D3.4 (V)LEO SPACE SEGMENT

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Abstract	This deliverable presents a first iteration of the constellation design for the (V)LEO space segment of the 6G-NTN and provides an initial estimation of the constellation capacity based on an initial assessment of the payload performance.
Keywords	NTN Constellation, Constellation Optimisation, Constellation Capacity

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DATA: Data sets, microdata, etc.

DMP: Data management plan

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EXECUTIVE SUMMARY

This deliverable provides an initial design and analysis of the (V)LEO space segment to deliver a 6G-NTN network. (MEO, GEO and HAPS elements are not considered in this activity). An optimum constellation in terms of minimum number of satellites has been defined to provide global coverage, and an initial assessment of the constellation capacity (based on assumed payload performance) has been made. Moreover, suggestions for refinement of this sizing are proposed for the next phase of the project.

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. 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°
- 600km altitude

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.

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. As the requirements for each constellation are matured and more detailed sizing of the capacity is performed it is expected that this may change in phase 2 of the project.

Sizing of the constellation capacity is relatively immature 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. Assuming each satellite can support up to 100 beams, each beam has a capacity of 48Mbps (C-Band) and that each cell on ground is approximately 45km across, we get a capacity per cell of ~14Mbps at the equator (as each satellite is required to support more than 100 cells). Only above latitudes of ~±65° does a cell receive the full beam capacity.

In future, the number of beams and number of satellites can be scaled to adjust the constellation capacity to achieve a desired level of service.

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ABBREVIATIONS

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

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1 INTRODUCTION

This task is focussed on the design of the (V)LEO space segment of the 6G NTN, based on the architecture(s) described as part of task 3.1 [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 traffic scenarios defined in WP2 [2][3][4], launcher/deployment constraints, constellation size etc. This task only looks at the main (V)LEO portion of the space segment – the design of potential GEO, MEO or HAPS parts of the system are not considered here.

The parameters of the payload (capacity, size, mass and power) are inputs from tasks 3.2 [5] and 3.3[6]. The sizing of the constellation and the payload is an iterative process to converge on an optimal level of performance.

It is not intended to design a constellation optimised to deliver a specific service/capacity, but rather to give an indication of the services/capacities that can be delivered by the NTN.

2 CONSTELLATION SIZING

The aim of the constellation sizing activity is to determine the minimum number of service satellites required to provide the defined coverage. 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.

Also, as this activity looks at providing coverage to users, it only considers the satellites that directly communicate with the UE – other satellites (such as those that provide feeder connections in the case of a distributed architecture) are not considered, therefore details of the Radio Access Network (RAN) architecture are not accounted for here. Once models for the constellation capacity have been developed, the constellation sizing can be revisited and the number of satellites increased to increase capacity 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 with 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 2-1 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 7kms^{-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.

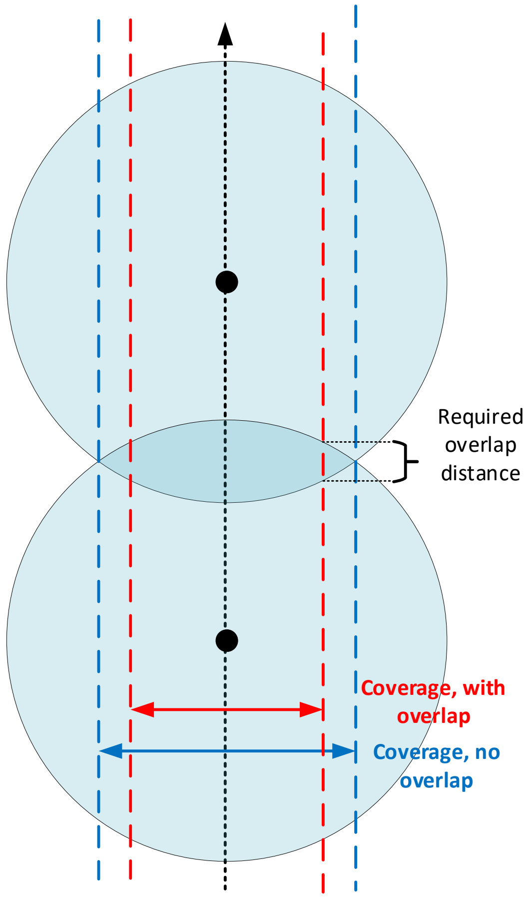

FIGURE 2-1"STREET" OF COVERAGE FOR A SINGLE PLANE OF SATELLITES, WITH AND WITHOUT A MINIMUM OVERLAP DURATION

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[1], therefore the satellite planes can be more widely spaced, requiring fewer satellites for coverage.

Having the planes orbiting in alternating directions also has the disadvantage that it only works for a constellation in a 90° 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° - 20° = 70° and the other has 90° + 20° = 110°) -

[1] 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.

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.

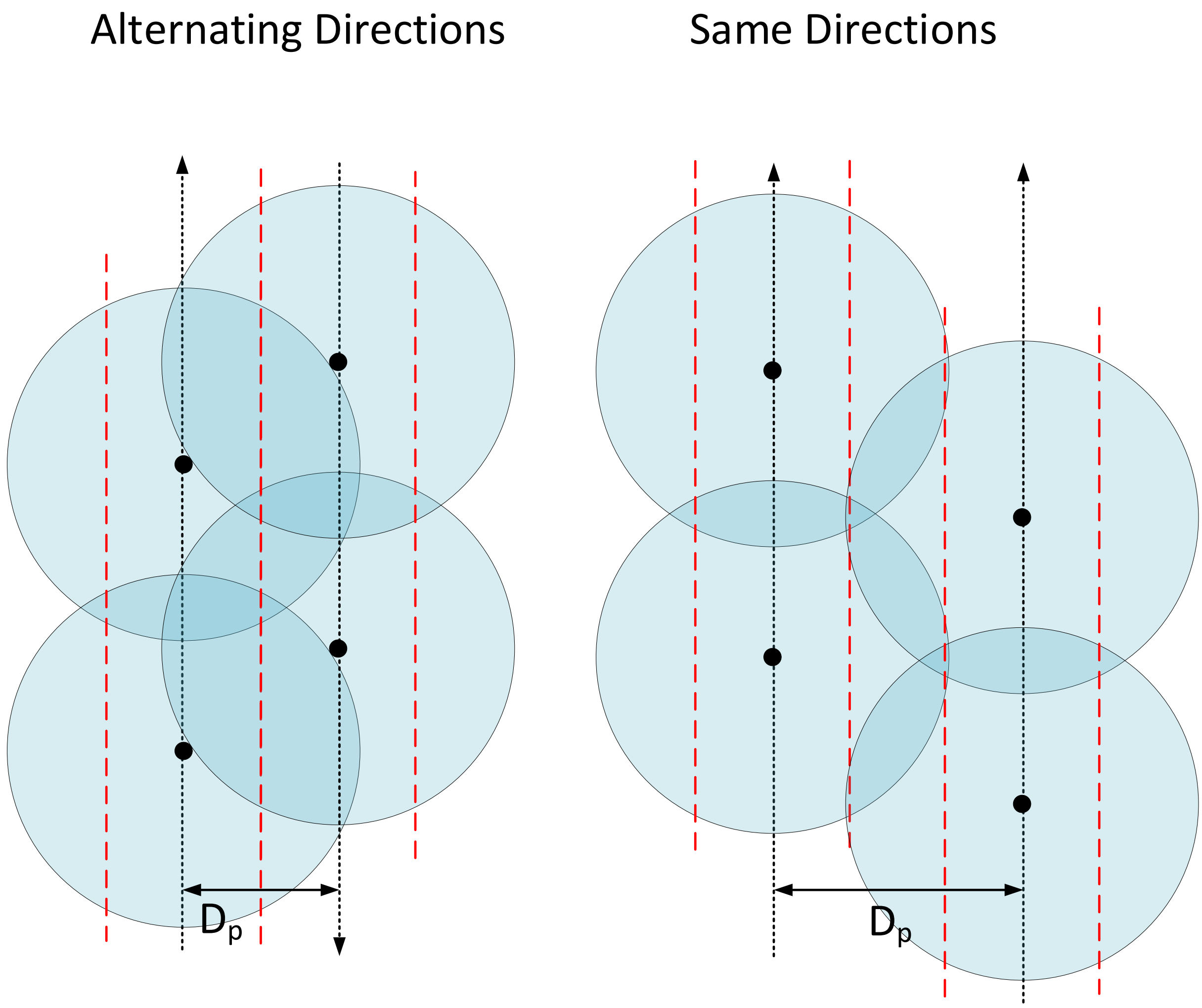

FIGURE 2-2 OVERLAP REQUIRED TO PROVIDE FULL COVERAGE, FOR SATELLITE PLANES ORBITING IN ALTERNATING DIRECTIONS (LEFT) AND IN THE SAME DIRECTION (RIGHT). D_P IS THE DISTANCE BETWEEN ADJACENT PLANES

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

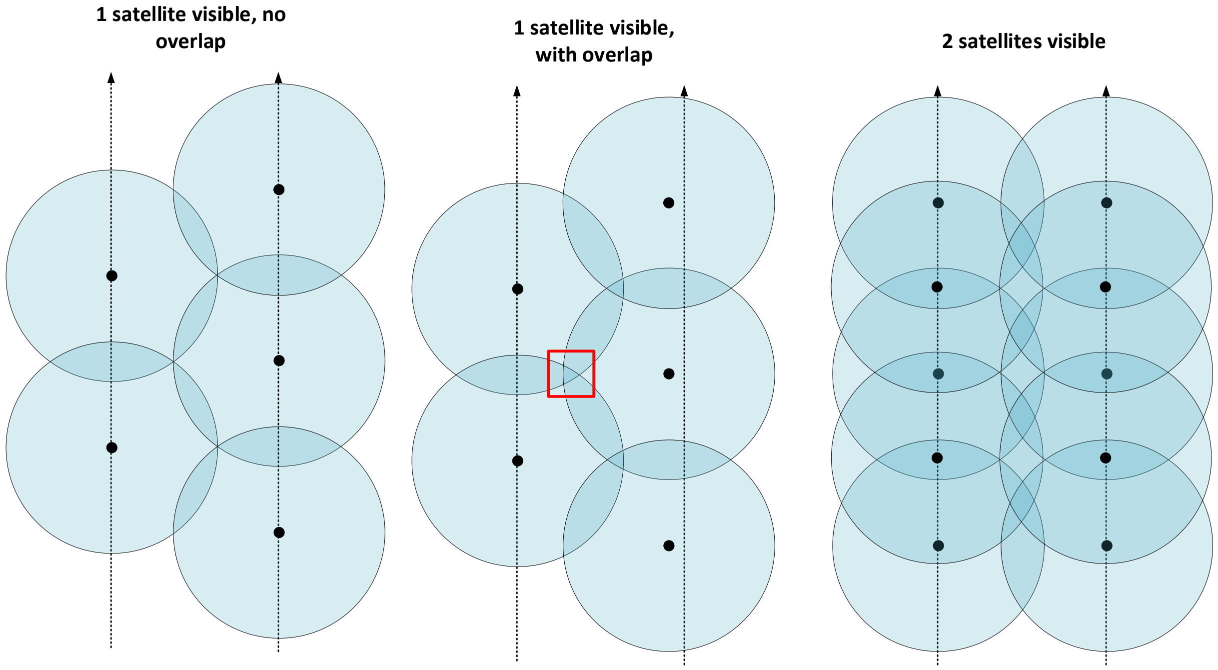

FIGURE 2-3 OVERLAP REQUIRED TO PROVIDE FULL COVERAGE WITH 1 SATELLITE VISIBLE (LEFT), 1 SATELLITE VISIBLE WITH MINIMUM OVERLAP DURATION (MIDDLE), 2 SATELLITES VISIBLE (RIGHT)

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 250km to 900km.

2.4 FEEDER LAYER

As discussed in D3.5 [**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. It has therefore been decided that the feeder layer will occupy the same orbit (inclination and altitude) as the service later, 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.

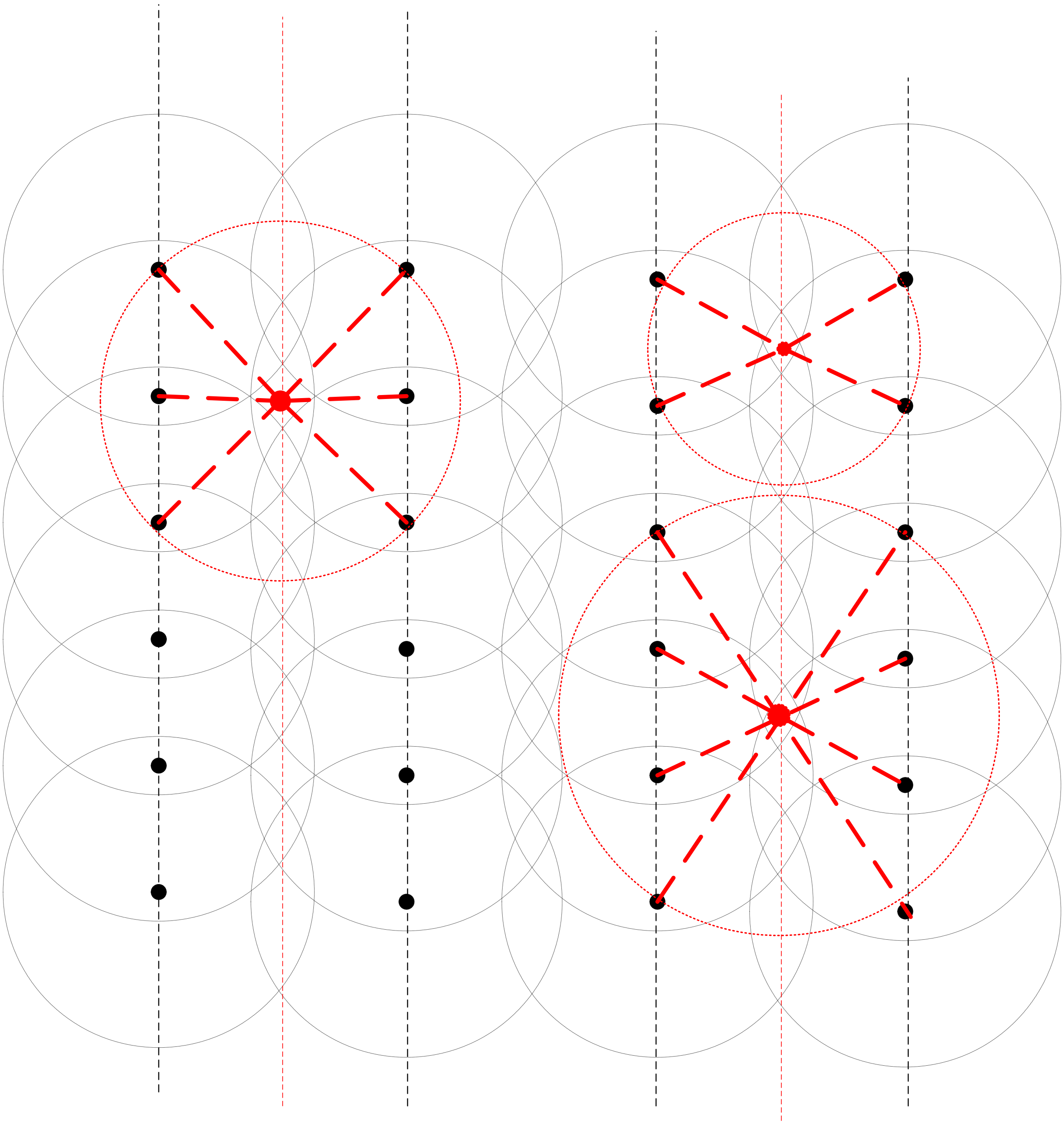

FIGURE 2-4 POSSIBLE CONFIGURATIONS OF FEEDER-SERVICE OISLS, FOR 4,6, AND 8 SERVICE SATELLITES PER FEEDER, FOR SERVICE CONSTELLATIONS WITH AN EVEN NUMBER OF MINIMUM VISIBLE SATELLITES.FEEDER SATELLITES IN RED, SERVICE SATELLITES IN BLACK

