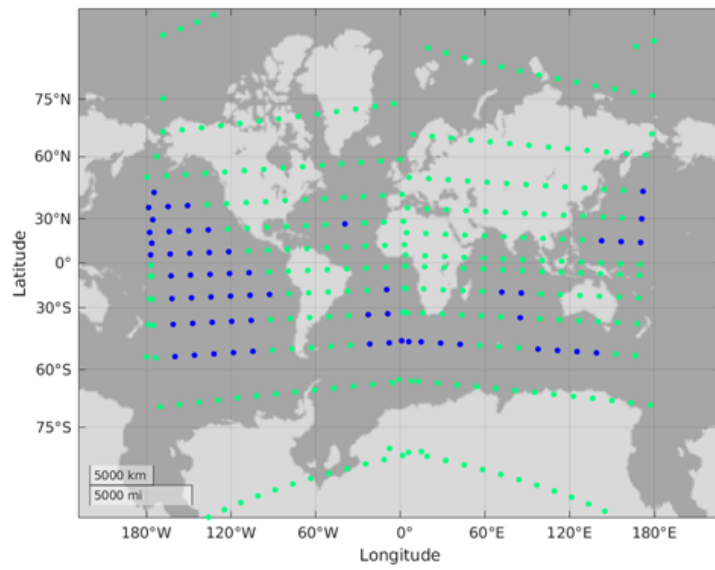


FIGURE 9-6 FEEDER SATELLITE SERVED (●)277/336, SATELLITE OVER SEAS CONNECTION VIA OISL 277/336)

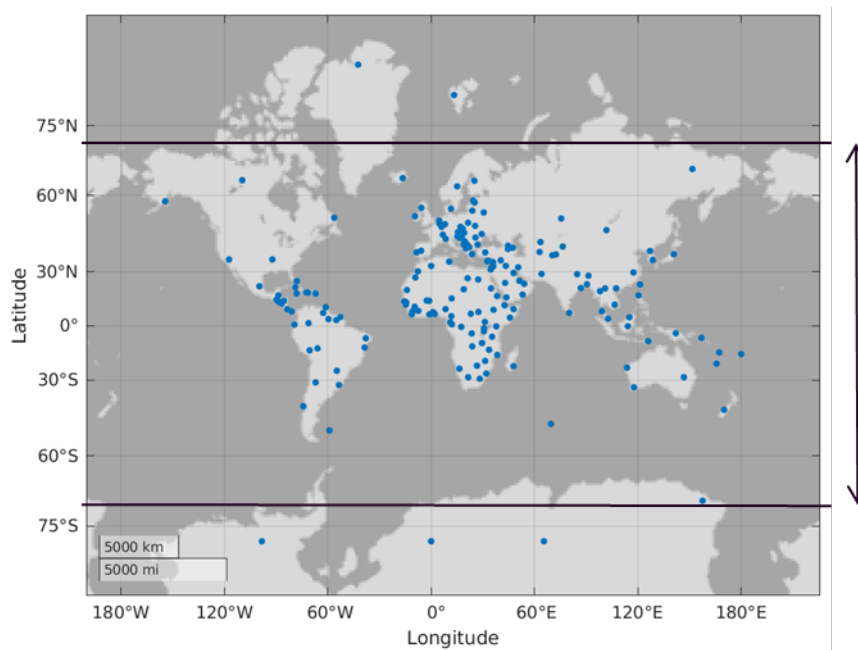


FIGURE 9-7 POSSIBLE GATEWAYS POSITION 186 GATEWAYS 10° ELMIN

The table gives the number of needed gateways according to the minimum elevation angle

n gw allocated = 1	elevation min	number GW
	10	42
	15	48
	20	57
n gw allocated = 2	elevation min	number GW
	10	78
	15	92
	20	115

FIGURE 9-8 NUMBER OF GATEWAYS NEEDED

### 9.2.3 Summary comparison architecture 1 & Architecture 2,

The Elmin that shall ensure architecture 1 shall be 20°. The number of gateways needed (condition 1 gateway in visibility) is therefore 85 gateways. Likewise, the Elmin that shall ensure the feeder satellite shall be 10° and the number of Gateways needed is 42.

Architecture 2 allows to divide by 2 the number of gateways needed.

## 9.3 SATELLITE GATEWAY COVERAGE VLEO CONSTELLATION 350 KM

### 9.3.1 Coverage view

As for LEO constellation, for VLEO 350 km coverage the Appendix 15 gives the view of the coverage.

### 9.3.2 Architecture 1

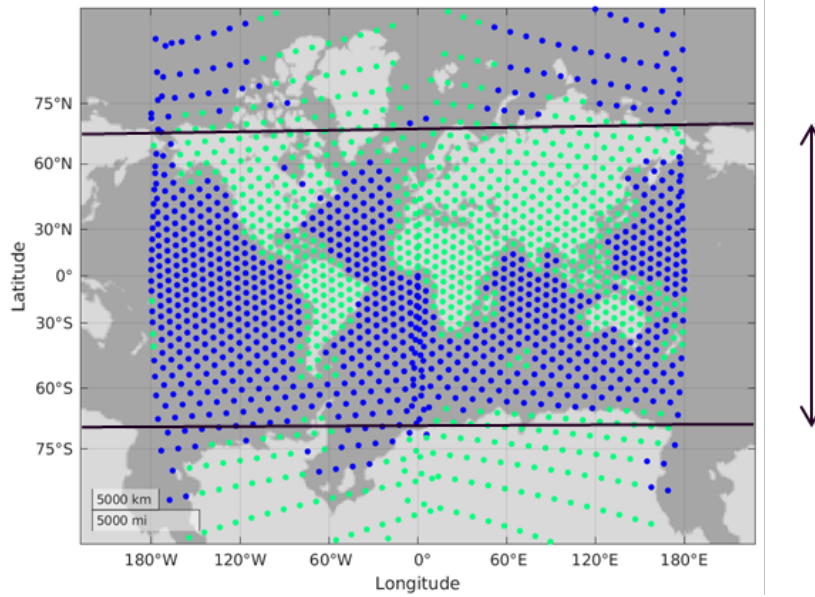


FIGURE 9-9 SATELLITE SERVICE SERVED 830/1760

n gw allocated =	elevation	nGW
	20	140
	25	199
	30	218
	35	250
n gw allocated =	elevation	nGW
	20	248
	25	325
	30	358
	35	348
	40	416

FIGURE 9-10 NUMBER OF GATEWAYS NEEDED

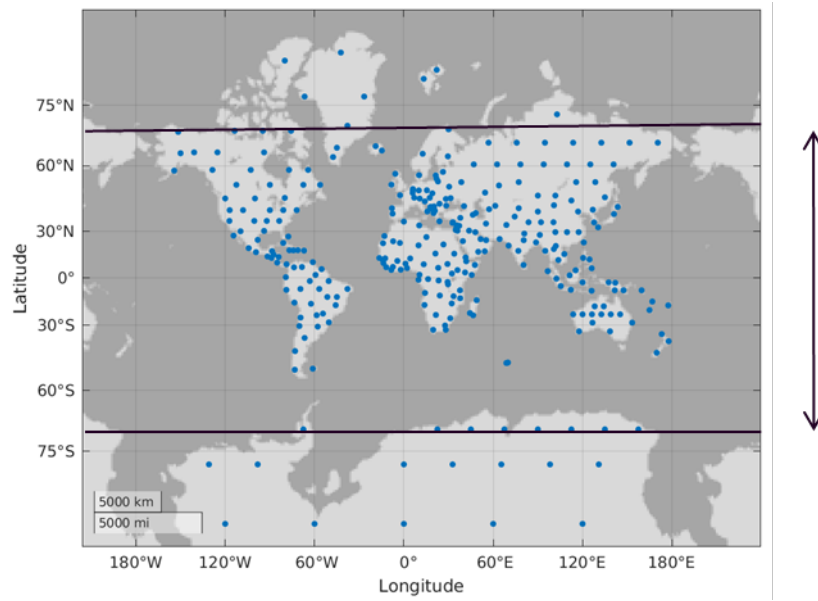


FIGURE 9-11 POSSIBLE GATEWAYS 310 AFTER FILTERING AT LATITUDE 70° (ELEVATION MIN 30°)

### 9.3.3 Architecture 2 or 2'

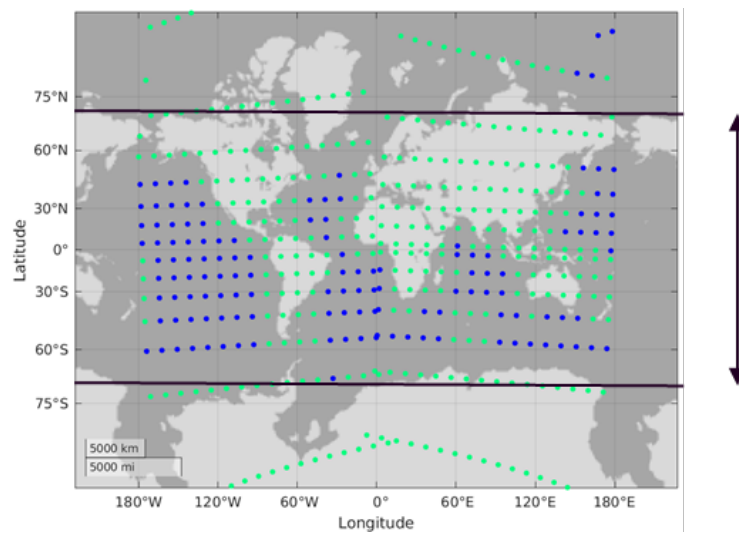


FIGURE 9-12 SATELLITE SERVED 316/448

n gw allocated = 1	elevation	nGW
	10	59
	15	72
	20	95
n gw allocated = 2 min	elevation	nGW
	10	109
	15	135
	20	181

FIGURE 9-13 NUMBER OF GATEWAYS NEEDED

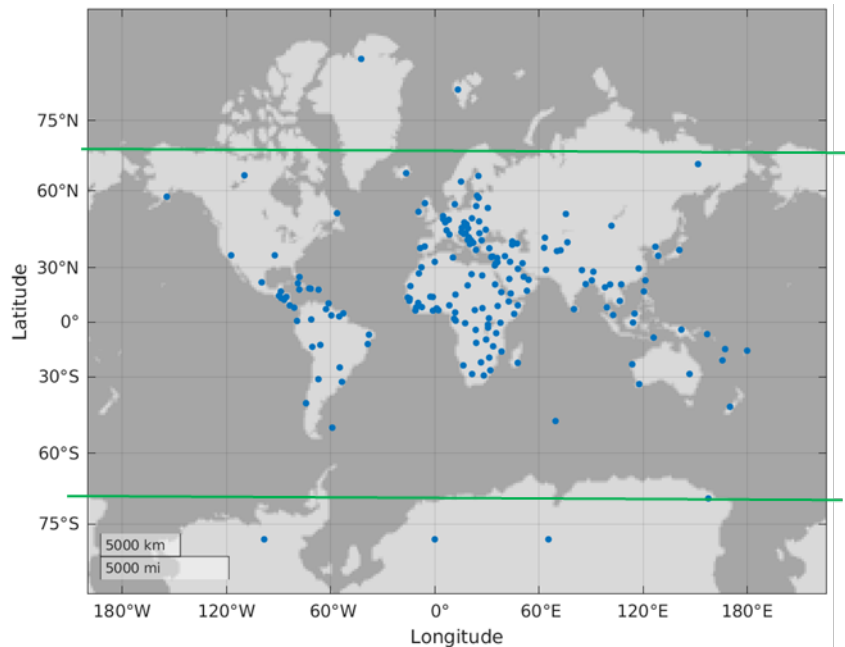


FIGURE 9-14 POSSIBLE GATEWAYS EXEMPLE 10° WITH CONSTRAINT OF 1 PER COUNTRY (196 GW)

### 9.3.4 Resume

As for LEO constellation The  $EI_{min}$  that shall ensure architecture 1 shall be  $20^\circ$  the number of gateways needed (condition 1 gateway in visibility) is 140 gateways. The  $EI_{min}$  that shall ensure the feeder satellite shall be  $10^\circ$  and the number of Gateways needed is 59.

The architecture 2 allow to divide by 2.4 the number of gateways needed.

## 9.4 NUMBER OF SATELLITE IN VIEW OF FIXED GATEWAY

The objective is to determine the number of satellites connected to a given number of Gateways.

constellation 600 km : number of Satellites in view versus elevation					
	(EL min that the feeder shall ensure)				
	(°)	(°)	(°)	(°)	(°)
number of GW	10	12.5	15	17.5	20
10	88	77	66	60	54
12	102	89	78	70	64
14	116	101	90	80	72
16	128	113	101	89	80
18	140	124	110	97	88
20	154	134	118	105	96

FIGURE 9-15 CONSTELLATION FEEDER LEO 600 KM

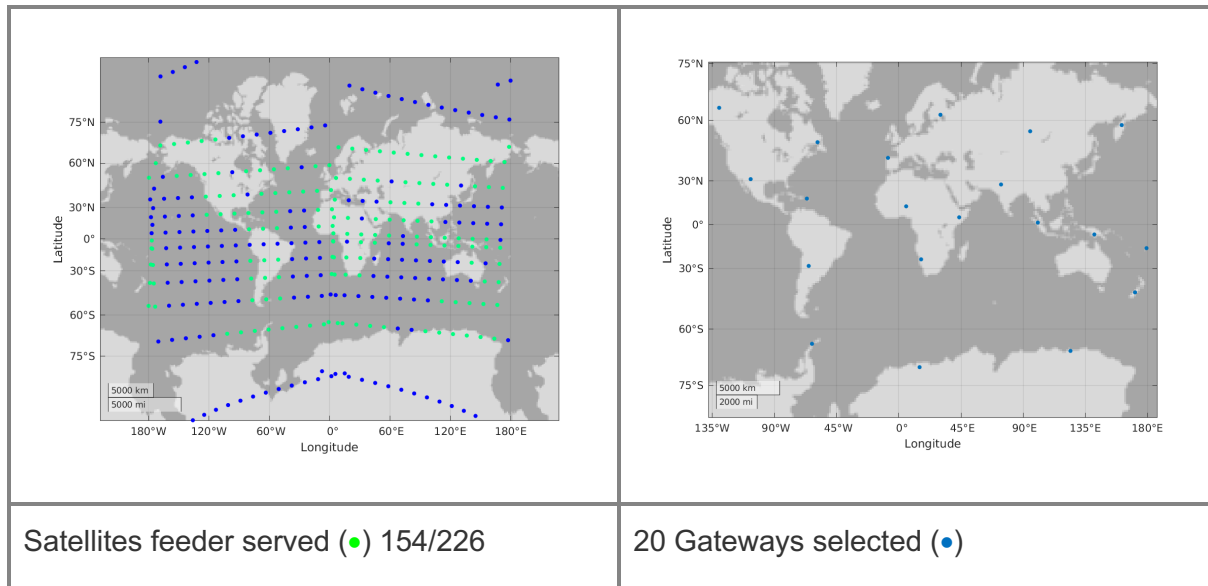


FIGURE 9-16 VLEO 350 KM

constellation 350 km : number of Satellites in view versus elevation					
	(EL min that the feeder shall ensure)				
	(°)	(°)	(°)	(°)	(°)
number of GW	10	12.5	15	17.5	20
10	65	59	48	41	37
12	76	69	56	49	43
14	86	77	64	57	49
16	96	85	72	63	55
18	105	93	80	69	61
20	113	101	88	75	67

FIGURE 9-17 CONSTELLATION FEEDER VLEO 350 KM

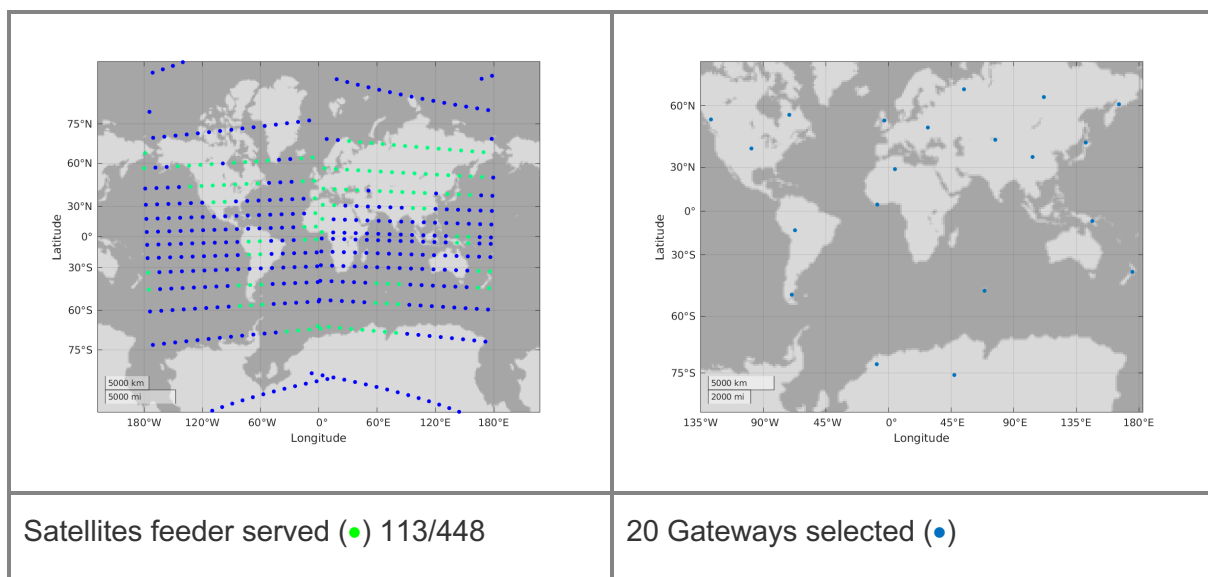


FIGURE 9-18 VLEO 350 KM

If the minimum elevation angle for each feeder is  $10^\circ$  and the 20 gateways are selected, the 45 % of feeder satellites are connected for the LEO constellation at 600 km and 25% of feeder satellites are connected to a gateway for VLEO constellation at 350 km. This results is coherent with the coverage on each case.

