KTH ROYAL INSTITUTE
OF TECHNOLOGY

Degree Project in Space Technology

Second Cycle 30 credits

Design of a Satellite Constellation Intended for Use With a Small User Terminal

MATHIAS AXELSSON

Stockholm, Sweden 2022

Design of a Satellite Constellation Intended for Use With a Small User Terminal

Mathias Axelsson

***Abstract*—Satellite constellations intended for communications services are becoming increasingly relevant with multiple companies such as Starlink and OneWeb launching constellations consisting of hundreds or thousands of satellites. This thesis investigated how such a constellation can be designed for a small user terminal with a diameter of approximately 15 cm. Four constellations, two at 8500 km altitude and two at 1200 km altitude, were proposed. Methods for systematic placement of satellites in orbital planes, aspects going into the link budget, and relevant regulations on the international level were investigated. It was found that the most favourable constellation was a medium Earth orbit constellation with a minimum elevation of 30°. The primary reason for this choice was the limited budget which did not allow for a large amount of satellites being launched. Finally, the concept of a hybrid constellation with both geostationary satellites and non-geostationary satellites was considered.**

***Sammanfattning*—Satellitkonstellationer inriktade på satellitkommunikation har ökat i relevans i och med att ett flertal företag, i synnerhet Starlink och OneWeb, skjutit upp konstellationer bestående av hundratals eller tusentals satelliter. Det här examensarbetet undersökte hur sådana konstellationer kan designas för en liten markterminal med en diameter på omkring 15 cm. Fyra konstellationer, två med banhöjd 8500 km och två med banhöjd 1200 km föreslogs. Metoder för en systematisk placering av satelliter i banplan, aspekter i länkbudgeten, samt relevanta föreskrifter på ett internationellt plan undersöktes. En konstellation med en banhöjd på 8500 km och minsta elevation 30° var den mest fördelaktiga konstellationen. Den primära anledningen till detta var att budgeten för konstellationen tillät endast att en liten mängd satelliter skjuts upp. Slutligen undersöktes konceptet av en hybrid konstellation som består av både geostationära och icke-geostationära satelliter.**

LIST OF ABBREVIATIONS

CER	Cost Estimating Relationship
ECEF	Earth Centred, Earth Fixed
EIRP	Effective Isotropic Radiated Power
FER	Frame Error Rate
FSS	Fixed Satellite Services
GEO	Geostationary Equatorial Orbit
GNSS	Global Navigation Satellite Systems
GSO	Geosynchronous Orbit
GTO	Geostationary Transfer Orbit
ISL	Inter Satellite Link
ITU	International Telecommunications Union
LFC	Lattice Flower Constellation
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MSS	Mobile Satellite Services
NGSO	Non-Geosynchronous Orbit
PFD	Power Flux-Density
RAAN	Right Ascension of Ascending Node
RF	Radio Frequency

Mathias Axelsson is a MSc student at KTH, Royal Institute of Technology, Stockholm, Sweden.

I. INTRODUCTION

IN the last five years the interest for satellite communications constellations in non-geosynchronous orbits (NGSO) have resurfaced. Last time, in the early 1990s a number of NGSO constellations were proposed [1] in various types of orbits. Today only three of the ten presented companies provide satellite service: Iridium, Globalstar, and Orbcom. Moving forward to today the focus has shifted from providing mobile satellite service (MSS) to fixed satellite service (FSS). Companies like SpaceX, OneWeb, Telesat, and Amazon are creating constellations capable of transmitting at estimated speed of 10-50 Tbps [2]. All of these constellations will operate exclusively in Low Earth Orbit (LEO). Other constellations such as the Arctic Satellite Broadband Mission [3] and O3b [4] propose to use fewer satellites, 2 and 70 respectively. In the case for O3b they already have a constellation in Medium Earth Orbit (MEO). These constellations have a relatively high orbits when compared with the big LEO constellations mentioned earlier gives them a much larger coverage per satellite.

Satellite orbit design is an integral part of a satellite constellation. The altitude of the satellites influence among other things the area in which the satellite is visible, the number and placement of ground stations, the satellite to Earth and Earth to satellite communication performance as expressed by the link budget, and the launch costs. The inclination of the orbits will determine which latitudes will be serviced by the constellation. Furthermore, the number and types of orbital planes, the satellite's spacing within the planes and the number of satellites will determine the type of coverage. The altitude and inclination will also influence the risk of collisions with space debris, man made or natural. Coverage can range from intermittent coverage over specific areas to multiple satellites visible from all points of Earth. As an example one can consider a Global Navigation Satellite Systems (GNSS) constellation. To calculate a position a minimum of four satellites need to be visible [5, p. 654]. The Galileo constellation fulfills this requirement with 27 satellites at an altitude of 23 222.1 km [5, p. 685]. While this altitude is preferable for GNSS constellations, it is not a good orbit for satellite communications systems. This is because a geostationary satellite would share the same disadvantages, high launch cost and latency, while having an additional advantage in being stationary in the sky.

Work on the design of satellite constellations have been ongoing for a long time. In some early systems the satellites

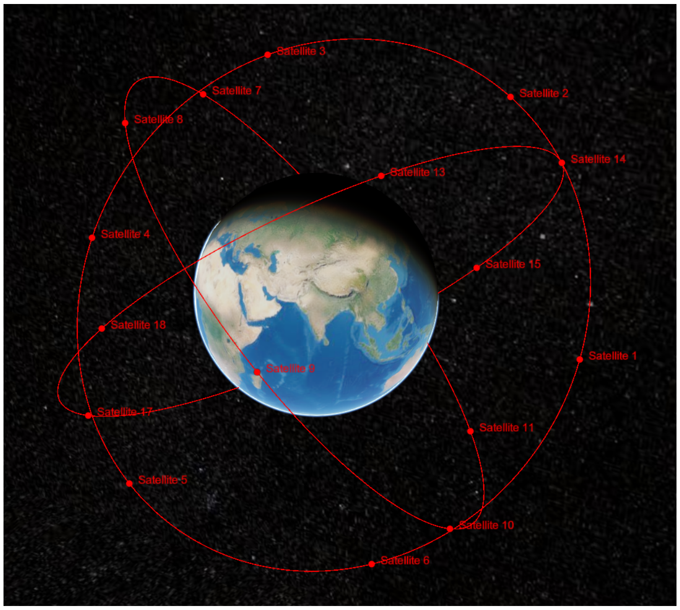

Fig. 1. A 18/3/2-50° Walker constellation at an altitude of 8000 km.

are placed in the (Ω, M) space, Ω being the Right Angle Of Ascension (RAAN) and M being the mean anomaly of the orbit. This placement of satellites are done according to some rules while keeping the remaining Keplerian elements equal among themselves. Early constellations include the Walker constellations [6] and Rosette constellations [7]. These constellations share the common property that a number of satellites T is spread evenly over P planes such that $T = S \times P$ where S is the satellites per plane. Walker constellations add an additional pattern unit F which offsets the mean anomaly for consecutive planes by $F \times \frac{360}{T}$ with $F = (0, 1, 2, \dots, P-1)$. A Walker constellation is described by the notation $T/P/F-I$, where I is the inclination. Rosette constellations similarly consist of a number of satellites spread out over a number of planes P with Right Angle of Ascending Node (RAAN) $\Omega_i = 2\pi i/P$. Instead of having a fixed phase between planes the satellites have true anomaly $\nu_i = m\Omega_i$ where i is an integer in $(0, 1, \cdots, N-1)$ and m is a fraction $(0, 1/Q, \cdots, (N-1)/Q)$ where Q is the number of satellites in each plane. In their work both Walker [6] and Ballard [7] provide some constellations which are by different measurements optimal. Later work has been put into 2D Lattice Flower Constellations (LFC) [8] which unifies Harmonic Flower constellations and Walker constellations into a single mathematical framework. Here a constellation is defined as earlier by the number of planes N_o, satellites per plane N_{so}, and a configuration number $0 \leq N_c$. An example of an 18/3/2-50° Walker constellation can be seen in fig. 1.

The mentioned constellation design methods assume that the goal of the constellation is to have uniform coverage between certain latitudes. Methods for providing coverage to specific areas have also been developed [9]. Here a "seed satellite" has its access intervals calculated, then additional satellites are added with their RAAN and mean anomaly shifted such that it passes over the target with the same ground track, but some time afterwards. This provides a simple method for creating coverage over one or multiple regions.

A user terminal that is as small as possible is desirable for applications such as vehicle mounted terminals or similarly portable ones. Since for a terminal the antenna size will be correlated with the gain of the antenna [10], a larger antenna will be able to establish a stronger link between the satellite and the user terminal. However, a smaller user terminal will, by virtue of its size, be more portable. Another challenge present in smaller antennas is that their beams are wider, increasing the risk of interference with other satellites close to the antenna boresight. This thesis will consider a small terminal with an antenna size of approximately 15 cm across.

The aim of this thesis is to investigate the different aspects that make up the design of a communications satellite network using GEO and/or NGSO satellites. Strengths and weaknesses of both GEO and NGSO satellites will be presented together with a comparison of GEO and NGSO systems which could provide broadband coverage in similar areas. This comparison will take costs, manufacturing, operation, and launches into account over the service lifetime of the GEO and NGSO systems. The possibility of combining GEO and NGSO systems into a hybrid system to cover the respective systems weaknesses will be investigated.

This will be done by introducing the reader to satellite communications. Strengths and weaknesses of GEO and NGSO constellations will be discussed. Then two existing satellite constellations will be briefly investigated; One active and one planned. Then the design considerations to be taken into account when designing communications satellite constellations are presented including considerations in the design of the satellites themselves. Five candidate constellations are designed and presented: a GEO, two MEO, and two LEO constellations. These constellations are then compared against each other and their strengths and weaknesses are discussed. Finally, the possibility of constructing a hybrid system is considered.

II. Communications satellite constellations

A satellite constellation is a system containing a minimum of two satellites that work together for a common mission. Examples of types of systems that use satellite constellations are global navigational satellite systems, Earth observation systems, and communications systems.

Fig. 2 shows an overview of a communication system and its different communications radio links. A satellite can provide coverage to an area below to which it has line of sight. Depending on the satellite design the signal may be forwarded to a gateway connecting to an Earth based network, another satellite terminal or another satellite that then continues to forward the signal to its intended destination.

A communications satellite generally consists of two parts, the satellite bus and the payload. The satellite bus provides the basic functions that are required for a satellite to operate such as stabilization, pointing, orbit maintenance, and electrical power generation. A typical payload consists of the systems for Radio Frequency (RF) communications, i.e. antennas and transponders. Many communication satellites work as a relay, forwarding the analog signal it receives to another downlink channel. This is called ”bent-pipe” mode. For a satellite working in bent-pipe mode any disturbances during the uplink transmission will be retransmitted on the downlink transmission. With a digital payload a satellite network can facilitate routing between satellites or between user terminals similarly to a regular local area network. Furthermore, the satellite may perform demodulation and error correction for its received signals decreasing the error rate.

In general terms, a transponder receives a signal and then transmits it in a different frequency. They operate with a specified bandwidth, for example 36 MHz [11]. A channel refers to a transponder operating at a specific carrier frequency. Finally, an antenna on a satellite can have multiple transponders connected to it.

The gateway or feeder link connects a satellite in the constellation to another network, often but not necessarily the internet. These links are meant to carry all user traffic from the satellite, and therefore they will have a larger throughput than a user terminal link.

Inter Satellite Links (ISLs) are communications links between satellites in a constellation. A simple implementation would be a link forwards and backwards in a satellite plane. This thesis will denote these links as in-plane ISLs. With in-plane ISLs, if any satellite in the orbital plane sees a ground station all satellites within that plane would be able to communicate with it through the other satellites. This network can also be expanded by adding links between the planes, Cross-plane ISLs. These links are harder to engineer since the antennas on the two satellites would have to track each other, as two satellites in different orbital planes would be moving relative to each other. This could however allow for any satellite to send data to the ground as long as at least one satellite could access a ground station.

Since bandwidth is limited in the frequency spectrum, methods to increase the maximum throughput are often implemented in communications satellites. The main methods for increasing the maximum throughput are geographical frequency reuse, polarization, modulation, and coding [12]. Fig. 3 shows how each frequency is used in multiple geographically distinct areas. Two beams will not interfere if they are sufficiently separated. The interference between two beams vary depending on the antenna used. In the case of using four different frequencies as pictured in fig. 3 the distance between the beams is approximately $(1+\sqrt{3}) \times D$ where D is the beamwidth. When using only three different frequencies the distance between the centres of the beams decrease to $\frac{3}{2} \times D$. Following International Telecommunications Union (ITU) recommendations for the design objective for antennas in NGSO satellites [13] these separations correspond to approximately -15 dB and -5 dB of signal to interference levels respectively, the former being set by the near-in-side-lobe level. An example can be seen in Fig. 4. In this way the maximum throughput of the satellite is proportional to the number of beams in addition to the available bandwidth. The available bandwidth can be doubled if two channels

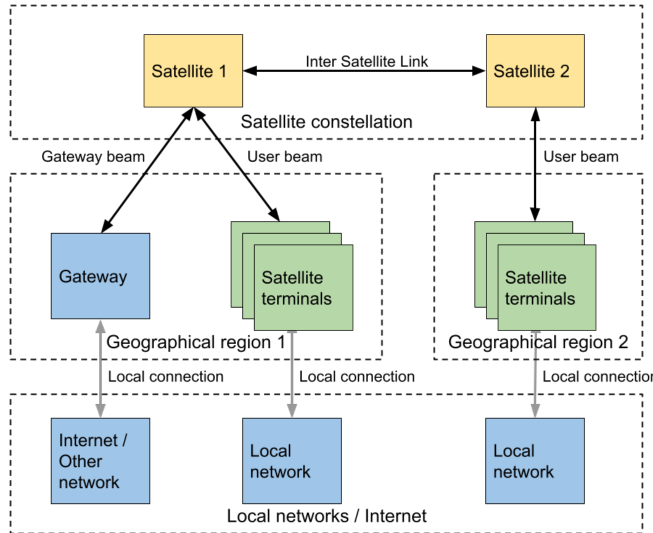

Fig. 2. Overview of the different types of network links within a satellite communications constellation.

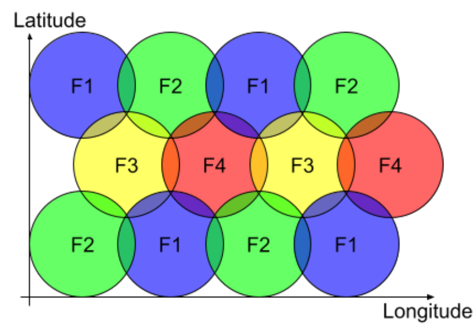

Fig. 3. Example of geographical frequency reuse using multiple beams and four frequency bands F1-F4.

transmit and receive with opposite polarization. For linear polarization this means that the polarization needs to be rotated 90° with respect to the other channel. Circular polarization can also be used where one channel uses Right Handed Circular Polarization (RHCP) and the other uses Left Handed Circular Polarization (LHCP). The main advantage of circular polarization over linear polarization is that when used it does not put a constraint on the orientation of the receiving terminal [14] when directed at the transmitting source. While linear and circular polarization have their differences the function they provide is equivalent.

Finally, spectral efficiency, the number of bits that can be transmitted per Hz of bandwidth, can be increased by implementing digital modulation. There are three different ways to impress a signal onto a carrier wave. The amplitude, phase, and frequency [15] of the carrier wave can be varied. There are multiple strategies to encode a symbol. One of the simplest methods, phase-shifting relies on the fact that any sine wave can be split into an in-phase cosine wave and quadrature

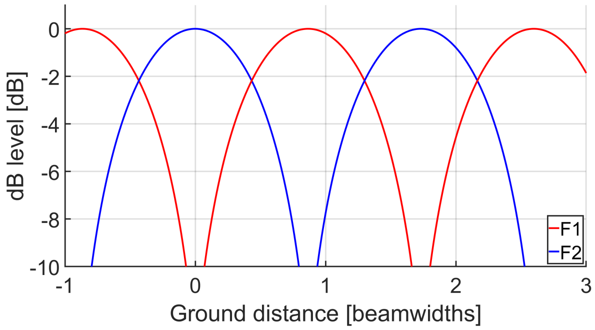

Fig. 4. Frequency reuse dB levels as a function of ground distance expressed in beamwidths.