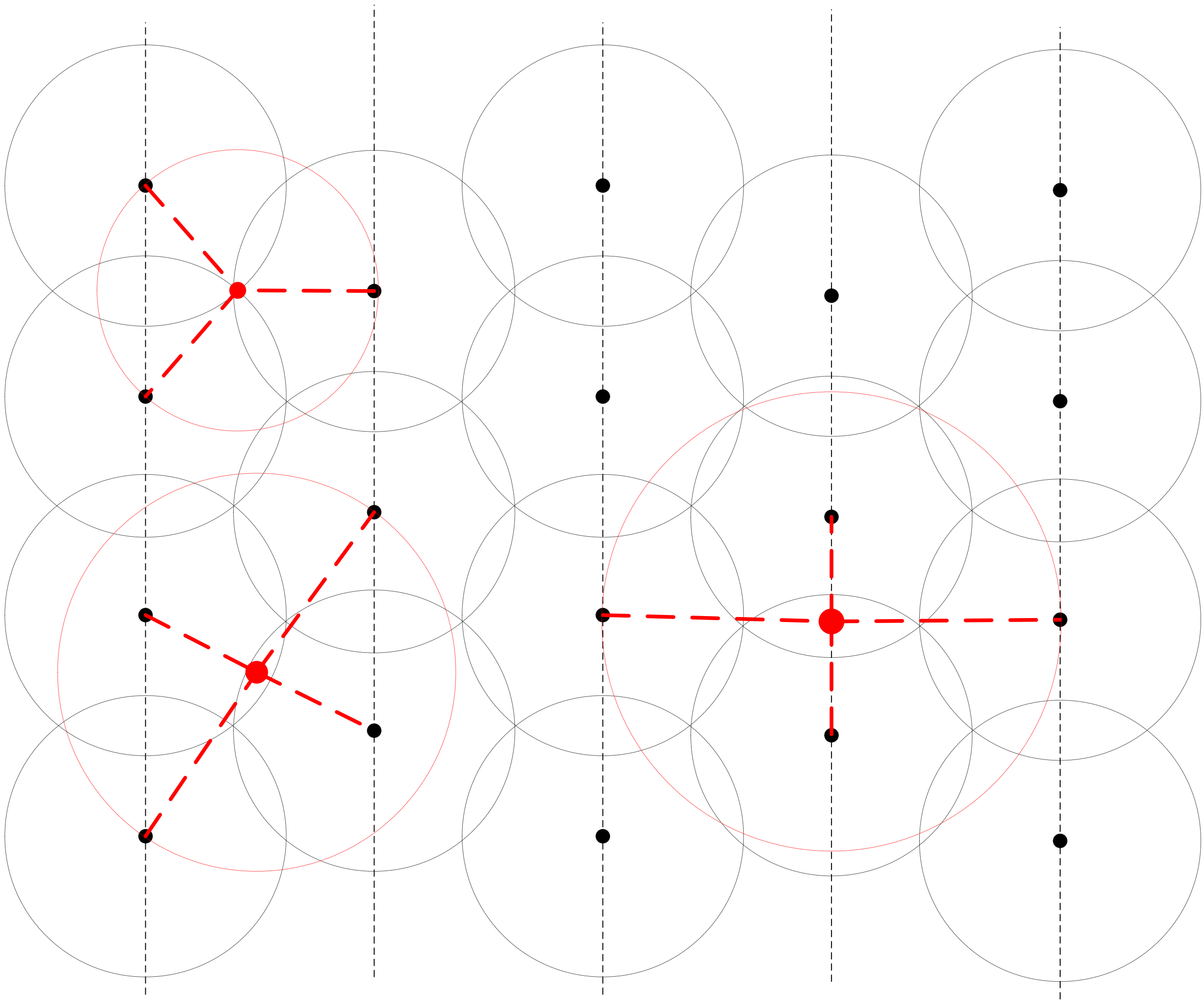

FIGURE 2-5 POSSIBLE CONFIGURATIONS OF FEEDER-SERVICE OISLS, FOR 3 AND 4 SERVICE SATELLITES PER FEEDER, FOR SERVICE CONSTELLATIONS WITH AN ODD NUMBER OF MINIMUM VISIBLE SATELLITES.FEEDER SATELLITES IN RED, SERVICE SATELLITES IN BLACK

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.

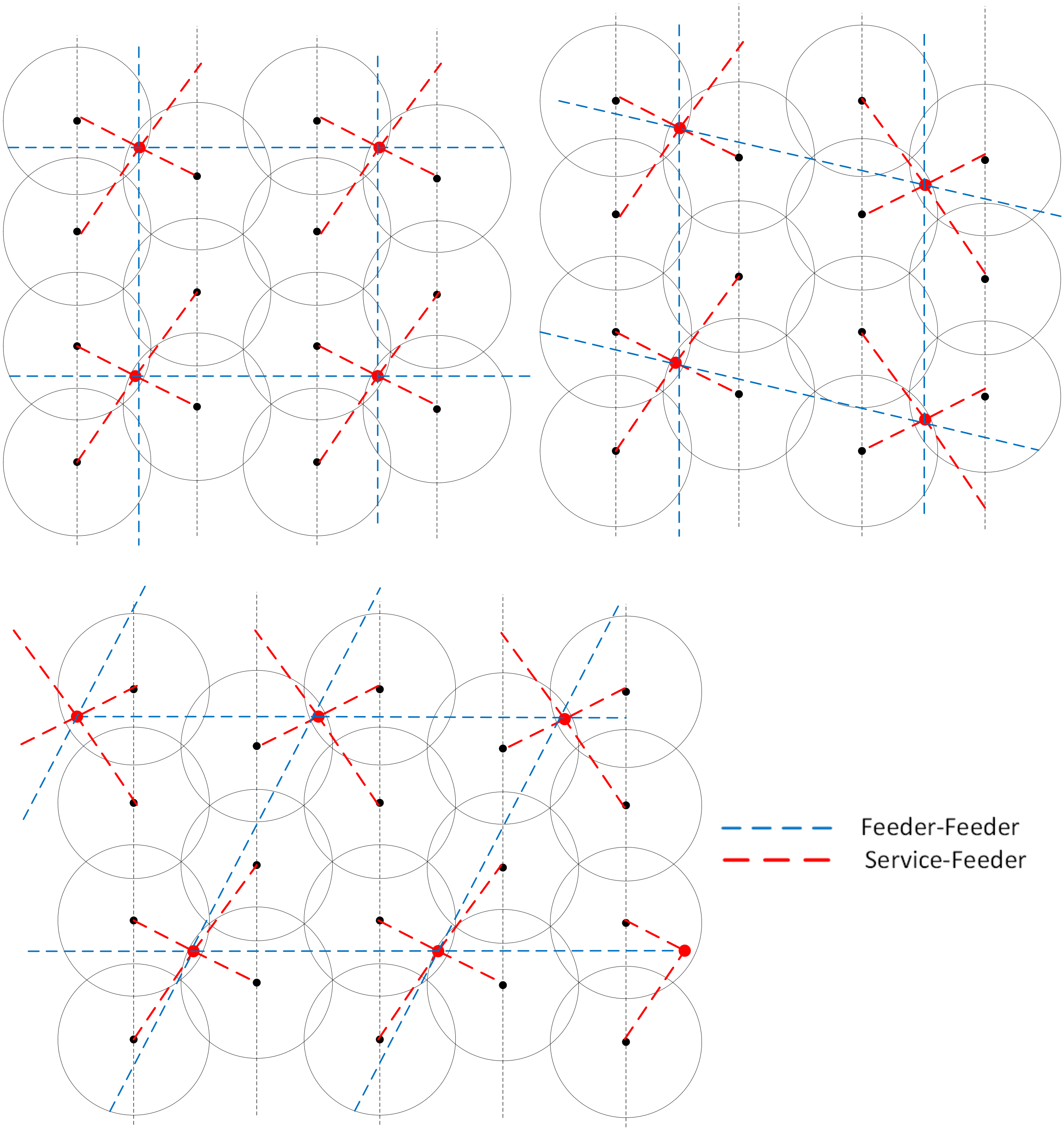

FIGURE 2-6 SOME POSSIBLE CONFIGURATIONS OF THE FEEDER CONSTELLATION, ASSUMING EACH FEEDER SATELLITE SERVES 4 SERVICE SATELLITES, AND 1 A MINIMUM OF 1 SERVICE SATELLITE VISIBLE TO THE USER

3 IMPACT OF ALTITUDE

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 mean 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.

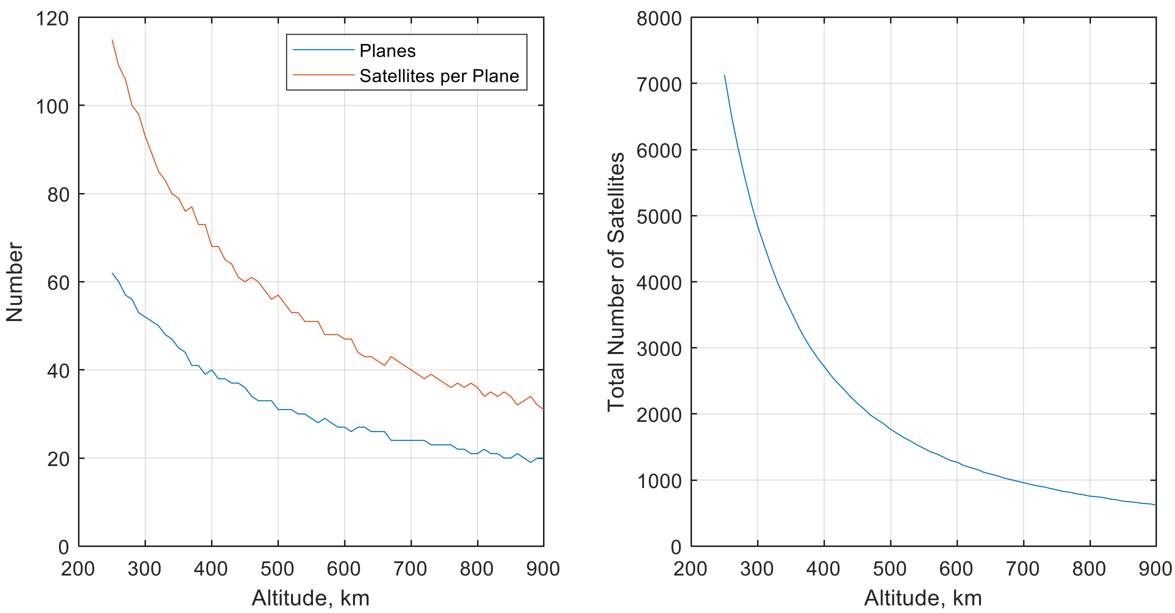

FIGURE 3-1: OPTIMAL NUMBER OF PLANES AND SATELLITES PER PLANE (LEFT) AND TOTAL NUMBER OF SATELLITES (RIGHT) FOR A NEAR-POLAR ORBIT, MINIMUM OF 1 SATELLITE VISIBLE WITH MINIMUM 10 SECOND OVERLAP, MINIMUM USER ELEVATION OF 45°

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.

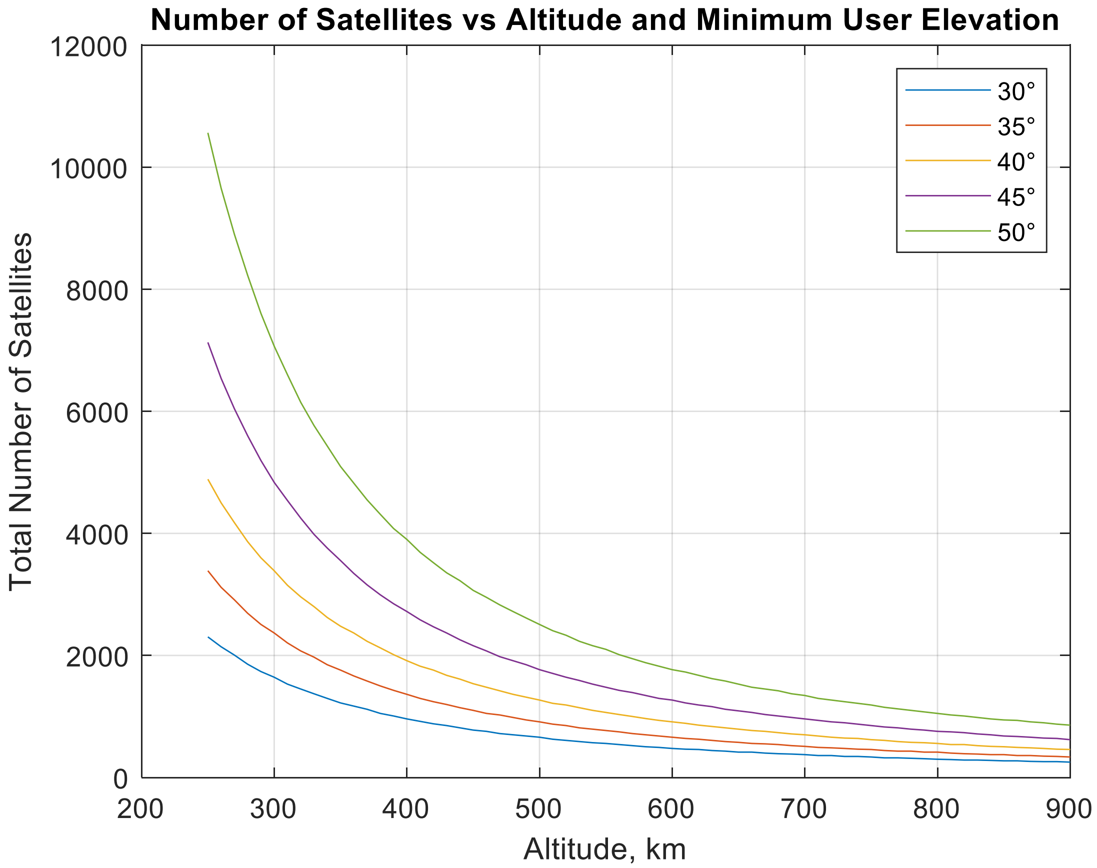

FIGURE 3-2 TOTAL NUMBER OF SATELLITES FOR A NEAR-POLAR ORBIT, MINIMUM OF 1 SATELLITE VISIBLE WITH MINIMUM 10 SECOND OVERLAP, FOR VARIOUS MINIMUM USER ELEVATIONS

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 1.63×10^{-5}, so for a nominal frequency of 4GHz, the user will experience a Doppler shift of ±65kHz. Over the full altitude range, at 250km the worst-case Doppler shift would be ±70kHz and at 900km would be 61kHz. Whilst the Doppler shift is worst at the lowest altitudes compared to the highest, the difference is not huge.

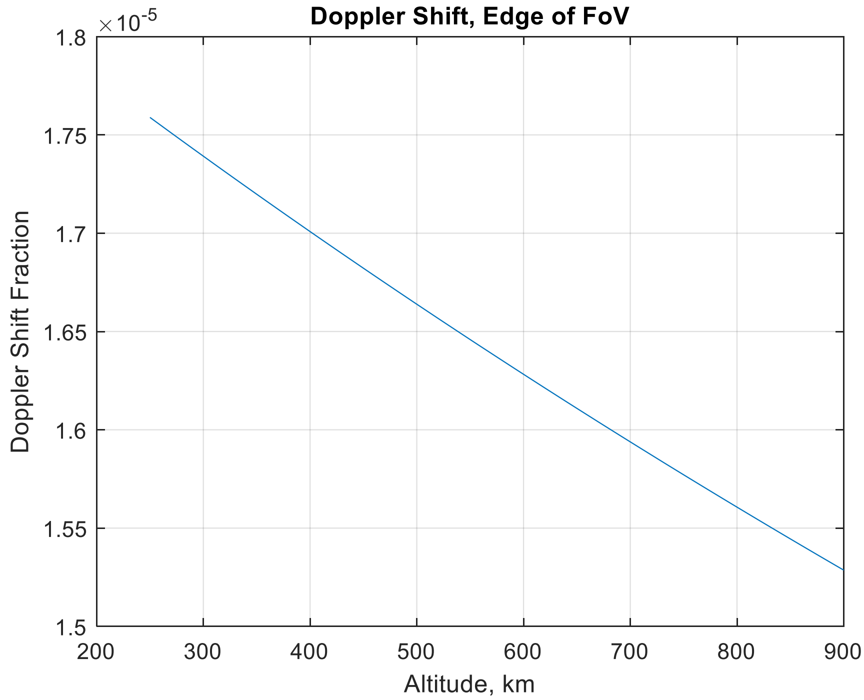

FIGURE 3-3 RELATIVE DOPPLER SHIFT EXPERIENCED BY A USER AT THE EDGE OF THE SATELLITE FOV (WHICH IS THE WORST CASE), FOR A MINIMUM USER ELEVATION OF 45°, FOR A RANGE OF SATELLITE ALTITUDES

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.