The gateway positions are provided in the appendix for both cases.

## 9.5 SUMMARY

According to the results presented in the previous chapter:

### Case A and C (LEO 600 Km) :

Architecture: 1 : 85 gateways (EL min  $20^\circ$ ) to connect satellites in visibility.

Architecture 2 & 2' : 42 gateways ( EL min 10) to connect the satellites in visibility

**Case B (VLEO 350 km):**

Architecture: 1: 140 gateways ( EL min 20°) to connect satellites in visibility.

Architecture 2 & 2': 59 gateways (EL min 10°) to connect satellites in visibility.

If the number of gateway is limited then the number of satellites connected depends on the field of view of the feeder (see 9.4).

The analysis so far is based on the field of view (FoV) of the gateways and satellites to determine the theoretical number of gateways. Naturally, this is not sufficient to accurately size the number of gateways; it is necessary to have a clear understanding of the traffic model to estimate the throughput to be managed at the gateways and their exact locations.

## 10 MISSION DEFINITION INVESTIGATION

This section discusses the current work to assess the capacity of the constellation, and in particular what level of service/data rate an individual user would receive. As this calculation requires many variables as inputs (UE distribution, UE performance, payload gain, payload power, processing split, number of visible satellites, inter-satellite and feeder link performance etc), this section currently only presents some of the considerations that go into the sizing, and the data rates that can be achieved based on the initial sizing of the constellation and the payload. Further optimisation of the constellation is planned for the next phase.

### 10.1 MAPPING USERS TO SATELLITES BASED ON POPULATION DENSITIES

One option to estimate that number of users of the NTN is to base the number off of the population density across the Earth, with various assumptions regarding the number of user equipment (UE) connected to the NTN. Figure 10-1 shows the global population density used in this analysis, in population per km<sup>2</sup>. The density data has a resolution of 0.25° latitude/longitude.

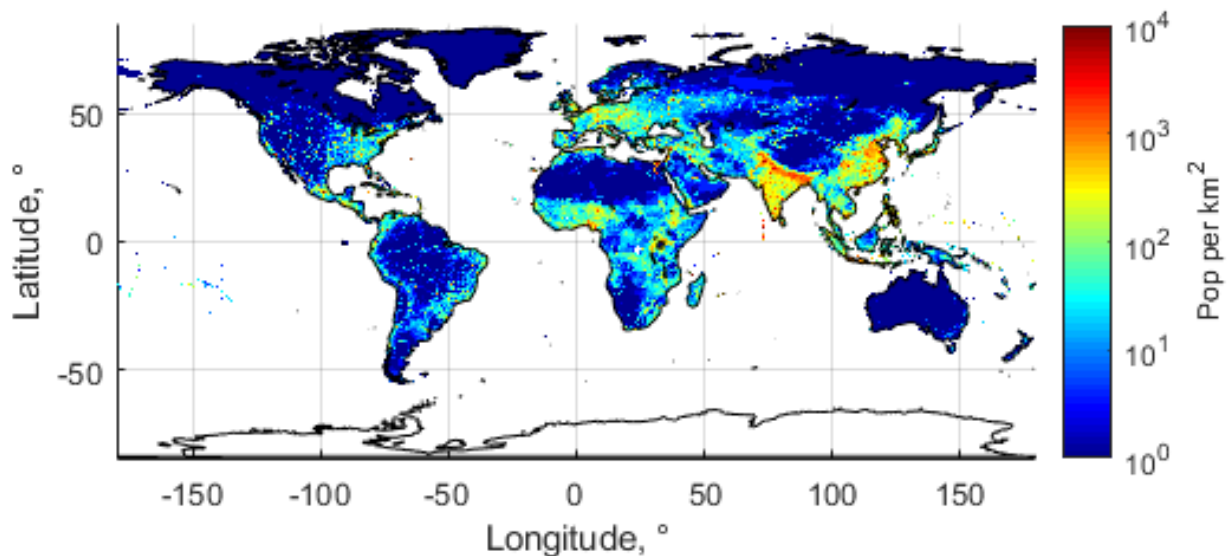


FIGURE 10-1 GLOBAL POPULATION DENSITY

#### 10.1.1 Assumptions on Number of UE

*Note that the assumptions in this section are very preliminary and are intended to illustrate the challenge of sizing the constellation based on global population distributions.*

To relate the user density to the number of UE utilising the NTN, the following assumptions are made. The assumptions are:

- The NTN will only serve non-urban areas, as it is assumed that urban areas will be well served by the TN. This is implemented by defining a threshold, referred to as the Urban Density Threshold (UDT) to determine whether an area is served by the NTN or not. Two initial thresholds of 50 and 350 population per km<sup>2</sup> have been proposed as the population density criterion to differentiate between urban area and non-urban area..

- In non-urban areas, 95% of the area is still well served by the TN, therefore the NTN only needs to serve 5% of users in these areas.
- 10% of the population in the areas served by the NTN will have a UE.

Figure 10-2 and Figure 10-3 show the estimated number of UE in each  $0.25^\circ$  region based on the above assumptions, for UDTs of 50 and 350 population per  $\text{km}^2$  respectively. Regions over land in white are where the density is above the threshold and therefore ignored for the NTN. By using the lower threshold of 50 population per  $\text{km}^2$ , large regions Asia (India and China), Europe and Africa are omitted.

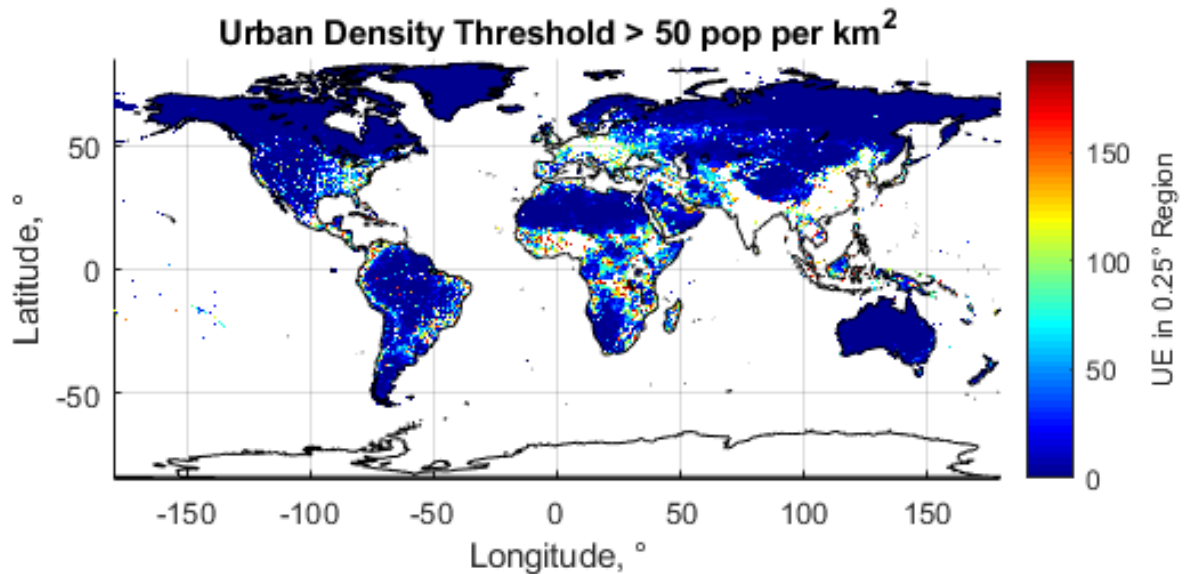


FIGURE 10-2 UE PER  $0.25^\circ$  REGION, WITH AN URBAN DENSITY THRESHOLD OF 50 POPULATION PER  $\text{KM}^2$

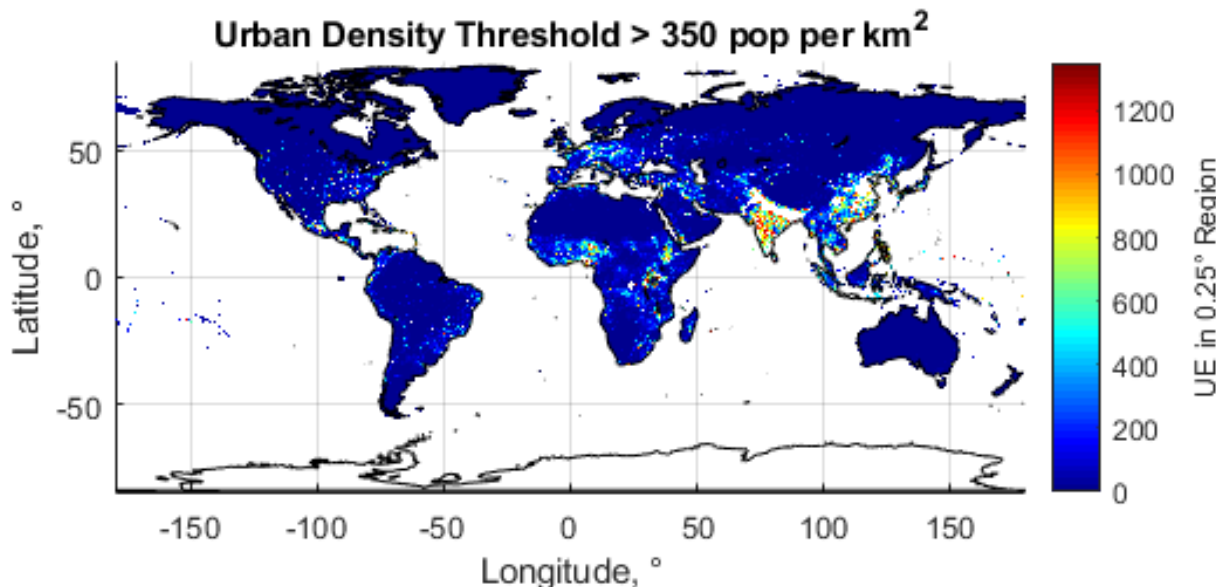


FIGURE 10-3 UE PER  $0.25^\circ$  REGION, WITH AN URBAN DENSITY THRESHOLD OF 350 POPULATION PER  $\text{KM}^2$

### 10.1.2 Mapping UEs to Cells

The 0.25° grid corresponds to squares approximately 27km across at the equator, reducing in size towards the poles. The cells generated by the NTN are currently assumed to be 45km across and hexagonal in shape.

Figure 10-4 and Figure 10-5 show the numbers of UE per 45km cell across the Earth, for UDT of 50 and 350 population per km<sup>2</sup> respectively.

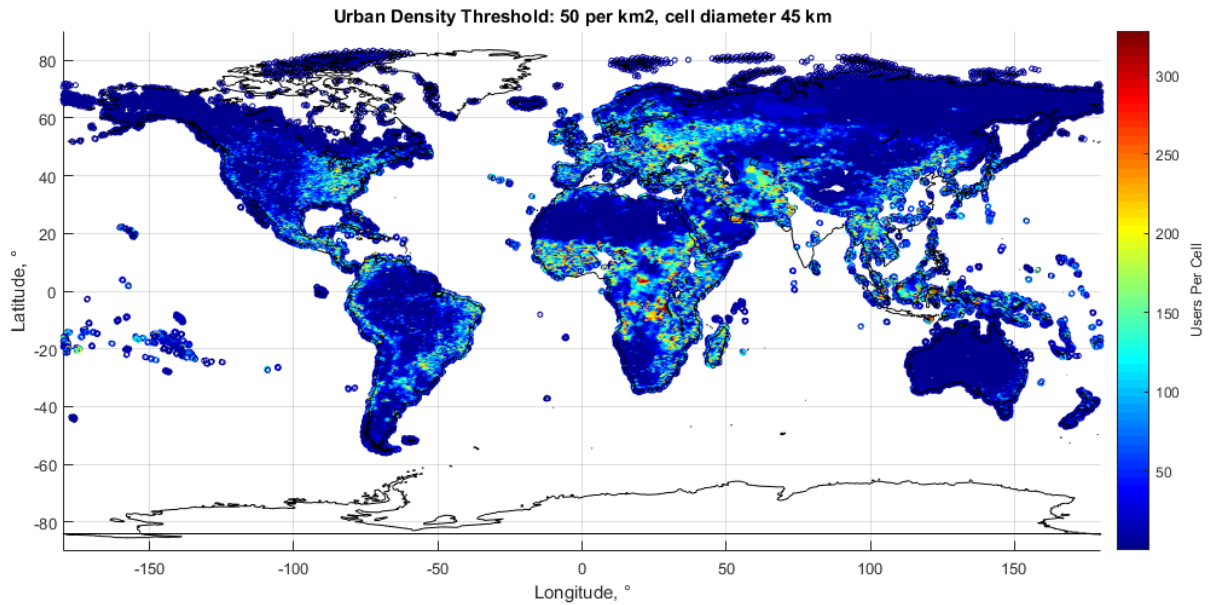


FIGURE 10-4 NUMBER OF UE PER CELL, URBAN DENSITY THRESHOLD OF 50 POPULATION PER KM<sup>2</sup>

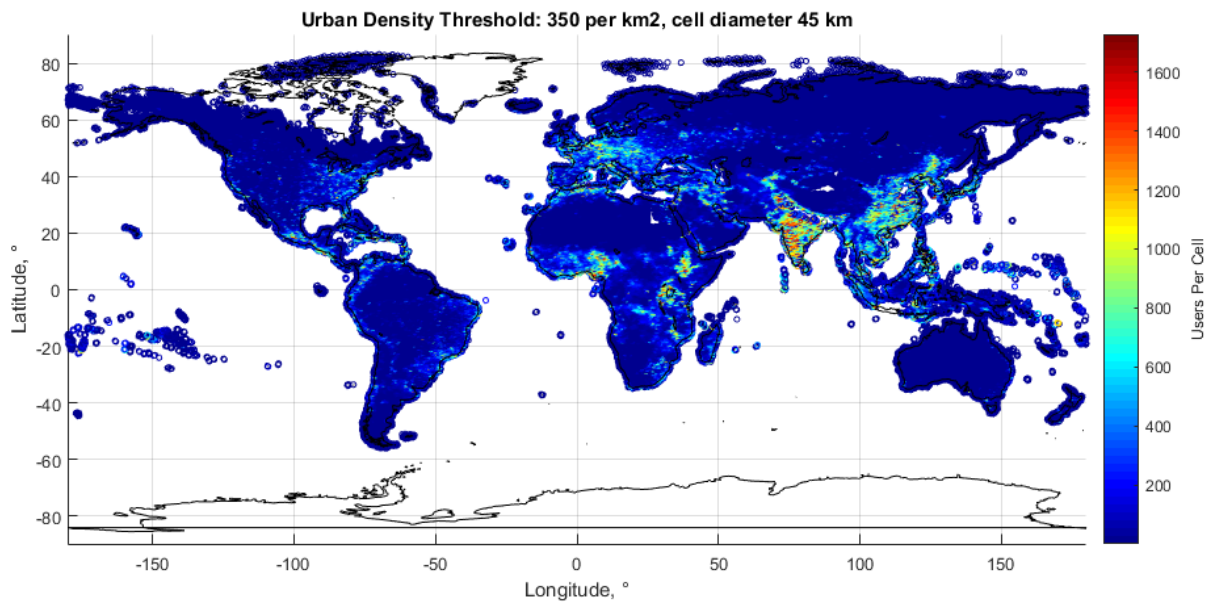


FIGURE 10-5 NUMBER OF UE PER CELL, URBAN DENSITY THRESHOLD OF 350 POPULATION PER KM<sup>2</sup>

Figure 10-6 shows an example of the calculated number of UE per cell, for a single satellite over France with an urban density threshold of 50 population per km<sup>2</sup>. Cells over the sea are blank, as currently it is assumed there are no users here, and cells around major cities such as Paris, Toulouse and Lyon are empty as these cells cover regions defined as urban according to the above assumptions.