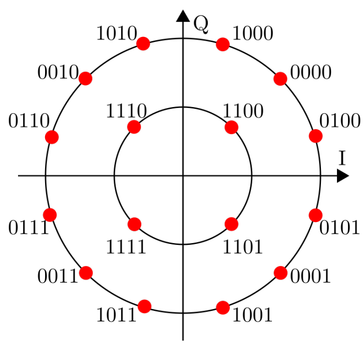

Fig. 5. 16-APSK constellation diagram combining amplitude- and phase-shift keying. Each symbol represents four bits.

sine wave

$$\sin(t+\psi) = \sin(t)\cos(\psi) + \sin(t+\pi/2)\sin(\psi)\,, \quad (1)$$

with t, being the time and ψ being the phase. Then, $I = \cos(\psi)$ and $Q = \sin(\psi)$. As a simple example one can have the phase shifted 180° represent a zero and a non-shifted carrier represent a one. This method is called BPSK or Bipolar Phase-Shift Keying. In higher order modulation schemes, amplitude, and phase shifting can be combined into constellation diagrams. One such diagram called 16-APSK has a symbol representing four bits. This constellation diagram can be seen in Fig. 5.

A. Fixed and mobile satellite service

Satellite constellations in this thesis are intended to deliver Fixed Satellite Services (FSS). This type of service is defined by the International Telecommunications Union (ITU) in their Radio Regulations [16, Articles 1.21, 1.25] as

> A *radiocommunication service* between *earth stations* at given positions, when one or more *satellites* are used; the given position may be a specified fixed point or any fixed point within specified areas; in some cases this service includes satellite-to-satellite links, which may also be operated in the *inter-satellite service*; the fixed-satellite service may also include *feeder links* for other space *radiocommunication services*.

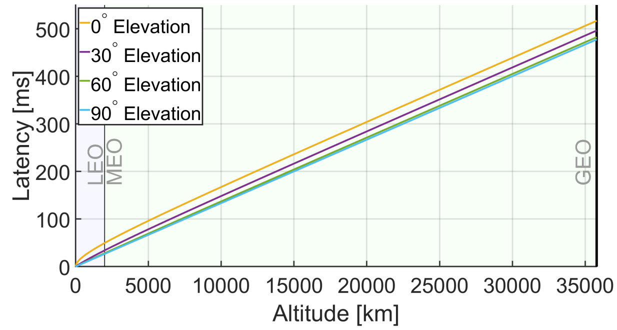

Fig. 6. Minimum round trip latency for communications in a satellite communications constellation as a function of the altitude of a transmitter and with the receiver at the sub-satellite point.

In ITU publications the term space station is sometimes used. A space station in this case is a number of transmitters and/or receivers beyond Earth's atmosphere which carry out a radiocommunication service or radio astronomy service. While the ITU distinguishes between satellites and space stations for the purposes of this thesis they are equivalent. Therefore, satellites will be used to refer to space stations as well.

Along with FSS there are other types of services such as Mobile Satellite Service (MSS). In addition to the differences in the service provided FSS and MSS have different frequency bands allocated to them by the ITU. This thesis will only consider operations in the frequency bands 10.7-10.95 (space-to-Earth), 11.2-11.45 (space-to-Earth) and 12.75-13.25 (Earth-to-space) GHz. In this thesis space-to-Earth frequencies will be referred to as downlink frequencies and Earth-to-space frequencies will be referred to as uplink frequencies. These frequency bands are not allocated for MSS services.

B. Differences between geostationary equatorial orbit and non-geosynchronous orbit communications satellites

One of the main differences between a LEO or MEO satellite and a GSO satellite is the link latency due to the distance. The distance between a satellite and a ground station can be calculated with the Law of Sines. The maximum separation between a ground station and a satellite happens when the satellite is at the lowest elevation allowed with respect to the ground station. Similarly, the shortest path will occur when the ground station is at the satellite's sub-satellite point, right below the satellite. Fig. 7 shows how the distance $d(e)$ changes depending on the position of the ground station relative to the satellite's sub-satellite point. Unless the ground station is communicating with the satellite the signal must be forwarded to a gateway. Then the gateway would process the ground stations request before sending it back via the satellite. From this the worst case minimal round trip latency can be determined. A comparison for different round trip latencies depending on the satellite altitude and elevation can be found in Fig. 6. For a satellite at an altitude of 1200 km the best case round trip latency becomes 8ms. That is when the sub-satellite point is on the ground station. In contrast, a GEO satellite will

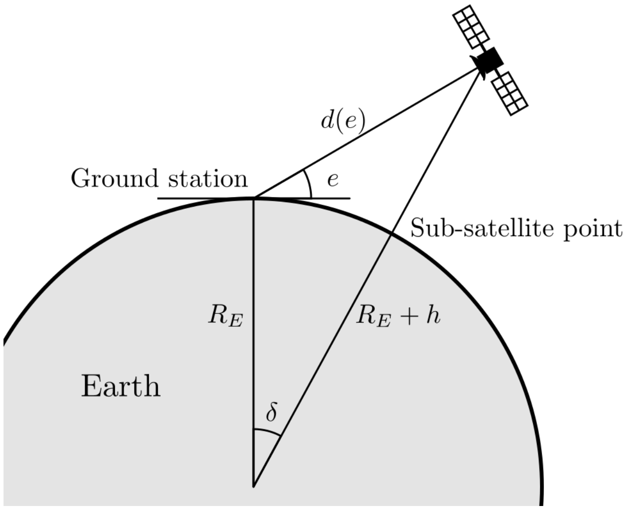

Fig. 7. Geometry for a satellite and ground station communications link showing how the distance between the satellite and ground station depends on the elevation and altitude of the satellite relative to the ground station. Here e is the elevation, δ is the angle between the sub-satellite point and the ground station, $d(e)$ is the distance between the ground station and satellite, h is the altitude of the satellite and R_E is the radius of Earth.

have a minimum round trip latency of between 475 ms and 500 ms.

The main advantage of a GEO communications satellite is that a ground station will not have to track the satellite across the sky. Since a GEO satellite stays at the same sub-satellite point throughout its orbit it will also stay at the same point in the sky for good link performance. Therefore, there is no need to reorient the ground station antenna during operation. For NGSO communications satellites the antenna will need to reorient to maintain the communications link. In addition, when satellites pass below the horizon the ground station will need to reacquire the link with another satellite. During the time the ground station redirects its beam to a new satellite it will no longer have a connection to the constellation. To have a near continuous connection either two mechanical antennas or a single electronically steered antenna would be needed. The time for the ground station to reacquire the satellite will entirely depend on the technology used in it.

As will be shown later in this thesis, a longer communications distance between a satellite and a ground station increases the free space loss in the link budget. The loss increases proportionally with the square of the distance. The direct result of this is that satellite and ground station antennas will have to compensate for this loss by a combination of larger antennas and transmitting with more power. Larger antennas and transmitters capable of transmitting with more power then result in larger costs for the satellite components and user terminals. This provides an advantage for NGSO satellites when compared with GEO satellites. On the other hand, ITU regulates the power flux-density (PFD) at Earth's surface from satellites. The maximum PFD at a terminal is therefore similar for both GEO and NGSO constellations. An antenna communicating with a NGSO constellation would regularly have to switch which satellite it communicates with, which gives a clear disadvantage due to the increased complexity of the antenna, data routing, and hand-over procedures. However, as Fig. 7 shows, the higher the altitude of the satellite is the larger the angle δ between the sub-satellite point and the ground station becomes for a given elevation which means that satellites in higher orbits can serve a larger area on Earth for any given elevation when compared with satellites in lower orbits.

When comparing the GEO satellite launch cost and mass to orbit with LEO and MEO satellites, LEO, and MEO satellites can launch more mass to their intended orbit per rocket. Due to the smaller distance a signal needs to travel the antennas on a satellite in a lower orbit can be much smaller compared to the antennas on a GEO satellite. This difference in distance can also affect the output power of the transceiver, lowering the required power due to a shorter distance. The result is that a single communications satellite in a lower orbit is generally cheaper than a single GEO satellite. However, to provide a continuous link for a MEO or LEO constellation there is a need for more satellites.

Finally, it is pertinent to briefly consider the radiation environments of LEO, MEO, and, GEO. In LEO Earth's magnetic field protects against large amounts of radiation when compared with GEO [17]. Similarly to LEO satellites, MEO satellites are somewhat shielded by Earth's magnetic field. However, the Van Allen belts are still a significant source of radiation which necessitates additional shielding or redundancy when compared to a LEO satellite [18]. In the worst case scenario, a satellite in MEO may require six times the shielding when compared with a satellite in LEO. In practice, an environment with more radiation necessitates stronger shielding and hardened components, which increases the cost and mass of the satellite.

C. *O3b, an active satellite constellation*

The O3b constellation is a satellite constellation orbiting in circular non-inclined orbits above the equator providing its service to locations within ± 45° latitude [19]. The constellation have limited reach up to ± 62° latitude. Table I shows the orbital parameters of the constellation. The early constellation consisted of 12 satellites spread evenly around the equatorial orbital plane. The total throughput of the these 12 satellites is 126 Gbps using 105 beams. At the time of writing this thesis the number of satellites in the constellation has increased to 20 [20]. The orbits of the O3b constellation can be seen in Fig. 8.

Since the constellation orbits at 8 062 km the latency is much lower when compared to a GEO constellation while also providing similar throughput. As will be discussed later in this thesis, NGSO constellations working in specific frequencies need to abide by regulations limiting their emissions when transmitting in-line with GEO satellites. This makes it effectively impossible to transmit from NGSO satellites in equatorial orbits onto the equator. As an example, Fig. 9 shows the areas where a satellite in the O3b constellation would not be able to transmit to due to this restriction. The O3b

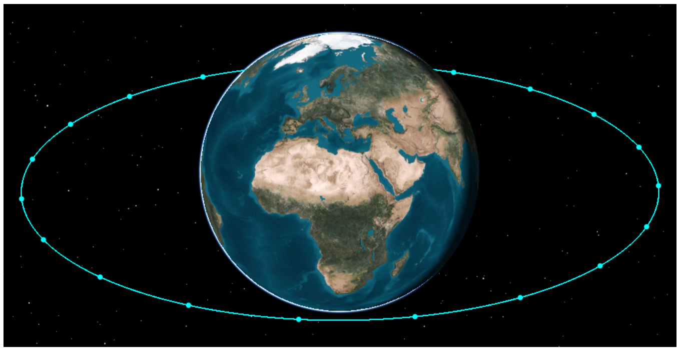

Fig. 8. The orbits of the O3b constellation.

TABLE I
ORBITAL CONFIGURATION FOR THE O3B CONSTELLATION.

Apogee altitude	8 062 km
Perigee altitude	8 062 km
Inclination	0°
Orbital period	1/5 Sidereal day

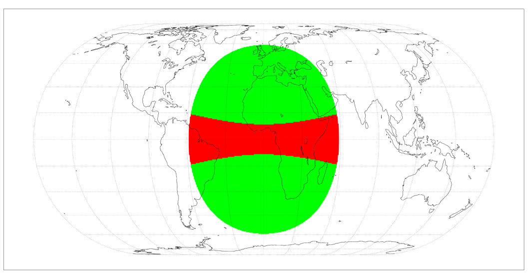

Fig. 9. Stay-out zone for a satellite at 8062 km altitude in an equatorial orbit such as the satellites in the O3b MEO constellation. The minimum elevation for the satellite is 5° and the minimum allowed angle between the satellite transmission and a potential GEO transmission is 5°. The green area is the area where the satellite can communicate with a user terminal and the red area is where the angle between the satellite transmission and GEO transmission is smaller than 5°.

constellation works around this limitation by partially using frequency bands not constrained by this regulation.

For an end user this constellation would result in satellite arching over the sky reaching a maximum elevation depending on latitude of the user. For users in lower latitudes the satellites would pass overhead and in higher latitudes the satellites would pass closer to the horizon. The satellites make five orbits per day which results in a handover between satellites approximately every two hours at the equator. This time decreases with higher latitudes. For this constellation a tracking antenna is required.

D. Arctic satellite broadband mission, a planned satellite constellation

The Arctic Satellite Broadband Mission (ASBM) is a proposed satellite constellation consisting of two satellites in critically inclined orbits [3]. The two satellites orbit in an eccentric orbit separated by a mean anomaly of 180°, placing them on opposite sides of the orbit. Table II shows the orbital parameters of the ASBM. The longitude of apogee have been included instead of the Right Ascension of Ascending Node (RAAN) since the RAAN will depend on the reference epoch. Fig. 10 shows the ground track of the constellation and Fig. 11 shows the orbits. The satellites will be active for eight hours centred on Apogee.

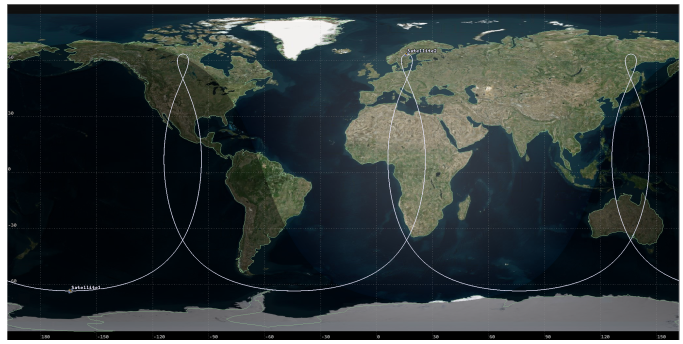

Fig. 10. The ground track for the Arctic Satellite Broadband Mission constellation.

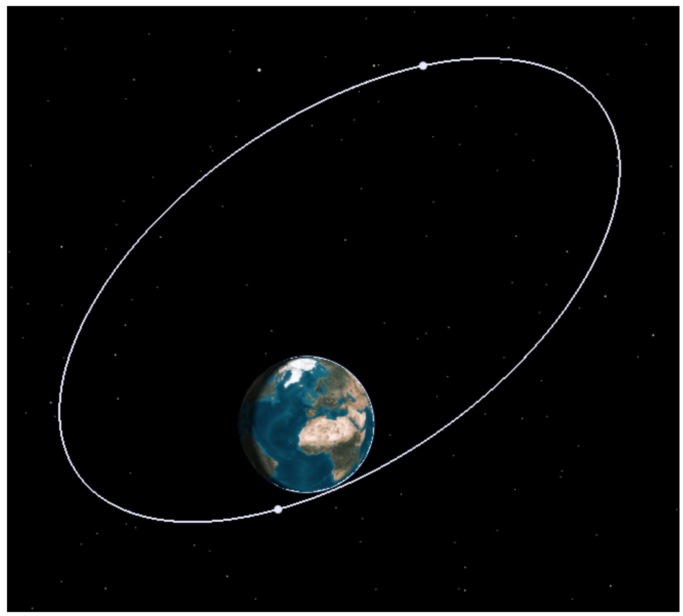

Fig. 11. The orbits for the Arctic Satellite Broadband Mission constellation.

This constellation has been designed to provide coverage to the Arctic region using a small number of satellites in orbits such that the tracking requirement for a ground station less severe than that of a lower orbit constellation. An additional advantage of the ASBM constellation when compared to a GEO satellite is that the elevation of the satellites will be much higher. A terminal operating with a GEO satellite would have to operate at elevations lower than 25° to reach into the coverage area. In section III-D it will be discussed how this can provide an advantage due to PFD limits. Due to the distance

TABLE II
ORBITAL CONFIGURATION FOR THE ASBM CONSTELLATION

Apogee altitude	43 509 km
Perigee altitude	8 089 km
Inclination	63.4°
Argument of perigee	270°
Longitude of apogee	19°E, 139°E and 259°E
Orbital period	2/3 Sidereal day

between ground stations and the satellites during the active period the round-trip latency will be between 250 and 300 ms. Furthermore, when compared to a LEO or MEO constellation the free space loss will be high.

For an end user this constellation would provide a satellite communication with fairly high elevation. At any point in time one of three areas in the sky would have a satellite present. This point would change every eight hours. In some respects this would provide an easier tracking than the O3b constellation since when the satellite has reached apogee it will move slowly before the user has to switch to a new target. This constellation would require tracking, although not as fast tracking as the O3b constellation.

III. DESIGN OF A SATELLITE CONSTELLATION FOR A SMALL USER TERMINAL

A. The small user terminal

The constellations in this thesis will be designed for a user terminal from now on referred to as the small terminal. It will have an antenna gain of 24 dBi corresponding to an antenna with a diameter of approximately 15 cm at a frequency of 10.7 GHz. The system temperature for the terminal will be assumed to be 140 K. This represents a measurement of the noise in the system. The value 140 K approximately corresponds to an antenna pointed into space where the noise levels are relatively low. For a satellite in the constellation the noise temperature is assumed to be 600 K, corresponding to an antenna with noise levels at 300 K that is pointing towards Earth.