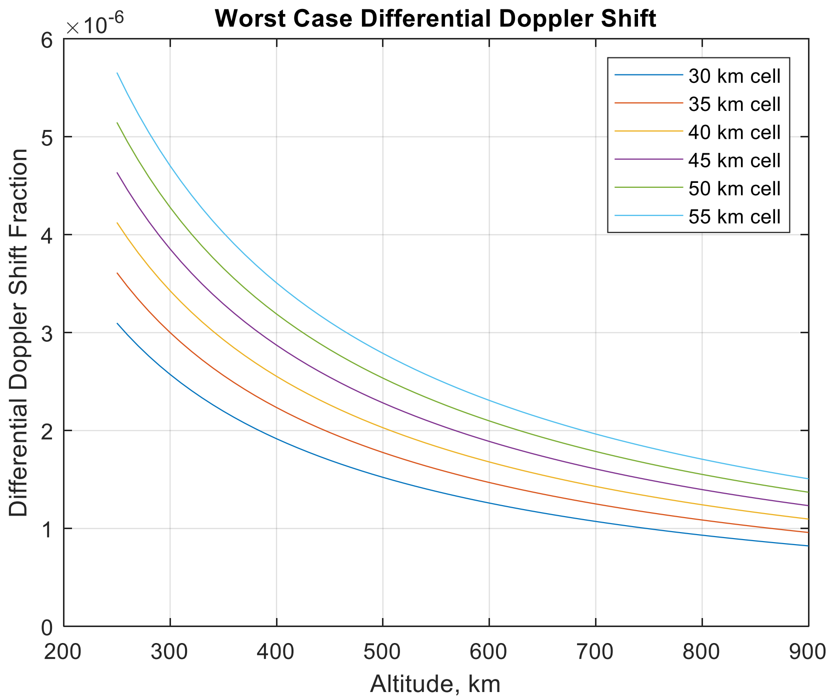

FIGURE 3-4 WORST CASE RELATIVE DIFFERENTIAL DOPPLER SHIFT EXPERIENCED ACROSS ONE CELL/BEAM, FOR DIFFERENT ALTITUDES AND CELL SIZES.

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°.

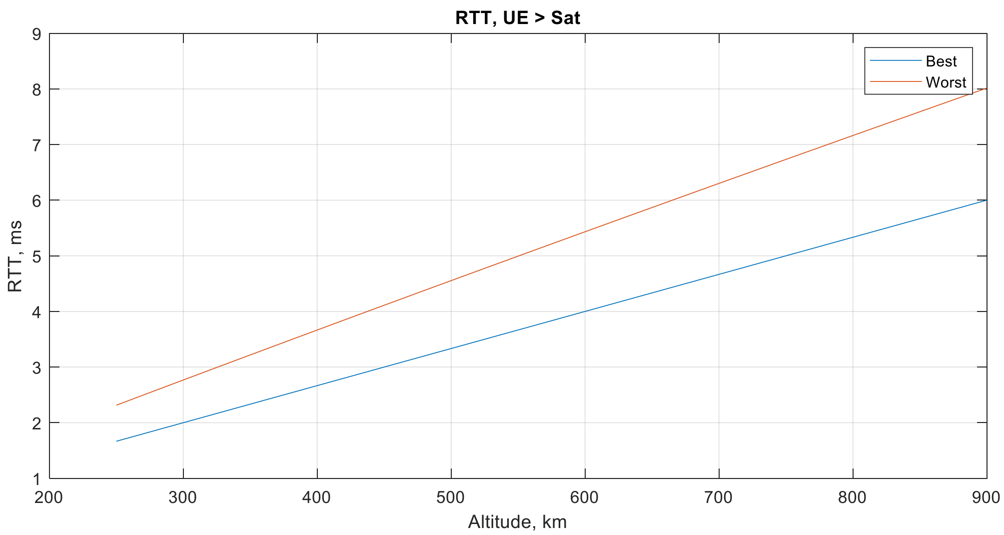

FIGURE 3-5 RTT FOR A USER TO SATELLITE VS ALTITUDE. BEST – UE DIRECTLY BELOW THE SATELLITE, WORST – UE AT EDGE OF FOV

3.3.2 UE -> Service Satellite -> Feeder Station

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).

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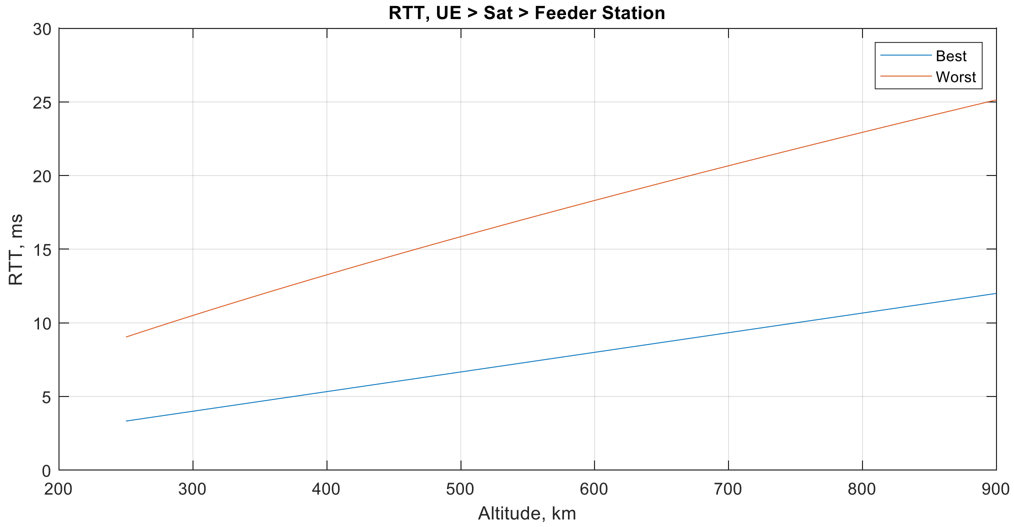

FIGURE 3-6 RTT FOR A USER TO FEEDER STATION VIA 1 SATELLITE VS ALTITUDE. BEST – UE AND FEEDER STATION DIRECTLY BELOW THE SATELLITE, WORST – UE AND FEEDER STATION AT EDGE OF FOV

3.3.3 UE -> Service Satellite -> Feeder Satellite ->Feeder Station

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 4.3. Here it is assumed that each feeder satellite serves 4 service satellites, and they are arranged as shown in Figure 4-1.

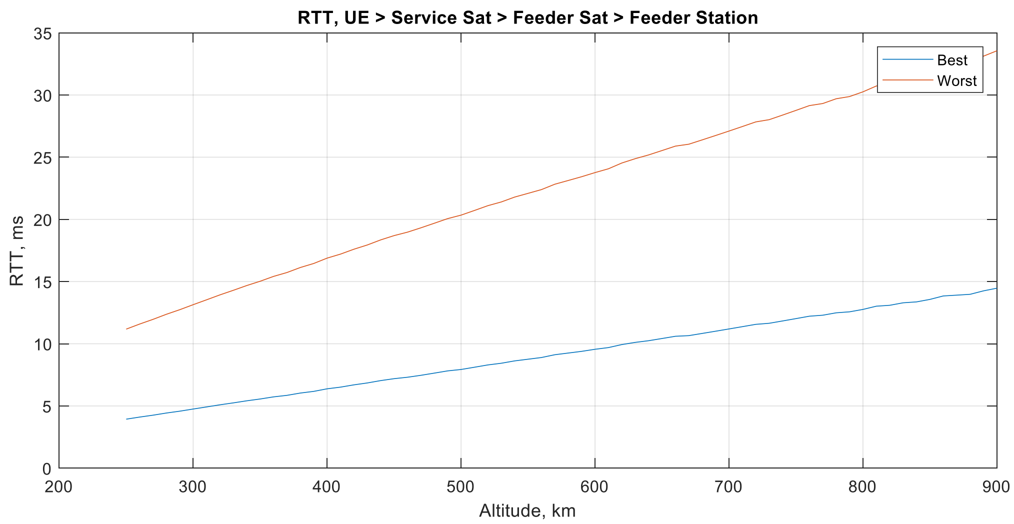

FIGURE 3-7 RTT FOR A USER TO FEEDER STATION VIA 2 SATELLITES (SERVICE SATELLITE AND FEEDER SATELLITE) VS ALTITUDE. BEST – UE AND FEEDER STATION DIRECTLY BELOW THE SATELLITES AND THE SERVICE/FEEDER SATELLITES AT THEIR MINIMUM SEPARATION, WORST – UE AND FEEDER STATION AT EDGE OF FOV AND THE SERVICE/FEEDER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

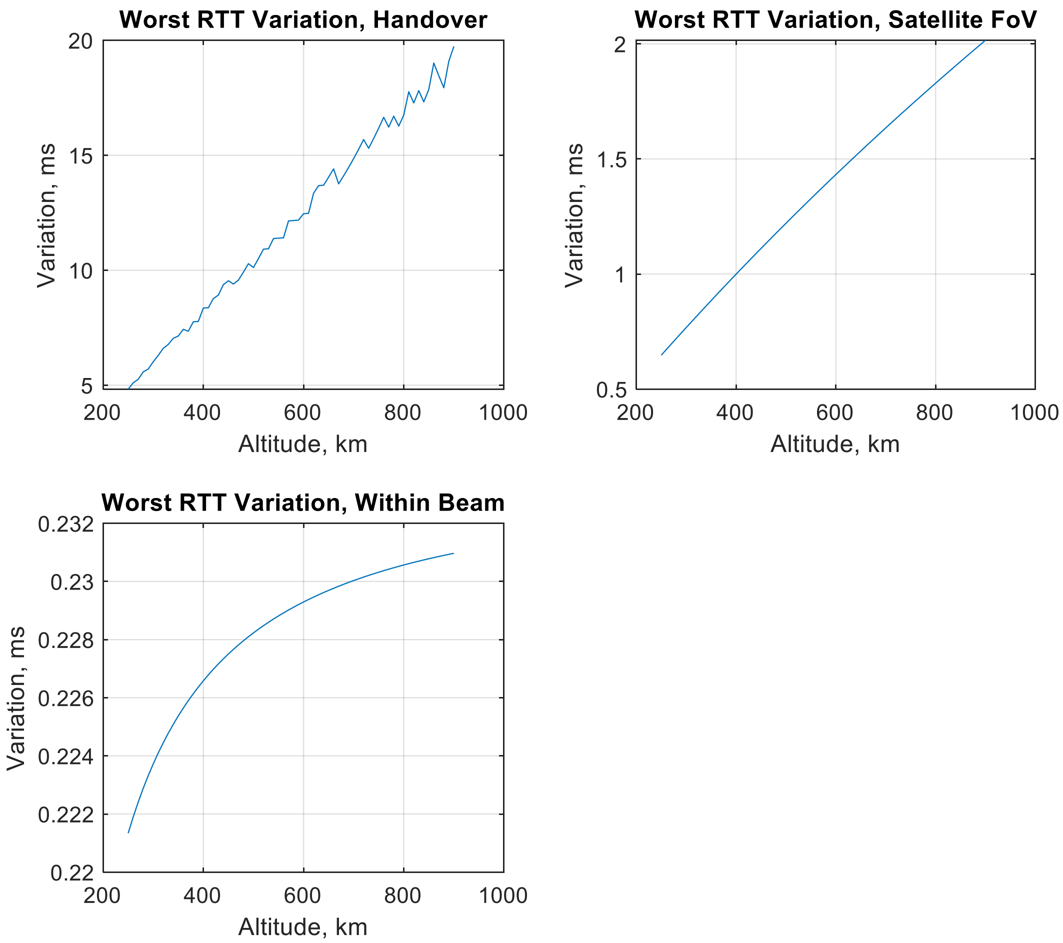

FIGURE 3-8 WORST CASE RTT VARIATION VS ALTITUDE, MINIMUM OF 1 SATELLITE VISIBLE WITH MINIMUM 10 SECOND OVERLAP, MINIMUM USER ELEVATION OF 45°.

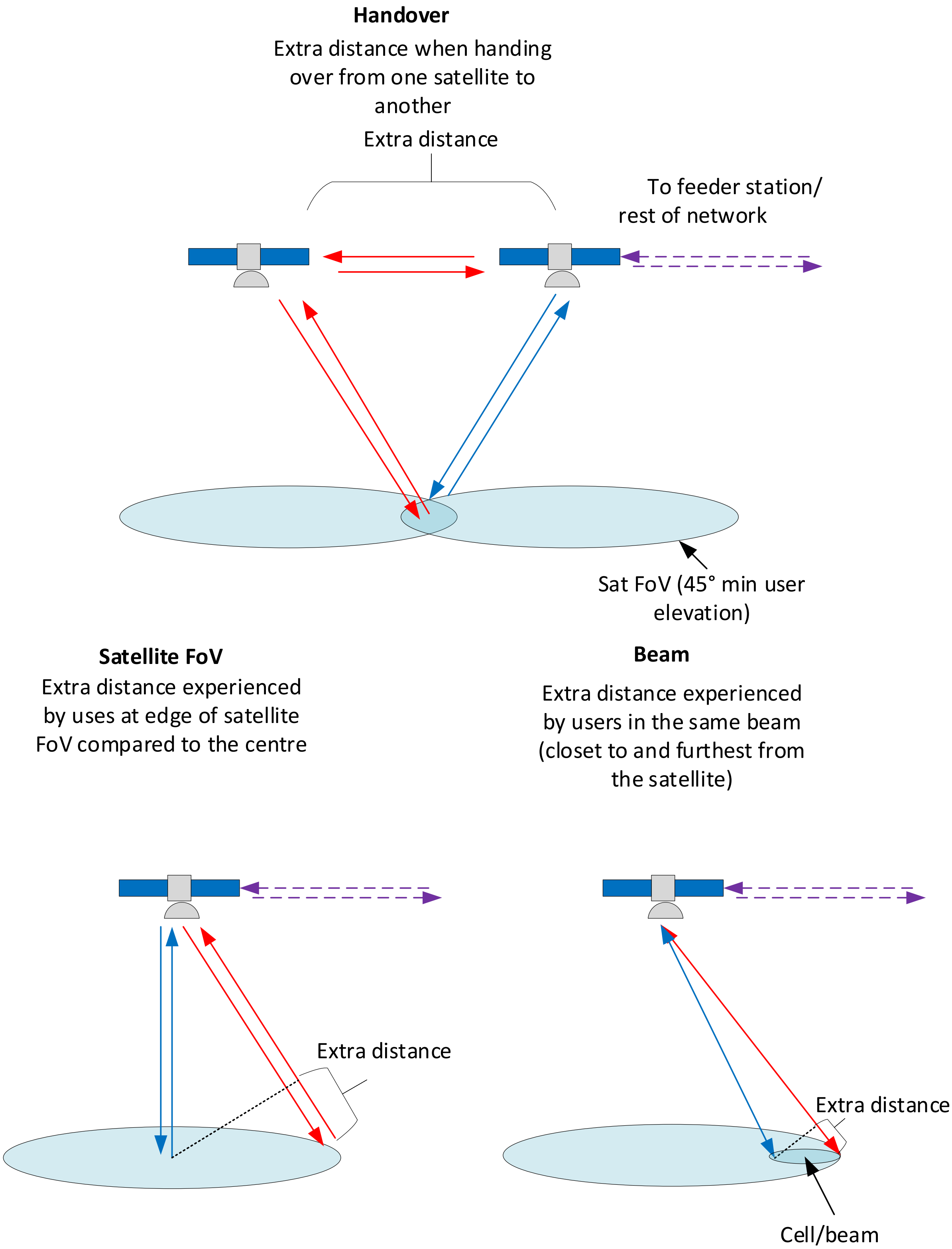

FIGURE 3-9 DIAGRAM OF HOW THE DIFFERENT RTT VALUES ARE COMPUTED FOR THE DIFFERENT CASES

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°. At 600km directly below the satellite the ground error would be 1km, and at an elevation angle of 45° round 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° 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 10’s 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.