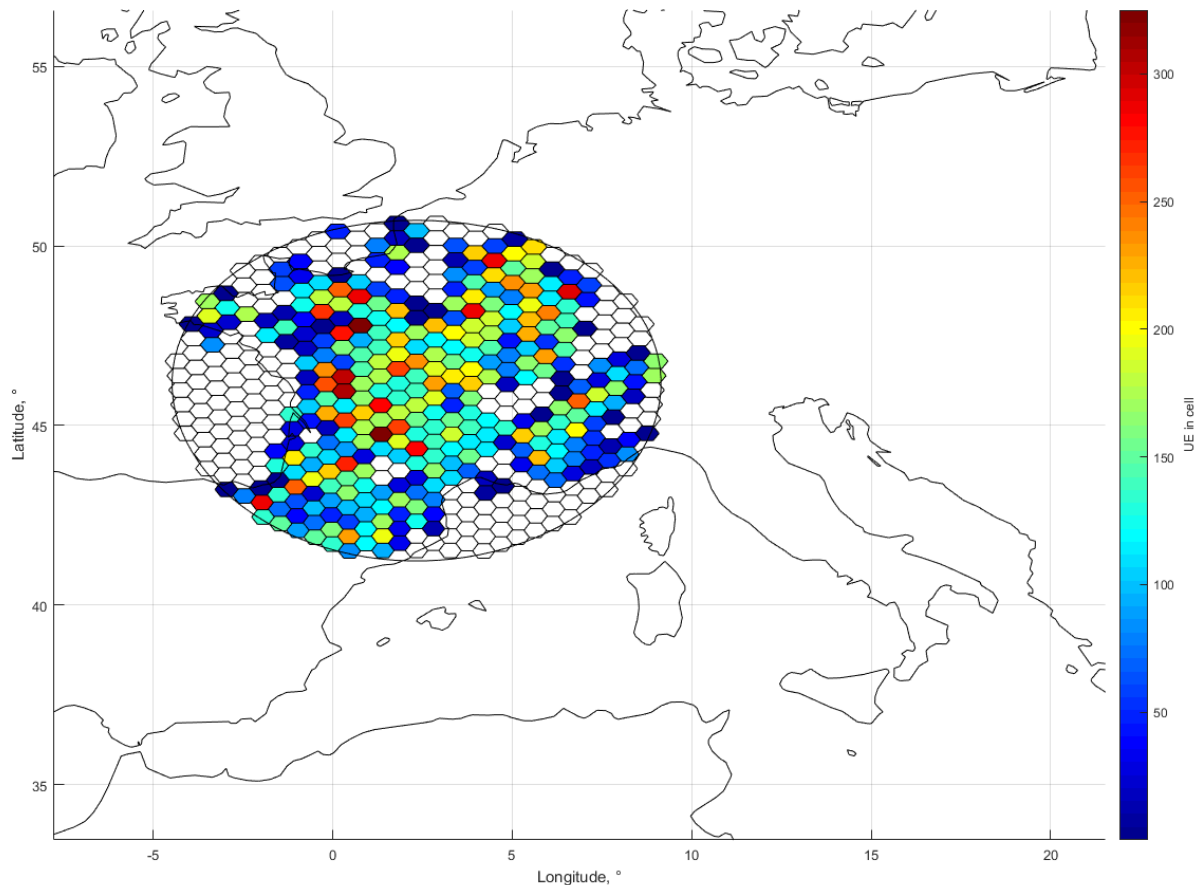


FIGURE 10-6 EXAMPLE OF NUMBER OF UE PER CELL, FOR CELLS IN A SINGLE SATELLITE FOV, URBAN DENSITY THRESHOLD OF 50 POPULATION PER KM<sup>2</sup>

Note that in Figure 10-4 and Figure 10-5 it appears that the cells cover a lot of area that is supposedly empty of NTN users according to Figure 10-2 and Figure 10-3 respectively, for example in Western Africa and Central/Eastern Europe. This is partly due to the fact that each cell covers a larger area than the 0.25° grid, but it is mostly just an artefact of plotting the cells on the map – the marker used for each cell is significantly larger than the actual cell would be if plotted to scale on the map, so that the markers overlap some of the areas that actually are not covered. This is done simply to reduce the computing resources to generate the images – plotting every cell to the correct size (like in Figure 10-6) requires a prohibitive amount of memory, and so this shortcut is taken to simplify processing.

### 10.1.3 Mapping Cells and UE to Satellites

With the number of UE mapped to each cell, cells can be mapped to satellites to determine the number of UE served by each satellite.

Figure 10-7 and Figure 10-8 show the number of UE supported by each satellite for the different UDTs, for the reference constellation of 1269 service satellites. This shows there is a very large variation in the number of UE depending on where the satellite is – many satellites (over the oceans) are supporting no UE at any given time, whereas satellites over areas over Africa, China and India support many.

Figure 10-9 and Figure 10-10 show what percentage of satellites are supporting what number of UE at any given time. This is calculated for two cases – one is that each cell is connected to the closest satellite, and the other is that users in each cell are spread over all satellites that are visible.

For a UDT of 50 population per km<sup>2</sup>, the maximum number of UE supported by a single satellite is 51,000, however 95% of satellites support 17,000 UE or fewer, and 50-60% of satellites are supporting 1 UE or fewer.

For a UDT of 350 population per km<sup>2</sup>, the relative distribution is the same. Here the maximum number of UE supported by one satellite is 292,000, with 95% of satellites supporting 54,000 UE or fewer.

As stated above, the specific numbers of the UE per cells/satellite are highly dependent on the assumptions – the main aim here is to demonstrate the huge variation in user density across the Earth and how this needs to be taken into account when sizing the constellation.

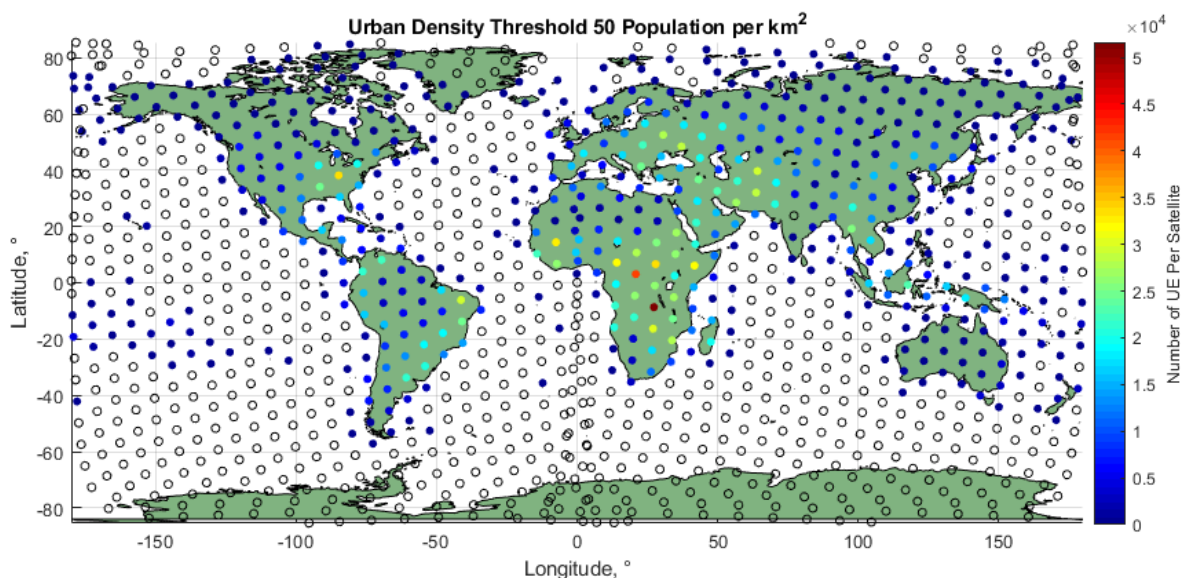


FIGURE 10-7 NUMBER OF UE PER SATELLITE, ASSUMING EACH CELL IS CONNECTED TO THE NEAREST SATELLITE, URBAN THRESHOLD DENSITY OF 50 POPULATION PER KM<sup>2</sup>.

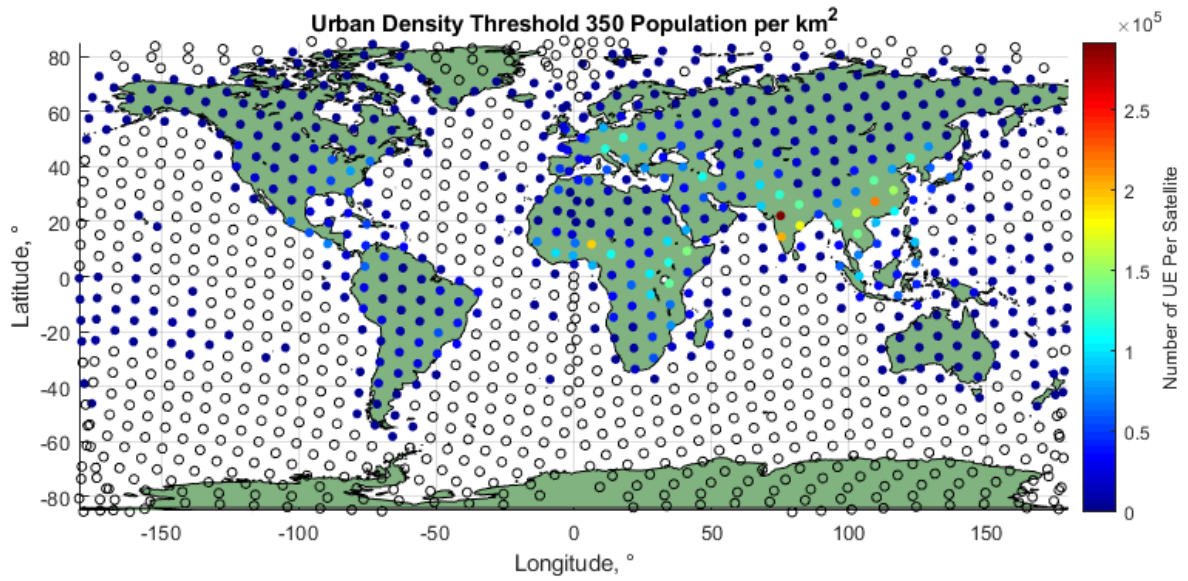


FIGURE 10-8 NUMBER OF UE PER SATELLITE, ASSUMING EACH CELL IS CONNECTED TO THE NEAREST SATELLITE, URBAN THRESHOLD DENSITY OF 350 POPULATION PER KM<sup>2</sup>.

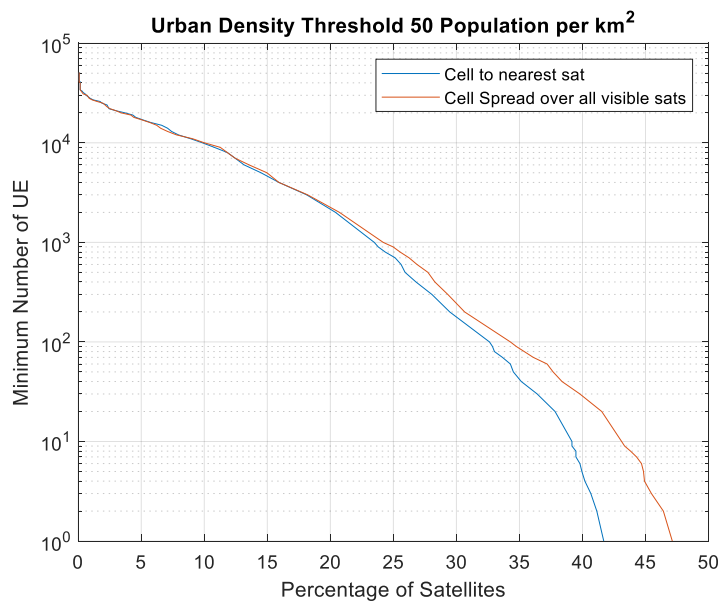


FIGURE 10-9 DISTRIBUTION OF NUMBER OF UE SUPPORTED PER SATELLITES, URBAN THRESHOLD DENSITY OF 50 POPULATION PER KM<sup>2</sup>

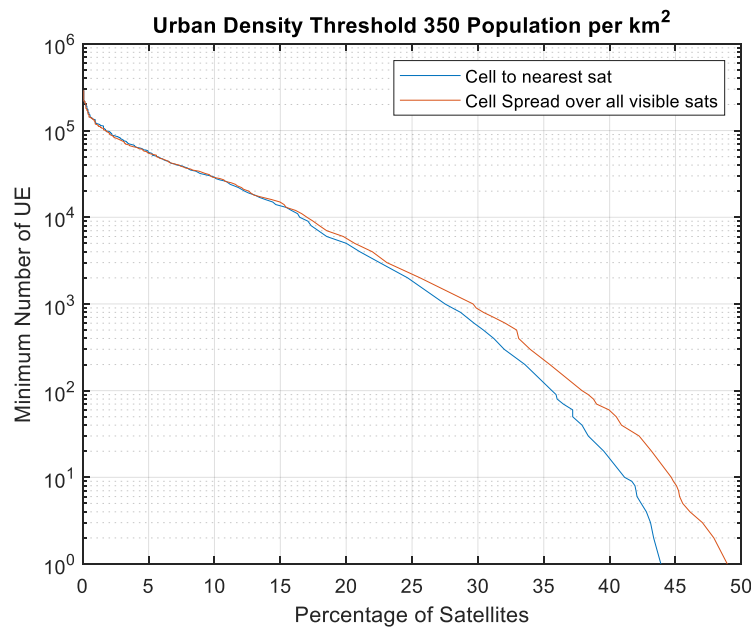


FIGURE 10-10 DISTRIBUTION OF NUMBER OF UE SUPPORTED PER SATELLITES, URBAN THRESHOLD DENSITY OF 350 POPULATION PER KM<sup>2</sup>

## 10.2 CELL CAPACITY BASED ON BEAM CAPACITY

The data rate available on ground can also be determined based on the capacity of the constellation (instead of sizing the constellation based on the number of UE).

It is assumed that each satellite will be able to support a maximum number of beams, each with a certain capacity, and each beam will correspond to a cell on the ground. At lower latitudes, a satellite may have to support more cells than it has beams – in this case, beams will need to ‘hop’ between cells, splitting the capacity of the beam between these cells.

By defining the number of beams a satellite can support, and a data rate per beam, the data rate per cell on ground can be computed.

Figure 10-11 shows the capacity per cell (relative to the capacity of an individual beam) at a single moment, if each satellite can support a maximum of 100 beams. This image essentially shows the ratio of the number of beams a satellite can support to the number of cells the satellite needs to support. This shows that above latitudes of about 65°, each satellite is supporting less than 100 cells and therefore each cell receives the full capacity of the beam, whereas at lower latitudes beams need to be spread over cells – at the equator each satellite is supporting more than 300 cells, so the capacity per cell is less than 1/3 the capacity of an individual beam. For an assumed beam capacity of 48Mbps, we can expect a cell capacity of ~14Mbps for a cell near the equator.

The regions of higher capacity at 0° and 180° longitude are where the ascending and descending arcs of the constellation planes meet, resulting in increased overlap, and therefore requiring each satellite in these planes to support fewer cells each. This region of overlap will remain approximately fixed in space while the Earth rotates below it, causing these regions to ‘drift’ westward at rate of 15° per hour.

This assumes that satellite splits the beams equally across all cells it supports. However as shown in the example in Figure 10-6, the demand in cells supported by one satellite can vary

significantly, and therefore it may be possible to optimise the beam sharing such that cells with high demand receive the full capacity of a beam, and ones with low demand receive less.

This currently does not take into account the fact that cells that are being handed over between satellites may need to be supported by two satellites simultaneously, increasing the number of cells each satellite needs to support.

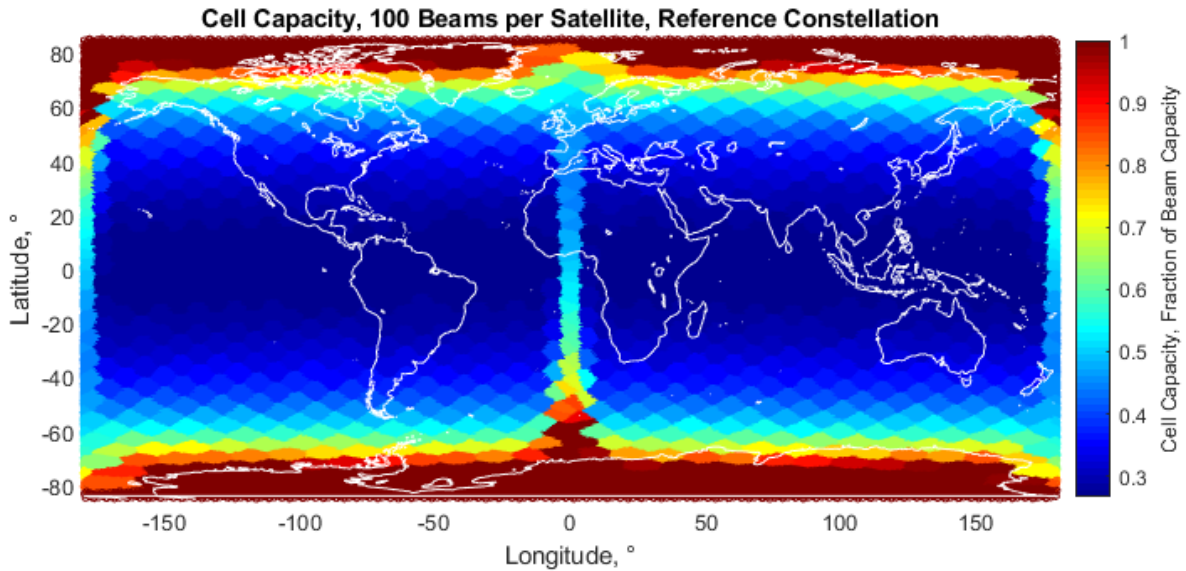


FIGURE 10-11 CELL CAPACITY (RELATIVE TO BEAM CAPACITY) FOR THE REFERENCE CONSTELLATION, ASSUMING A MAXIMUM OF 100 BEAMS PER SATELLITE

Figure 10-12 shows the cell capacity vs latitude for the reference constellation (averaged over longitude), showing how the cell capacity varies with the number of beams a satellite can support. Alternatively, with a defined beam capacity and a target capacity per cell, we can estimate the number of beams that would be required to meet that capacity, or if the number of beams remains fixed, the number of satellites required.