It will be assumed that the maximum amplifier power in the small terminal is 10 dBW corresponding to 10 W. This ensures that the power source for the terminal can be portable as well. When a tracking antenna is required for NGSO constellations the small array is assumed to be a planar phased array antenna. In this case the small terminal will be assumed to have a minimum elevation of 45°. This assumption is reasonable since the gain loss from transmitting at an angle below 45° from the planar phased array antenna boresight quickly increases. Following the example of [21] the element power pattern is assumed to be $20\log_{10}(|\cos\nu|)$ where ν is the angle from the antenna boresight. ν can be related to the elevation e by $\nu = \frac{\pi}{2} - e$. With this element power pattern communications at an elevation of 45° incurs a transmission loss of 3 dB. For an elevation of 30° this loss increases to 6 dB. The final antenna gain can be calculated from

$$G = G_{\nu=0} + 20\log_{10}(|\cos\nu|) \tag{2}$$

where $G_{\nu=0}$ is equal to 24 dBi.

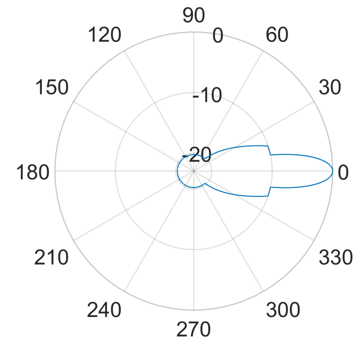

Fig. 12. Antenna radiation pattern used in this thesis for the small antenna. Modelled by ITU reference pattern [22].

TABLE III
REFERENCE VALUES FOR DECIBEL UNITS

Unit	Reference value
dBW	1 W
dBi	Isotropic antenna gain
dBW/m^2	1 W/m^2

The radiation pattern of the small antenna is modelled as the ITU reference pattern [22]. The half-power beamwidth which is the angle from the antenna boresight where the antenna gain is halved, or 3 dB lower than the maximum gain, for the small antenna is 13°. Furthermore, the beamwidth at which the gain has decreased by 10 dB is 24°. The radiation pattern for the small antenna can be seen in Fig. 12.

B. The decibel unit

When discussing communications links the convention is to use decibels (dB) rather than SI units. As will be seen in section IV-E using values in dB instead of SI unit allows them to be added together. Furthermore, it will be shown that the spectral efficiency can be approximated by a second degree polynomial when expressed as a function of the carrier to noise ratio expressed in dB. The conversion from SI units to dB is given by

$$U_{dB} = 10\log_{10}\left(\frac{U_{SI}}{U_{Ref}}\right), \tag{3}$$

where U_{dB} is the value in dB, U_{SI} is the value expressed in SI units and U_{Ref} is the reference value expressed in SI units. Table III shows some example units and their respective reference value that will be used in this thesis. Variables which are expressed in dB will be indicated with the subscript $_{dB}$.

C. Requirements

The requirements reflect a system that could be fulfilled by a number of GEO satellites at approximately the same cost. The requirements are found in Table IV.

TABLE IV
REQUIREMENTS FOR THE SATELLITE CONSTELLATION

Requirement ID	Requirement description
10	The constellation shall have uninterrupted coverage over latitudes between 70°N and 70°S.
20	The constellation shall transfer data between two small terminals on any two locations within the coverage area of one satellite at speeds of at least 2Mbps.
21	The constellation shall transfer a total of 5 Gbps in each direction between small terminals and other small terminals or gateways.
30	The constellation shall operate on the frequencies 10.7-10.95, 11.2-11.45 (Downlink) and 12.75-13.25 (Uplink) GHz.
40	The constellation shall have a satellite visible 100 % of the time within its coverage area during its lifetime.
50	The constellation shall cost less than \$1 billion over its lifetime.
60	The constellation shall have a lifetime of 15 years.

Requirement 10 has been set to mimic what can be achieved with a GEO constellation. The feasibility of extending the constellation to also cover the poles will be considered later in the thesis.

Requirement 20 provides an absolute minimum for each link. Since the communication between two small terminals is constrained by the slowest of the terminal uplink and downlink this provides a minimum value for both. If the constellation has ISLs connecting all satellites it is theoretically possible for any two small terminals to connect with each other if they are inside the constellation's coverage area. The next requirement, 21, provides a minimum throughput for the constellation.

The frequency bands that the constellation will operate in are specified in requirement 30. These frequencies are subject to constraints and requirements defined by the ITU [16]. These constraints and requirements are covered in section III-D.

The visibility set in requirement 40 directly influence the number of required satellites in orbit as well as the spares used since if any satellite breaks it needs to be replaced. This increases the cost of the constellation. If these constellations were to be constructed for real this requirement would have to change to an availability requirement. Phenomena such as the weather, interference from other constellations, or breakdowns will influence the availability of a constellation. These factors are not included in this requirement. Instead, it strictly concerns itself with the visibility of satellites.

Finally, requirement 50 sets the maximum cost for the whole system during its lifetime set by requirement 60.

D. Frequency regulations

In this thesis it will be assumed that the downlink frequency bands are 10.7-10.95 GHz and 11.2-11.45 GHz. The uplink frequency band will be 12.75-13.25 GHz. These frequency bands have regulations imposed on them by the ITU. This section will cover these regulations. In their regulations the ITU classifies these frequency bands fixed-satellite space-to-Earth and fixed-satellite Earth-to-space respectively.

Article 21 in [16] covers the sharing of frequency bands over 1 GHz. These regulations will constrain where and how much power can be radiated from terrestrial and space services. ITU defines a terrestrial station as "A station effecting terrestrial radiocommunication." [16] and terrestrial radiocommunication as "Any radiocommunication other than space radiocommunication or radio astronomy.". The small terminal and gateway stations are classified by the ITU as earth stations. Therefore, for the frequencies used in the uplink sections I, III, and IV apply. The downlink from the satellites in the constellation, defined as space stations in the ITU regulations, have to abide by section V.

Section I contains two regulations for the choice of sites and frequencies. The first regulation mandates that earth stations and terrestrial stations shall be geographically separated. The second regulation provides maximum value for the Equivalent Isotropic Radiated Power (EIRP) emitted from transmitting stations in fixed or mobile services close towards GEO orbit. When transmitting close to the orbit of GEO satellites. For frequencies in the 10-15 GHz band this maximum value for the EIRP is 45 dBW. If transmission is to be conducted above this value the minimum separation from any point in GEO is 1.5°. In any case the EIRP may not exceed 55 dBW. To reach this limit of 45 dBW with the small terminal it would have to have a transmitted power of over 20 dBW, which corresponds to 100 W transmitted power. 20 dBW or 90 W over the limit stated earlier. This is because the gain of the small terminal is 24 dBi. Furthermore, since the gateway links will be assumed to have infinite throughput no link budget will be calculated. Therefore, in this thesis section I of article 21 will not have an impact on the results.

Section II only applies to terrestrial stations. Therefore, it is not applicable to this thesis.

Section III limits the EIRP transmitted within 5° of the horizon. Since the small terminal has a minimum elevation of 45° these regulations are not applicable to it. Furthermore, with a similar reasoning as with section I section III will be assumed to not be applicable for both the small terminal and gateway. It is worth noting that the gateways operate at a minimum elevation of 5° making them exempt from this section as well.

Section IV limits the minimum elevation of earth stations to 3° over the horizon. Since the gateway operates at a minimum elevation of 5° and the small terminal operates at a minimum elevation of 45° the regulations in this section is fulfilled.

Section V limits the power flux-density (PFD) measured at the ground from space stations. It therefore sets a limit to the downlink. With the downlink operating in the 10.7-10.95 GHz and 11.2-11.45 GHz frequency bands there are three cases to be considered. The first case is for a GEO satellite. The second is a NGSO satellite. The final is a NGSO satellite with an apogee of more than 18 000 km and inclination between 35° and 145°. The PFD limits are summarized in Table V. Conversion from EIRP to PFD can be done by

$$PFD = EIRP_{dB} - 10\log_{10}\left(4\pi d^2\right) + 10\log_{10}\left(B_R/B_C\right), \tag{4}$$

TABLE V
POWER FLUX-DENSITY LIMITS

Case	Limit in dBW/m^2 for different elevations ϵ			Reference bandwidth
	0°-5°	5°-25°	25°-90°	
GEO	-150	$-150+0.5(\epsilon-5)$	-140	4 kHz[a]
NGSO	-126	$-126+0.5(\epsilon-5)$	-116	1 MHz
NGSO[b]	-129	$-129+0.75(\epsilon-5)$	-114	1 MHz

[a] The difference in reference bandwidth between the GEO and first NGSO case causes a difference of 24 dB. Therefore, the first two rows in the table could be considered equal. The limits have been written as they appear in ITU regulations.
[b] Apogee above 18 000 km and inclination between 35° and 145°.

where d is the distance, B_c is the channel bandwidth and B_R is the reference bandwidth.

The second article of note for this thesis is article 22. It places further limits on emissions from NGSO constellations. It does this by limiting the equivalent power flux-density (EPFD) calculated by

$$epfd_{dB} = 10\log_{10}\left[\sum_{i=1}^{N_a}\left(10^{P_i/10}\times\frac{G_t(\theta_i)}{4\pi d_i^2}\times\frac{G_r(\varphi_i)}{G_{r,max}}\right)\right]+ + 10\log_{10}\left(B_R/B_C\right), \quad (5)$$

where i iterates over all visible satellites N_a. P_i is the transmitted power from satellite i in dBW. $G_t(\theta_i)$ is the NGSO transmission antenna gain towards the target GEO receiving station. Since the NGSO constellation should be able to transmit to any point within the coverage area $G_t(\theta_i)$ will be equal to the maximum transmission antenna gain. $G_r(\varphi_i)$ is the antenna gain in the direction of the transmitting satellite when the receiving antenna of the GEO ground station is pointed towards the target GEO satellite. Smaller angles causes larger interference between the two satellites. This can be seen in Fig. 13. $G_{r,max}$ is the maximum gain of the same antenna. Similarly to equation 4 the ratio of the reference and channel bandwidth will need to be taken into account when calculating $epfd_{dB}$ values. This can be done by adding $10\log_{10}\left(B_R/B_C\right)$ to $epfd_{dB}$.

The $epfd_{dB}$ values are calculated with different types of reference antennas. In this thesis calculations will be made using the smallest ITU reference antenna in each case. For the satellite to ground interference this antenna has a diameter of 60 cm. This is because this antenna has the largest beamwidth and therefore will have the largest potential for interference. The small terminal would have an even larger potential for interference. In the case of a GEO constellation this would have to be considered. Transmissions close to or in line with the reference antenna boresight are not feasible. The values for the reference antenna can be found in [23].

φ_i can be found by taking the vector between the considered receiving antenna and the transmitting satellite $\mathbf{S}_i$ and then finding the vector from the receiving antenna to the GEO positions $\mathbf{S}_{i,GEO}$ that produce the smallest angle with $\mathbf{S}_i$. This angle is φ_i. The distance can simply be calculated from $d_i = \|\mathbf{S}_i\|$. With the smallest reference antenna the angle φ required for minimum interference is approximately 30°,

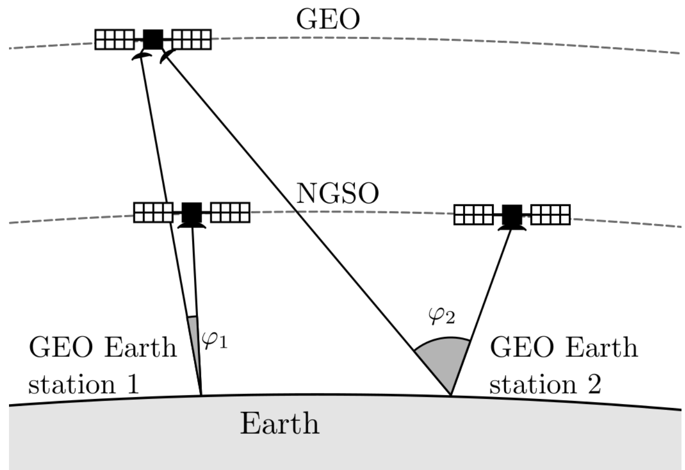

Fig. 13. Downlink interference from NGSO satellite into a receiving GEO earth station. GEO Earth station 1 shows the case where the angle φ_1 between the NGSO and the GEO satellite is small. This causes high interference. GEO Earth station 2 shows the case where the angle φ_2 between the NGSO and the GEO satellite is large. This causes low interference.

corresponding to the start of the region where the reference antenna has the lowest gain. This creates a stay-out zone in the NGSO satellites coverage area. An example of a stay out zone can be seen in Fig. 9

The maximum allowed $epfd_{dB}$ value allowed at a GEO ground station at all times is -175.4 dBW/m^2 for a 60 cm reference antenna in the frequency band 10.7-11.7 GHz. In addition this value is allowed to be exceeded a percentage of time. The points in Table VI form a curve which limits the time each EPFD value may be exceeded.

There are further limits for the $epfd_{dB}$ value at GEO satellites from both the NGSO system earth stations and space stations. For the $epfd_{dB}$ value at GEO from all earth stations in the constellation the limit is -160 dBW/m^2 for the frequency band 12.75-13.25 GHz with a reference antenna beamwidth of 4° and radiation pattern defined by [24] and $L_s = -20$. L_s is a parameter in the ITU antenna model which states at what level relative the maximum gain the sidelobes are at.

Finally, the $epfd_{dB}$ value at GEO from all NGSO satellites in the constellation combined is limited at -160 dBW/m^2 for the frequency band 10.7-11.7 GHz with a reference antenna beamwidth of 4° and radiation pattern defined by [24] and $L_s = -20$. This corresponds to a 45 cm antenna on the GEO satellite. Both of these limits have the reference bandwidth 40 kHz. If transmissions are done over a larger bandwidth the power limit is shared over the full bandwidth. As an example a transmission over double the reference bandwidth would allow for an $epfd_{dB}$ 3 dB higher than when calculated for the reference bandwidth.

In an absolute worst case scenario the $epfd_{dB}$ value from a small terminal situated at the equator pointed directly at zenith with a GEO satellite straight overhead pointing its antenna at the small terminal is $-170 + P_{dB}$ dBW/m^2. Then, to fulfil the limit of $epfd_{dB}$ from earth stations in the NGSO

TABLE VI
EPFD LIMITS

EPFD value (dBW/m^2)	Percentage of time EPFD value may not be exceeded
−175.4	0
−174	90
−170.8	99
−165.3	99.73
−160.4	99.991
−160	99.997
−160	100

system the amplifier power in the small terminals must not exceed 10 dBW. When multiple terminals are transmitting towards the same GEO spot separate channels can be used, thus allowing the terminals to transmit at full power and speeds without exceeding the $epfd_{dB}$ limit. Due to the EPFD limit imposed on the NGSO satellites this worst case scenario will not happen. The small terminals will transmit with an angle φ to the GEO satellites. With a separation angle of 10° the gain of the small terminal decreases by 10 dBi. At $\varphi = 30°$, the loss of gain is 17 dBi. In the 10° and 30° case the $epfd_{dB}$ value from a small terminal at GEO would be 10 dB and 17 dB below the limit respectively. Therefore, this part of article 22 will not be considered applicable to this thesis.

Disturbances at GEO from NGSO satellites is harder to characterize. Since all satellites are pointing their antennas at Earth none of those signals will intersect with GEO satellites. However, the back-lobe of the radiation pattern may interfere with GEO satellites. From ITU recommendations [13] the back-lobe level is set at 0 dBi for an ideal antenna. In both the LEO (1300 km) and the MEO (8500 km) case this results in an $epfd_{dB}$ value of $-194 + P_{dB}$ dBW/m^2 in the LEO case and a value of $-192 + P_{dB}$ dBW/m^2 in the MEO case per visible satellite. It is assumed that the GEO antenna is pointed straight at the NGSO satellite with the shortest possible distance between the two satellites and assuming a bandwidth of 72 MHz. This allows for an amplifier power of up to 32 dBW.

E. Trade study parameters

The first parameter that will be considered in the trade study is the *total cost per satellite* measured in \$. This cost will be evaluated based on the power requirements, mass budget, and the antenna size.