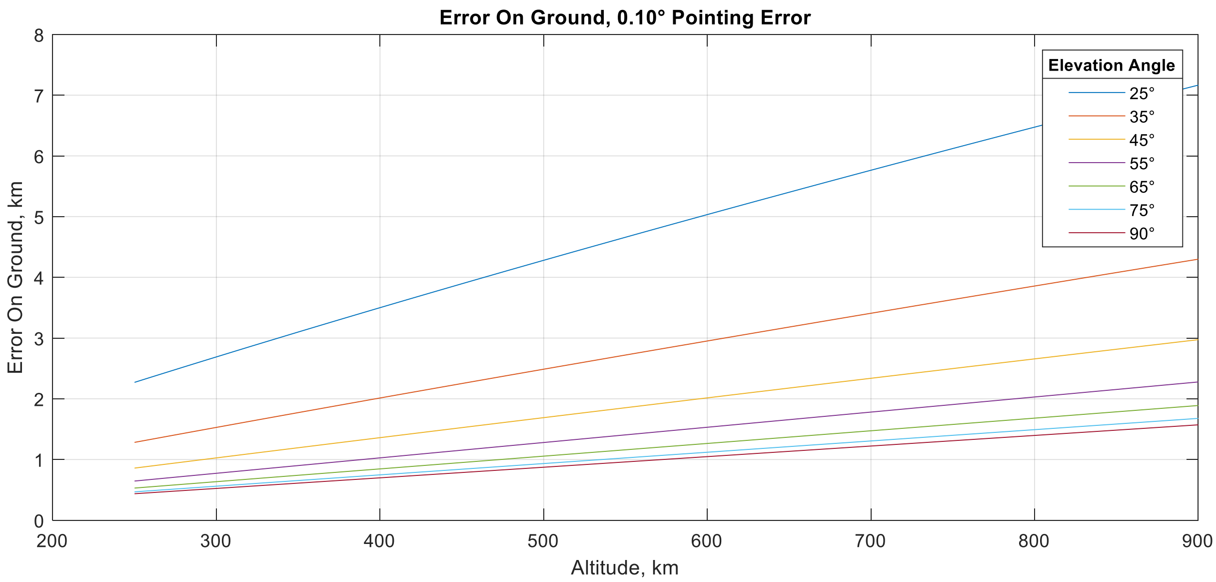

FIGURE 3-10 ERROR ON GROUND DUE TO SATELLITE POINTING ERROR OF 0.1°

4 REFERENCE CONSTELLATION

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 D3.3 [**Error! Bookmark not defined.**], the following technical 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

As discussed in D3.5, 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
- 336 feeder satellites
    - 14 planes of 24 satellites.

This configuration is shown in Figure 4-1. 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 ≈317).

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

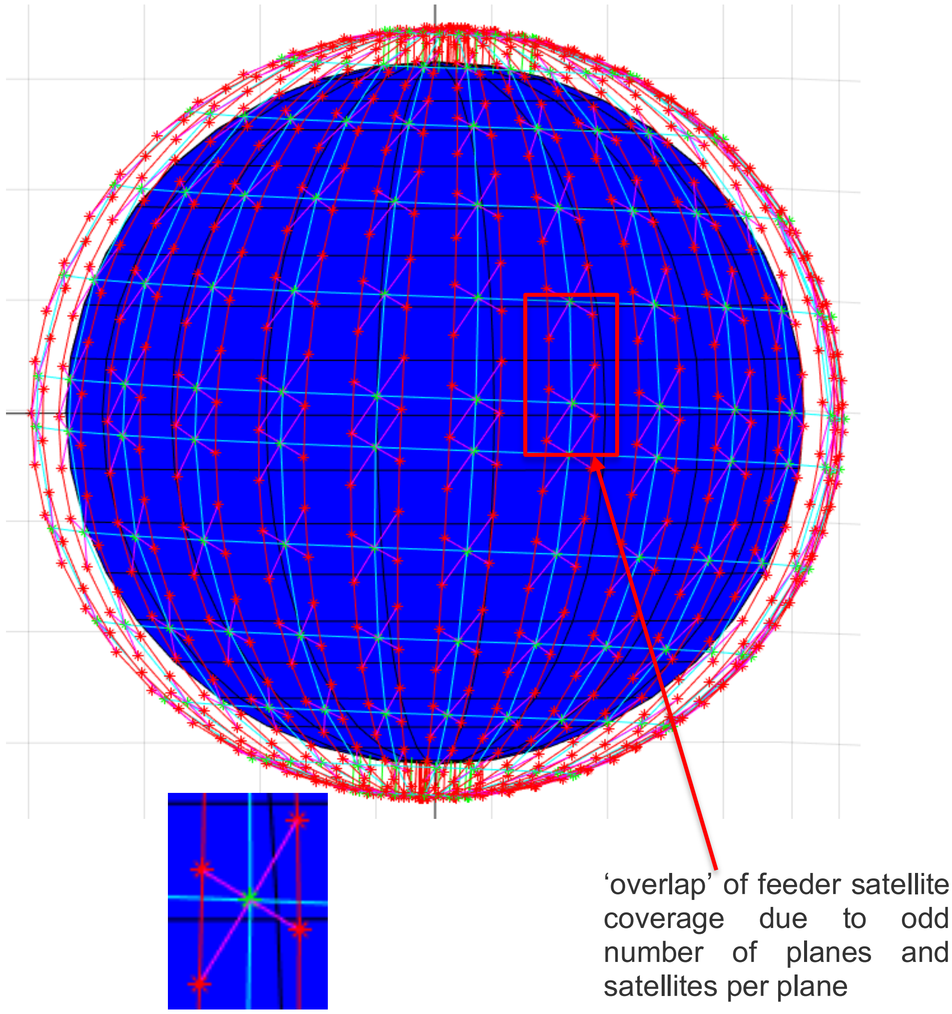

FIGURE 4-1 OVERVIEW OF REFERENCE CONSTELLATION. SERVICE SATELLITES SHOWN IN RED, FEEDER SATELLITES IN GREEN, SERVICE-FEEDER OISLS IN MAGNETA AND FEEDER-FEEDER OISLS IN CYAN

4.1 COVERAGE

Figure 4-2 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 4-3 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 4-4 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 4-5 shows a histogram of the number of cells[2] 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.

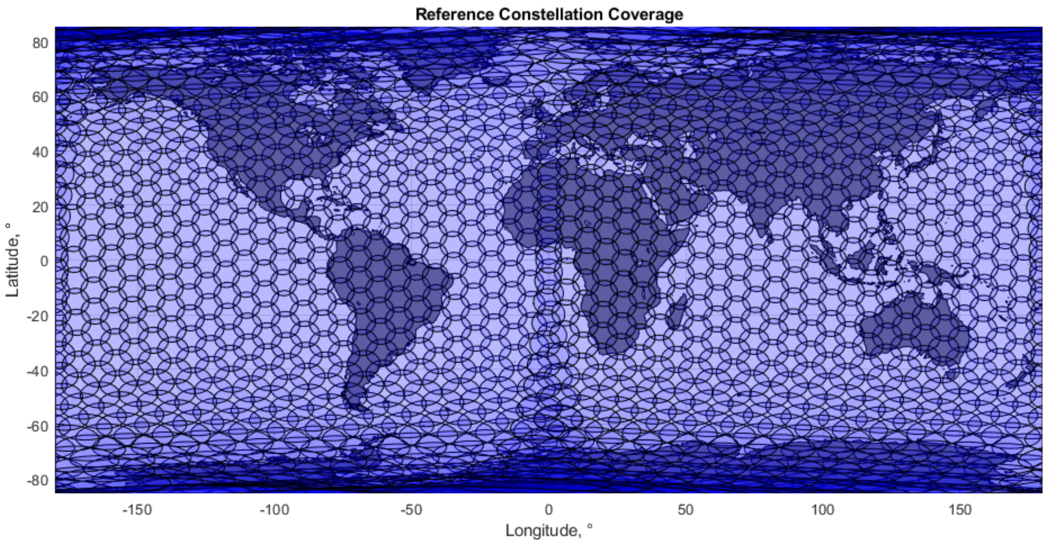

FIGURE 4-2 COVERAGE OF THE REFERNCE CONSTELLATION

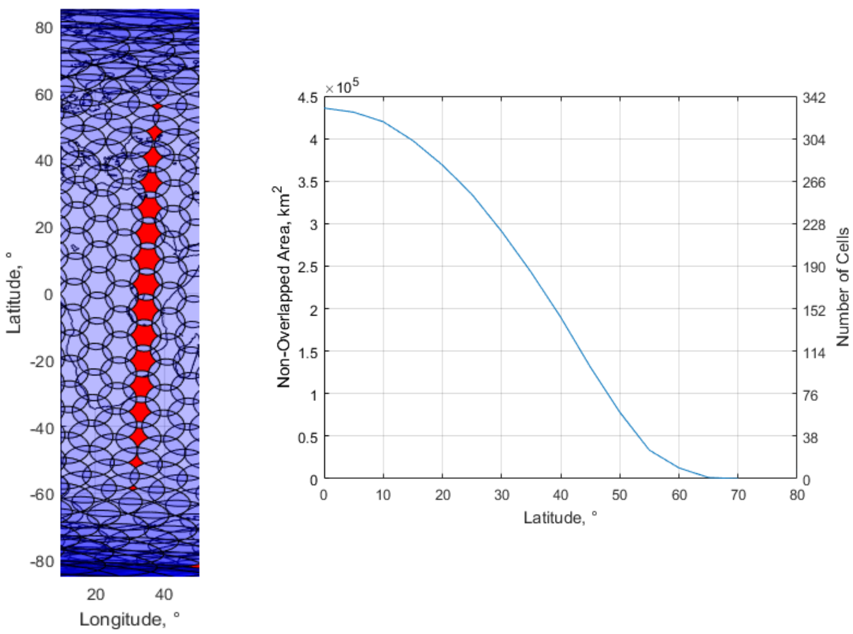

FIGURE 4-3 AREA OF SATELLITE FOV WITHOUT OVERLAP SHOWN (LEFT), AREA WIHTOUT OVERLAP IN KM^2 AND (APPROXIMATE) NUMBER OF CELLS, ASSUMING HEXAGONAL CELLS 45KM ACROSS.

[2] As regular hexagons of equal size do not tessellate on the surface of a sphere, here cells have been modelled as irregular hexagons evenly distributed over the surface of the Earth, with the same area as a regular hexagon 45km across.

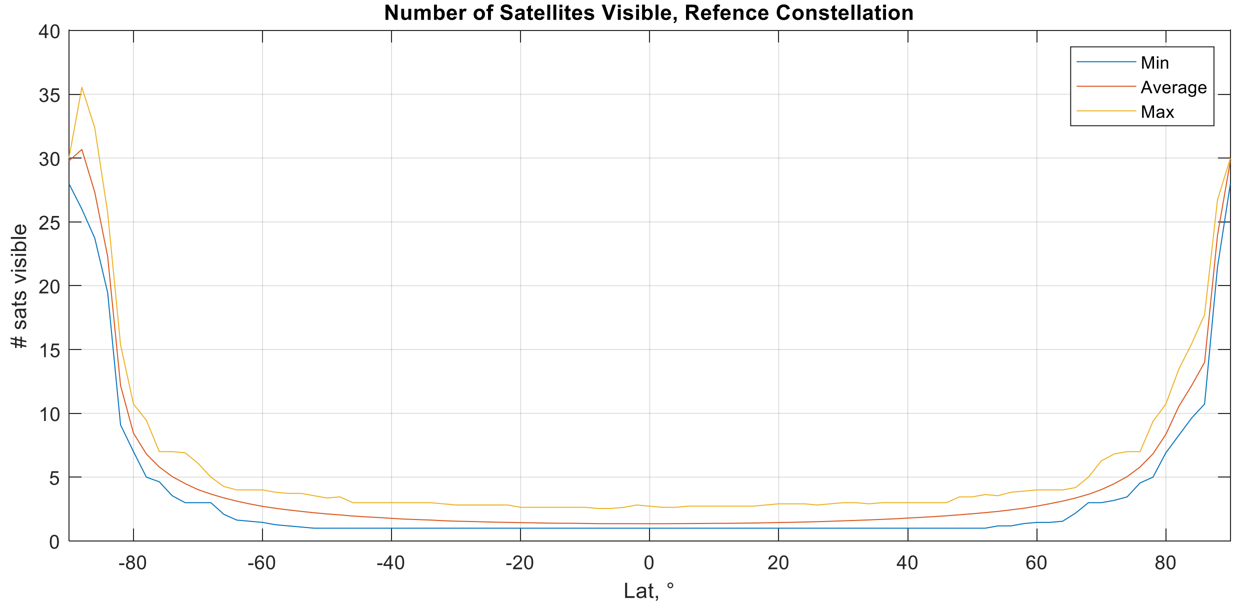

FIGURE 4-4 NUMBER OF SATELLITES VISIBLE (MINIMUM, AVERAGE AND MAXIMUM) VS LATITUDE, FOR THE REFERENCE CONSTELLATION

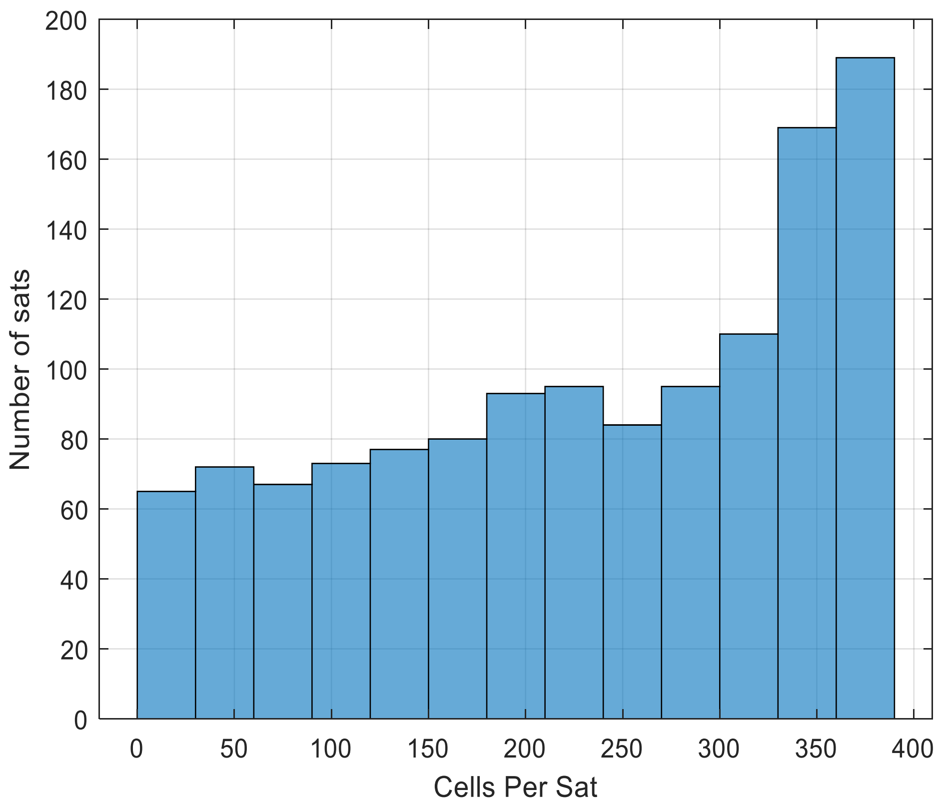

FIGURE 4-5 HISTOGRAM OF THE NUMBER OF CELLS SUPPORTED BY EACH SATELLITE FOR THE REFERENCE CONSTELLATION. THIS ASSUMES THAT EACH CELL IS SUPPORTED BY THE NEAREST SATELLITE ONLY – DUPLICATION OF CELL COVERAGE (WHERE A CELL WOULD NEED TO BE CONNECTED TO TWO SATELLITES SIMULTANEOUSLY) IS NOT ACCOUNTED FOR HERE.