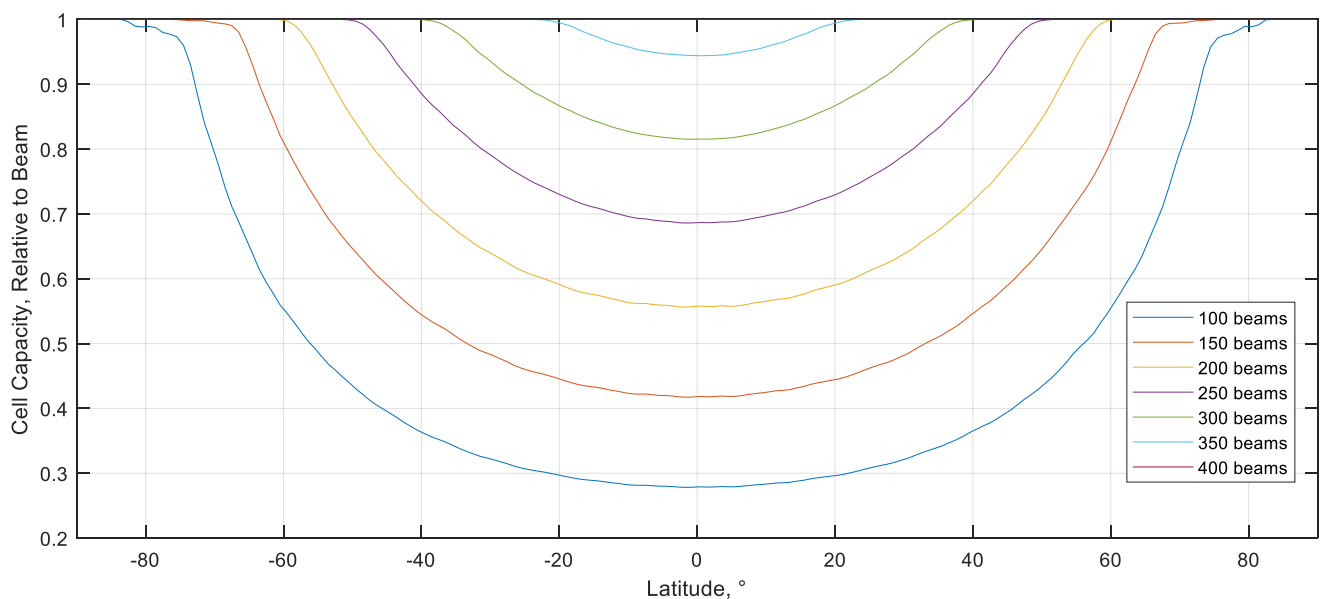


FIGURE 10-12 AVERAGE CELL CAPACITY (RELATIVE TO BEAM CAPACITY) VS LATITUDE

### 10.2.1 Data Rate per UE

The estimate of number of UE per cell can be combined with the calculated data rate per cell to estimate the data rate per UE. Figure 10-13 shows the data rate per UE assuming a maximum of 60 beams per satellite, 48 Mbps per beam (C-band) and a UDT of  $50\text{km}^{-2}$ . A minimum of one UE per cell has been assumed for cells with less than 1 UE (but not 0) to avoid unreasonably large values. For simplicity, currently it is assumed that each cell supported by a satellite receives the same amount of beam coverage (the average data rate of each cell is the same) – it does not yet consider optimisation of beam distribution, for example to provide increased capacity over cells containing more UE.

For users at very northern latitudes, where there is a lot of overlap and very low population densities, the UE data rate is greater than 10Mbps, however over many regions the rate is significantly less than 1Mbps.

Again, note that the assumptions are very preliminary, and do not take into account factors such as variation in demand, activity factors etc.

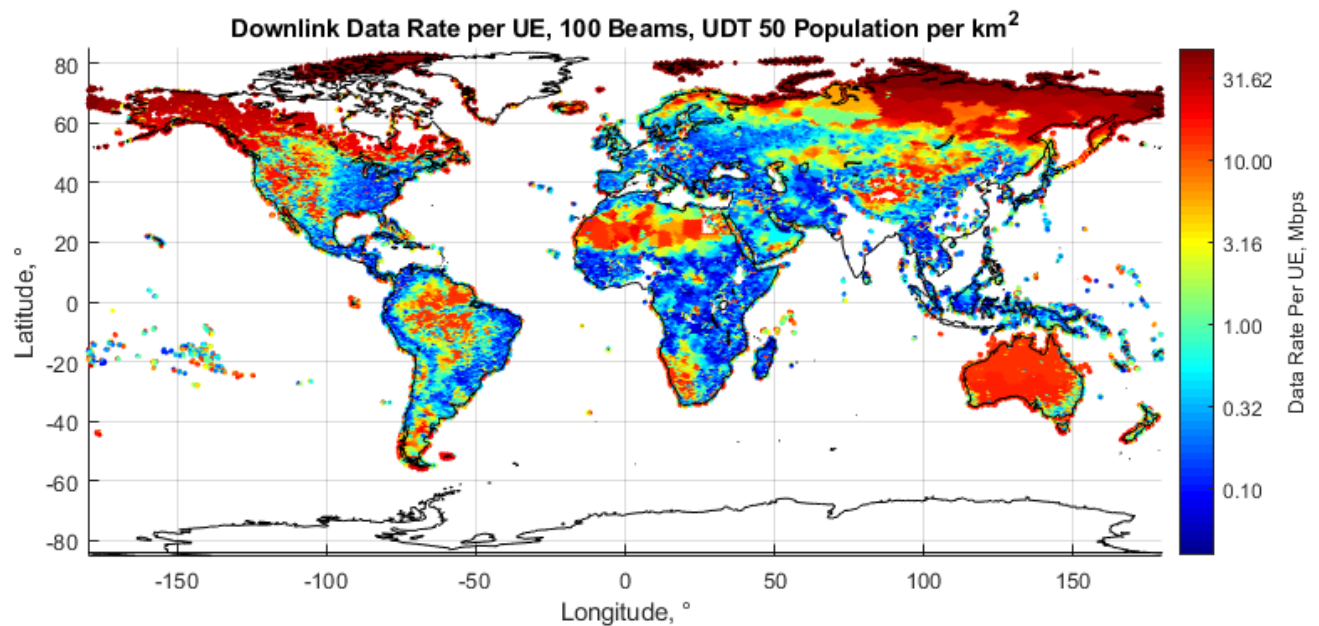


FIGURE 10-13 ESTIMATED DATA RATE PER UE, ASSUMING 100 BEAMS PER SATELLITE, 48MBPS PER BEAM, UDT OF  $50\text{KM}^{-2}$

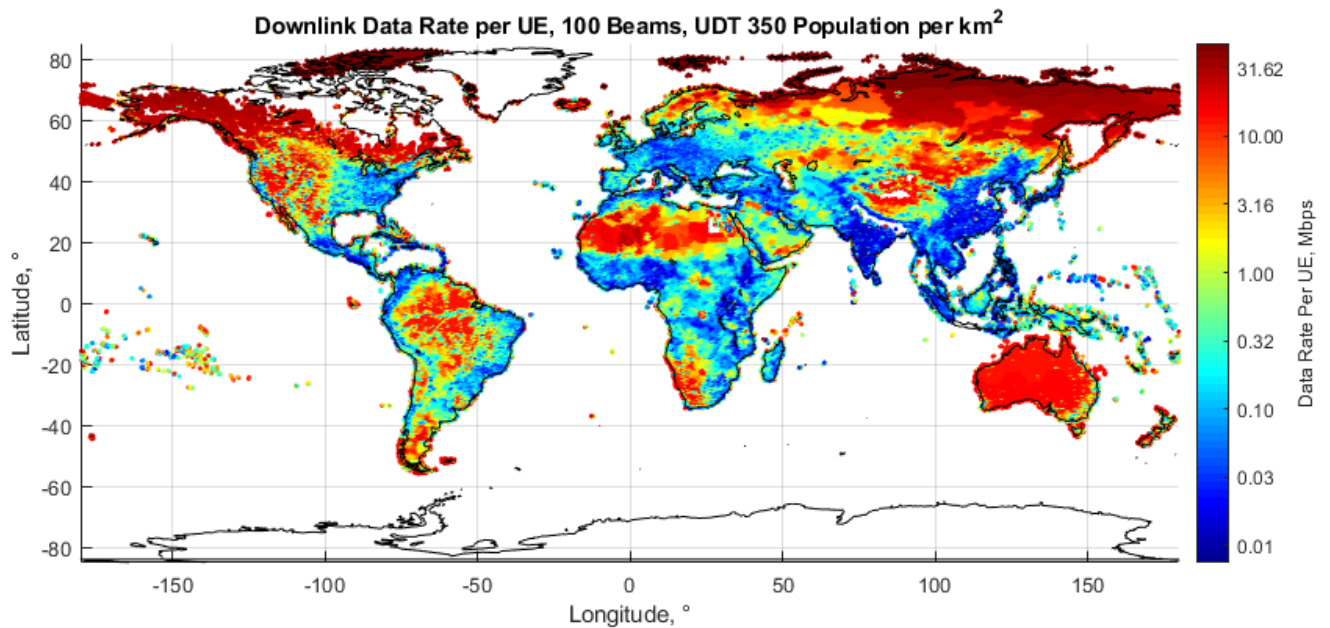


FIGURE 10-14 ESTIMATED DATA RATE PER UE, ASSUMING 100 BEAMS PER SATELLITE, 48MBPS PER BEAM, UDT OF 350 KM<sup>-2</sup>

## 10.2.2 Conclusion

In this chapters, an analysis based on population density and distribution was proposed. The objective is to advance the development of a distributed traffic model to enable an accurate assessment of the requirements and to identify the components that will ultimately allow optimization of the constellations and definition of the satellites comprising them.

For example for the estimation of user densities:

- Different types of terminals: as stated in D2.2 [**Error! Bookmark not defined.**], is expected that different types of terminal (such as handheld, vehicle mounted etc) will operate on different frequency bands. These will have different link budgets, data rate requirements, distributions etc. Distributions for each terminal type could be built up similarly to the global population shown in Figure 10-1 and then aggregated into cells
- Aviation and maritime: currently sizing is only based on population density, which does not provide any allocation for terminals serving aircraft or boats and ships. Estimations for the distribution and number of such terminals could be made by taking tracking data for aircraft and ships, and assuming a certain proportion of them will have NTN terminals. These can then be aggregated with other terminals as described above
- Urban coverage: it has currently been assumed that the NTN provides no urban coverage, however some of the use cases described in D2.2 [**Error! Bookmark not defined.**] (such as Urban Air Mobility) require NTN coverage even in urban areas. As such it may be beneficial to not completely exclude urban areas from the NTN sizing, but instead just assume an upper limit on the number of UE/data rate to be supplied in these areas.

With the UE distribution more defined, it will be possible to estimate the data rate along the lines of the calculation in Section 10.2.1, based on the performance of the payloads. This will then allow variation of the space segment parameters (number of satellites, number of beams per satellite, power per beam etc, and potentially the altitude) to optimise the delivered capacity. This will be an iterative process, taking into account updates to the system architecture [1], payload performance [6] and terminal performance [5].



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## 11 CONCLUSION

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This document presents the investigations conducted on LEO and VLEO constellations, which could contribute to define the constellations best suited for 6G NTN. These solutions are derived from trade-offs analyses integrating multiple parameters.

In connection and interaction with tasks 3.1 (3D multilayered NTN architecture) and 3.3 (software defined payload and its scalability), the analysis of parameters affecting constellation performance enabled the definition of configurations in LEO and VLEO, operating in the C and Q/V bands."

Moreover, the constellation parameters were defined and provided, including altitude, inclination, and number of satellites, latency, speed, round-trip time (RTT), Doppler shift, and other relevant factors. A dedicated section of the document estimates the number of gateways required under various scenarios and assumptions, while another focuses on the deployment of constellations, with particular emphasis on identifying potential launch vehicles suitable in the coming years. Furthermore, a preliminary needs analysis has been initiated to eventually estimate the constellations' capacity to meet demand. It is acknowledged that the capacity calculation remains at an early stage, with several factors yet to be considered or requiring further refinement.

All these elements provide an overview of the factors involved in defining the constellations and serve as input data for the analyses conducted in the other tasks.

Furthermore, considerations on other possibilities have been included in the appendix to broaden and continue future discussions on alternative solutions.

The primary objective of the 6G NTN study is to guide the development towards a flexible constellation associated with payloads in order to contribute to general "scalability concept", as defined in task 3.3 [6], meaning it can progressively adapt to demand without requiring the full redeployment of a new system.

However, the analysis shows that the cost effort associated with NTN quickly becomes significant depending on the configurations: a high number of satellites (more than 1,000 to 2,000), a substantial number of launches (ranging from 80 to 140), and a deployment of ground stations exceeding 50. Of course, these values will need to be adjusted and optimized as requirements become clearer. Several directions should be pursued to optimize NTN, notably continuing efforts to reduce satellite manufacturing costs (through technology and design simplification, as proposed with the distributed architecture), as well as improving their design in terms of volume and mass.

The goal of this study was to identify and highlight key parameter sensitivities that could influence the future design and deployment of 6G NTN constellations. It involves participating in the evaluation and identification of improvements to be implemented, with the aim of ultimately achieving a system optimized in terms of both performance and cost.

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## 13 APPENDIX

### 13.1 APPENDIX A

Table 13-1 and Table 13-2 summarise the Doppler shift experienced for a range of altitudes and frequencies, for a minimum user elevation of 20° and 45° respectively.

TABLE 13-1 SUMMARY OF WORST CASE DOPPLER SHIFT FOR A MINIMUM USER ELEVATION OF 20°

Minimum Elevation 20°				
Frequency (GHz)	Altitude (km)	Max Doppler Shift(kHz)	Relative Doppler Shift	Max Doppler Shift Change (Hz/s)
3	250	70.2	0.0023%	2317
	400	67.8	0.0023%	1385
	600	64.9	0.0022%	871
	800	62.2	0.0021%	617
4	250	93.5	0.0023%	3090
	400	90.5	0.0023%	1846
	600	86.6	0.0022%	1161
	800	83.0	0.0021%	823
40	250	935.4	0.0023%	30896
	400	904.5	0.0023%	18464
	600	865.9	0.0022%	11613
	800	829.9	0.0021%	8231
50	250	1169.3	0.0023%	38619
	400	1130.7	0.0023%	23080
	600	1082.4	0.0022%	14516
	800	1037.4	0.0021%	10288

TABLE 13-2 SUMMARY OF WORST CASE DOPPLER SHIFT FOR A MINIMUM USER ELEVATION OF 45°

Minimum Elevation 45°				
Frequency (GHz)	Altitude (km)	Max Doppler Shift(kHz)	Relative Doppler Shift	Max Doppler Shift Change (Hz/s)
3	250	52.8	0.0018%	2317
	400	51.0	0.0017%	1385
	600	48.9	0.0016%	871
	800	46.8	0.0016%	617
4	250	70.4	0.0018%	3090
	400	68.1	0.0017%	1846
	600	65.2	0.0016%	1161
	800	62.4	0.0016%	823
40	250	703.9	0.0018%	30896

	400	680.6	0.0017%	18464
	600	651.6	0.0016%	11613
	800	624.5	0.0016%	8231
<b>50</b>	250	879.9	0.0018%	38619
	400	850.8	0.0017%	23080
	600	814.5	0.0016%	14516
	800	780.6	0.0016%	10288

### 13.2 APPENDIX B : INCLINED CONSTELLATION 600 KM

The inclined constellation has been defined based on the following coverage parameters:

- Minimum of 1 satellite visible at any time
- Minimum of 10s overlap between satellites
- Global coverage

Altitude of 600km

- Each feeder satellite connected to 4 service satellites.
- Each feeder satellite is connected to 4 other feeder satellites
- Inclined 53°

This results in the following constellation configuration:

- 1287 service satellites
  - 33 planes of 39 satellites

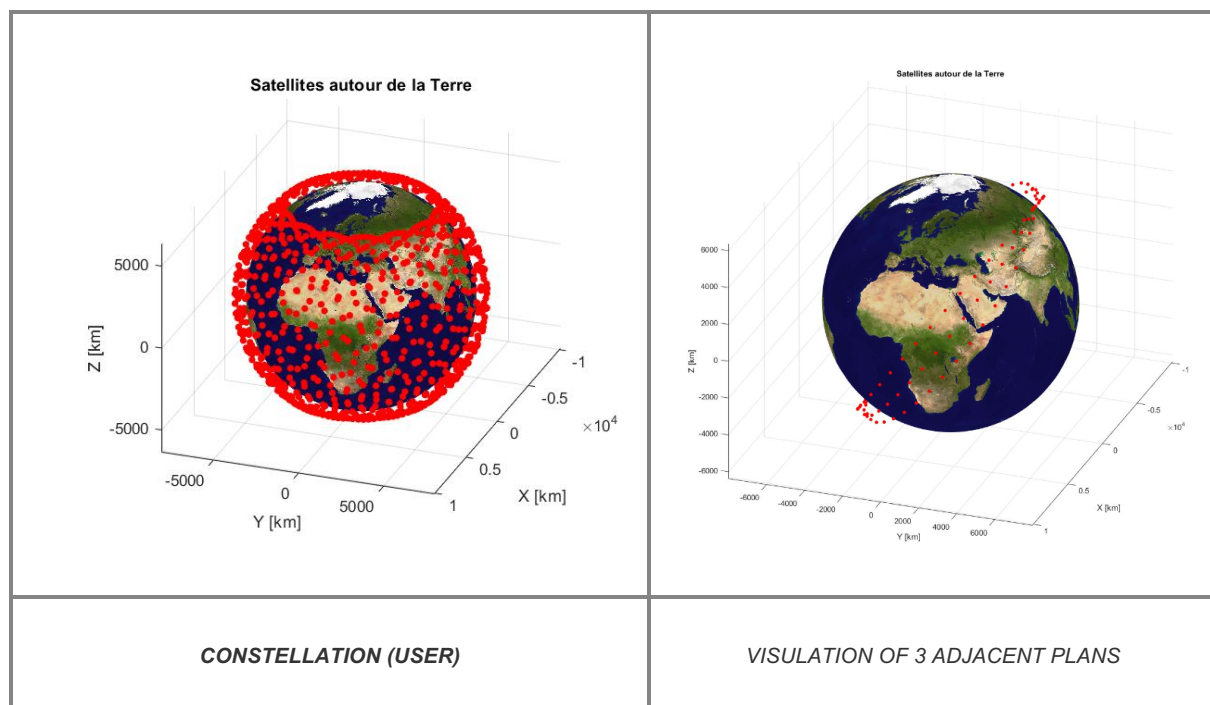


FIGURE 13-1 CONSTELLATION SERVICE+FEEDER OR SERVICE

- 340 feeder satellites
  - 17 planes of 20 satellites.