The second parameter is the *amplifier power per 2 Mbps* from the small terminal measured in W. Since the small terminal will be mobile its power source will need to be transported with it. A lower transmission power will allow for a lighter overall system.

The third parameter that will be considered is the *launch and operations complexity* for the constellation. A large constellation with large amounts of satellites and ground stations will be harder to coordinate and operate. Due to the complexity of ranking constellations according some quantifiable measurement this will be a simple qualitative ranking from best to worst.

The fourth parameter that will be considered is the *EPFD margin* measured in dB. An EPFD margin over some areas would allow a constellation to increase the EIRP from its satellites over some geographical areas, thus increasing downlink speeds.

The fifth parameter will be *total capacity* measured in Mbps. This figure greatly influences the final cost of using the constellation for an end user as a constellation with a higher capacity would allow more users to communicate at the same time.

The final two parameters are *beam capacity density* measured in Mbps/km^2 and *capacity per visible satellite*, the highest possible capacity at one point, measured in Mbps. These parameters give an indication on the average performance as well as how many customers can fit into a smaller area.

IV. Modelling of a constellation

A. Method choices and simplifications

The modelling in this thesis is based around the MATLAB Aerospace Toolbox. It has an inbuilt access calculator. However, due to there being no way to calculate the distance and elevation between a ground station and a satellite it is not suited for this task. The distance is needed to calculate the link budget and thus the uplink and downlink data transfer speeds. Similarly, the elevation is needed to characterize antenna aperture efficiency in the small terminal as discussed in section III-A.

MATLAB also has a module for calculating link budgets in the Satellite Communications Toolbox. However, a simplified model which ignores rain attenuation and other losses is sufficient for this thesis. Losses not included are assumed to sum up to 3 dB. This simplification is made to decrease the complexity of the link budget.

In order to decrease the complexity of the constellations investigated they will all have circular orbits. This eliminates two parameters: the eccentricity and argument of perigee. Both of these provide interesting options when designing a satellite constellation as seen in the ASBM constellation [3] but are not required for the constellations considered in this thesis.

B. Satellite orbits

The satellite's orbits are propagated using MATLAB's `satelliteScenario` object from the Aerospace Toolbox. The orbit propagator used is the `two-body-Keplerian`. Each satellite is defined by its Keplerian elements. From the `satelliteScenario` the satellite's positions are then exported in Earth Centred, Earth Fixed (ECEF) coordinates.

Satellites in the constellation are put into the (Ω, M) space following Walker's method [6]. With T being the number of satellites, P the number of planes, S being the number of satellites per plane, and a pattern unit defined as $F = n \times 360°/T$, $n = (0, 1, 2, \ldots, P-1)$ the RAAN and mean anomaly for satellite k in plane $p = \lfloor (k-1)/S \rfloor$ can be calculated as

$$\Omega_k = p \times 360°/P \tag{6}$$

$$M_k = p \times 360°/F + ((k-1) \pmod S) \times 360°/S. \tag{7}$$

The satellites were placed in circular orbits as discussed above. Therefore, the available design parameters for the orbits of the satellite constellation are the semi-major axis a, the inclination i, the satellites per plane S, the number of planes P, and the pattern unit F.

This method of placing satellites will cause a high density of satellites around the top of the coverage area. In addition, the area with the lowest density of satellites will be around the equator.

The minimum angle any two satellites will have between each other when the constellation is in operation can be calculated as

$$\gamma = \arccos\left(\frac{a+d}{2} + \frac{\sqrt{(a-d)^2+(b+c)^2}}{2}\right), \quad (8)$$

where

$$\begin{aligned} a =& \cos(\Delta\Omega)\cos(\Delta M) - \sin(\Delta\Omega)\cos(i_1)\sin(\Delta M), \\ b =& -\cos(\Delta\Omega)\sin(\Delta M) - \sin(\Delta\Omega)\cos(i_1)\cos(\Delta M), \\ c =& \cos(i_2)\sin(\Delta\Omega)\cos(\Delta M) - \\ & - \cos(i_2)\cos(\Delta\Omega)\cos(i_1)\sin(\Delta M) + \\ & + \sin(i_2)\sin(i_1)\sin(\Delta M), \\ d =& -\cos(i_2)\sin(\Delta\Omega)\sin(\Delta M) + \\ & + \cos(i_2)\cos(\Delta\Omega)\cos(i_1)\cos(\Delta M) + \\ & + \sin(i_2)\sin(i_1)\cos(\Delta M), \end{aligned} \quad (9)$$

with $\Delta\Omega = \Omega_1 - \Omega_2$ and $\Delta M = M_1 - M_2$ [25]. This calculation is done for each satellite pair in the constellation. A nonzero angle would diminish or completely remove the need to perform inter-constellation collision avoidance manoeuvres, limiting collision avoidance to objects outside the constellation. An aspect not discussed in [25] is that a nonzero angle prevents complete overlap between two satellites and the higher the minimum angle is the lower the maximum overlap between any two satellites becomes. The overlap between two satellites can be considered as the area which both satellites can communicate to with any given elevation requirement. The closer two satellites are physically the more their coverage area overlap. Therefore, for any constellation the pattern unit was chosen such that the minimum angle between satellites is maximized. Thus minimizing the amount of satellites needed to cover the coverage area.

Due to the Earth having a nonuniform gravitational field because of a bulge around the equator each satellite in the constellation will have its RAAN change over time [26]. The equation for calculating this change is

$$\dot{\Omega} = -\frac{3nJ_2R_E^2}{2a^2\left(1-e^2\right)^2}\cos i, \quad (10)$$

with $n = \sqrt{\mu/a^3}$ being the mean motion and $J_2 = 0.001082$ [26]. To reduce complexity this thesis will not take this change into account in simulations. In all the constellations this will not have an effect as all satellites in the constellation share semi-major axis a and inclination i. Therefore, the effect on the satellites will be equal among all satellites. Assuming that all satellites in a constellation share semi-major axis and

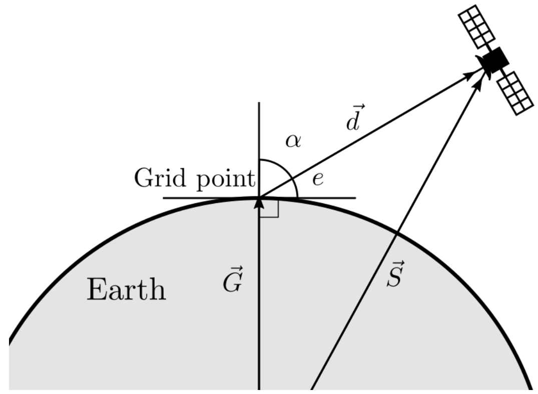

Fig. 14. Geometry of a typical elevation calculation where $\vec{S}$ is the satellite vector, $\vec{G}$ is the grid point vector, $\vec{d}$ is the distance between the satellite and grid point, α is the angle between $\vec{G}$ and d, and e is the elevation.

inclination is reasonable since the placement of satellites is done by varying the RAAN and true anomaly only.

C. *Satellite coverage*

To evaluate the satellite coverage the area of the Earth was discretized into a grid of points each spaced out by latitude and longitude. The grid points are spread out with a 2° separation between the latitudes 80°N and 80°S and over all longitudes, each acting as a potential ground station shown in Fig. 7. The 2° grid size was decided on as a trade-off between computational time and accuracy. This makes the grid area at the equator approximately equal in size to the beam area of the LEO constellations. A side effect of this distribution of grid points is that it causes a denser grid at higher latitudes. Each grid point was placed at a distance from the centre of the Earth equal to 6 371 km. These grid points were then translated to Cartesian coordinates in the ECEF (Earth Centred, Earth Fixed) for each timestep. Fig. 14 shows the geometry of a typical elevation calculation. For a satellite $\vec{S}_k$ at timestep n and a grid point $\vec{G}$ at position (i, j) and timestep n the distance $\vec{d}_{ijk}(n)$ and elevation angle $e_{ijk}(n)$ can be calculated as

$$\vec{d}_{ijk}(n) = \vec{S}_k(n) - \vec{G}_{(i,j)}(n) \quad (11)$$

and

$$e_{ijk}(n) = \frac{\pi}{2} - \arccos\left(\frac{\left(\vec{S}_k(n) - \vec{G}_{(i,j)}(n)\right)^T \cdot \vec{G}_{(i,j)}(n)}{\left\|\vec{d}_{ijk}(n)\right\| \left\|\vec{G}_{(i,j)}(n)\right\|}\right). \quad (12)$$

This follows directly from the vector dot product where

$$\left(\vec{S}_k(n) - \vec{G}_{(i,j)}(n)\right)^T \cdot \vec{G}_{(i,j)} = \left\|\vec{d}_{ijk}(n)\right\| \left\|\vec{G}_{(i,j)}\right\| \cos(\alpha). \quad (13)$$

For visualisation using `satelliteScenarioViewer` conical sensors were added. Using the law of sines the sensor angle corresponding to the chosen elevation for the

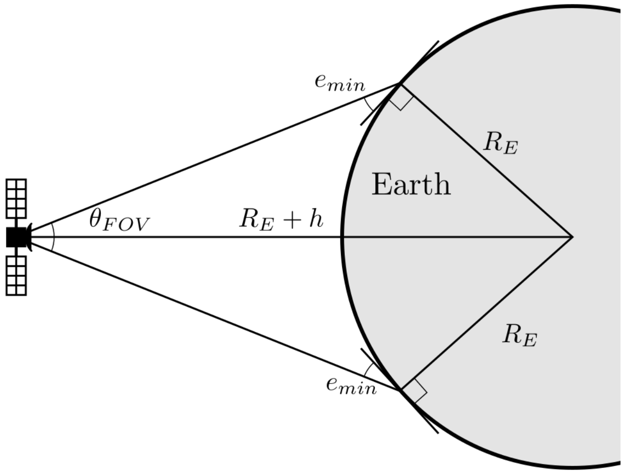

Fig. 15. Geometry of the calculation of the elevation mask with R_E being the radius of Earth, $R_E + h$ being the semi-major axis of the satellite, and e_{min} being the minimum elevation for the satellite. Using the law of sines the sensor angle of the satellite can be calculated.

Fig. 16. Elevation mask for a satellite at 600 km altitude and 45° minimum elevation. The satellite is not in the centre of the circle due to the viewing angle.

constellation can be calculated. Adding a sensor with field of view equal to this sensor angle shows the area on Earth where the elevation requirement is fulfilled with regard to a specific satellite. From the geometry in Fig. 15 and the law of sines it is found that

$$\frac{\sin\left(\frac{\pi}{2} + e_{min}\right)}{R_E + h} = \frac{\theta_{FOV}/2}{R_E}. \tag{14}$$

With the semi-major axis $a = R_E + h$ and the minimum required elevation e_{min} and Earth radius R_E the equation for the sensor field of view then becomes

$$\theta_{FOV} = 2\arcsin\left(\frac{R_E \sin\left(\frac{\pi}{2} + e_{min}\right)}{a}\right). \tag{15}$$

The resulting elevation mask can be seen in Fig. 16. While the `satelliteScenarioViewer` is not extensively used in the evaluation of the constellations it is useful for visualising and verifying the constellations.

D. The satellite network

This thesis will consider one configuration of Inter Satellite Links (ISLs). This configuration is in-plane ISLs where each satellite is connected to the satellites directly in front of and behind it in their shared orbital plane. Another configuration for ISLs is a cross plane connection where each satellite has in-plane ISLs as well as ISLs to the closest satellite in each of the two adjacent orbital planes.

The reason for adding ISLs is to enable satellites without gateway connection to be connected to another satellite in the constellation that has. The total output from one satellite should be transferable to adjacent satellites. Each satellite should therefore have the capacity to transfer all the data that it can receive and transmit from small terminals.

While adding ISLs would incur an extra cost to the satellites they recoup some of that cost by lowering the required amount of gateway stations since a satellite would not necessarily have to transmit directly to a gateway. In addition, with the inclusion of ISLs the resiliency of the system would increase since satellites can forward data even if they do not have a gateway available. Finally, adding ISLs decreases the number of gateways needed in low-traffic areas since traffic can be redirected through the ISL network.

E. Link budget

When designing a satellite communications system the link budget is of central importance. The design choices made when designing the constellation, such as frequency band, availability requirements, ground stations, and satellites will influence the link budget and determine the performance of the communications system. In this thesis only ISLs and the link between the satellites and small terminals will be considered. Gateways will be assumed to have infinite throughput. The reason for this is that gateways can generally have much larger antennas to mitigate link budget losses.

The antennas in the system will be modelled as parabolic antennas. The antenna gain can then be calculated using the formula

$$G = \eta\left(\frac{\pi D}{\lambda}\right)^2 \tag{16}$$

and the 3 dB beamwidth in radians can be found using

$$\theta_{3\text{dB}} = 1.2\left(\frac{\lambda}{D}\right), \tag{17}$$

where D is the diameter of the parabolic antenna, λ is the wavelength of the transmitted signal and η is the efficiency of the antenna [10]. The 3 dB beamwidth or the half power beamwidth is two times the angle from the antenna boresight to the point in the antenna pattern where the gain has deceased with 3 dB. Equation 17 assumes a $(\cos)^2$ aperture illumination. The nonuniform illumination is a more conservative choice when compared to a uniform illumination.

The link budget is a way to estimate the link quality and results in a carrier to noise ratio, C/N. The baseline equation that will be used is given as

$$C/N_{dB} = EIRP_{dB} - L_{dB} + (G_R/T_S)_{dB} - 10\log_{10}(kB_N), \quad (18)$$

where $EIRP_{dB}$ is the Effective Isotropic Radiated Power, L_{dB} is any losses expressed in dB, G_R is the receiving antenna gain, T_S is the system temperature, k is the Boltzmann constant and B_N is the noise bandwidth [27]. The noise bandwidth will be assumed to be equal to the symbol rate R_s, for a more in depth discussion see [10]. The path loss can be calculated from

$$L_{P,dB} = (4\pi d)^2/\lambda^2, \quad (19)$$

where d is the distance between the transmitter and receiver and λ is the wavelength of the carrier wave. The total loss is then

$$L_{dB} = L_{P,dB} + L_{G,dB} + L_{O,dB} \quad (20)$$

where $L_{G,dB} = 20\log_{10}\left(\left|\cos\left(\frac{\pi}{2} - e\right)\right|\right)$ is the lower antenna gain compared to the antenna gain at antenna boresight and in the link budget this is taken as a loss from the antenna element pattern with e being the elevation and $L_{O,dB} = 3$ being a combination of other losses. This assumes the antenna boresight is pointed at zenith. As noted earlier this part of the loss takes into account other losses that are outside the scope of this thesis. These losses are assumed to sum up to 3 dB. The wavelength dependence is separate from the path loss but is calculated as a part of it by convention.

The Effective Isotropic Radiated Power (EIRP) is the power that an isotropic antenna would have to emit to have a PFD at the receiver antenna equal to the transmitting antenna. It can be calculated from the transmission antenna gain G_T and power P_T which is the RF power input at the antenna

$$EIRP_{dB} = (G_T)_{dB} + (P_T)_{dB}. \quad (21)$$

To calculate a link transmission speed the spectral efficiency needs to be determined. It can be shown that $C/N_{dB} = (E_s/N_0)_{dB}$ [15], where E_s/N_0 is the energy per symbol to noise spectral density ratio. Since the channel data rate f_b, the channel bandwidth B and the spectral efficiency ρ have the relation

$$\frac{f_b}{B} = \rho \quad (22)$$

and

$$C/N = E_b/N_0 \times \frac{f_b}{B} = E_s/N_0 \times \frac{f_b}{B\rho} = E_s/N_0. \quad (23)$$

$(E_s/N_0)_{dB}$ can be related to the spectral efficiency as shown in [28, p. 53]. By multiplying the spectral efficiency ρ with the symbol rate the transmission speed of the link can be calculated. Fig. 17 shows the spectral efficiency for some carrier to noise ratios. In this thesis the spectral efficiency will be calculated using a second degree polynomial curve fit to $(E_s/N_0)_{dB}$ values and their corresponding spectral efficiency from [28]. The domain in which this curve is considered accurate will be between the lowest and highest carrier to noise ratio in the dataset.