4.2 DOPPLER SHIFT

Table 4-1 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 4-1 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

4.2.1 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 4-6 (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 ±1.6x10^{-5}, experienced when the satellite first enters/exits visibility, for a user directly on the satellite's ground track.

Figure 4-6 (right) shows the greatest difference between the relative Doppler shift experienced by users within a single cell. Here the greatest value is 1.9x10^{-6}, experienced in the cell directly below the satellite.

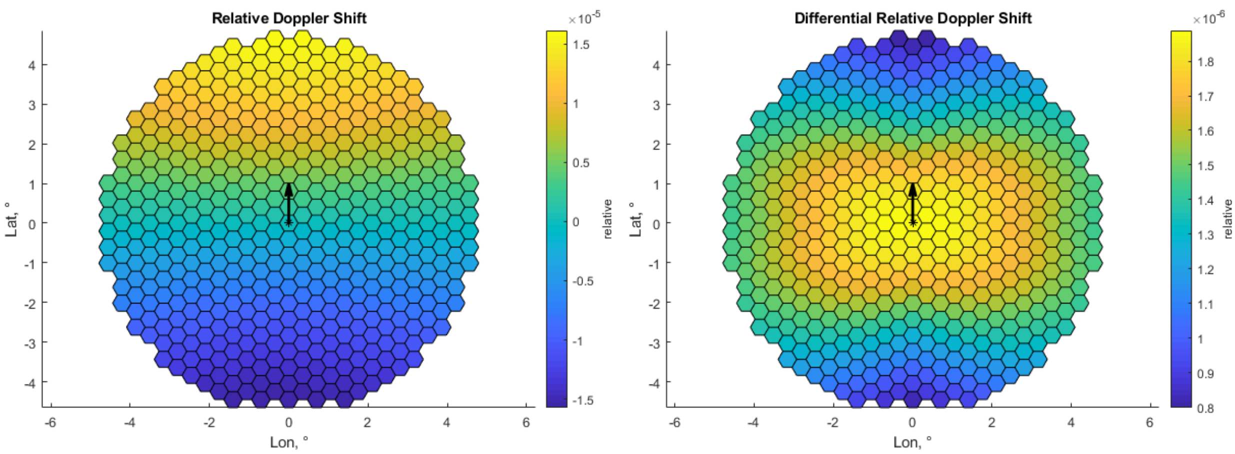

FIGURE 4-6 RELATIVE DOPPLER SHIFT VARIATION AND DIFFERENTIAL RELATIVE DOPPLER SHIFT ACROSS SATELLITE FOV

4.3 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.

4.3.1 Service-Feeder OISLs

Figure 4-7 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 the of the satellites. Figure 4-8 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 4-9 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°, however the azimuth range is much greater, approximately ±50°. The greatest angular rate of the OISLs is about 0.1° in azimuth. This occurs at the poles when the satellites swap sides relative to the feeder satellite.

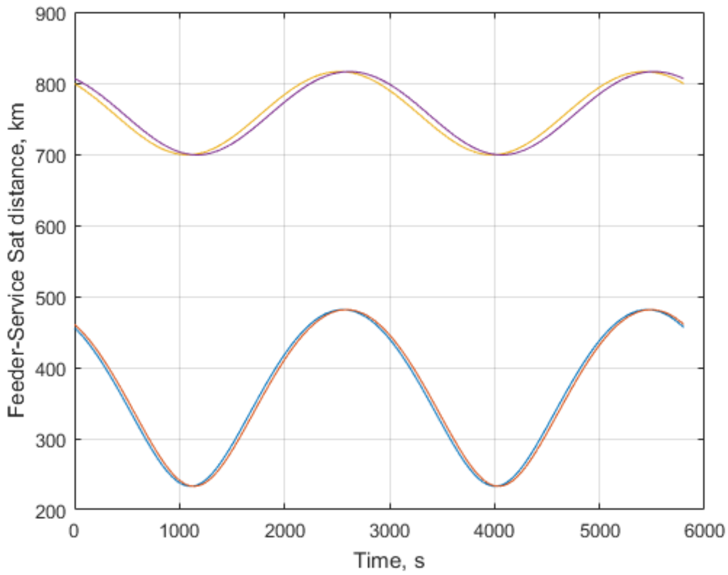

FIGURE 4-7 DISTANCE BETWEEN FEEDER AND SERVICE SATELLITES, OVER ONE ORBIT

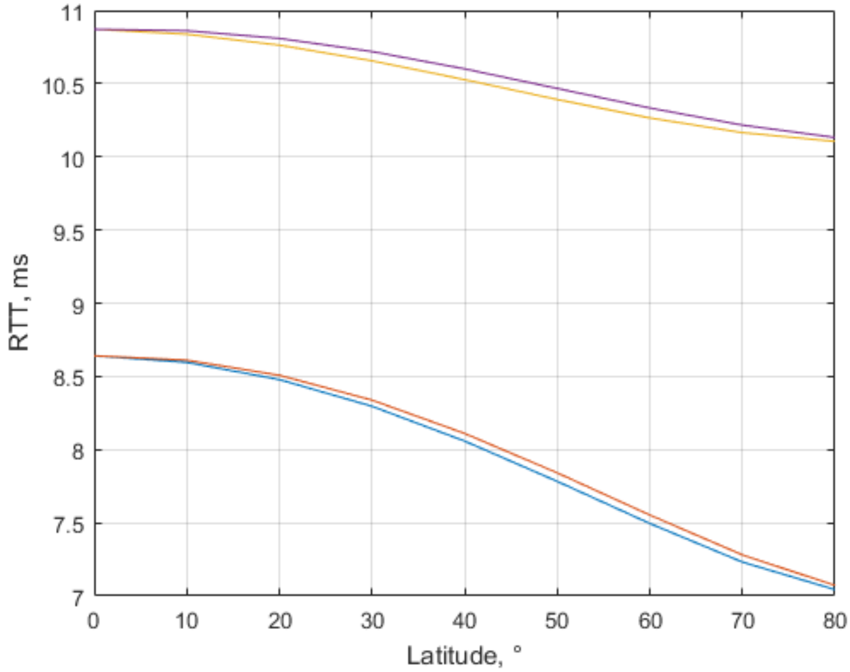

FIGURE 4-8 RTT (USER -> SERVICE SATELLITE -> FEEDER SATELLITE ->SERVICE SATELLITE ->USER) FOR A USER AT THE EDGE OF THE SERVICE SATELLITE FOV

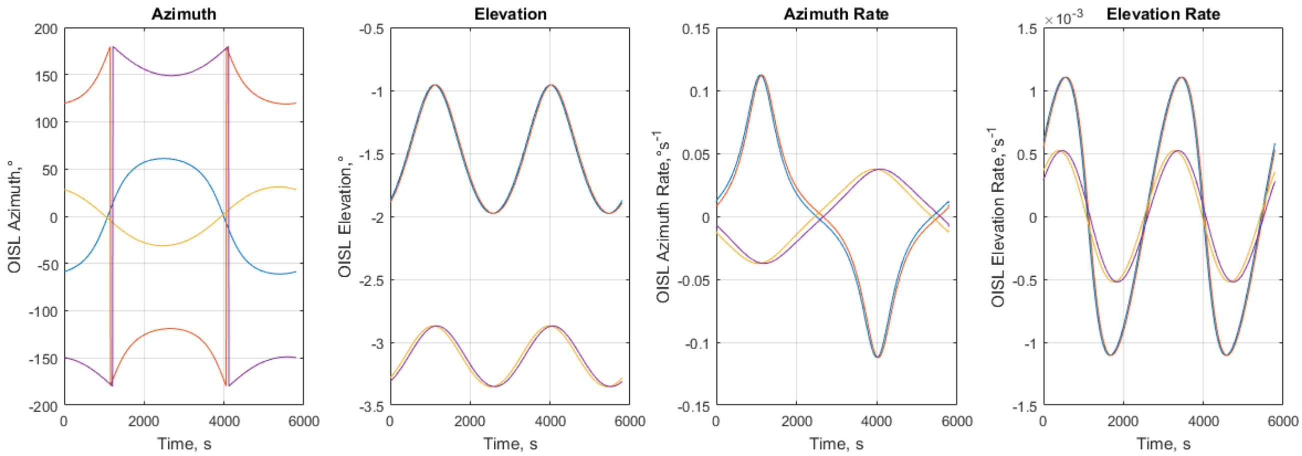

FIGURE 4-9 ANGLES AND ANGULAR RATES FOR FEEDER-SERVICE OISLS ON THE FEEDER SATELLITES

4.3.2 Feeder-Feeder OISLs

Figure 4-10 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 4-11 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.

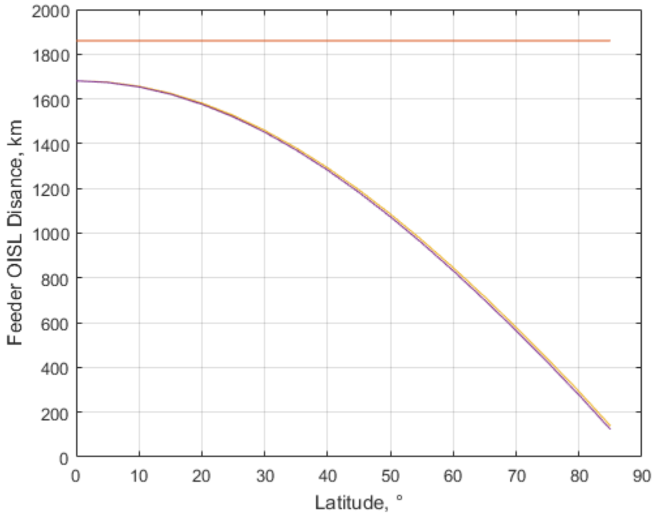

FIGURE 4-10 FEEDER-FEEDER SATELLITE DISTANCE, REFERENCE CONSTELLATION

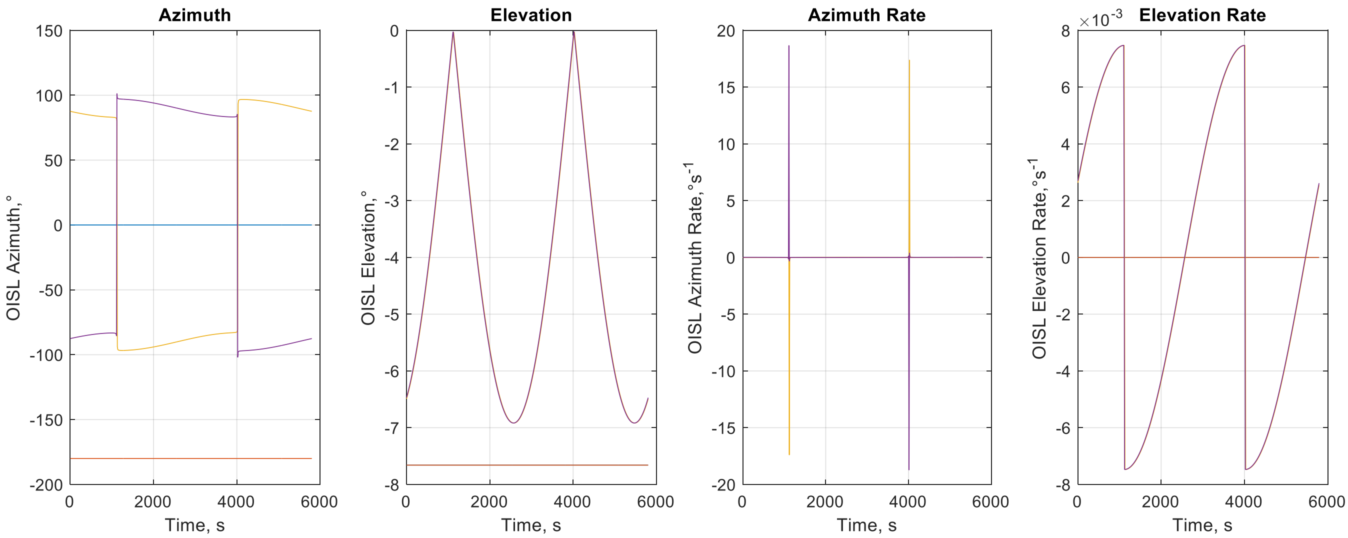

FIGURE 4-11 ANGLES AND ANGULAR RATES FOR FEEDER-FEEDER OISLS

4.4 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 4-12. 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 4-12 and Figure 4-13. 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.

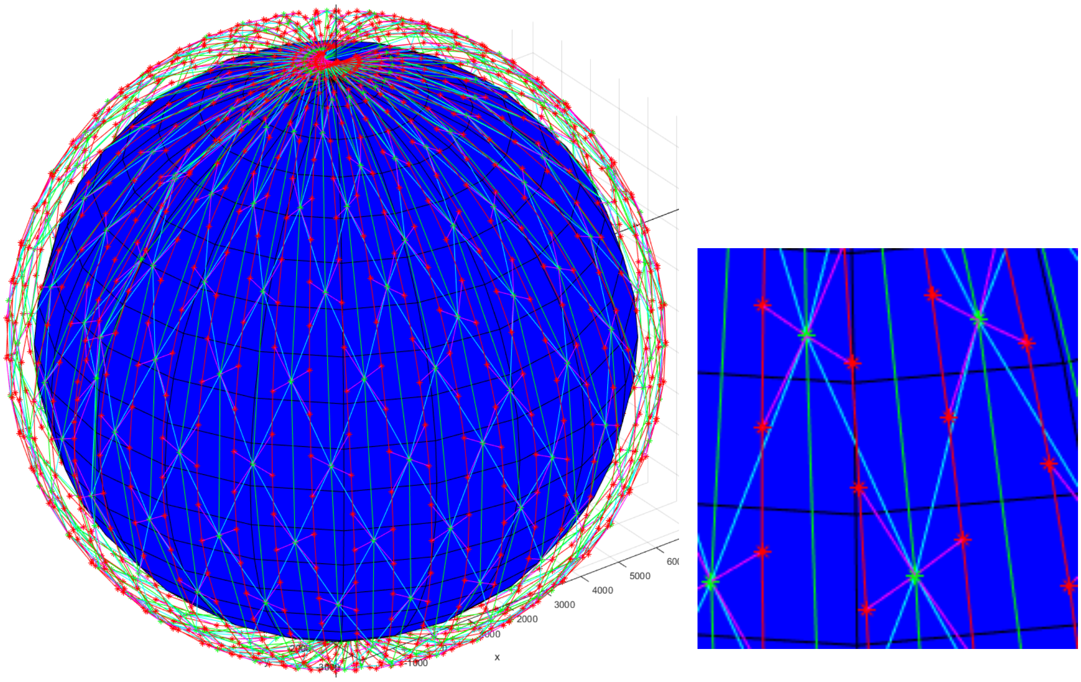

FIGURE 4-12 ALTERNATIVE CONFIGURATION OF THE FEEDER LAYER

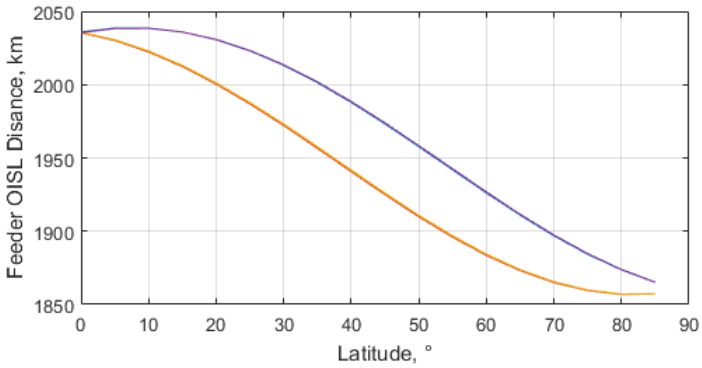

FIGURE 4-13 FEEDER-FEEDER OISL DISTANCES, FOR ALTERNATIVE FEEDER CONFIGURATION FOR THE REFERENCE CONSTELLATION

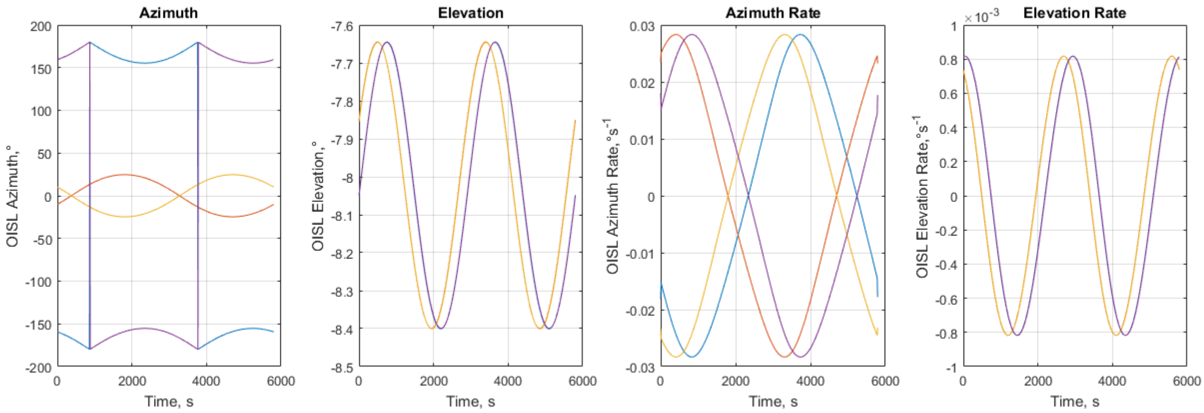

FIGURE 4-14 FEEDER-FEEDER OISL ANGLES AND RATES, , FOR ALTERNATIVE FEEDER CONFIGURATION FOR THE REFERENCE CONSTELLATION

4.5 REDUNDANCY

4.5.1 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 $4.5 \times 10^5 km^2$ without coverage, as shown in Figure 4-3. 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 $7 kms^{-1}$, 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 ±65°, 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.