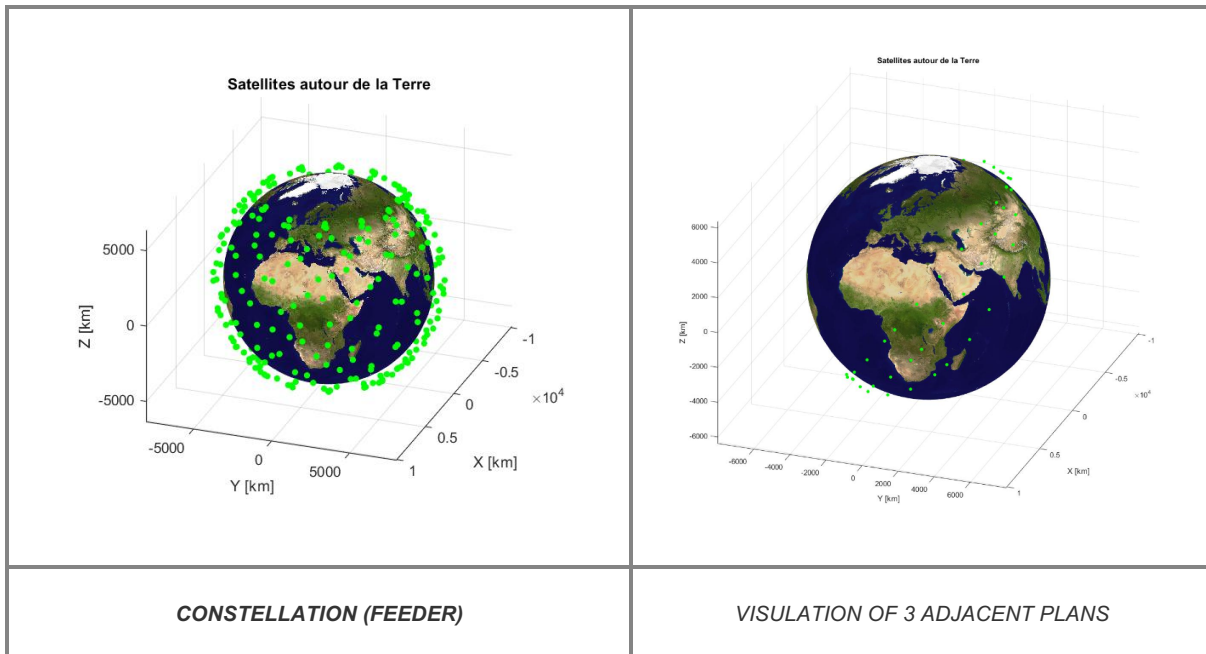


FIGURE 13-2 CONSTELLATION FEEDER

**Coverage**

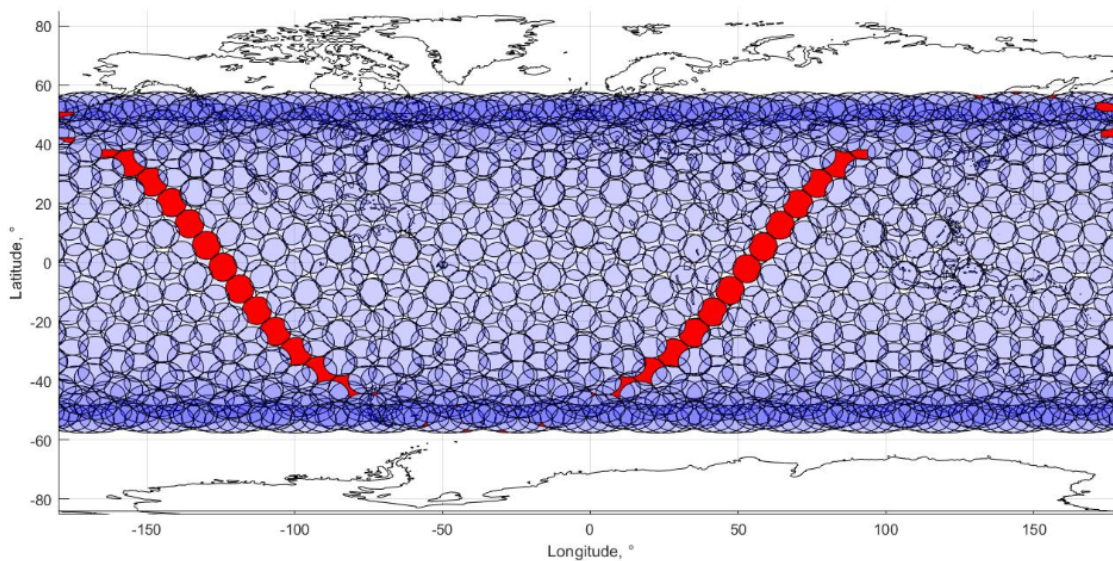


FIGURE 13-3 COVERAGE OF THE INCLINED CONSTELLATION

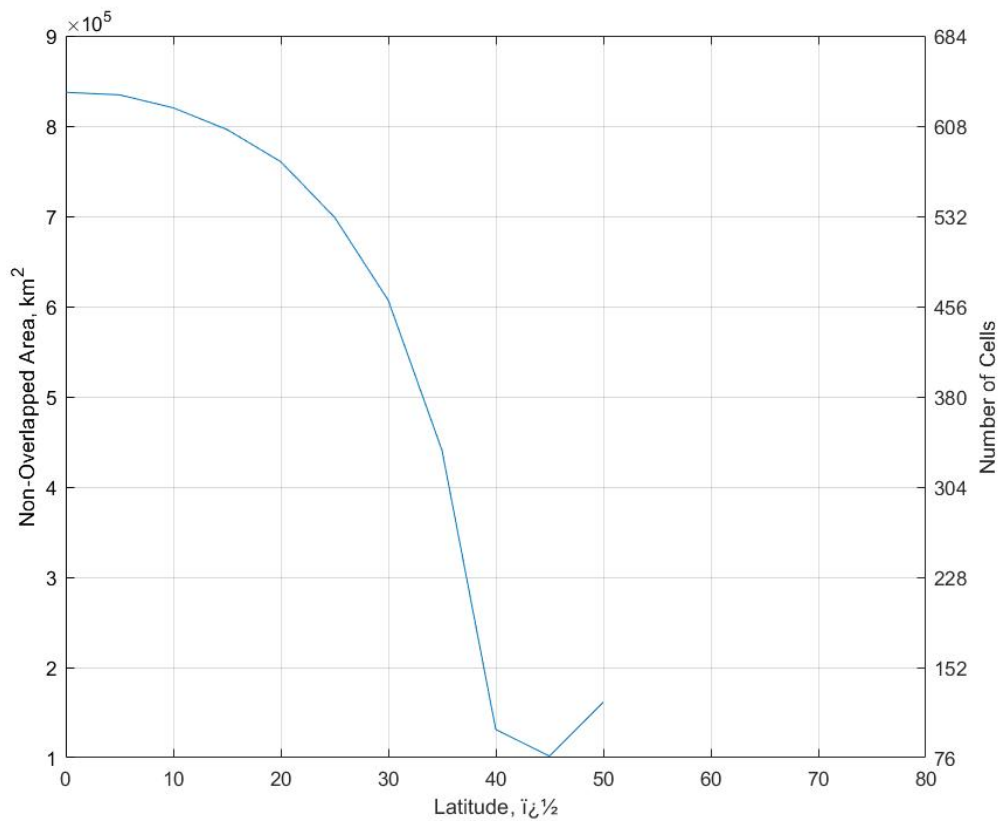


FIGURE 13-4 OVERLAP REGION (VERSUS LATITUDE)

## OISLs

As the relative positions of the satellites change over the orbit, the distance and orientation of the OISLs also needs to change. This section calculates the required distances, and the azimuth and elevation ranges and angular rates required to support the links. The sizing on the OISLs is discussed in D3.5 [Error! Bookmark not defined.], and the feasibility of these requirements will be assessed in the next phase.

### Service-Feeder OISLs

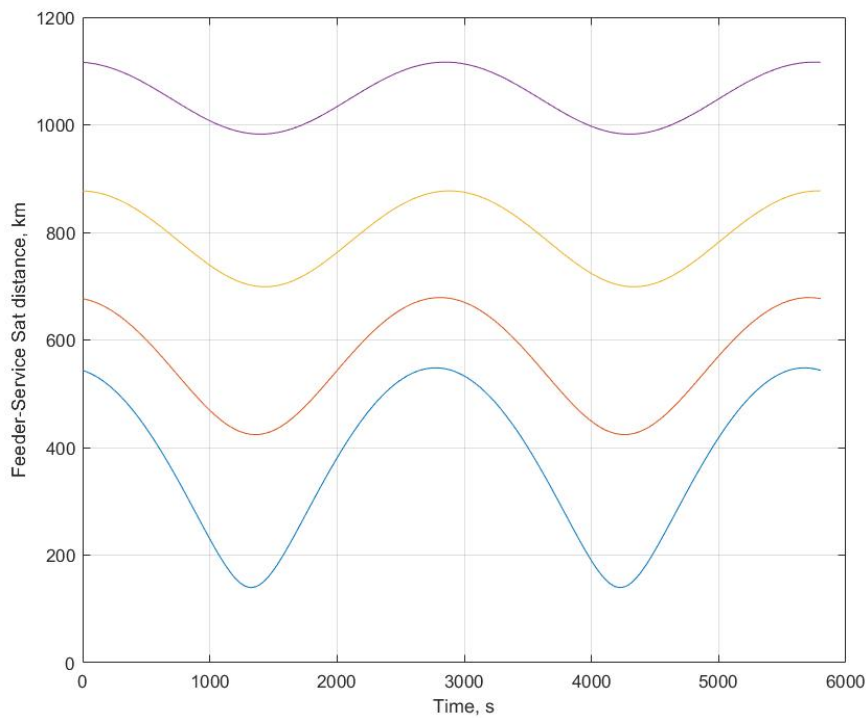


FIGURE 13-5 DISTANCE BETWEEN FEEDER AND SERVICE SATELLITES, OVER ONE ORBIT

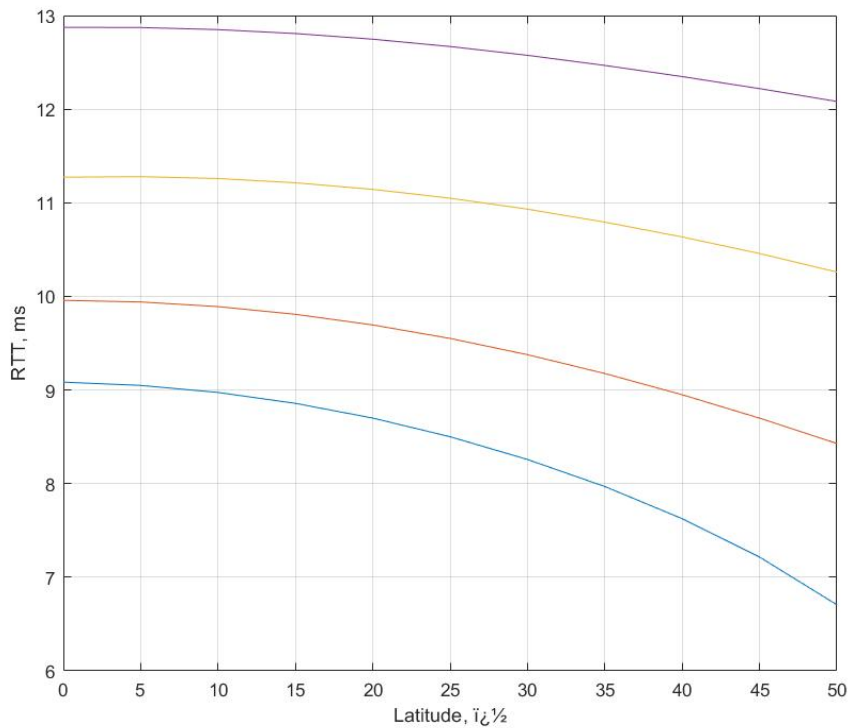


FIGURE 13-6 RTT (USER -> SERVICE SATELLITE -> FEEDER SATELLITE ->SERVICE SATELLITE ->USER) FOR A USER AT THE EDGE OF THE SERVICE SATELLITE FOV

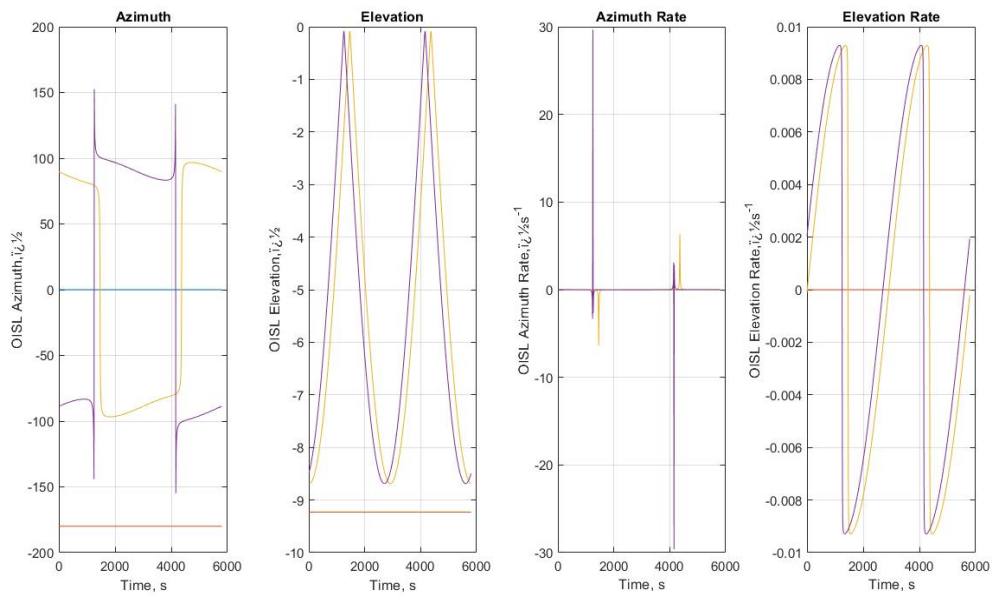


FIGURE 13-7 ANGLES AND ANGULAR RATES FOR FEEDER-SERVICE OISLS ON THE FEEDER SATELLITES

### Feeder-Feeder OISLs

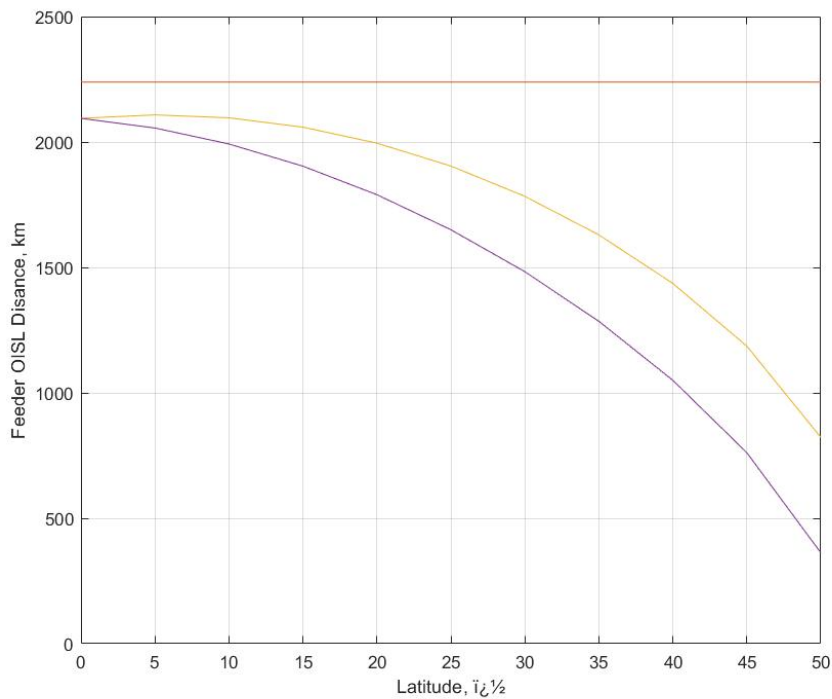


FIGURE 13-8 FEEDER-FEEDER SATELLITE DISTANCE, REFERENCE CONSTELLATION

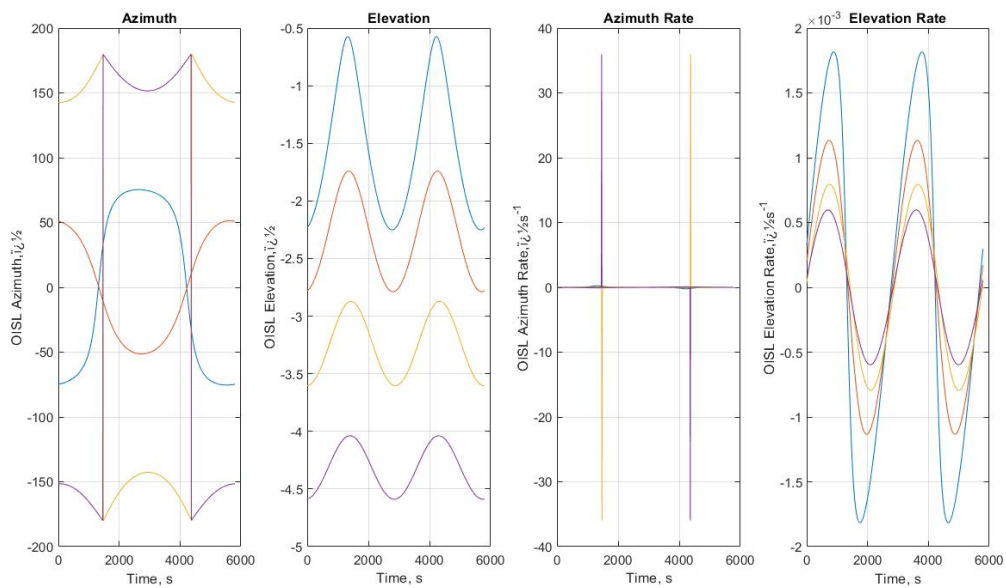


FIGURE 13-9 ANGLES AND ANGULAR RATES FOR FEEDER-FEEDER OISLS

### 13.3 APPENDIX C : INCLINED CONSTELLATION 350 KM

The inclined constellation VLEO has been defined based on the following coverage parameters:

- Minimum of 1 satellite visible at any time
- Minimum of 10s overlap between satellites
- Global coverage

Altitude of 350km

- Each feeder satellite connected to 4 service satellites.
- Each feeder satellite is connected to 4 other feeder satellites
- Inclined 53°

This results in the following constellation configuration:

- 1710 service satellites
  - 38 planes of 45 satellites

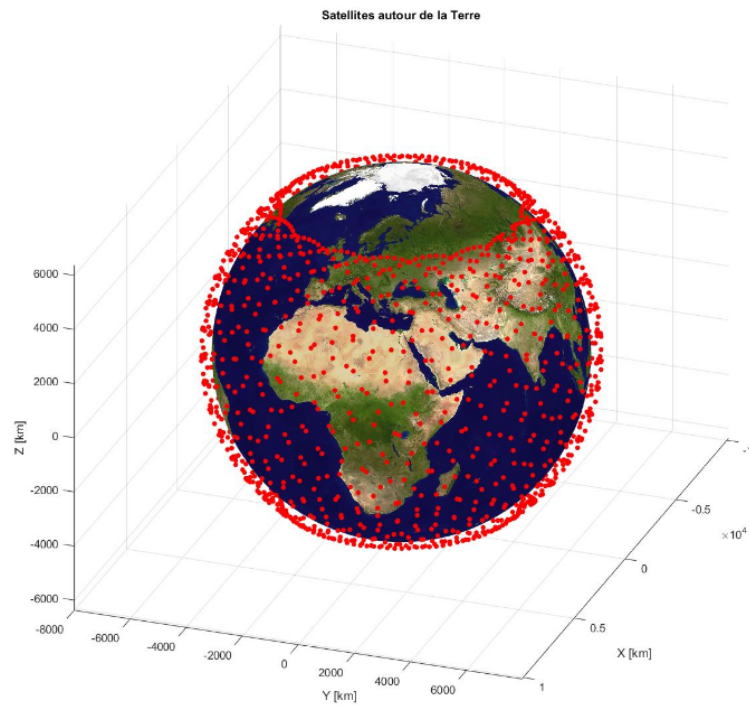


FIGURE 13-10 CONSTELLATION SERVICE+FEEDER OR SERVICE

- **340 feeder satellites**
  - 17 planes of 20 satellites.

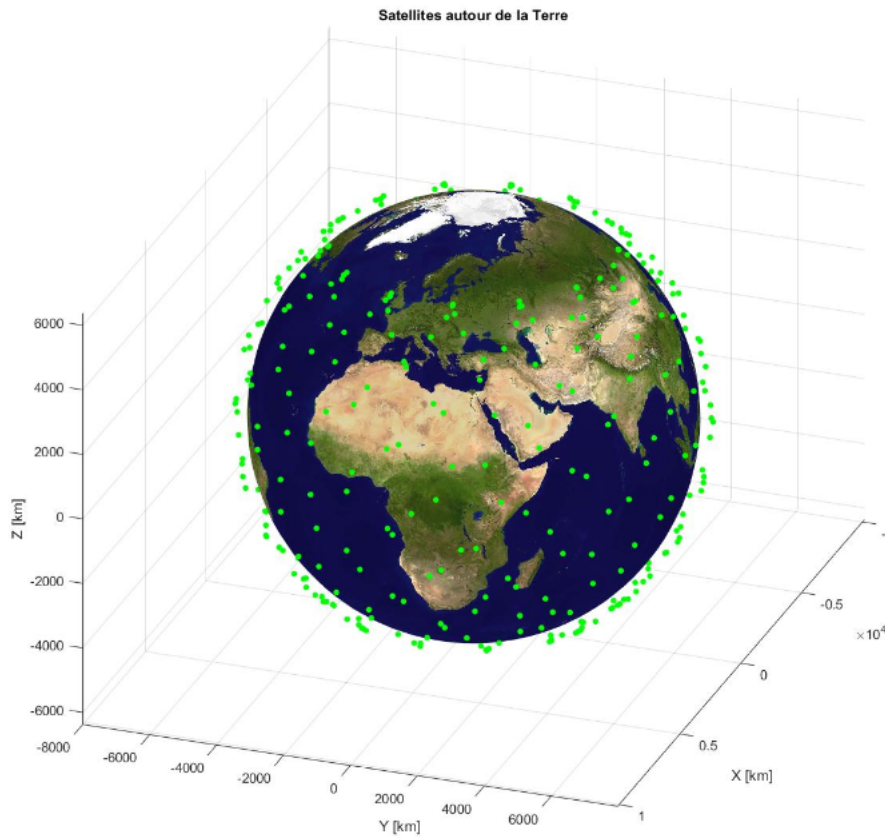


FIGURE 13-11 CONSTELLATION FEEDER

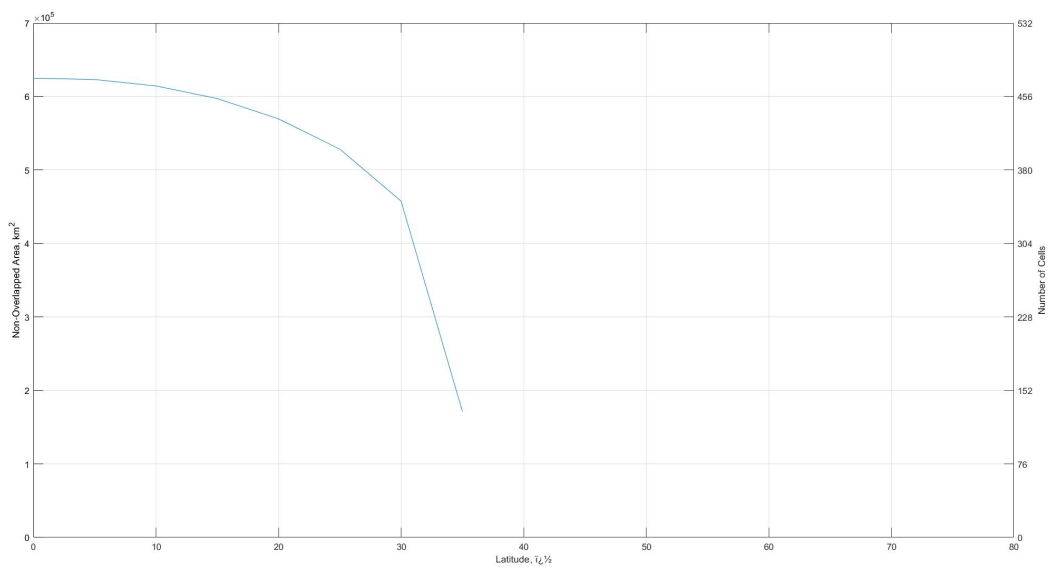


FIGURE 13-12 OVERLAP REGION (VERSUS LATITUDE)

## OISLs

As the relative positions of the satellites change over the orbit, the distance and orientation of the OISLs also needs to change. This section calculates the required distances, and the azimuth and elevation ranges and angular rates required to support the links. The sizing on the OISLs is discussed in D3.5 [Error! Bookmark not defined.], and the feasibility of these requirements will be assessed in the next phase.

## Service-Feeder OISLs

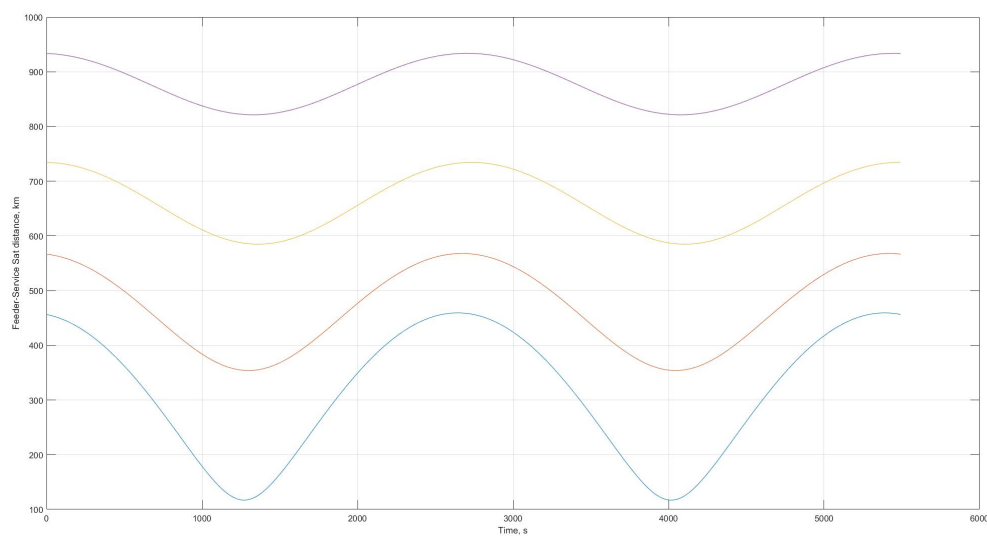


FIGURE 13-13 DISTANCE BETWEEN FEEDER AND SERVICE SATELLITES, OVER ONE ORBIT

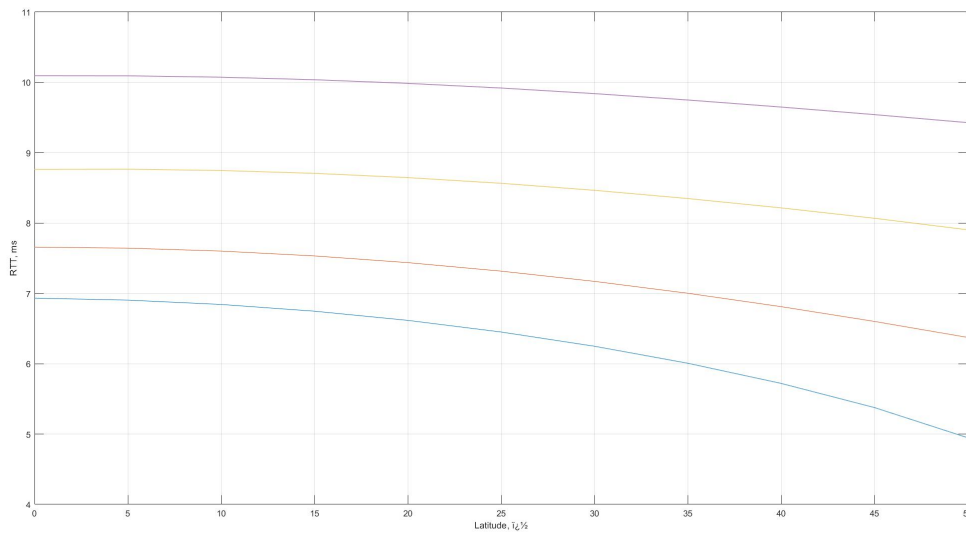


FIGURE 13-14 RTT (USER -> SERVICE SATELLITE -> FEEDER SATELLITE ->SERVICE SATELLITE ->USER) FOR A USER AT THE EDGE OF THE SERVICE SATELLITE FOV