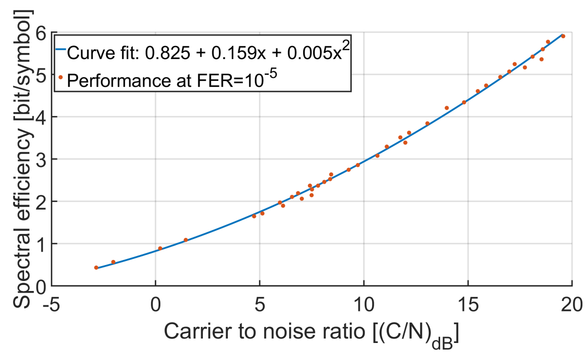

Fig. 17. Spectral efficiency as a function of C/N_{dB} using data from [28]. Dots specify performance figures at a Frame Error Rate (FER) of 10^{-5}.

After a transmission speed has been determined for a channel the bandwidth can be further divided. Multiple methods for this division exist, in this thesis it will be assumed that the channel is divided frequency-wise using an access technique such as Frequency Division Multiple Access or Multiple Frequency Time Division Multiple Access [15]. Assuming that each terminal must be capable of transmitting at a speed of 2 Mbps the number of terminals connected in one channel is approximately

$$C = \left\lfloor \frac{T}{2\text{ Mbps}} \right\rfloor \quad (24)$$

where T is the transmission speed in Mbps. This way the individual terminal transmission power becomes

$$(P_i)_{dB} = (P_T)_{dB} - 10\log_{10}(C) \quad (25)$$

where $(P_T)_{dB}$ is the total power transmitted in the channel.

F. Transceivers and channel bandwidth

Instead of modelling individual transceivers each satellite in the constellation will be assumed to have the full spectrum available to it. Interference between satellites in the constellation will thus not be modelled. Each satellite will then have a total of 1000 MHz of total bandwidth in both the uplink and downlink, since the same frequencies can be used for multiple transmissions utilizing polarization. While each satellite would be able to have multiple user beam antennas it will be assumed that each satellite has only one user beam antenna. In addition, the uplink and downlink will be balanced, meaning that the transmission speed will be equal in both directions. This antenna is complemented with a dedicated gateway antenna.

A roll-of factor of $\alpha = 1/5$ will be used to determine the symbol rate using the equation

$$\text{Occupied bandwidth} = \text{Symbol rate} \times (1 + \alpha) \quad (26)$$

which then for a channel bandwidth of 72 MHz becomes 60 MBd [15]. As noted earlier, using the spectral efficiency that corresponds to the carrier to noise ratio of the link, the data transmission speed can be determined.

G. Inter satellite links

One configuration of Inter Satellite Links are considered in this thesis, in-plane ISLs. For in-plane ISLs each satellite communicates with the satellites in front of and behind them. This thesis assumes for the calculation of the ISL link budget that the distance is always equal to the distance between two adjacent satellites in one plane. It further assumes that the ISLs use the frequency band 22.55-23.55 GHz for communication. Finally, it will be assumed that there is no interference between the satellites in the constellation.

Similarly to the link budgets with the small terminals a 3 dB loss will be introduced which will be assumed to account for all losses. The system temperature will be assumed to be 140 K since the antennas will be pointing away from Earth. This assumption will always be true since this thesis only considers in-plane ISLs. Therefore, since the minimum elevation used is 30° and satellites will be spaced close enough in their planes that their coverage areas overlap they will never transmit through the Earth or its atmosphere. The total bandwidth available for an ISL will be 250 MHz.

The distance between two satellites in a plane is fixed and can using the law of sines be calculated by

$$d_{ISL} = a\frac{\sin\left(2\pi/S\right)}{\sin\left(\frac{\pi-2\pi/S}{2}\right)} \tag{27}$$

where a is the semi-major axis of the satellite plane and S is the number of satellites in a plane.

H. Frequency regulations

As discussed in section III-D there are two frequency regulations that will need to be considered for this thesis, article 21 section V and article 22.

For article 21, section V the worst case scenario will be evaluated; a ground station on the equator pointed at zenith. For such a ground station the distance to GEO is approximately 35 786 km. Using equation 4 and the limits from Table V results in a limit for the PFD on the ground from the transmitting satellite, that can be either a GEO or NGSO.

To calculate EPFD values for article 22 only the best satellite will be considered for each discretized point. In this case the best satellite is the one that generates the lowest EPFD. For each discretized point, satellite, and timestep the angle to a reference antenna pointing at GEO will be calculated. This is done by finding the point in GEO where the angle between the reference antenna boresight and $S_k(n)-G_{(i,j)}(n)$, the signal path between the satellite and discretized point is the smallest. This angle is φ in the EPFD equation discussed earlier. Only the 60 cm antenna will be considered since it has the largest beamwidth and thus the largest potential for interference. The interference from another NGSO constellation seen in the small terminal operating with a GEO constellation would be even larger since it has an even larger beamwidth and thus a higher φ would be needed to avoid interference when compared to the reference antenna. However, the small terminal has a smaller gain which could lessen the severity of the interference.

In general, it is not feasible to transmit from a satellite to a location with low values of φ. The EPFD value at a discretized point (i,j) becomes

$$epfd_{dB,(i,j)}(n) = \min_k\left(10\log_{10}\left[10^{P_{sat}/10}\times\frac{G_{max}}{4\pi d_{ijk}(n)^2}\times\frac{G_r(\varphi)}{G_{r,max}}\right]\right), \tag{28}$$

with P_{sat} being the transmitted power of the satellite and G_{max} being the antenna gain of the satellite. The resulting value will then need to be adjusted by $10\log_{10}\left(\frac{4\times10^4\text{ Hz}}{72*10^6\text{ Hz}}\right)\approx -32.6$ dB to take the reference bandwidth into account with 4×10^4 Hz being the reference bandwidth and $72*10^6$ Hz being the channel bandwidth.

The link budget will be constructed to maximize the EPFD value while keeping it within the allowed limits. The EPFD value at a discretized point will be considered within the limit if all time limits in Table. VI are fulfilled. Since one set of parameters for the link budget will be used for all points there will be spots that have additional margin to an EPFD value of -175.4 dBW/m^2 available and spots which do not. With this strategy multiple satellites will therefore not be able to transmit to some locations using the same frequency since it would increase the EPFD value by about 3 dB. This increase may push the EPFD value over allowed limits. This effectively reduces the available bandwidth to some locations to 500 MHz since differently polarized beams still transmit on the same frequency. Two satellites transmitting on the same frequencies would increase the EPFD value by 3 dB assuming similar angles φ and distance.

The EPFD values provide two important data points for the design of a constellation. The EPFD map that shows the maximum EPFD value reached during the simulation for each discretized point and the article 22 compliance map which shows if each point in the constellation complies with the limits shown in Table VI. For a compliant constellation the article 22 compliance map will not show anything. Therefore, that map will not be shown in this thesis.

I. Collision risk

An assessment of the risk of in-orbit collisions for the satellites in a constellation is essential as an in-orbit collision is itself a high risk event. For collisions in LEO particles larger than 1 mm are enough to destroy satellite subsystems. Particles larger than 1 cm may damage a satellite beyond functioning and even larger particles can cause the satellite to be completely destroyed [29]. This would cause additional objects in orbit and therefore further increase the risk of collisions for other satellites.

The mean number of collisions c for a satellite with collision cross-section A_C during the time Δt can be calculated as

$$c = FA_C\Delta t, \tag{29}$$

where F is the impact flux [30]. Since collisions are independent of each other the probability of n collisions for a satellite $P_S(X=n)$ can be modelled as a Poisson distribution

$$P_S(X=n) = \frac{c^n}{n!}e^{-c}. \tag{30}$$

Using the properties of the Poisson distribution the collision risks for the whole constellation can be calculated. Since all satellite's RAAN in the constellation will slowly drift due to Earth's oblateness it will be assumed that the collision probability is independent of the RAAN. Therefore, the probability of collision is equal among all satellites. Then the probability of n collisions in the whole constellation is

$$P_C(X = n) = \frac{(cS)^n}{n!}e^{-cS}, \tag{31}$$

where S is the number of satellites. From this the mean number of collision can be calculated as

$$E[X] = \lambda = cS. \tag{32}$$

The impact flux can be estimated using ESA's MASTER-8 model [31]. A large number of sources of debris are modelled. These sources can be split into two groups, man-made and natural. While particles as small as 1 µm are modelled this thesis will only consider objects larger than 1 mm. This is because objects larger than 1 mm have the potential to disable either a satellite subsystem or the satellite itself [29]. Furthermore, the constellations will be evaluated using the most current non-simulated data. Therefore, the evaluation period will be the year 2017.

J. Cost model

Estimating costs for satellites is notoriously difficult using openly available sources. Therefore instead of finding a total cost for the constellation it will be assumed that the whole available budget of $1B is spent on the constellation. Then the resulting budget for satellites, launches, and ground stations can be assessed to be reasonable. To do this the budget will be split, half of it will be used for the design and manufacturing of the satellites. A third will be used on the launch and one sixth will be used for the ground segment. The resulting costs per ground station, satellite, and launch will then be discussed. The total number of satellites manufactured will be the number of satellites in each constellation plus a number of satellites equal to the mean number of collisions expected. These additional satellites will not be launched.

The launch vehicle will be assumed to be a Falcon 9 rocket costing $62 million per launch [32] for a reusable rocket. The launch mass to LEO will be assumed to be equal to the launch mass of 60 Starlink satellites, 15 600 kg [33]. The launch mass to MEO is not public information either. Therefore, an estimate based on known figures will be used. As the first data point the GPS III satellite [34] which mass is 4311 kg and is going to a 20 200 km orbit will be used. Similarly, three O3b mPower satellites which mass is 1800 kg each are launched using a Falcon 9 rocket [35] to an 8000 km altitude orbit. This launch will be used as a second data point. The launch mass to 8000 km will then be assumed to be 5400 kg. This figure will decrease linearly to 4311 kg at 20 200 km. It is important to note here that these MEO satellites are likely being put into a transfer orbit to MEO considering the proximity of these masses to the mass to Geostationary Transfer Orbit (GTO) found in [32].

Taking the average of these with the budget allocation detailed above this would allow 26 773 kg split over 5 launches to be launched to MEO and 78 000 kg split over 5 launches to be launched to LEO. Dividing this by the number of satellites gives the max mass per satellite. Similarly, dividing the respective budget with the number of satellites and ground stations gives the available funds for each individual satellite and ground station. A constraint is that a launch can not launch a fraction of a satellite. Therefore, it will be assumed that each launch will have the same number of satellites.

It will further be assumed that the lifetime of a LEO satellite is 7.5 years, or half of the intended lifetime for the constellation. This means that for every one satellite in the LEO constellation, two will be launched during the lifetime of the constellation. Furthermore, the lifetime of a MEO satellite will be assumed to be equal to that of a GEO satellite in the reference constellation, 15 years.

The resulting cost per satellite will then be compared with Cost Estimating Relationships (CER) detailed in [36] and [37]. These works use parameters from previous satellites and correlates them with the cost of the satellite. The result is a number of relationships in the form of

$$\text{Cost} = a + bx^c, \tag{33}$$

with different values for a, b, and c. Each of these relationships have an applicable range and an error. For all satellites the Spacecraft bus weight CER from CERs for Large Satellites [36] will be used. It will be assumed that the spacecraft bus weight is 70% of the total launch weight. To account for the discount from having multiple satellites produced at the same time a learning curve will be used. The total cost for the production of this part of the satellites will be

$$\text{Total production cost} = TFU \times L, \tag{34}$$

where TFU is the Theoretical First Unit cost which will be set equal to the Prod. cost component. L is the Learning Curve Factor and is calculated with $L = N^B$ where N is the number of satellites and

$$B = 1 - \frac{\ln(100\%/S)}{\ln 2}, \tag{35}$$

with $S = 95\%$ when $N < 10$, $S = 90\%$ when $10 \leq N \geq 50$, and $S = 85\% \text{when} N > 50$. This total production cost is then added to the RDT&E cost component to receive the final cost for the satellites. The cost for the communications payload will be calculated using [37]. Here the cost is split into four parts, the non-recurring engineering CER, the non-recurring manufacturing CER, the recurring unit one engineering CER, and the recurring unit one manufacturing CER. The first two added together can be thought of as analogous to the RDT&E cost and the last two as analogous to Theoretical First Unit Cost. The discount given to the Theoretical First Unit cost in [36] will be given to the sum of the recurring unit one engineering and manufacturing CERs. This usage of two different sources for the CERs for the satellites occurs since the payload is more detailed than the required satellite bus. For satellite bus only the weight is taken into account in the CER. For the payload additional factors are taken into account.

These are the frequency, number of channels, design lifetime, and weight. The non-recurring CER for the communications payload is dependent on the design lifetime and has a range of 24 to 120 months. It is assumed that the relation still holds for the design lifetime of the MEO satellites which is 180 months. Furthermore, it is assumed that the satellites do not have antijamming technology. For the frequency parameter the highest frequency used in the satellites (13.25 GHz) will be used as this will give an upper bound.

The resulting cost per satellite is expressed in 1992 dollars. Therefore, an adjustment for inflation to 2022 dollars needs to be accounted for. According to [38] this adjustment factor becomes 2.0039.

Since CERs should not be used as a budgeting tool but as a comparison tool the results will be compared to the satellite Ovzon-3 [39] where the total project costs was estimated at 1 500 MSEK. This includes insurance, launch costs, manufacturing costs, and development costs. It will be assumed that $1 equals 9 SEK. Then the total cost for the project is approximately $167M.

Another comparison will be made with the Iridium NEXT constellation. It consists of 66 satellites in orbit, with six in-orbit spares and an additional nine ground spares [40]. Each satellite weighs 860 kg and has a propellant mass of 141 kg, resulting in a dry mass of 719 kg. 450 kg of which is the satellite bus. This leaves a payload weight of 269 kg. For the purpose of estimating the satellite costs using the CERs outlined above the Iridium NEXT satellites will be assumed to have 48 channels, corresponding to the number of transmit and receive beams per satellite. The design life of the satellites is 12.5 years and the operating frequency is 1 626.5 MHz. The total cost for the satellites was $2.1B.

K. Geostationary benchmark constellation

A GEO constellation consisting of six satellites separated by 60° in their orbital plane will be used as a benchmark for the resulting NGSO constellations. Since a tracking antenna is not required for a GEO constellation the minimum elevation was set to 5°. The resulting coverage map can be seen in Fig. 18.

This constellation operates at a minimum elevation of 5°. Therefore, only section V in article 21 of the ITU regulations is applicable to this constellation. This section imposes a limit on the PFD from the GEO satellite at a location. In the best case scenario the less restrictive elevation at 90°-25° will be considered. Then the limit is then -140 dBW/m^2. The worst case scenario will be considered at 5° elevation. For that elevation the limit decreases to -150 dBW/m^2. Both a best and worst case are shown to provide an approximate range of performance of the constellation. The best and worst case link budgets are found in Table VII. With polarization a total bandwidth of 1000 MHz is available per satellite in both the uplink and downlink. This bandwidth is then split into four antennas per satellite, each with three 72 MHz channels. Each of the three 72 MHz channels would be able to serve between 20 and 74 small terminals at 2 Mbps for a total of 60 to 222 small terminals depending on the elevation.

TABLE VII
LINK BUDGET FOR A 72 MHZ CHANNEL GEO BENCHMARK CONSTELLATION

Input values		
	Best case	**Worst case**
Distance	$35\ 786 \times 10^3$ m	$41\ 121 \times 10^3$ m
Elevation	90°	5°
Downlink frequency	10.7 GHz	
Uplink frequency	12.75 GHz	
Symbol rate	60 MBd	
Satellite antenna gain	42 dBi	
Satellite system G/T	15 dB/K	
Satellite amplifier power	22 dBW	14 dBW
Terminal antenna gain	24.5 dBi	
Terminal system G/T	1.5 dB/K	
Terminal amplifier power	8.3 dBW	6.0 dBW

Results				
	Best case		**Worst case**[a]	
	Uplink	**Downlink**	**Uplink**	**Downlink**
$EIRP_{dB}$	32.8 dBW	63.7 dBW	30.5 dBW	55.7 dBW
C/N_{dB}	8.3 dB	8.1 dB	-0.9 dB	-1.1 dB
Channel transmission speed	151 Mbps	148 Mbps	42 Mbps	40 Mbps
Small terminals per channel	74		20	

[a] Worst case transmission speed is significantly lower due to stricter PFD limits when operating at low elevations. Both channels operate close to their respective PFD limits.