4.5.2 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 4-15. 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.

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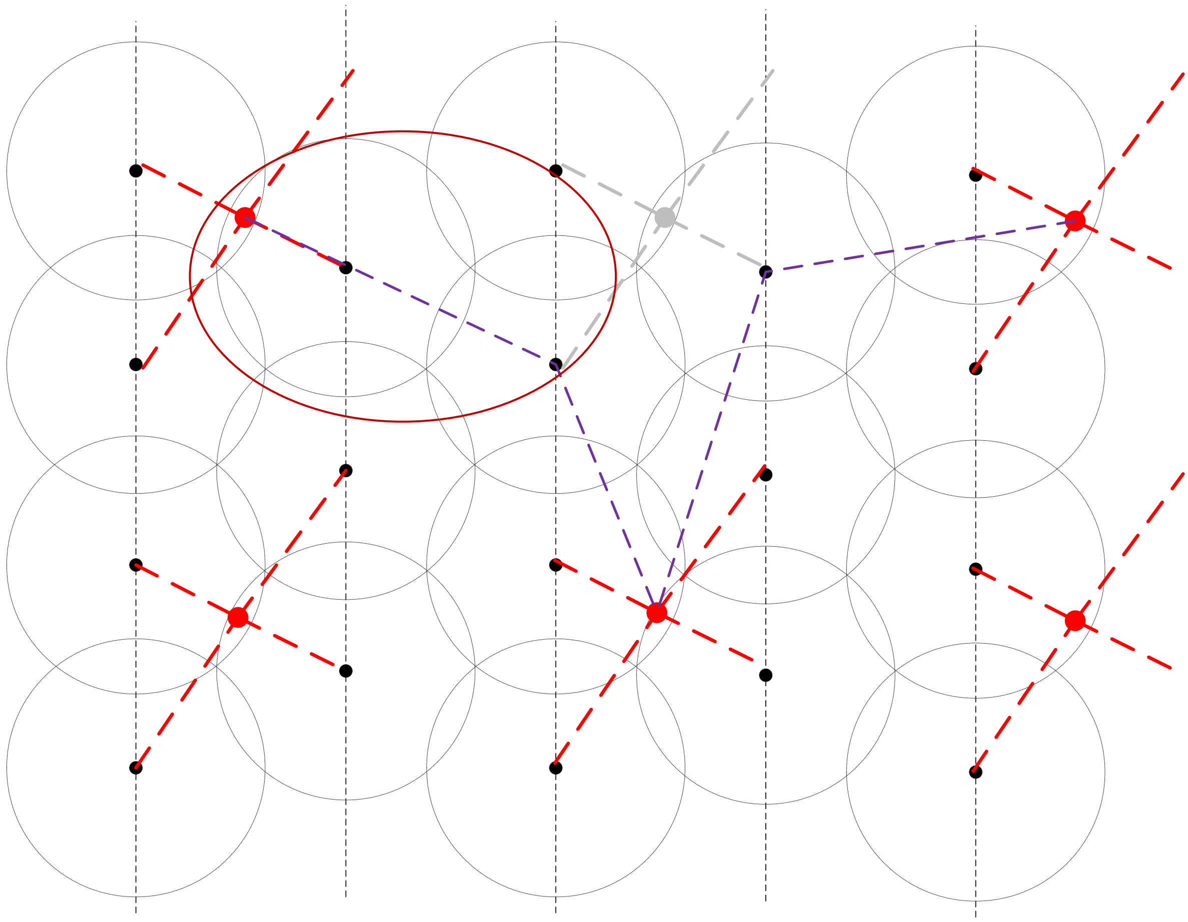

FIGURE 4-15 POSSIBLE REDUNDANCY SCHEME FOR FEEDER SATELLITES SHOWING SERVICE SATELLITES REDISTRIBUTED AMONG ADJACENT FEEDER SATELLITES.

4.5.3 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.

Further analysis in the next phase will assess the required propellant to perform these relocation manoeuvres, and will be accounted for in the satellite sizing as discussed in Section 6.

5 MISSION DEFINITION

This section will discuss details of the mission definition/operation of the constellation once this work is performed in the next phase. This will include launch and deployment, and manoeuvres to reposition spare satellites.

Investigation of the constellation deployment will consider different deployment strategies, which will depend on the number of satellites that can fit in a single launcher, and will hence have a strong dependence on the satellite sizing discussed in Section 6. Methods for progressive deployment of the constellation will also be investigated – for example, the initial planes of satellites could be launched at a higher altitude to increase the area of coverage of each one (accepting that this will initially result in higher latency/RTT and lower data rates), with the altitude reduced as more planes of satellites are launched to fill in the gaps.

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6 SATELLITE SIZING

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 [**Error! Bookmark not defined.**]. 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 parameters of the payload elements will account for the RAN architecture split – I.E. what equipment and processing is performed on which satellite(s).

The expected outputs from task 3.3 [**Error! Bookmark not defined.**]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

6.1 INITIAL ASSUMPTIONS

Some initial assumptions have already been generated from task 3.3 [**Error! Bookmark not defined.**] regarding the payload antenna. These are:

- C-Band: 200cm square, 35cm thick, 250kg mass
- Q/V-Band: 35 and 45cm square, 20cm thick, 50kg mass

An efficiency of the antenna radiating elements of 25% is also assumed.

7 CONSTELLATION CAPACITY

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.

7.1 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 7-1 shows the global population density used in this analysis, in population per km^2. The density data has a resolution of 0.25° latitude/longitude.

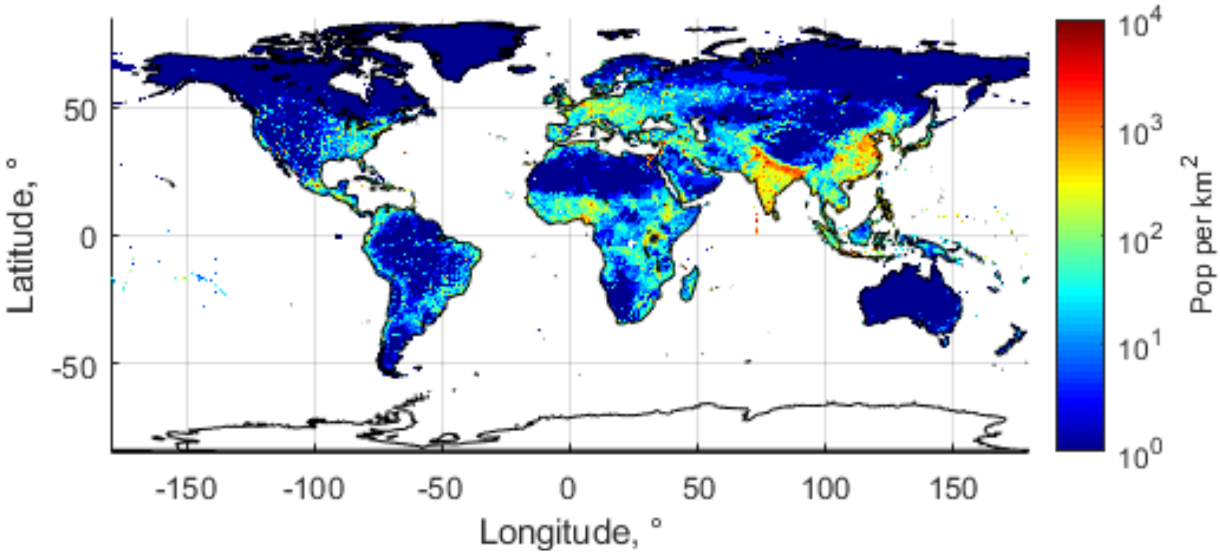

FIGURE 7-1 GLOBAL POPULATION DENSITY

7.1.1 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^2 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 7-2 and Figure 7-3 show the estimated number of UE in each 0.25° region based on the above assumptions, for UDTs of 50 and 350 population per 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 km^2, large regions Asia (India and China), Europe and Africa are omitted.

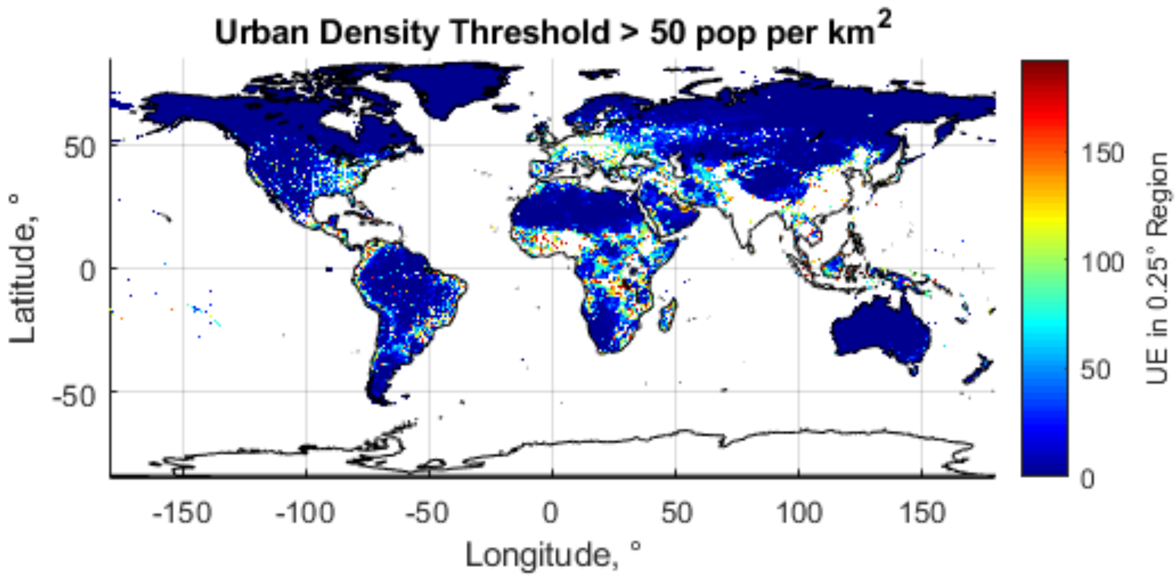

FIGURE 7-2 UE PER 0.25° REGION, WITH AN URBAN DENSITY THRESHOLD OF 50 POPULATION PER KM^2

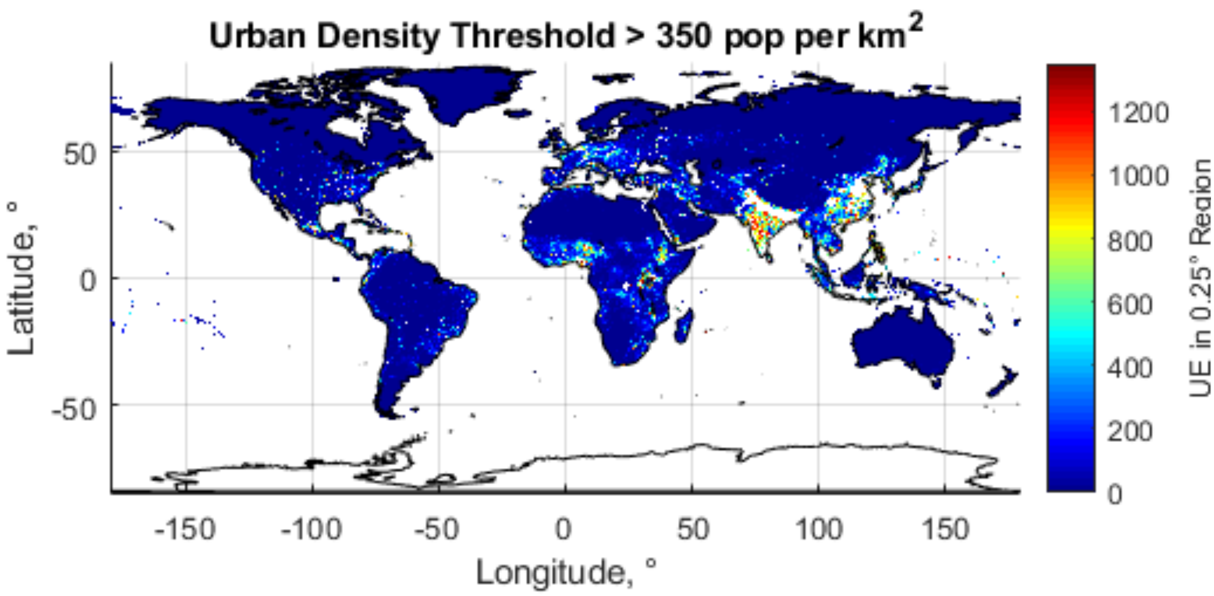

FIGURE 7-3 UE PER 0.25° REGION, WITH AN URBAN DENSITY THRESHOLD OF 350 POPULATION PER KM^2

7.1.2 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 7-4 and Figure 7-5 show the numbers of UE per 45km cell across the Earth, for UDT of 50 and 350 population per km^2 respectively.