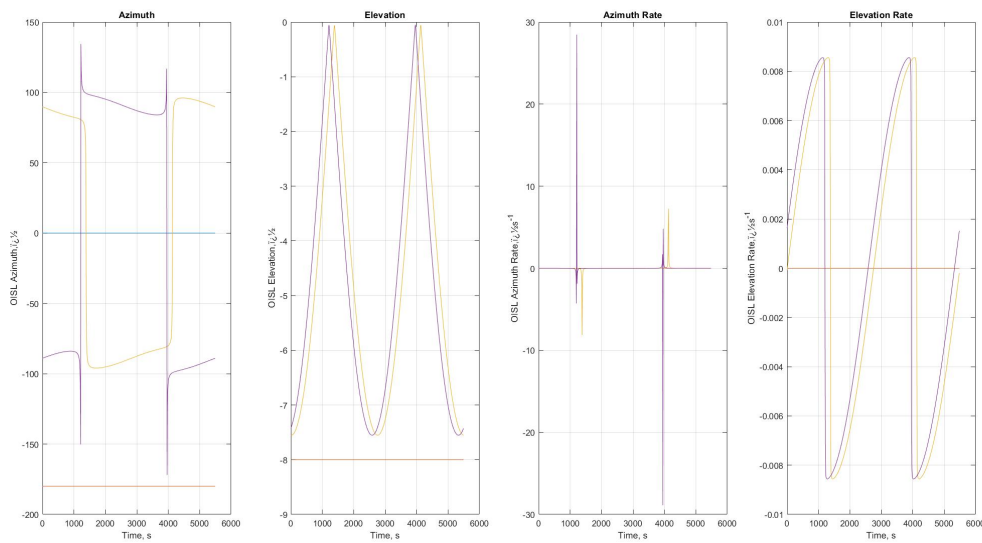


FIGURE 13-15 ANGLES AND ANGULAR RATES FOR FEEDER-SERVICE OISLS ON THE FEEDER SATELLITES

### Feeder-Feeder OISLs

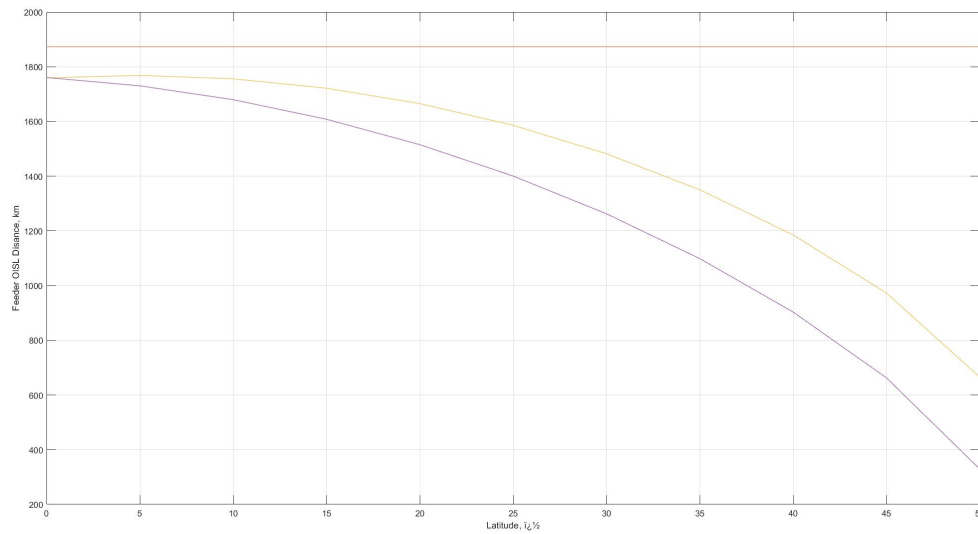


FIGURE 13-16 FEEDER-FEEDER SATELLITE DISTANCE, REFERENCE CONSTELLATION

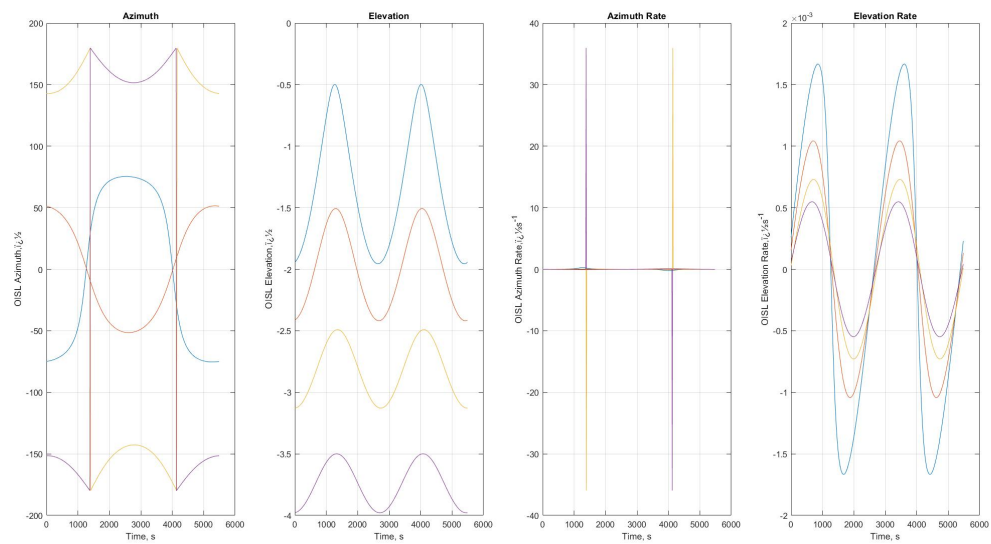


FIGURE 13-17 ANGLES AND ANGULAR RATES FOR FEEDER-FEEDER OISLS

## 13.4 APPENDIX D : SATELLITE ACCOMODATION

### 13.4.1 Architecture 1

#### 13.4.1.1 User satellite (contains all links) architecture 1

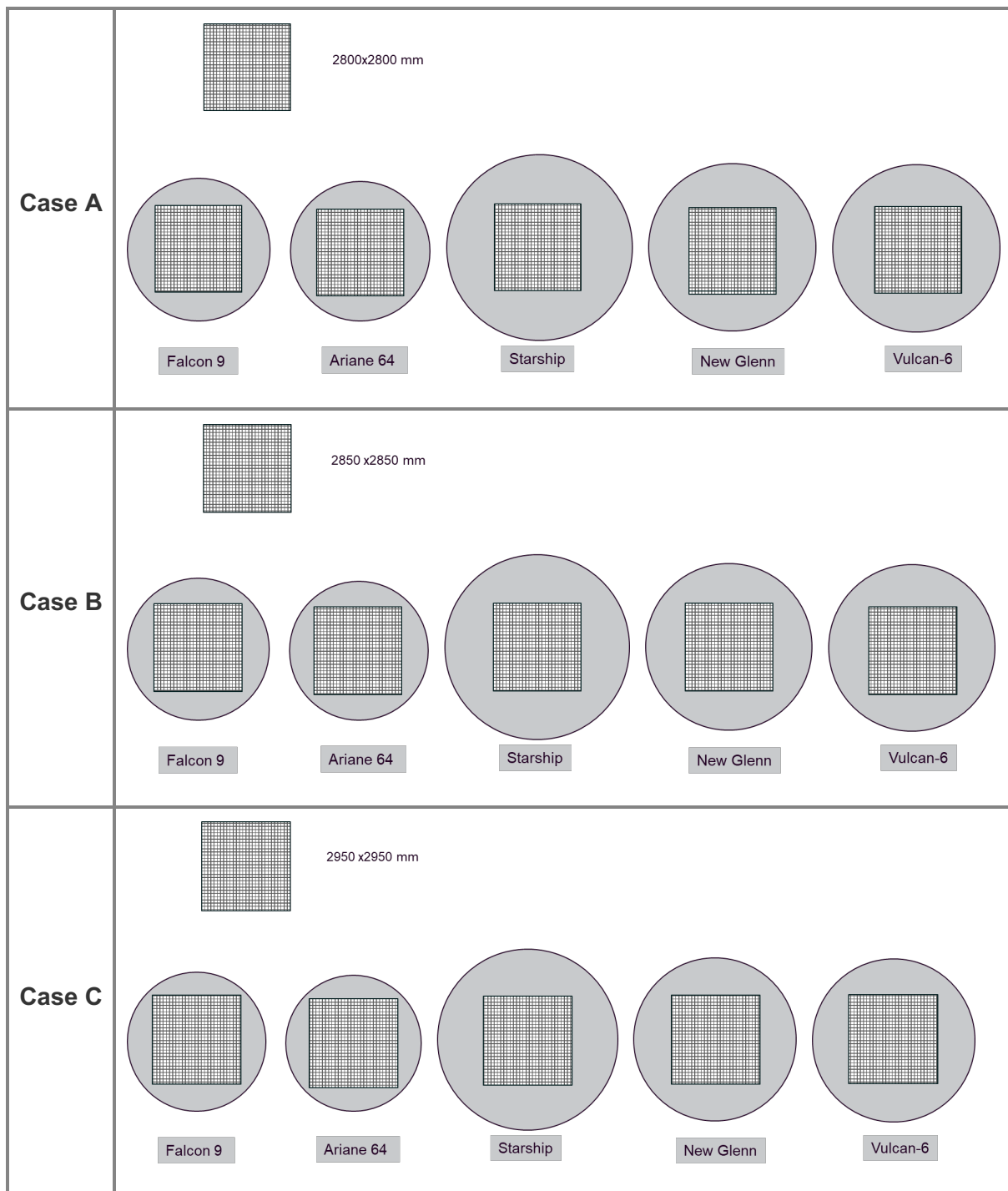


FIGURE 13-18 FOOTPRINT SATELLITE VERSUS LAUNCHERS

### 13.4.2 Architecture 2

#### 13.4.2.1 User satellite (architecture 1)

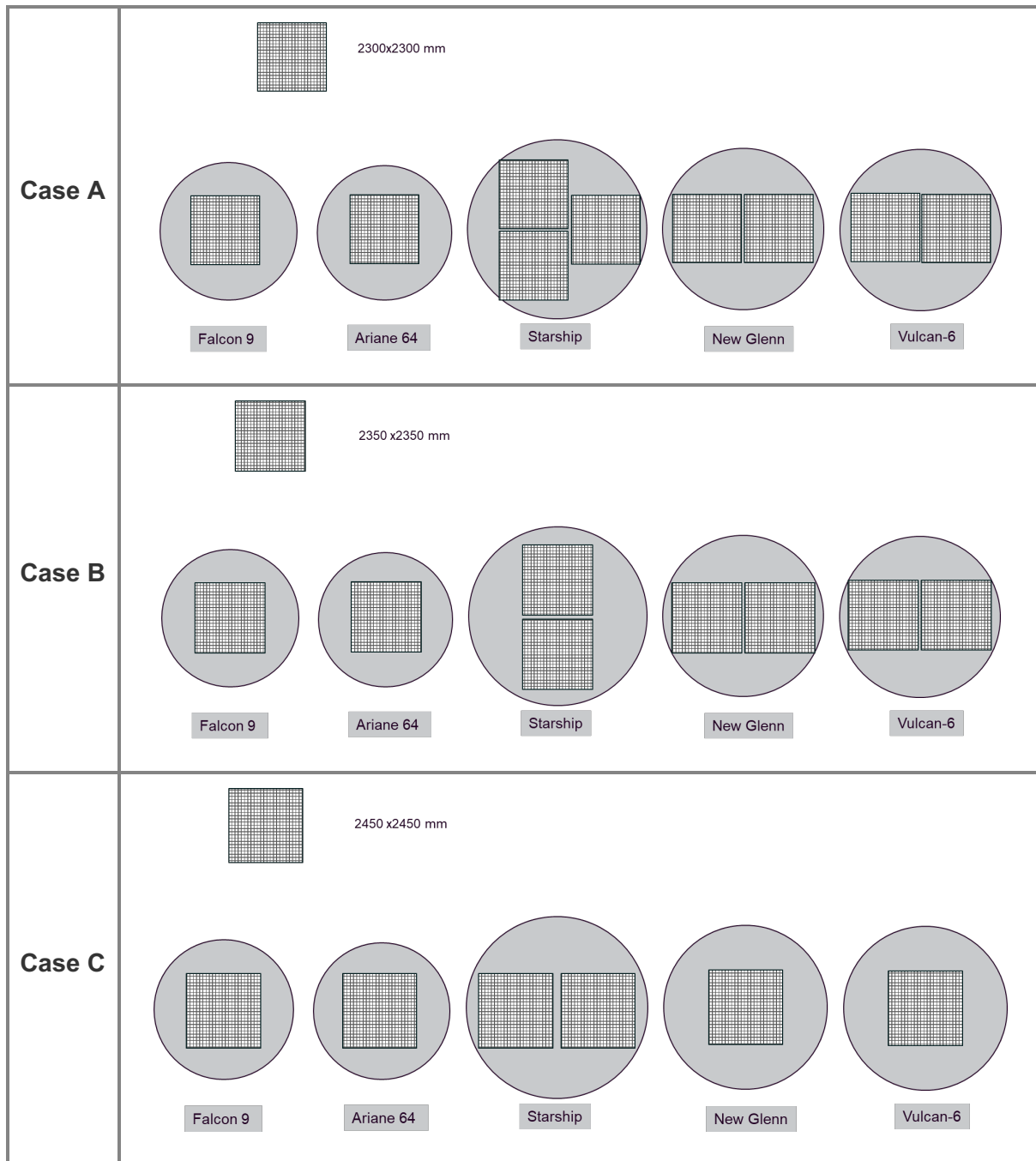


FIGURE 13-19 FOOTPRINT SATELLITE VERSUS LAUNCHERS

#### 13.4.2.2 Feeder satellite (architecture 2)

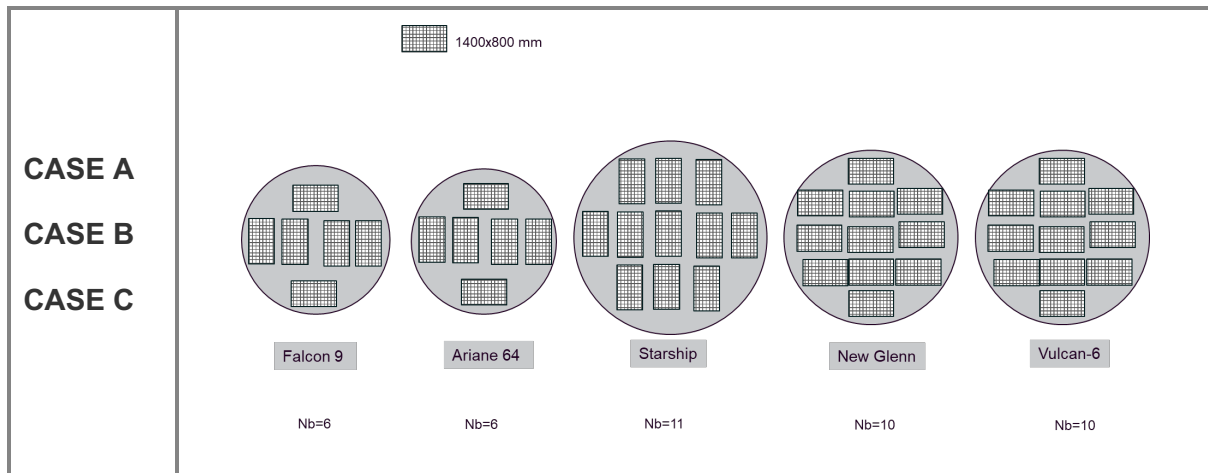
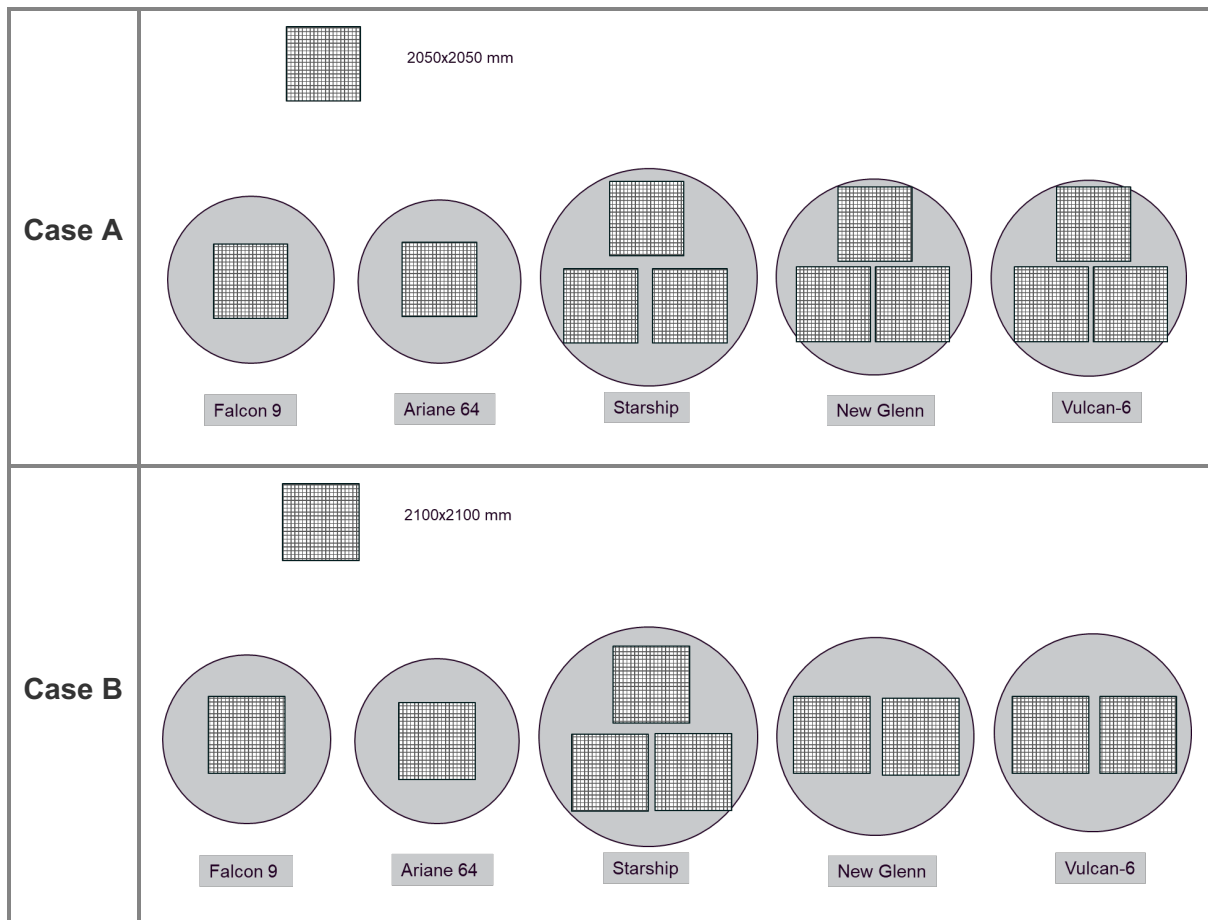


FIGURE 13-20 FEEDER SATELLITE ACCOMODATION

### 13.4.3 Architecture 2'

#### 13.4.3.1 User satellite (architecture 2')



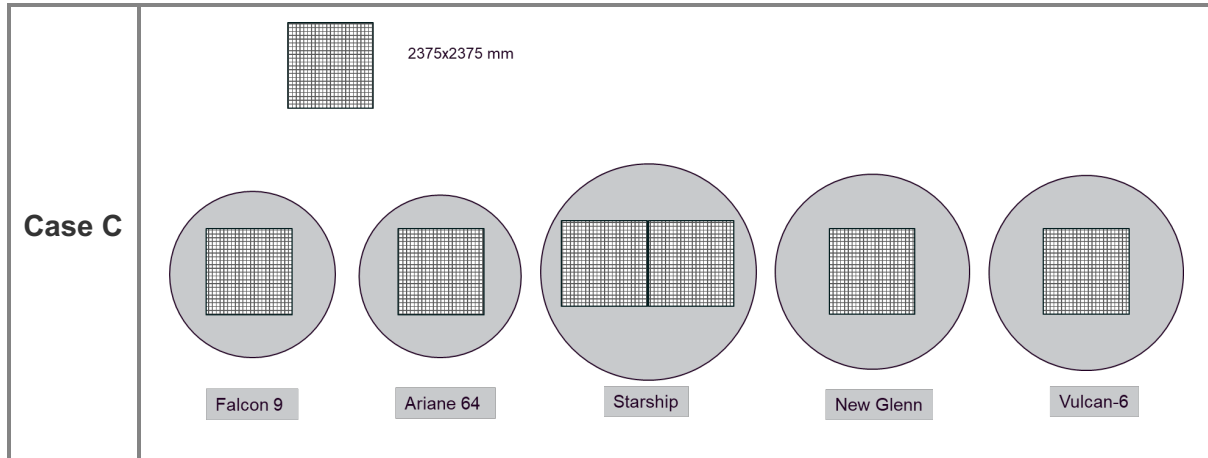


FIGURE 13-21 FOOTPRINT SATELLITE VERSUS LAUNCHERS

### 13.4.3.2 Feeder satellite (architecture 2')

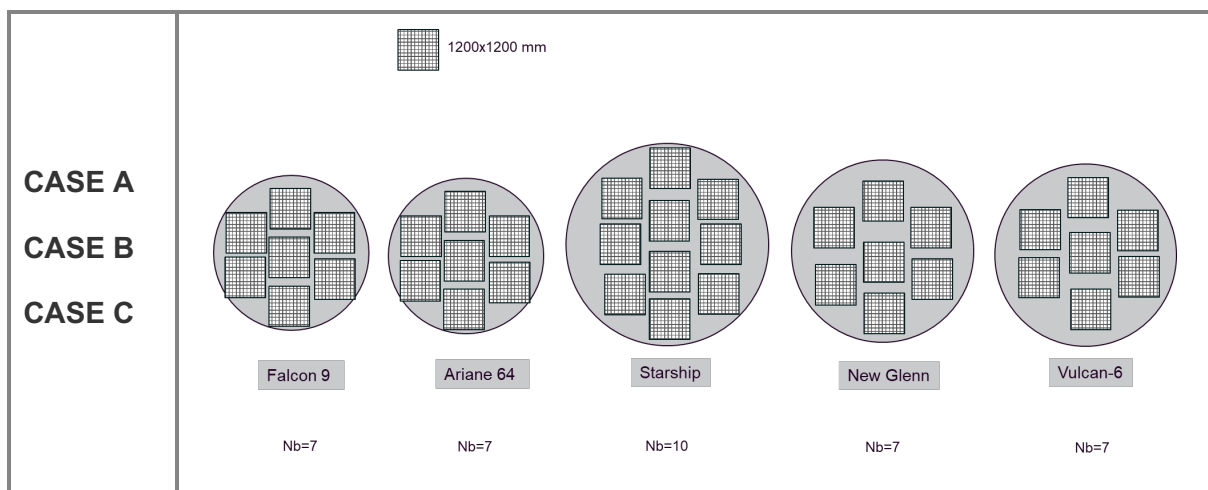


FIGURE 13-22 FEEDER SATELLITE ACCOMODATION

## 13.5 APPENDIX E LAUNCHERS CAPACITIES

### 13.5.1 Ariane 64

ARIANE 64	CASE A - 600km / 1056 RE			CASE B - 350km/ 1536 RE			CASE C - 600km / 2048 RE		
	Architecture 1	Architecture 2	Architecture 2'	Architecture 1	Architecture 2	Architecture 2'	Architecture 1	Architecture 2	Architecture 2'
Satellite mass (t)	1000	933	563	1008	940	563	1050	982	563
Diameter	2.8	2.3	N/A	2.85	2.35	N/A	2.95	2.45	N/A
Height (2)	1.05	0.65	0.95	1.05	0.65	0.95	1.05	0.65	0.95
Length (m)	2.8	2.3	1.4	2.85	2.35	1.4	2.95	2.45	1.4
Width (m)	2.8	2.3	0.8	2.85	2.35	0.8	2.95	2.45	0.8
Height (m)	0.8	0.4	0.7	0.8	0.4	0.7	0.8	0.4	0.7
# sats	1269	336	336	1760	1760	448	1269	336	336
# planes	27	14	14	32	32	14	27	14	27
Sats/Plane	47	24	24	55	55	32	47	24	24
# sats / level	1	1	6	1	1	6	1	1	6
# sats / launch (mass)	15	16	26	15	16	26	14	15	26
# sats / launch (volume)	11	17	71	11	17	71	11	17	71
# launch required	135	81	14	192	128	28	135	108	14