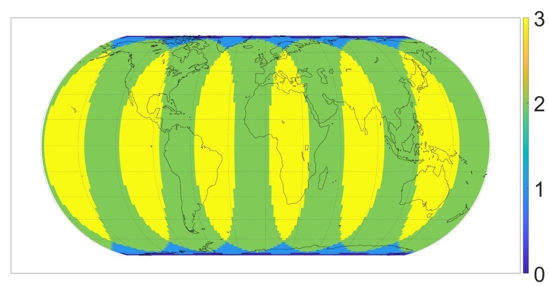

Fig. 18. Number of satellites visible for a six satellite GEO constellation.

Each satellite would then be able to serve 240 to 888 small terminals transmitting at 2 Mbps. Then the full six satellite GEO constellation will be able to serve 1440 to 5328 terminals with a maximum total transmission speed of 10656 Mbps.

Since the antennas do not share channels and are therefore steerable anywhere in the coverage area the average capacity per area will be the total capacity divided by the coverage area. While the constellation has coverage north of 70° N and south of 70° S these areas are not the primary concern of this thesis. Therefore, the areas outside 70° N and 70° S will be ignored. The maximum concentrated capacity is related to the number of visible satellites as seen in Fig. 18.

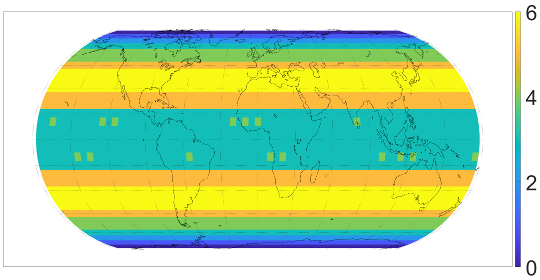

Fig. 19. Number of satellites visible for the 104 satellite MEO constellation.

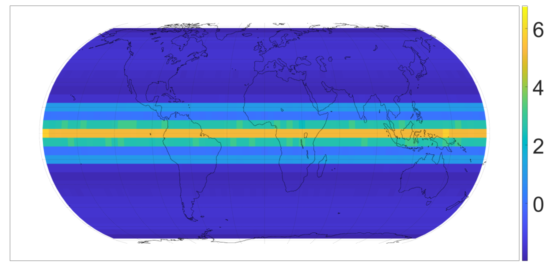

Fig. 20. Maximum EPFD value relative -175.4 dBW/m^2 reached for each discretized point during the simulation.

V. Candidate constellations

A. Two medium Earth orbit constellations

The first constellation to be presented, a 104/8/4-48° constellation using Walker notation operates at a 48° inclination and an altitude of 8 500 km. The altitude was chosen primarily to be close but still significantly separated from the O3b constellations altitude which increases the accuracy of the cost model. Fig. 19 shows the coverage of the 104 satellite constellation. The high number of satellites is needed to ensure that the angle φ between the constellation-ground station signal path and GEO-ground station signal path is sufficiently large for all discretized points. The EPFD map in Fig. 20 shows that for latitudes above 15°N and below 15°S there is approximately 2-3 dB available.

Each antenna on the satellites in the constellation will need to be 0.7 m in diameter to allow for a similar transmission speed as for the GEO reference constellation. In addition, the antennas have to be electronically steered so that each satellite can work with multiple terminals within the area where it is visible. The link budget for the best and worst case transmission cases are shown in Table VIII. Just like the reference GEO constellation it is assumed that each channel has the bandwidth 72 MHz which results in a symbol rate of 60 MBd. This results in a beam that can serve 58 small terminals at the minimum required transmission speed in the best case scenario and 36 small terminals in the worst case scenario.

With the budget allocated as detailed in the cost model each satellite would have a maximum mass of less than 255 kg. In each launch 21 of these satellites would be brought into a MEO transfer orbit. The satellites would then have to circularize their orbits themselves. Then the constellation would consist of 104 satellites with one spare. For each satellite \$4.6M would be available for development and production. Any additional spares would further lower the satellite mass and increase the number of satellites per launch.

By placing gateway stations as shown in Table IX and having them operate at an elevation of 5° all satellites in the constellation will be visible from at least one ground station at almost all times. The gaps present can be seen in Fig. 21. These last areas can be covered by in-plane ISLs.

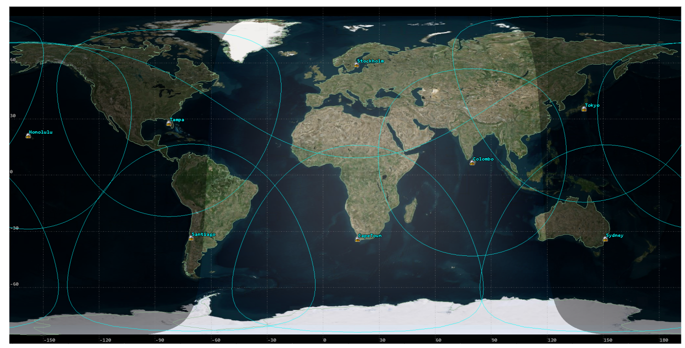

Fig. 21. Coverage at 8500 km altitude from gateway stations for a MEO constellation.

TABLE VIII
Link Budget for First MEO Constellation

Input values				
	Best case		**Worst case**	
Distance	$8\ 500 \times 10^3$ m		$9\ 142 \times 10^3$ m	
Elevation	90°		45°	
Downlink frequency	10.7 GHz			
Uplink frequency	12.75 GHz			
Symbol rate	60 MBd			
Satellite antenna gain	31 dBi			
Satellite system G/T	4.6 dB/K			
Satellite amplifier power	18 dBW			
Terminal antenna gain	24.5 dBi		21.5 dBi	
Terminal system G/T	1.5 dB/K		-1.5 dB/K	
Terminal amplifier power	5.4 dBW		7.4 dBW	
Results				
	Best case		**Worst case**[a]	
	Uplink	**Downlink**	**Uplink**	**Downlink**
$EIRP_{dB}$	29.9 dBW	48.9 dBW	28.9 dBW	48.9 dBW
C/N_{dB}	6.0 dB	5.8 dB	2.4 dB	2.2 dB
Channel transmission speed	118 Mbps	116 Mbps	74 Mbps	72 Mbps
Small terminals per channel	58		36	

[a] Worst case transmission speed is slightly lower due to losses from low elevation in the small user terminal.

TABLE IX
MEO CONSTELLATION GATEWAY LOCATIONS

Location	Latitude	Longitude
Stockholm, Sweden	59.3° N	18.1° E
Tampa, FL, USA	28.0° N	82.4° W
Sydney, Australia	33.8° S	151.2° E
Cape Town, South Africa	33.9° S	18.4° E
Colombo, Sri Lanka	6.9° N	79.9° E
Santiago, Chile	33.3° S	70.9° W
Tokyo, Japan	35.7° N	139.8° E
Honolulu, HI, USA	21.3° N	157.9° W

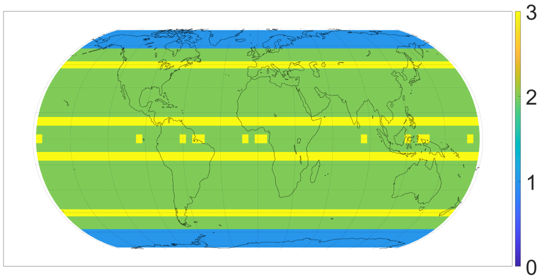

Fig. 22. Number of satellites visible for the 32 satellite MEO constellation.

To provide an alternative for the 45° elevation MEO constellation a similar constellation have been constructed with a minimum elevation of 30°. This significantly decreases the number of satellites needed to 32. However, the small terminal will need to operate with a lower elevation. This increases the loss in the worst case from 3 dB to 6dB resulting in a lower carrier to noise ration C/N. To compensate for these losses the antenna size for each satellite is increased to 1 m. The constellation is a 32/4/1-45° constellation using Walker notation. The coverage map can be seen in Fig. 22 and the maximum EPFD value relative to 175.4 dBW/m^2 during the simulation can be seen in Fig. 23. While the constellation maximum EPFD values are above 175.4 dBW/m^2 around the equator they are compliant with ITU regulations since the higher EPFD values are only reached rarely during the simulation. The best and worst case link budgets of the constellation can be found in Table X.

Using the cost model each satellite would have a maximum cost of \$14.7M. With five launches available there are two options. Either the satellites are launched into their respective planes with four launches. Then nine satellites would be launched on each rocket. Each satellite would have a mass of 668 kg. This would provide approximately \$1.9M extra budget per satellite from using one less launch. An alternative is launching satellites into multiple planes with the same launch. Then the mass for each satellite increases to 765 kg since five launches can be utilized. For the discussion this slightly higher number will be used.

The Inter Satellite Link budgets for the MEO constellations can be seen in Table XI. The link budget is dimensioned in

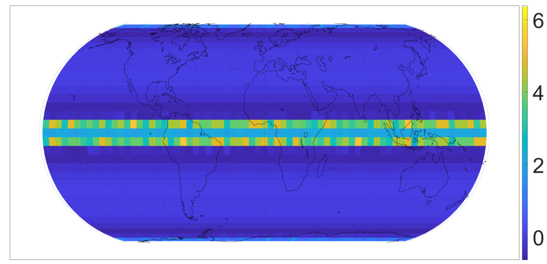

Fig. 23. Maximum EPFD value relative -175.4 dBW/m^2 reached for each discretized point during the simulation for the 32 satellite MEO constellation.

TABLE X
LINK BUDGET FOR SECOND MEO CONSTELLATION WITH INCREASED ELEVATION

Input values		
	Best case	**Worst case**
Distance	$8\ 500 \times 10^3$ m	$10\ 624 \times 10^3$ m
Elevation	90°	30°
Downlink frequency	10.7 GHz	
Uplink frequency	12.75 GHz	
Symbol rate	60 MBd	
Satellite antenna gain	32 dBi	
Satellite system G/T	5.8 dB/K	
Satellite amplifier power	18 dBW	
Terminal antenna gain	24.5 dBi	18.5 dBi
Terminal system G/T	1.5 dB/K	-4.5 dB/K
Terminal amplifier power	4.9 dBW	10 dBW

Results				
	Best case		**Worst case**[a]	
	Uplink	**Downlink**	**Uplink**	**Downlink**
$EIRP_{dB}$	29.4 dBW	50.0 dBW	28.5 dBW	50.0 dBW
C/N_{dB}	7.7 dB	7.5 dB	-0.8 dB	-1.0 dB
Channel transmission speed	134 Mbps	131 Mbps	42 Mbps	41 Mbps
Small terminals per channel	65		20	

[a] Worst case transmission speed is significantly lower due to losses from low elevation in the small user terminal.

such a way that it should be able to supply a satellite without a ground link by connecting to two adjacent satellites. For the first MEO constellations this means that two ISL links should be able to transmit at a total speed of 13×116 Mbps $= 1508$ Mbps or 754 Mbps per link. This results in an antenna size of 0.3 m for the ISL and a bandwidth of 250 MHz. Similarly, the second MEO constellation should be able to transmit 852 Mbps per link. In this case a bandwidth of 250 MHz and an antenna size of 0.4 m was chosen

B. Two low Earth orbit constellations

Two Low Earth Orbit (LEO) constellations will be considered. Similarly to the MEO constellations the LEO con-

TABLE XI
LINK BUDGET FOR IN-PLANE INTER SATELLITE LINKS FOR MEO CONSTELLATIONS

	Input values	
	First MEO	**Second MEO**
Distance	$7\ 118 \times 10^3$ m	$11\ 382 \times 10^3$ m
Link frequency	22.55 GHz	
Symbol rate	208 MBd	208 MBd
ISL antenna gain	35 dBi	38 dBi
ISL system G/T	14 dB/K	17 dB/K
ISL amplifier power	18 dBW	19 dBW
Results		
	Link	
$EIRP_{dB}$	53.5 dBW	57.0 dBW
C/N_{dB}	12.5 dB	14.4 dB
Transmission speed	759 Mbps	879 Mbps

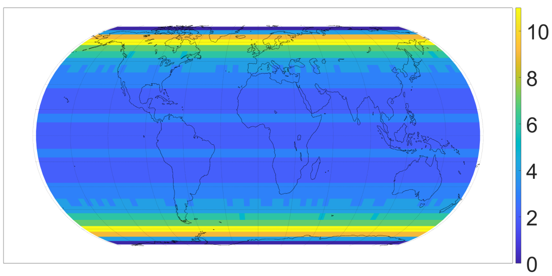

Fig. 24. Number of satellites visible for the 800 satellite LEO constellation.

TABLE XII
LINK BUDGET FOR FIRST LEO CONSTELLATION

	Input values			
	Best case		**Worst case**	
Distance	$1\ 350 \times 10^3$ m		$1\ 766 \times 10^3$ m	
Elevation	$90°$		$45°$	
Downlink frequency	10.7 GHz			
Uplink frequency	12.75 GHz			
Symbol rate	60 MBd			
Satellite antenna gain	20 dBi			
Satellite system G/T	-6.2 dB/K			
Satellite amplifier power	10 dBW			
Terminal antenna gain	24.5 dBi		21.5 dBi	
Terminal system G/T	1.5 dB/K		-1.5 dB/K	
Terminal amplifier power	-1.0 dBW		3.5 dBW	
Results				
	Best case		**Worst case**[a]	
	Uplink	**Downlink**	**Uplink**	**Downlink**
$EIRP_{dB}$	23.5 dBW	30.0 dBW	25.0 dBW	30.0 dBW
C/N_{dB}	3.1 dB	2.9 dB	-2.2 dB	-2.4 dB
Channel transmission speed	82 Mbps	80 Mbps	30 Mbps	28 Mbps
Small terminals per channel	40		14	

[a] Worst case transmission speed is lower due to losses from low elevation in the small user terminal and the increase in distance.

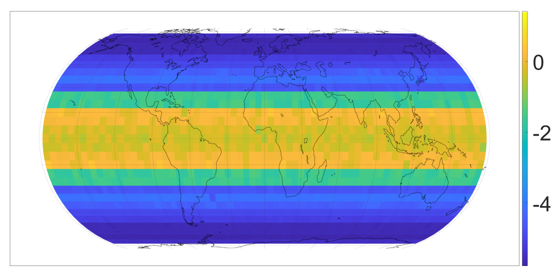

Fig. 25. Maximum EPFD value relative -175.4 dBW/m^2 reached for each discretized point during the simulation for the 800 satellite LEO constellation.

stellations will consist of two constellations with a minimum elevation angle of 45° and 30° degrees respectively.

The first constellation will be a 800/20/9-65° constellation using Walker notation placed at 1350 km. This creates a high density of satellites around 65°N/S. The coverage of the constellation is shown in Fig. 24.

The antennas on the satellites would be 0.2 m in diameter. The link budget for the best and worst cases can be found in Table XII. Since neither the satellite antenna input power nor the small terminal antenna input power is constrained by their maximum values these values can be increased to compensate for the distance losses in the worst case scenario. The EPFD limits impacts this constellation hard around the equator as seen in Fig. 25. At some latitudes the EPFD value is below -181.4 dBW/m^2, 6 dBW/m^2 below the lowest limit. Increasing the antenna input power by 6 dBW in the small terminal and satellite would double the transmission speeds due to the possible increase in spectral efficiency.

Applying the cost model, if one only considers the first wave of satellites that would last 7.5 years to be launched, it is found that each satellite would have to have a mass of approximately 99 kg. The development and manufacturing cost would have to be less than $598 000. With five launches almost 157 satellites would have to be launched per rocket. If the full cost of the two waves of the constellation are considered then the mass and satellite cost would be halved to 48.8 kg and $299 000. These numbers are clearly not feasible as will be shown in the discussion.

The second LEO constellation with the decreased elevation requirement is similar to the first LEO constellation in that it consists of only one of the two sub-constellations. Using Walker notation it is a 392/14/7-60° constellation operating at an altitude of 1300 km. Due to the decreased elevation requirement the constellation can have a slightly smaller inclination compared to the first LEO constellation. The coverage area can be seen in Fig. 26. There is a concentration of satellites around 50°N and 50°S with areas having a minimum of eight satellites visible and at least three satellites visible around the equator.

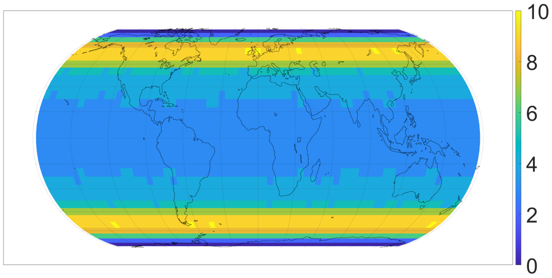

Fig. 26. Number of satellites visible for the 392 satellite LEO constellation.