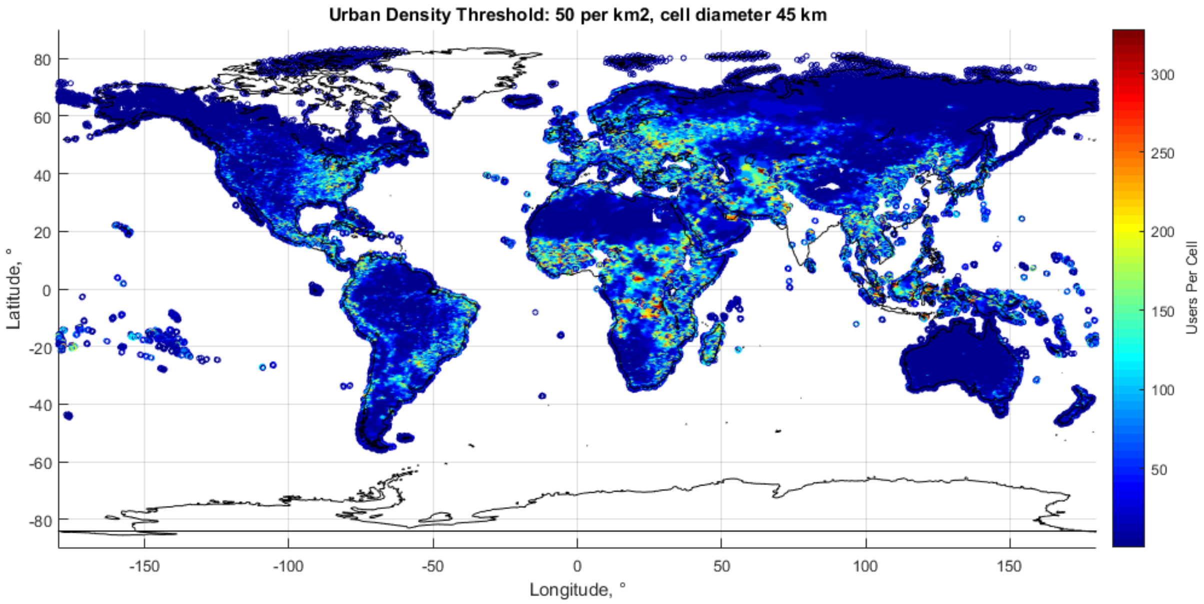

FIGURE 7-4 NUMBER OF UE PER CELL, URBAN THRESHOLD DENSITY OF 50 POPULATION PER KM^2

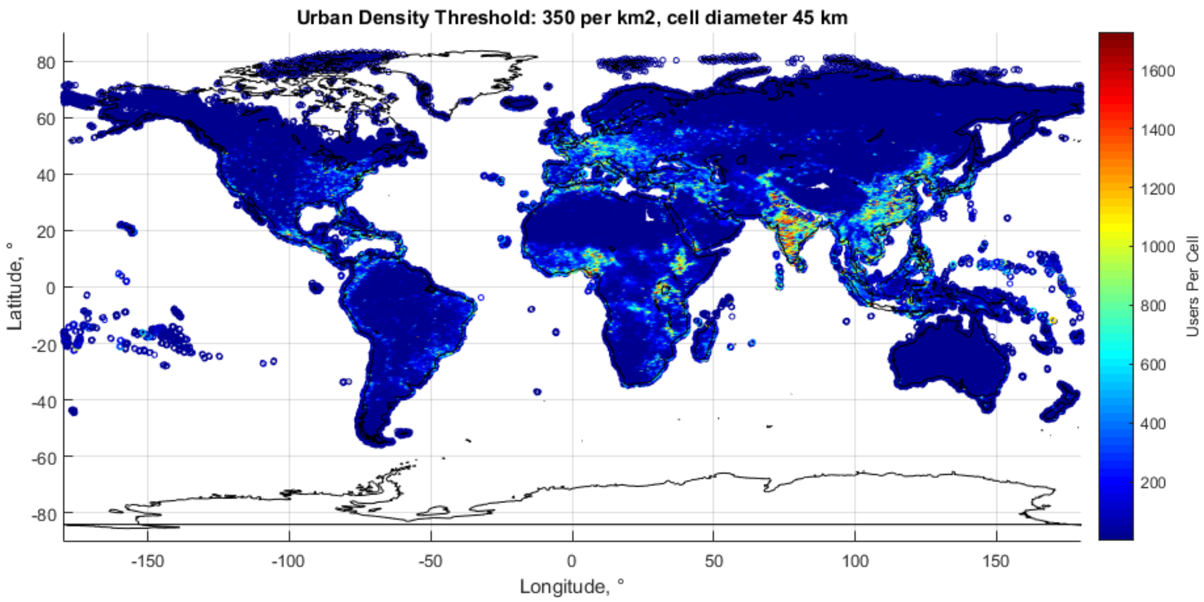

FIGURE 7-5 NUMBER OF UE PER CELL, URBAN THRESHOLD DENSITY OF 350 POPULATION PER KM^2

Figure 7-6 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^2. 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.

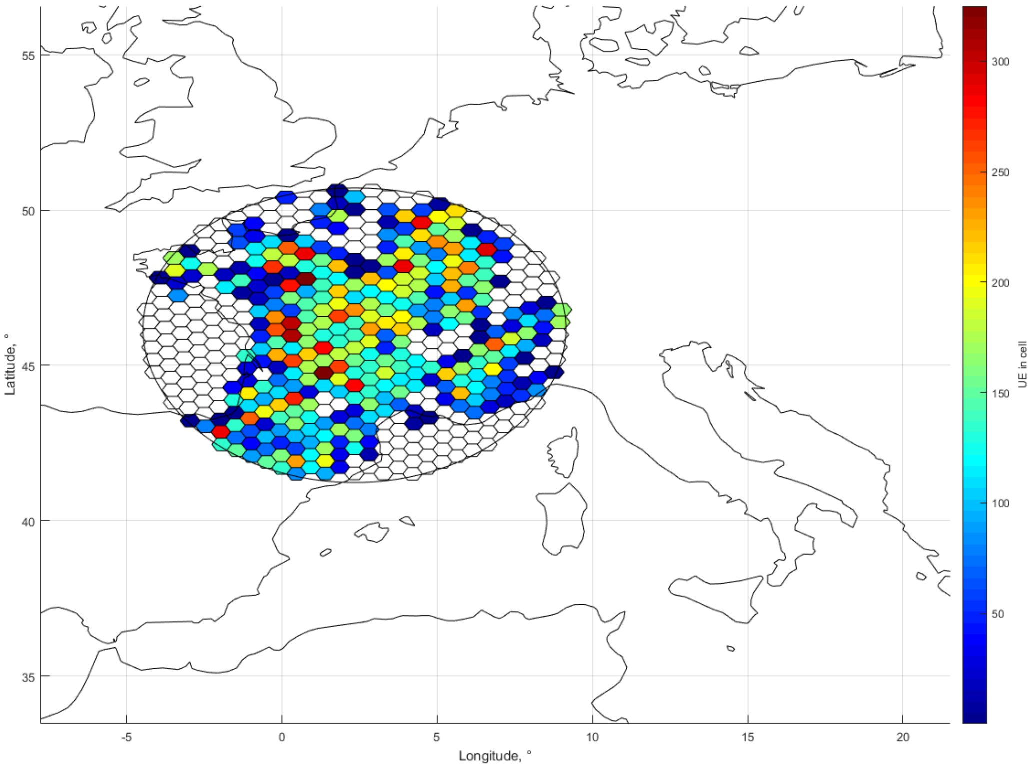

FIGURE 7-6 EXAMPLE OF NUMBER OF UE PER CELL, FOR CELLS IN A SINGLE SATELLITE FOV, URBAN DENSITY THRESHOLD OF 50 POPULATION PER KM^2

NOTE THAT IN FIGURE 7-4 AND FIGURE 7-5 IT APPEARS THAT THE CELLS COVER A LOT OF AREA THAT IS SUPPOSEDLY EMPTY OF NTN USERS ACCORDING TO FIGURE 7-2 AND FIGURE 7-3 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 REDUCES THE COMPUTING RESOURCES TO GENERATE THE IMAGES – PLOTTING EVERY CELL TO THE CORRECT SIZE (LIKE IN FIGURE 7-6) REQUIRES A PROHIBITIVE AMOUNT OF MEMORY, AND SO THIS SHORTCUT IS TAKEN TO SIMPLIFY PROCESSING.

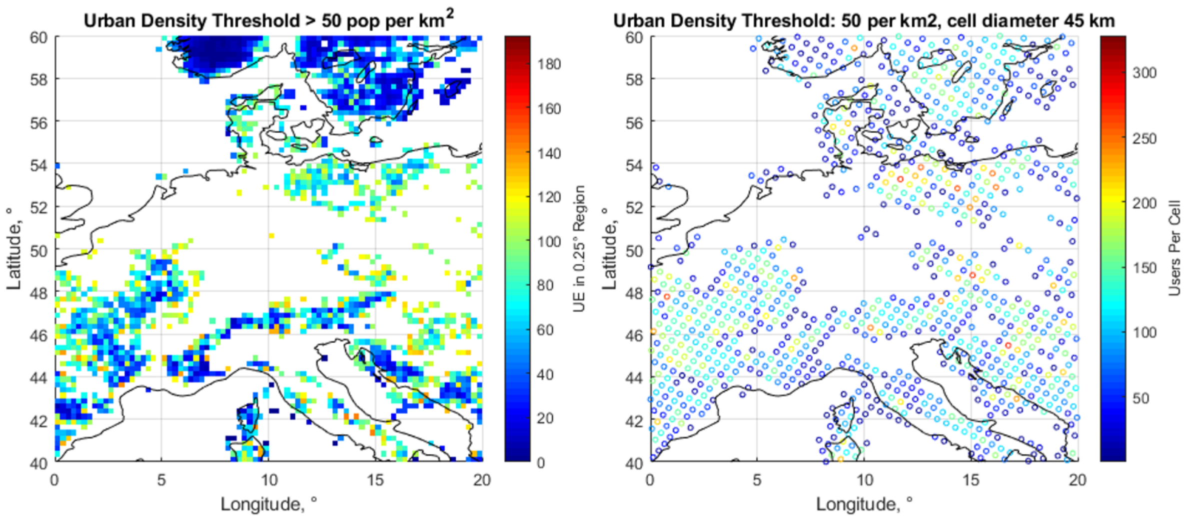

Figure 7-7 demonstrates that the mapping of UE to cells in Figure 7-4 and Figure 7-5 correctly covers the population/UE densities in Figure 7-2 and Figure 7-3, by focussing on a smaller region for the UDT of 50 population per km^2.

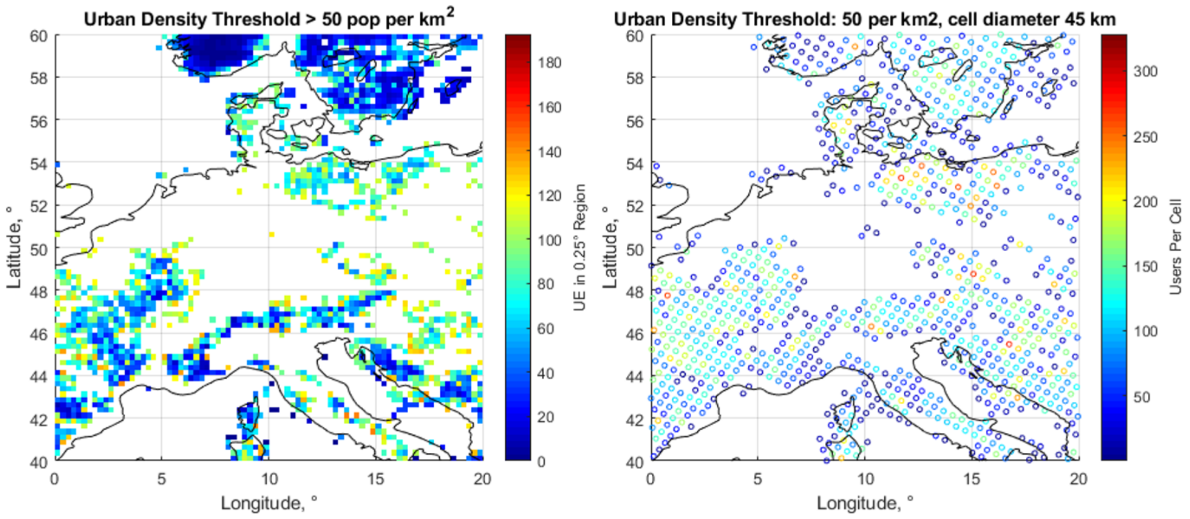

FIGURE 7-7 ZOOMED IN COMPARISON OF UE DENSITY AND UE PER CELL FOCUSSING ON CENTRAL EUROPE TO DEMONSTRATE THAT THE MAPPING OF CELLS CORRECTLY COVERS THE DEFINED POPULATION/UE DISTRIBUTION.

7.1.3 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 7-8 and Figure 7-9 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 7-10 and Figure 7-11 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^2, 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^2, 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.

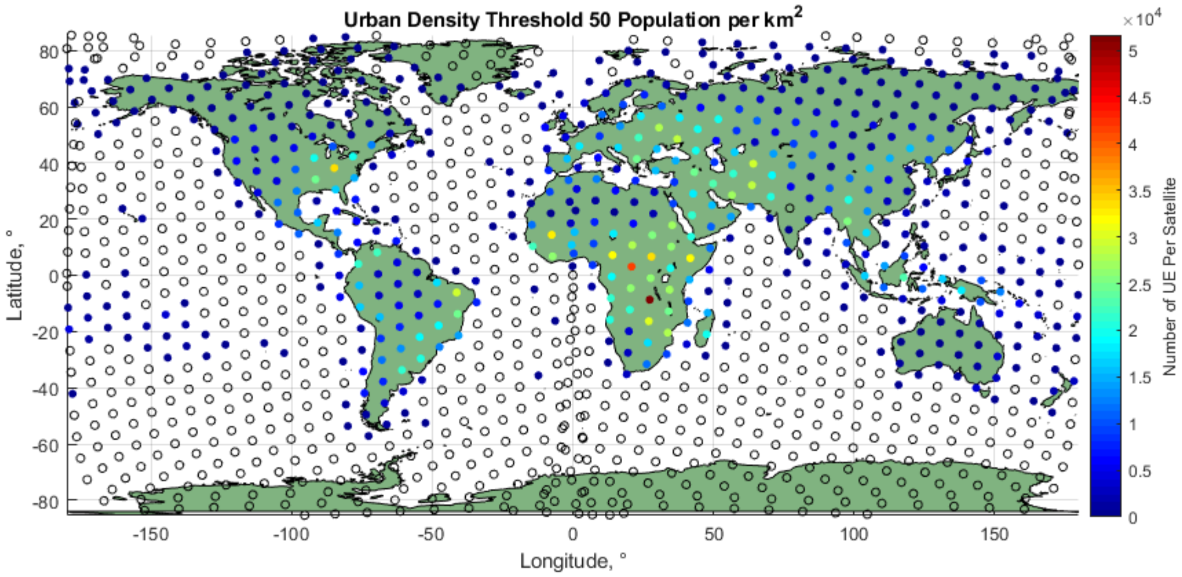

FIGURE 7-8 NUMBER OF UE PER SATELLITE, ASSUMING EACH CELL IS CONNECTED TO THE NEAREST SATELLITE, URBAN THRESHOLD DENSITY OF 50 POPULATION PER KM^2.

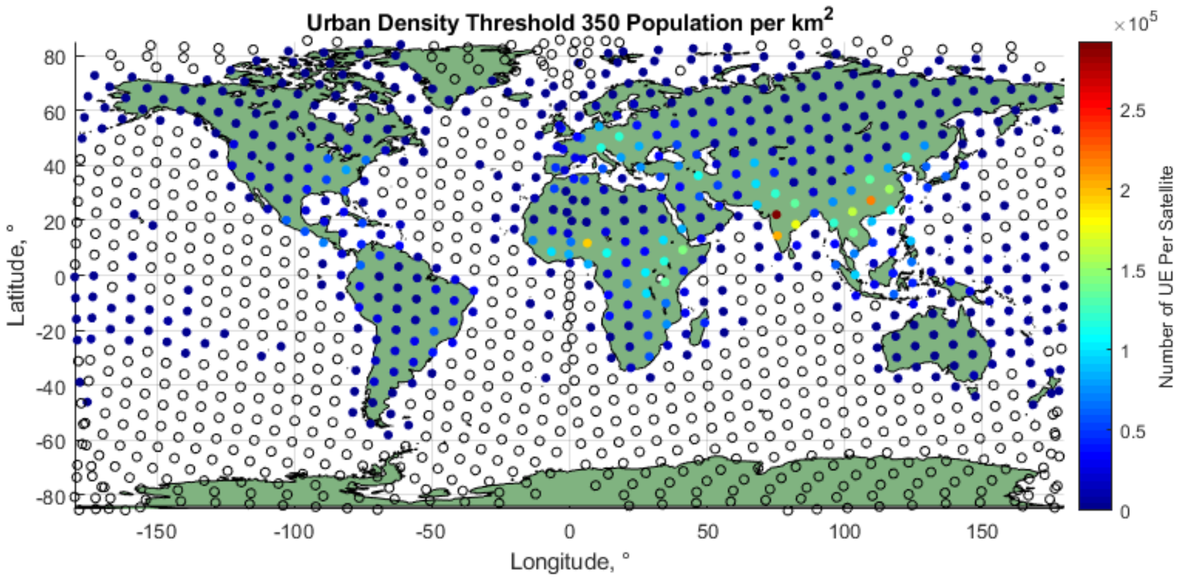

FIGURE 7-9 NUMBER OF UE PER SATELLITE, ASSUMING EACH CELL IS CONNECTED TO THE NEAREST SATELLITE, URBAN THRESHOLD DENSITY OF 350 POPULATION PER KM^2.