FIGURE 13-23 ARIANCE 64

### 13.5.2 Falcon 9-6500

Falcon 9-6500	CASE A - 600km / 1056 RE			CASE B - 350km / 1536 RE			CASE C - 600km / 2048 RE		
	Architecture 1 Sat User	Architecture 2 Sat Feeder	Architecture 2' Sat User	Architecture 1 Sat User	Architecture 2 Sat Feeder	Architecture 2' Sat User	Architecture 1 Sat User	Architecture 2 Sat Feeder	Architecture 2' Sat User
Satellite mass (t)	1000	563	533	1008	563	533	1050	563	977
Diameter	2.8	N/A	N/A	2.85	N/A	N/A	2.95	N/A	2.45
Height (2)	1.05	0.95	0.95	1.05	0.95	0.95	1.05	0.95	0.6
Length (m)	2.8	2.3	2.3	2.85	2.35	2.35	2.95	2.45	2.375
Width (m)	2.8	1.4	1.2	2.85	1.4	1.2	2.95	1.4	2.375
Height (m)	0.8	0.7	0.7	0.8	0.7	0.7	0.8	0.7	0.35
# Sats	1269	336	336	1760	448	448	1269	336	1269
# planes	27	14	14	32	14	14	27	14	27
Sats/Plane	47	24	24	55	32	32	47	24	47
# sats / level	1	6	7	1	6	7	1	6	1
# sats / launch (mass)	13	24	25	13	24	25	13	24	14
# sats / launch (volume)	11	76	88	11	76	88	11	76	20
# launch required	135	28	14	160	28	28	135	28	108

FIGURE 13-24 FALCON 9-6500

### 13.5.3 Starship

Starship	CASE A - 600km / 1056 RE				CASE B - 350km/ 1536 RE				CASE C - 600km / 2048 RE			
	Architecture 1 Sat User	Architecture 2 Sat User	Architecture 2' Sat Feeder	Architecture 2 Sat Feeder	Architecture 1 Sat User	Architecture 2 Sat User	Architecture 2' Sat Feeder	Architecture 2 Sat Feeder	Architecture 1 Sat User	Architecture 2 Sat User	Architecture 2' Sat Feeder	Architecture 2 Sat Feeder
Satellite mass (1)	1000	933	563	928	1008	940	563	982	1050	982	563	977
Diameter	2.8	2.3	N/A	2.3	2.85	2.35	N/A	2.45	2.95	2.45	N/A	2.45
Height (2)	1.05	0.65	0.95	0.55	1.05	0.65	0.95	0.65	1.05	0.65	0.95	0.6
Length (m)	2.8	2.3	1.4	2.05	2.85	2.35	1.4	2.1	2.95	2.45	1.4	2.375
Width (m)	2.8	2.3	0.8	2.05	2.85	2.35	0.8	2.1	2.95	2.45	0.8	2.375
Height (m)	0.8	0.4	0.7	0.3	0.8	0.4	0.7	0.3	0.8	0.4	0.7	0.35
# Sats	1269	1269	336	1269	1760	1760	448	1760	1269	1269	336	1269
# planes	27	27	14	27	32	32	14	32	27	27	14	27
Sats/Plane	47	47	24	47	55	55	32	55	47	47	24	47
# sats / level	2	2	11	2	2	2	11	2	2	2	11	2
# sats / launch (mass)	100	107	178	108	99	106	178	107	95	102	178	102
# sats / launch (volume)	23	37	139	44	23	37	139	44	23	37	139	40
# launch required	81	54	14	54	96	64	14	64	81	54	14	54

FIGURE 13-25 STARSHIP



### 13.5.5 Vulcan 6

Vulcan 6	CASE A - 600km / 1056 RE				CASE B - 350km / 1536 RE				CASE C - 600km / 2048 RE			
	Architecture 1		Architecture 2		Architecture 1		Architecture 2		Architecture 1		Architecture 2	
	Sat User	Sat Feeder	Sat User	Sat Feeder	Sat User	Sat Feeder	Sat User	Sat Feeder	Sat User	Sat Feeder	Sat User	Sat Feeder
Satellite mass (1)	1000	933	563	533	1008	940	563	533	1050	982	563	533
Diameter	2.8	2.3	N/A	N/A	2.85	2.35	N/A	N/A	2.95	2.45	N/A	2.45
Height (2)	1.05	0.65	0.95	0.95	1.05	0.65	0.95	0.95	1.05	0.65	0.95	0.6
Length (m)	2.8	2.3	1.4	2.05	2.85	2.35	1.4	2.1	2.95	2.45	1.4	2.375
Width (m)	2.8	2.3	0.8	2.05	2.85	2.35	0.8	2.1	2.95	2.45	0.8	2.375
Height (m)	0.8	0.4	0.7	0.3	0.8	0.4	0.7	0.3	0.8	0.4	0.7	0.35
# Sats	1269	1269	336	336	1760	1760	448	448	1269	1269	336	336
# planes	27	27	14	14	32	32	14	14	27	27	14	14
Sats/Plane	47	47	24	24	55	55	32	32	47	47	24	24
# sats / level	1	1	10	7	1	1	10	7	1	1	10	7
# sats / launch (mass)	20	21	36	38	20	21	36	38	19	20	36	38
# sats / launch (volume)	11	18	126	88	11	18	126	88	11	18	126	88
# launch required	135	81	14	14	160	96	14	14	135	81	14	14

FIGURE 13-27

## 13.6 APPENDIX F : TOTAL LAUNCHES

	CASE A LEO 650 Km 1056 RE				
	Architecture 1	Architecture 2		Architecture 2'	
	Sat User	Sat User	Sat Feeder	Sat User	Sat Feeder
Ariane 64	135	81	14	81	14
Falcon 9-6500	135	108	28	108	14
New Glenn	108	81	14	54	14
Starship	81	54	14	54	14
Vulcan 6	135	81	14	81	14
TOTAL					
Ariane 64	135	95		95	
Falcon 9-6500	135	136		122	
New Glenn	108	95		68	
Starship	81	68		68	
Vulcan 6	135	95		95	

FIGURE 13-28 BAND C CASE A : NUMBER OF LAUNCHES

	CASE B : VLEO 350 KM 1536 RE				
	Architecture 1	Architecture 2		Architecture 2'	
	Sat User	Sat User	Sat Feeder	Sat User	Sat Feeder
Ariane 64	192	128	28	128	28
Falcon 9-6500	160	128	28	128	28
New Glenn	160	96	14	96	14
Starship	96	64	14	64	14
Vulcan 6	160	96	14	96	14
TOTAL					
Ariane 64	192	156		156	
Falcon 9-6500	160	156		156	
New Glenn	160	110		110	
Starship	96	78		78	
Vulcan 6	160	110		110	

FIGURE 13-29 BAND C CASE B : NUMBER OF LAUNCHES

CASE C : LEO 600 KM 2048 RE					
	Architecture 1	Architecture 2		Architecture 2'	
	Sat User	Sat User	Sat Feeder	Sat User	Sat Feeder
Ariane 64	135	108	14	108	14
Falcon 9-6500	135	108	28	108	14
New Glenn	108	81	14	81	14
Starship	81	54	14	54	14
Vulcan 6	135	81	14	81	14
TOTAL					
Ariane 64	135	122		122	
Falcon 9-6500	135	136		122	
New Glenn	108	95		95	
Starship	81	68		68	
Vulcan 6	135	95		95	

FIGURE 13-30 BAND C CASE C NUMBER OF LAUNCHES

## 14 APPENDIX G EFFORT (COST)

	CASE A : LEO 1056 RE 600 Km			CASE B : VLEO 1536 RE 350 Km			CASE C: LEO 2048 RE 600 Km		
	CASE A			CASE B			CASE B		
number of satellites users	1269	1269	1269	1760	1760	1760	1269	1269	1269
number of satellites feeder		336	336		448	448		336	336
	arch 1 (ref)	arch 2	arch 2'	arch 1	arch 2	arch 2'	arch 1	arch 2	arch 2'
constellation TOTAL	1.00	0.49	0.41	1.77	0.83	0.67	1.58	0.72	0.58

FIGURE 14-1 EFFORT EVALUATION (REFERENCE: CASE A ARCHITECTURE 1)

## 15 APPENDIX H : GATEWAYS VLEO COVERAGE

### 15.1 ARCHITECTURE 1

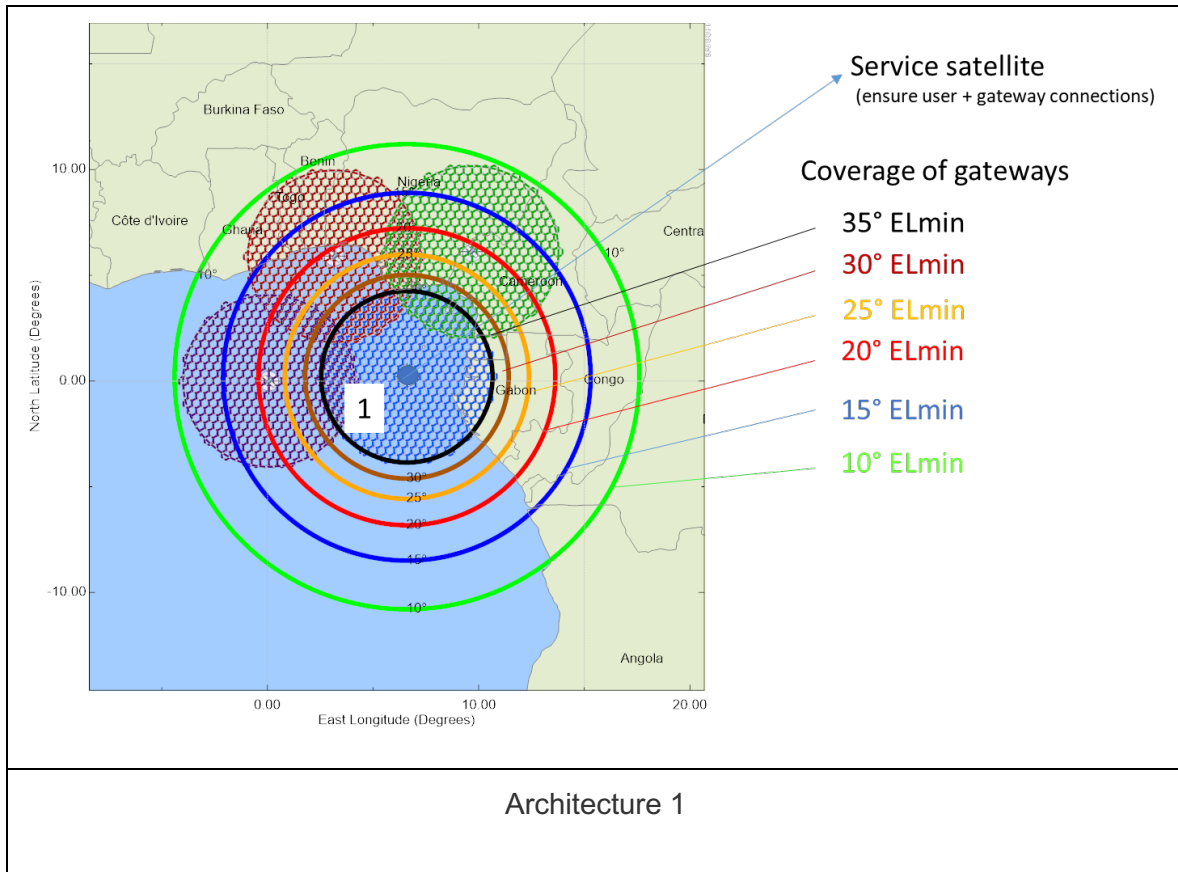


FIGURE 15-1 COVERAGE OF GATEWAYS (ARCHITECTURE 1) VLEO 350 KM

### 15.2 ARCHITECTURE 2

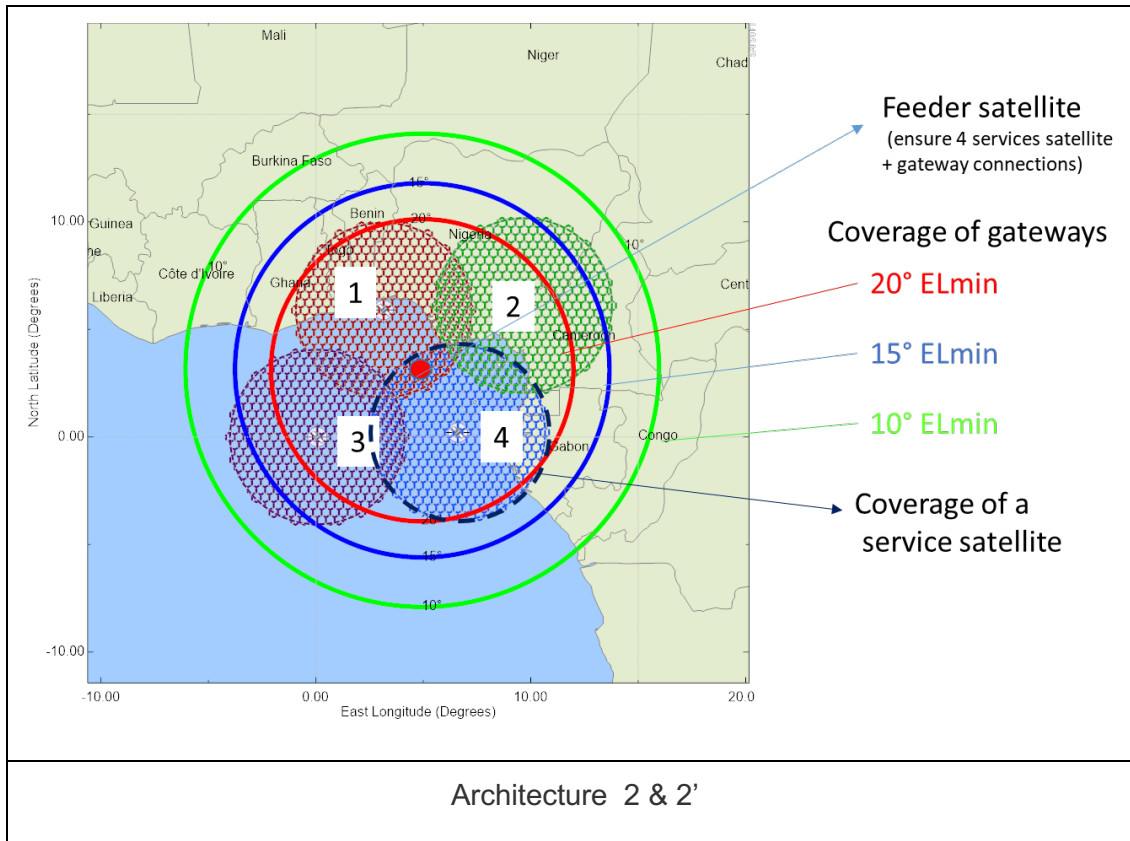


FIGURE 15-2 COVERAGE OF GATEWAYS (ARCHITECTURE 2) VLEO 350 KM

## 16 APPENDIX I

### 16.1 GATEWAYS POSITION (20) CONSTELLATION 600 KM

Alt. 600 km	Longitude	Latitude	Country
GW N°	(°)	(°)	
1	15.00	-71.16	Antarctica
2	124.14	-66.98	Antarctica
3	-62.86	-64.88	Antarctica
4	-65.22	-28.55	Argentina
5	-58.85	51.05	Canada
6	-130.00	64.18	Canada
7	43.64	5.30	Ethiopia
8	179.16	-16.72	Fiji
9	30.07	61.89	Finland
10	73.92	27.85	India
11	100.51	1.48	Indonesia
12	-107.21	31.21	Mexico
13	16.12	-24.28	Namibia
14	170.86	-43.87	New Zealand
15	5.27	13.13	Nigeria
16	141.40	-7.07	Papua New Guinea
17	-66.54	18.49	Puerto Rico
18	95.00	55.75	Russia
19	161.19	58.18	Russia
20	-7.87	43.38	Spain

FIGURE 16-1 SELECTION OF 20 GW

### 16.2 GATEWAYS POSITION (20) CONSTELLATION 350 KM

Alt. 350 km	Longitude	Latitude	Country
GW N°	(°)	(°)	
1	4.72	28.86	Algeria
2	47.37	-75.35	Antarctica
3	-8.37	-73.26	Antarctica
4	-69.44	-51.29	Argentina
5	-67.13	-13.56	Bolivia
6	-127.50	54.80	Canada
7	-71.21	56.68	Canada
8	103.60	36.20	China
9	69.07	-49.48	French Southern and Antarctic Lands
10	141.84	44.10	Japan
11	76.80	45.50	Kazakhstan
12	-7.98	4.74	Liberia
13	175.36	-39.86	New Zealand
14	146.51	-7.07	Papua New Guinea
15	165.71	60.61	Russia
16	111.72	63.04	Russia
17	54.34	65.48	Russia
18	28.35	51.32	Ukraine
19	-2.93	54.39	United Kingdom
20	-98.44	40.96	United States of America

FIGURE 16-2 SELECTION OF 20 GW