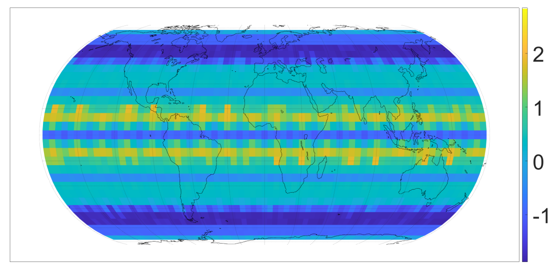

Fig. 27. Maximum EPFD value relative -175.4 dBW/m^2 reached for each discretized point during the simulation for the 392 satellite LEO constellation.

TABLE XIII
LINK BUDGET FOR SECOND LEO CONSTELLATION WITH INCREASED ELEVATION

Input values				
	Best case		Worst case	
Distance	$1\ 300 \times 10^3$ m		$2\ 143 \times 10^3$ m	
Elevation	90°		30°	
Downlink frequency	10.7 GHz			
Uplink frequency	12.75 GHz			
Symbol rate	60 MBd			
Satellite antenna gain	20 dBi			
Satellite system G/T	-6.2 dB/K			
Satellite amplifier power	15 dBW			
Terminal antenna gain	24.5 dBi		18.5 dBi	
Terminal system G/T	1.5 dB/K		-4.5 dB/K	
Terminal amplifier power	1.2 dBW		8.2 dBW	
Results				
	Best case		Worst case[a]	
	Uplink	Downlink	Uplink	Downlink
$EIRP_{dB}$	25.7 dBW	35.0 dBW	26.7 dBW	35.0 dBW
C/N_{dB}	8.4 dB	8.2 dB	-1.9 dB	-2.1 dB
Channel transmission speed	153 Mbps	150 Mbps	33 Mbps	31 Mbps
Small terminals per channel	75		15	

[a] Worst case transmission speed is significantly lower due to losses from low elevation in the small user terminal and a large increase in distance.

TABLE XIV
LINK BUDGET FOR IN-PLANE INTER SATELLITE LINKS FOR THE LEO CONSTELLATIONS.

Input values		
	First LEO	Second LEO
Distance	$1\ 219 \times 10^3$ m	$1\ 721 \times 10^3$ m
Link frequency	22.55 GHz	
Symbol rate	208 MBd	208 MBd
ISL antenna gain	32 dBi	32 dBi
ISL system G/T	10 dB/K	10 dB/K
ISL amplifier power	5 dBW	12 dBW
Results		
	Link	
$EIRP_{dB}$	36.9 dBW	43.9 dBW
C/N_{dB}	7.8 dB	14.8 dB
Transmission speed	497 Mbps	903 Mbps

The antenna size for the second LEO constellation is the same as for the first LEO constellation, 0.2 m. The best and worst case link budgets can be seen in Table. XIII. Compared to the first LEO constellation EPFD limits impact the second LEO constellation less. This can be seen in Fig. 27. There are large bands around the equator where the EPFD briefly exceeds -175.4 dBW/m^2. However, this only occurs for short periods and is therefore still within the EPFD limits.

For the second LEO constellation, the cost model gives that each satellite would have to have a mass of 99 kg, with two sets of 392 satellites that are launched 7.5 years from each other. The cost to develop and produce each satellite comes out to almost $638 000 per satellite excluding spares. If instead 6 launches were to be preformed, each satellite would have a maximum mass of 119 kg and a development and manufacturing cost per satellite of $588 000. While not explicitly feasible it is certainly more feasible than the larger 800 satellite LEO constellation.

When dimensioning in-plane ISLs for the LEO constellation the target was the same as for the MEO constellations. Two ISLs should be able to transmit at 12 times the transmission speed of a 72 MHz channel corresponding to 12 channels sharing a bandwidth of 500 MHz using polarization. The resulting ISL antenna would be 0.2 m in diameter. The resulting link budget can be found in Table XIV. For the first LEO constellation the ISLs would need a capacity of $6 \times 80 = 480$ Mbps. Similarly, for the second LEO constellation the capacity would be $6 \times 150 = 900$ Mbps.

C. Collision risk

Using ESA's MASTER-8 model an impact flux was calculated for a satellite in each of the proposed constellations. From this a mean number of collisions with satellites and other objects during the constellations' total active periods was then calculated. The results can be found in Table XV. Most of these collisions are with objects of a diameter between 1 mm and 1 cm.

TABLE XV
COLLISION RISK FOR THE FOUR CONSTELLATIONS OVER A 15-YEAR PERIOD

Constellation	Impact flux [1/m^2/yr][a]	Mean collisions[b]
104 Satellite MEO	2.793×10^{-3}	4.36
32 Satellite MEO	2.829×10^{-3}	1.36
800 Satellite LEO	6.245×10^{-3}	74.9
392 Satellite LEO	6.208×10^{-3}	36.5

[a] Impact objects $> 10^{-3}$ m diameter.
[b] Assuming a satellite collision cross-section of 1 m^2.

D. Constellation satellite costs

Using the CERs detailed in the cost model the RDT&E and manufacturing costs for the satellites in each of the four constellations can be calculated. It is found that the $500M for development and manufacturing is about half the actual cost needed. Table XVI shows the results of the CERs.

VI. DISCUSSION

In this section the four NGSO constellations will be compared with the reference GEO constellation. First a comparison between the constellations is done according to parameters defined earlier in section III-E. The parameters that will be used in this comparison are compiled in Table XVII. From this study a recommendation on the general parameters of a constellation which fulfills the requirements will be made. Afterwards the possibility of combining a GEO constellation consisting of three satellites with a NGSO constellation will be explored.

The results corroborate the previously discussed differences between GEO and NGSO communications constellations. Most importantly, the different distances to Earth for the different constellations greatly influence the design of both the whole constellation and the individual satellites. Satellites in LEO can use much smaller antennas while also needing a lower amplifier power to achieve similar PFD levels at Earth's surface than MEO or GEO constellations. However, the lower distance comes with a limitation in that the number of satellites needed to provide the coverage as stipulated by requirement 10 is significantly increased.

An aspect that have not been touched upon in this thesis is the availability of the constellation. Instead of requiring that satellites be visible at all times an availability requirement could be used instead. Then it would be required that it is possible to use the constellation a percentage of the time. With an availability requirement there are additional aspects that would be needed to be taken into account such as weather, satellite breakdowns, and EPFD restrictions.

A. Comparison of constellations

Starting with the number of satellites in the constellation it becomes clear that a lower altitude and a higher minimum elevation in a constellation results in a higher amount of satellites and a higher required Inclination for orbits of the satellites. All four NGSO constellations have the number of planes and the number of satellites per plane related such that $P \approx S/2$. This relation is expected since satellites between planes should overlap just enough to provide continuous coverage. Satellites in planes should overlap in a similar manner. Since each orbital plane crosses the equator twice it will take approximately half the amount of satellites when compared to the amount of satellites needed to fill a plane.

At its lowest point the minimum amount of visible satellites in the coverage area is fairly constant between constellations. Furthermore, the minimum number of gateway locations needed per constellation increases with a lower orbit altitude. This number only reflects the minimum number to provide a connection at all times to satellites. Additional gateway locations will be needed to provide redundancy and adaptability.

With more satellites less money can be spent on each individual satellite. For constellations with smaller amounts of satellites the development cost becomes a larger part of the cost per satellite. The change in cost depending on the number of satellites is very visible in the MEO constellation where the power and link budget of the satellites are otherwise fairly similar. Comparing the masses to OneWeb (145 kg) and SpaceX (386 kg) satellites [41] the mass of the satellites in the constellations is low except when compared with the second MEO constellation. A conclusion that can be drawn from this is that the launch cost is larger than expected in the cost model. Therefore, the launch costs constitute a larger part of the full constellation cost than anticipated. More launches would increase the mass per satellite. In addition, increasing the amount of launches decreases the number of planes satellites from each launch have to travel to. Alternatively the budget would have to be increased with additional funds going into launching satellites. The satellite user beam antennas in the LEO constellation are comparatively small. Increasing the size to 0.3 m or 0.4 m would increase the gain by 3.5 or 6 dB respectively and allow for a larger signal to interference ratio. A change like this would allow a lower minimum elevation or higher transmission capacity for the satellite.

When calculating the CERs for the satellites both Ovzon-3 and the Iridium NEXT constellation overshoot their respective budgets. As CERs should only be used for comparison and not budgeting the actual cost of the Ovzon-3 satellite and the satellites in the Iridium NEXT constellation will be compared to their respective CER. It could be argued that the satellite bus RDT&E for both the Iridium NEXT constellation and Ovzon-3 can be ignored since they utilize a completed satellite bus. In the case of Ovzon-3 this reduces the total cost by about half to approximately $400M, about $300M more than would be expected. This results in a cost about four times the expected cost when the launch costs and ground station costs are removed from the total budget of $167M. For Iridium NEXT the overshoot is less significant, a bit less than two times the actual cost of $2.1B. If the assumption is made that the actual cost for the satellites have a similar reduction the MEO constellations are possibly within the budget, assuming the actual cost for the satellites are one fourth of the cost. With this reasoning the LEO constellations remain unattainable with the given budget.

Even though the antenna size decreases with the altitude the amplifier power for the small terminal also decreases with

TABLE XVI
CERs for the Four Constellations Adjusted for Inflation From 1992 Dollars to 2022 Dollars. Given in $M.

Constellation	Satellite Bus RDT&E[a]	Satellite bus manufacturing[a]	Communications payload RDT&E[a]	Communications payload manufacturing[a]	Total cost per satellite	Total cost
1 reference GEO satellite	248.59	74.523	283.68	35.856	642.64	642.64
104 Satellite MEO	0.6598	6.6850	2.4473	9.2857	19.078	2079.5
32 Satellite MEO	4.4297	27.378	8.0919	18.124	58.024	19728
800 Satellite LEO	0.0458	1.1483	0.2025	5.5247	6.9213	6056.2
392 Satellite LEO	0.1117	2.3490	0.4161	6.5705	9.4473	4052.9
Iridium NEXT constellation	1.6679	14.692	7.7479	21.126	45.234	3573.5

[a] Cost per satellite.

it. If the antenna sizes were to scale with distance the MEO satellites would use antennas approximately 0.3 m in diameter and LEO satellites would have even smaller antennas. The conclusion is that the cost is much lower with lower altitudes. In GEO high power amplifiers need to be used in combination with large antennas. In LEO a high gain antenna could be combined with a lower power output. Similarly, a low gain antenna could be combined with a high power output for the same transmission speeds. This results in lower cost for the individual LEO satellites when compared to GEO satellites. However, in LEO more satellites are needed to cover the same area, thus increasing the cost for the whole constellation. For each satellite in each constellation, the maximum capacity per beam is fairly constant between all the constellations. However, as the elevation decreases to its minimum value the GEO, second MEO, and LEO constellations loose more than the first MEO. For the GEO constellation it is because of regulations limiting the PFD at low elevations. Had the constellation operated around 20° elevation there would have been an additional 10 dB to the regulation limit. This change would only impact small terminals around 60°-70° N/S. This would result in speeds comparable with the maximum elevation figure. The second MEO and LEO are limited by the small terminal having larger losses as the elevation decreases. In addition, at lower Satellite altitudes the ratio between the distance at minimum elevation and maximum elevation is larger than for higher altitudes. This causes additional losses unless compensated for. Finally, the first LEO constellation is limited by its inability to minimize its impact on GEO communications, causing a higher EPFD value at the Earth's surface. To alleviate this lower elevations or an increase in satellites could be considered. However, these changes would also impact other aspects of the constellation. In the case of lowered elevation this would put further constraints on the link budget for the small terminal to operate at low elevations. More satellites would increase both the cost of the constellation and the risk of collisions for satellites in the constellation with other satellites and debris.

The beam area decreases substantially with the lower altitude constellations. Even when considering the smaller antennas with larger beamwidth. Similarly, the capacity density of the beam increases as the altitude decreases. Despite halving the beam area the beam capacity density does not change significantly between the second MEO and first LEO constellations. This is because of the relatively low capacity per beam of the first LEO constellation which arise from the less optimal handling of EPFD values when compared to other constellations.

An important aspect of the constellation design is the small terminal amplifier power. As one would expect with lower losses from distance, the amplifier power of the small terminal decreases as the altitude decreases. For all constellations except for the GEO Reference constellation the terminal amplifier power increases in the worst case scenario. The GEO Reference constellation is an outlier since the downlink is constrained by ITU regulations and the link is balanced. Therefore, less power was needed from the small terminal to match the downlink C/N. In addition, there is a distinct increase of power in the worst case scenario when comparing the 45° and 30° minimum elevation constellations. Only in the worst case scenario of the second MEO constellation is the power limit for the small terminal reached.

The third trade study parameter, launch and operations complexity of the constellations, need to be considered. While this would be hard to quantify a relative ranking has been made. More gateways and satellites increase the complexity. In addition, lower risk of collisions with space debris would decrease complexity as fewer satellites would have to be launched and fewer avoidance maneuvers would have to be preformed. In LEO more satellites are needed in any given constellation. As can be seen in Table XV the mean number of collisions are the highest for the LEO constellations. While in both the LEO and MEO case collisions with other debris is expected the number of collisions are much larger for the LEO constellations giving it a higher complexity.

All constellation except for the first LEO constellation operate close to the maximum allowed EPFD value over the coverage area. However, the first LEO constellation has up to 6 dB margin outside the 30° N/S latitude band. As noted earlier, to make this margin available closer to the equator the amount of satellites would need to increase or the elevation they operate at would need to decrease.

Despite having a lower maximum capacity per beam the first LEO constellation has the highest max capacity at 90° elevation. This is because of the large amount of satellites in the constellation. The maximum capacity of the LEO constellations is significantly smaller than the early stages of the Starlink, OneWeb, and Telesat constellations [41]. The primary reason for this is that the constellations in this thesis do not consider frequency reuse and operate with a total bandwidth

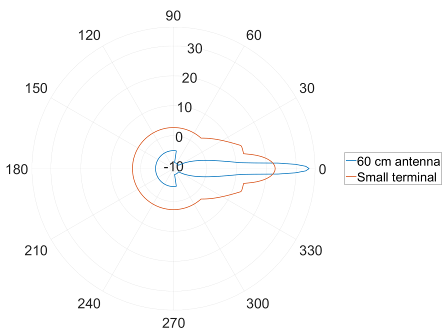

Fig. 28. Comparison of the gain of the small terminal and the 60 cm EPFD reference antenna.

of 1000 MHz compared to the 2000 MHz (downlink) of Starlink and OneWeb and 3600 MHz (downlink) of Telesat. To compete with the bandwidth of these constellations frequency reuse or additional bandwidth will therefore be required.

The final two parameters of interest are the beam capacity density and the capacity per visible satellite. As expected the beam capacity density increase as the satellite's altitude decrease. In addition, the total capacity per visible satellite stays fairly constant due to EPFD limits as noted earlier. Therefore, the capacity per visible satellite stays fairly constant given that a similar bandwidth is used for all satellites. If a customer were to buy bandwidth in the constellation is a specific area, the area in which the customer may influence other customers decrease as the constellation decrease in altitude. Generally, buying bandwidth will reduce the available bandwidth in at most two adjacent satellites. On average only one satellite will be used. However, during handovers two satellites are needed for a seamless transition.

Finally, it is worth commenting on how other constellations may interfere with the small terminal. Fig. 28 shows a comparison of the gain of the small terminal and the 60 cm EPFD reference antenna. As can be seen in the picture the small terminal has a much higher gain than the 60 cm antenna at most angles off boresight. A constellation at the EPFD limit transmitting at an off-angle into the small terminal would therefore cause a noise than for the theoretical 60 cm antenna. How much noise the small antenna receives and if it would interfere with normal reception is outside the scope of this thesis. It is however a part of the constellation that would have to be characterized before construction.

B. Choosing a constellation

While the LEO constellations provide the best capacity for any of the examined constellations their low mass per satellite when compared with Starlink and OneWeb [41] indicates that the budget for launches and by extension the possible mass to orbit is too small for this type of constellation. To make the mass per satellite consistent the amount of launches would have to be doubled for the second LEO and increased to four times the original amount for the first LEO constellation. This would significantly increase the cost of these constellations.