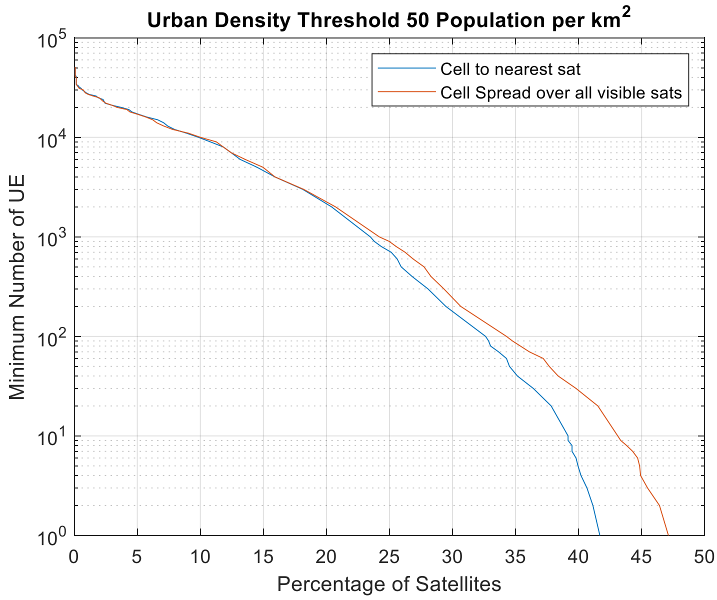

FIGURE 7-10 DISTRIBUTION OF NUMBER OF UE SUPPORTED PER SATELLITES, URBAN THRESHOLD DENSITY OF 50 POPULATION PER KM^2

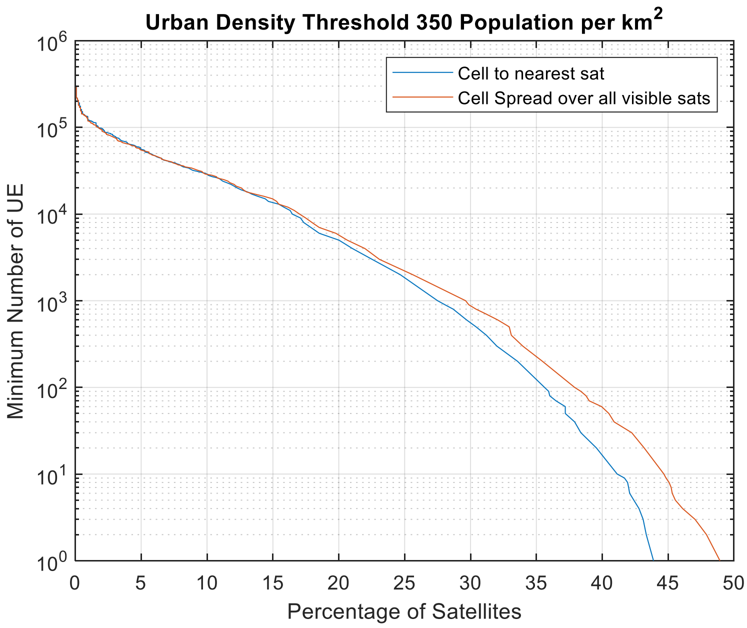

FIGURE 7-11 DISTRIBUTION OF NUMBER OF UE SUPPORTED PER SATELLITES, URBAN THRESHOLD DENSITY OF 350 POPULATION PER KM^2

7.2 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 7-12 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 7-6, 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.

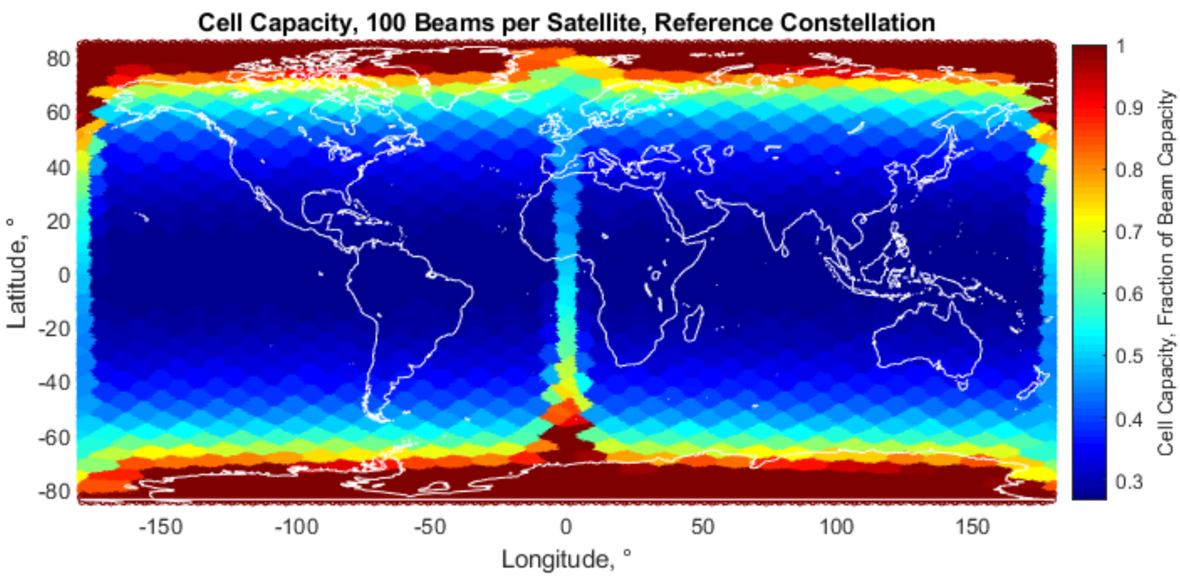

FIGURE 7-12 CELL CAPACITY (RELATIVE TO BEAM CAPACITY) FOR THE REFERENCE CONSTELLATION, ASSUMING A MAXIMUM OF 100 BEAMS PER SATELLITE

Figure 7-13 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.

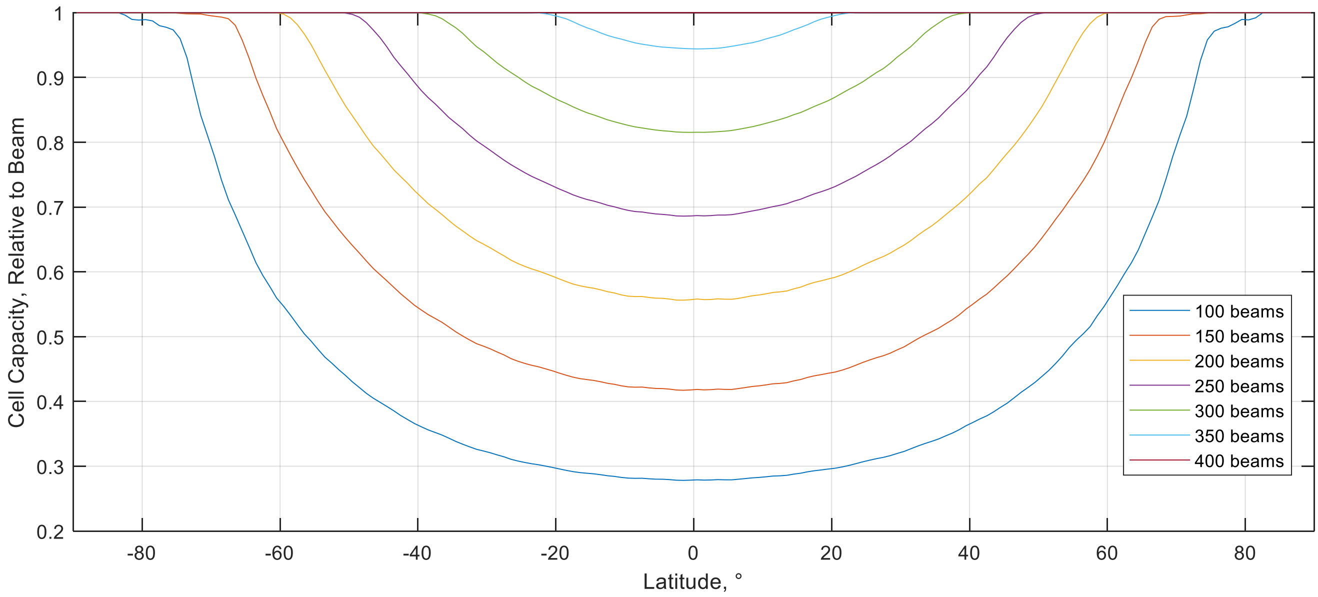

FIGURE 7-13 AVERAGE CELL CAPACITY (RELATIVE TO BEAM CAPACITY) VS LATITUDE

7.2.1 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 7-14 shows the data rate per UE assuming a maximum of 100 beams per satellite, 48Mbps per beam (C-band) and a UDT of 50km^{-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.

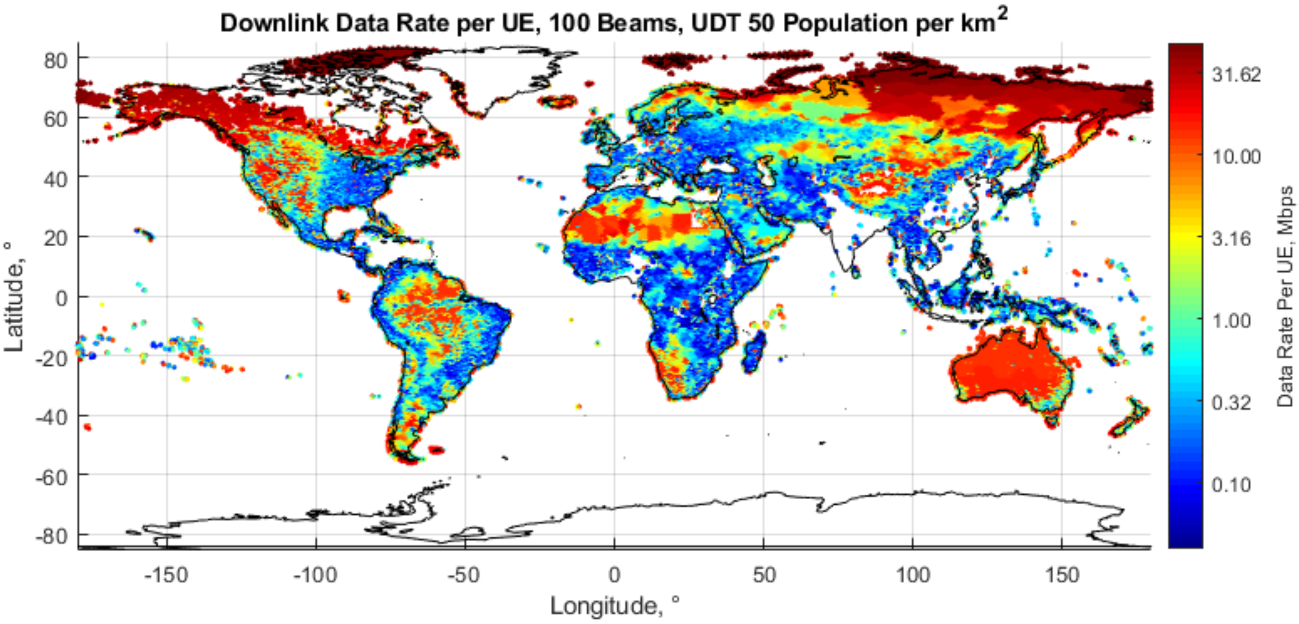

FIGURE 7-14 ESTIMATED DATA RATE PER UE, ASSUMING 100 BEAMS PER SATELLITE, 48MBPS PER BEAM, UDT OF 50 KM^{-2}

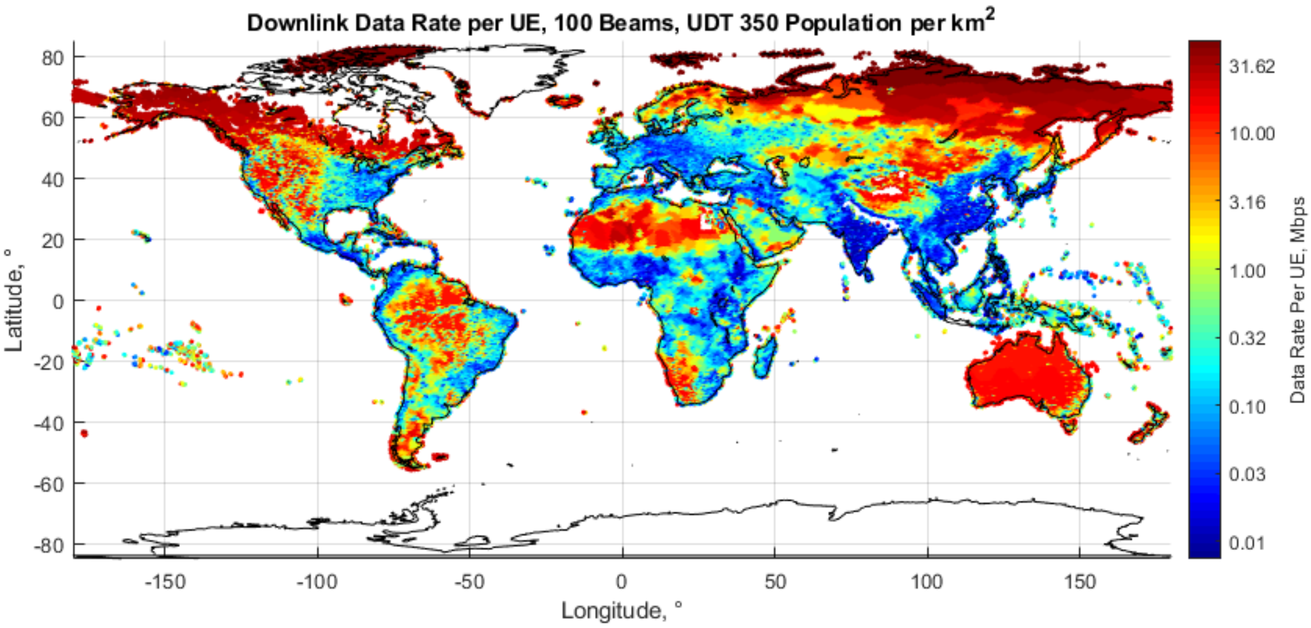

FIGURE 7-15 ESTIMATED DATA RATE PER UE, ASSUMING 100 BEAMS PER SATELLITE, 48MBPS PER BEAM, UDT OF 350 KM^{-2}

8 CONCLUSIONS

The main outcomes of this deliverables are already summarized in the executive summary. Hence, this concluding chapter is focussing on the next steps.

It is acknowledged that the constellation capacity calculation is at an early stage and there are several factors that have not yet been considered or require further refinement.

For example for the estimation of user densities:

- Different types of terminal: as stated in D2.2 [**Error! Bookmark not defined.**], there are expected to be different types of terminal (such as handheld, vehicle mounted etc) operating 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 7-1 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 Section7.2.1, based on the performance of the payload. 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 architecture, payload performance and terminal performance coming from the rest of Task 3.

REFERENCES

[1] 6G-NTN Deliverable 3.5, “Report on 3D/Multilayered NTN Architecture”, V1.0

[2] 6G-NTN deliverable 2.1, “Use Case Definition,” V1.0

[3] 6G-NTN deliverable 2.2, “User Requirements” V01

[4] 6G-NTN deliverable 2.3, “Service and Technical Requirements” V01

[5] 6G-NTN Deliverable 3.2 “Terminals”, v1.0

[6] 6G-NTN Deliverable 3.3 “Software Defined Payload and its Scalability”, v1.0

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APPENDIX A – DOPPLER SHIFT VALUES

Table 8-1 and Table 8-2 summarise the Doppler shift experienced for a range of altitudes and frequencies, for a minimum user elevation of 20° and 45° respectively.

TABLE 8-1 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 8-2 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

50	250	879.9	0.0018%	38619
	400	850.8	0.0017%	23080
	600	814.5	0.0016%	14516
	800	780.6	0.0016%	10288