Between the two MEO constellations the second MEO constellation is also favoured for reasons of mass. Since the MEO constellation are launched to a MEO transfer orbit each satellite will have to circularize its orbit under its own power, increasing its mass as it must carry additional fuel. With that in mind, without increasing the launch budget the satellites in the first MEO constellation would be similar in mass to LEO satellites.

All four of the constellations and the reference GEO constellation fulfil requirements 10, 20, 21, 30, 40, and 60 under the current assumptions. Additionally, the second MEO and the reference GEO The launch cost for the LEO constellations and the first MEO constellation would need to be increased from that of the cost model for the constellations to become feasible. Only the MEO constellations are close to fulfilling requirement 60 since both of the LEO constellations become too expensive even when compared with the CERs and actual cost for Ovzon-3.

The individual satellites in each of the constellations reach similar transmission speeds per beam since these are constrained by EPFD limits. Therefore, in this regard more satellites in orbit will always be favourable. With smaller beams the beam capacity density increase. Therefore, if the aim is to maximize throughput and exceed the throughput set in requirement 21, LEO constellations will be superior to any other type of constellation.

C. A hybrid constellation

By combining a GEO and a NGSO constellation one can obtain a hybrid constellation. To properly use a hybrid constellation the ground station antenna must be steerable since it must track satellites in the NGSO part of the constellation. As seen in Fig. 29 the EPFD value is for NGSO constellations, in this case the 32 satellite MEO constellation, is low with some higher points. These areas with higher EPFD values move as time goes on. A GEO constellation complementing a NGSO constellation would be able to keep the throughput high, albeit with a much larger latency. Furthermore, a hybrid constellation would be less sensitive to the loss of a satellite or part of a satellite since the other part of the constellation could temporarily alleviate any outage while it is resolved in a more permanent way.

A GEO constellation provides the best service over the equator where NGSO constellations are constrained due to EPFD limits. While this can be designed around in the constellation as seen in the four NGSO constellations EPFD values may still constrain the EIRP from NGSO constellations. As can be seen with the NGSO constellations designed in this thesis they have the worst EPFD values around the equator. A hybrid constellation could alleviate this.

Naturally, a hybrid constellation will also come with drawbacks. The primary drawback of a hybrid constellation is the fact that it essentially consists of two individually functioning constellations, increasing the price significantly. Therefore, the cost of the hybrid constellation will be higher than either of the GEO or NGSO constellations. The GEO part of the constellation could potentially consist of three to four satellites

TABLE XVII
PARAMETERS FOR GEO, MEO, AND LEO CONSTELLATIONS IN TRADE STUDY

Parameters	**Constellation**				
	GEO Reference	**First MEO**	**Second MEO**	**First LEO**	**Second LEO**
Satellites	6	104	32	800	392
Orbital planes	1	8	4	20	14
Minimum elevation	5°	45°	30°	45°	30°
Altitude	35 786 km	8 500 km	8 500 km	1 350 km	1 300 km
Inclination	0°	48°	45°	65°	60°
Minimum visible satellites in coverage area	1	1	1	2	2
Minimum gateway locations needed	2	8	8	∼16	∼16
Satellite development and production cost	$105M[a]	$4.59M	$14.7M	$299 000	$609 000
Total cost per satellite	$167M	$9.17M	$29.4M	$597 000	$1.22M
Total mass per satellite	-	255 kg	765 kg	48.8 kg	99.5 kg
Total amplifier power per satellite[b]	1 902 W	883 W	916 W	126 W	411 W
Satellite antenna diameter	1.3 m	0.7 m	1 m	0.2 m	0.2 m
Satellite antenna beamwidth	1.5°	2.6°	1.9°	9.6°	9.6°
Best case small terminal amplifier power per 2 Mbps	8.3 dBW (6.8 W)	5.4 dBW (3.5 W)	4.9 dBW (3.1 W)	−1.0 dBW (0.8 W)	1.2 dBW (1.3 W)
Worst case small terminal amplifier power per 2 Mbps	6.0 dBW (4.0 W)	7.4 dBW (5.5 W)	10 dBW (10 W)	3.5 dBW (2.2 W)	8.2 dBW (6.6 W)
Maximum capacity per beam at 90° elevation	1776 Mbps	1392 Mbps	1572 Mbps	960 Mbps	1800 Mbps
Maximum capacity per beam at minimum elevation	480 Mbps	864 Mbps	492 Mbps	336 Mbps	372 Mbps
Maximum number of small terminals per beam	888	696	780	480	900
Minimum number of small terminals per beam	240	432	240	168	186
Beam area[c]	674 370 km^2	131 090 km^2	64 190 km^2	34 896 km^2	32 158 km^2
Beam capacity density [$Mbps/km^2$][c]	2.6×10^{-3}	1.1×10^{-2}	2.5×10^{-2}	2.8×10^{-2}	5.6×10^{-2}
Maximum capacity for constellation at 90° elevation[d]	10 656 Mbps	144 768 Mbps	50 304 Mbps	768 000 Mbps	705 600 Mbps
Maximum capacity for constellation at minimum elevation[d]	2 880 Mbps	89 856 Mbps	15 744 Mbps	268 800 Mbps	145 824 Mbps
Highest possible EPFD increase[e]	0	2 dB	0 dB	6 dB	2 dB
Launch and operations complexity[f]	1	3	2	5	4
Mean number of collisions from objects $> 10^{-3}$ m^2 cross-section area[g]	-	4.36	1.36	74.9	36.5

[a] Assuming a launch cost of $62M
[b] 12 72 MHz channels and two ISLs
[c] Beam pointed at nadir
[d] Assumes all satellites at full capacity and one beam
[e] Margin to −175.4 dBW/m^2 at the best location in EPFD map
[f] Relative ranking
[g] Assuming a satellite collision cross-section of 1 m^2

covering the equator. However, the NGSO part would have to have a high availability as well to be able to exploit its advantages. The low latency and small terminal amplifier power is only useful if it is consistent.

Therefore, for a hybrid constellation to work it would need a full scale NGSO constellation and a three to four GEO satellites. If both were to be launched at the same time the total cost would be larger than the cost for either a NGSO or GEO constellation. This is because while the GEO constellation would not need the 6 satellites as in the GEO reference constellation an almost complete NGSO constellation would be needed for the advantages of the NGSO constellation to be reliably available.

Thus, the ideal use for a hybrid constellation would be if a satellite-service provider already had one of the two parts of the hybrid constellation. Then a NGSO or GEO constellation would be able to complement the already present constellation.

D. Possible improvements and future work

To bring the proposed constellations further towards a real constellation the cost model would need to be improved. An important aspect to investigate would be the expected profit from each of the constellations. For this to be relevant the cost model would have to be improved as well. Investigating

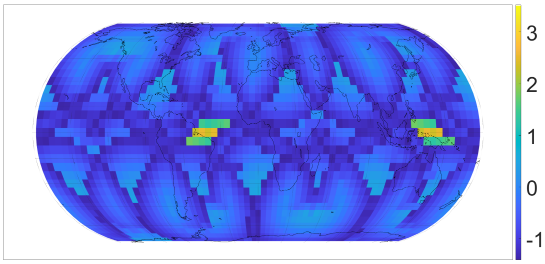

Fig. 29. Picture showing an example of the EPFD values in one timestep from the 32 satellite MEO constellation.

more closely power, antenna, and propulsion requirements for the satellites would provide the means to properly assess the development and manufacturing cost of the satellites. The cost model in this thesis is the weakest link in the analysis of the constellations and improvements there would improve the quality of the conclusions that could be drawn.

Another part in need for improvement is the link budget calculations and how it relates to ITU regulations. Most importantly losses should be modelled more accurately. With properly modelled losses availability would increase in importance since effects from weather would be included. This could potentially cause interruptions in service as the satellites and small terminals would not be able to establish a link. Availability can then be extended to a more general case where visible satellites, weather, and satellite damage can be taken into account.

Finally, the interference from other constellations in the small terminal operating with a GEO constellation needs to be characterized. Since the EPFD reference antenna is a 60 cm antenna there may be cases where another constellation is operating within the EPFD limits while still causing interference in the small terminal. This is because of the larger beamwidth of the small terminal compared to the 60 cm reference antenna.

VII. Conclusion

This thesis has investigated different aspects that have to be taken into account when designing a constellation. While the focus has been on the link budget and orbits of the satellites in the constellations this is not the only things that have to be taken into account during the design of a constellation. An area in need of further investigation is the costs from manufacturing and maintenance. This together with a model for the distribution of potential customers could greatly improve the ability to compare constellations.

For all the proposed NGSO constellations the limiting factor in the link budgets is the downlink speed which in all cases is limited by the EPFD limits imposed by the ITU. Therefore, to reach higher downlink speeds two options exist. By increasing the G/T of the small terminal a higher carrier to noise ration can be achieved, increasing the downlink speed. This could be done by either increasing the gain or decreasing the noise in the small terminal. The other option is to transmit on frequencies where EPFD limits do not apply, such as the V-band. While this would provide a small increase there are also PFD limits in Article 21 of the ITU radio regulations that would still limit the transmission speed.

A good way to reduce the number of satellites needed in a constellation is to reduce the minimum elevation angle of the ground terminals. However, operating at low elevations introduces larger losses in the ground terminal and satellites if their antennas are electronically steered. A solution to reduce this loss could either be to mechanically steer the antenna or increase the antenna size to account for the loss. Generally increasing the amplifier power or the gain of the transmitting antenna is not feasible since the EIRP should be close to the regulated max values to maximize the transmission speeds. The loss in the satellite antenna for transmissions off-angle has not been taken into account in this thesis. In any future work this loss needs to be accounted for as well.

The most promising NGSO constellation in this work was the second MEO constellation. The primary reason is that with the given budget and cost model it is the most feasible constellation among the NGSO constellations with regard to mass and the development and manufacturing cost of the satellites. The satellite mass budget and power requirements are similar to the Iridium NEXT satellites while about half the number of satellites are used. An important thing to note is that this constellation operates at MEO instead of LEO and therefore has larger launch costs associated with it. Because of the increase of satellites in the constellation when compared to the GEO benchmark constellation the total transmission speed is higher.

To conclude, the budget is likely not large enough for any of the constellations discussed in this thesis apart from the GEO reference constellation. Neither of the LEO constellations are close to being attainable with the given budget. Largely due to the manufacturing and launch costs associated with such a large constellation. Further studies should either focus on GEO or MEO constellation or increase the available budget. A more detailed analysis of the individual satellites and how the cost relates to the performance would also be of great importance before building any NGSO constellation.

Acknowledgment

I would like to thank my supervisors Kennet Lejnell and Sytze Verdman for both the opportunity to write this thesis and their support and guidance throughout this project. In addition, I would like to thank everyone else that I interacted with at Ovzon for their time.

Finally, I want to thank my mother with whom I have been sharing an office for the past two years.

References

[1] E. W. Ashford, "Non-geo systems—where have all the satellites gone?" *Acta Astronautica*, vol. 55, no. 3, pp. 649–657, 2004, new Opportunities for Space. Selected Proceedings of the 54th International Astronautical Federation Congress. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S009457650400181X

[2] N. Pachler, I. del Portillo, E. F. Crawley, and B. G. Cameron, "An updated comparison of four low earth orbit satellite constellation systems to provide global broadband," 2021.

[3] Space Norway AS, "SAT-PDR-20161115-00111," 2016. [Online]. Available: https://licensing.fcc.gov/myibfs/download.do?attachment_key=1158236

[4] O3b Limited, "SAT-MOD-20200526-00058," 2020. [Online]. Available: https://fcc.report/IBFS/SAT-MOD-20200526-00058/GOV

[5] M. Capderou, *Handbook of Satellite Orbits*. Springer, Cham, 2014.

[6] J. G. Walker, "Continious whole-earth coverage by circular-orbit satellite patterns," Royal Aircraft Establishment, Tech. Rep., 1977.

[7] A. Ballard, "Rosette constellations of earth satellites," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-16, no. 5, pp. 656–673, 1980.

[8] M. E. Avendaño, J. J. Davis, and D. AU Mortari, "The 2-d lattice theory of flower constellations," *Celestial Mechanics and Dynamical Astronomy*, vol. 116, pp. 325–337, 2013.

[9] H. W. Lee, S. Shimizu, S. Yoshikawa, and K. Ho, "Satellite constellation pattern optimization for complex regional coverage," *Journal of Spacecraft and Rockets*, vol. 57, no. 6, pp. 1309–1327, 2020. [Online]. Available: https://doi.org/10.2514/1.A34657

[10] J. E. Allnutt, *Satellite-to-Ground Radiowave Propagation*, 2nd ed. Institution of Engineering and Technology, 2011, ch. 1. [Online]. Available: https://app.knovel.com/hotlink/khtml/id:kt00A7BCR4/satellite-ground-radiowave/radiowave-earth-introduction

[11] D. R. Glover, *Handbook of Satellite Applications*. Springer, Cham, 2017, ch. Satellite Radio Communications Fundamentals and Link Budgets.

[12] E. Hudson, *Handbook of Satellite Applications*. Springer, Cham, 2017, ch. Broadband High-Throughput Satellites.

[13] International Telecommunications Union, "Satellite antenna radiation patterns for non-geostationary orbit satellite antennas operating in the fixed-satellite service below 30 GHz," 2001. [Online]. Available: https://www.itu.int/rec/R-REC-S.1528/en

[14] M. Bousquet, *Handbook of Satellite Applications*. Springer, Cham, 2017, ch. Satellite Communications and Space Telecommunication Frequencies.

[15] P. T. Thompson, *Handbook of Satellite Applications*. Springer, Cham, 2017, ch. Satellite Communications Modulation and Multiplexing.

[16] International Telecommunications Union, "ITU Radio Regulations," 2020. [Online]. Available: https://www.itu.int/en/myitu/Publications/2020/09/02/14/23/Radio-Regulations-2020

[17] S. Bourdarie and M. Xapsos, "The near-earth space radiation environment," *IEEE Transactions on Nuclear Science*, vol. 55, no. 4, pp. 1810–1832, 2008.

[18] J. A. Bolin, "Comparative analysis of selected radiation effects in medium earth orbits," Master's thesis, Monterey, California. Naval Postgraduate School, 1997.

[19] J. N. Pelton and B. Jacqué, *Handbook of Satellite Applications*. Springer, Cham, 2017, ch. Distributed Internet-Optimized Services via Satellite Constellations.

[20] N2YO.com, "O3b networks satellites," 2021. [Online]. Available: https://www.n2yo.com/satellites/?c=43

[21] H. J. Visser, *Array and Phased Array Antenna Basics*. John Wiley & Sons Ltd, 2005, ch. 4, 9.

[22] International Telecommunications Union, "Appendix 30B reference Earth station pattern with the improved side-lobe for coefficient A = 29." Oct 2020. [Online]. Available: http://www.itu.int/en/ITU-R/software/Documents/ant-pattern/APL_DOC_BY_PATTERN_NAME/APERR_002V01.pdf

[23] ——, "Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 GHz and 30 GHz," 2001. [Online]. Available: https://www.itu.int/rec/R-REC-S.1428/en

[24] ——, "Satellite antenna radiation pattern for use as a design objective in the fixed-satellite service employing geostationary satellites," 1997. [Online]. Available: https://www.itu.int/rec/R-REC-S.672/en

[25] M. Avendaño, D. Arnas, R. Linares, and M. Lifson, "Efficient search of optimal flower constellations," *Acta Astronautica*, vol. 179, pp. 290–295, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094576520306214

[26] W. E. Wiesel, *Spaceflight Dynamics*, 3rd ed. CreateSpace, 2010, pp. 94–97.

[27] M. J. Miller, B. Vucetic, and L. Berry, Eds., *Satellite Communications, Mobile and Fixed Services*. Springer, Boston, MA, 1993, ch. 1.

[28] ETSI, "ETSI EN 302 307-2 Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 2: DVB-S2 Extensions (DVB-S2X)," 2020. [Online]. Available: https://www.etsi.org/deliver/etsi_en/302300_302399/30230702/01.03.01_20/en_30230702v010301a.pdf

[29] H. Klinkrad, *Handbook of Satellite Applications*. Springer, Cham, 2017, ch. Orbital Debris and Sustainability of Space Operations.

[30] ——, *Space Debris Models and Risk Analysis*. Springer, Berlin, Heidelberg, 2006, ch. 3.

[31] A. Horstmann, S. Hesselbach, and C. Wiedemann, "Enhancement of s/c fragmentation and environment evolution models," Technische Universität Braunschweig, Institute of Space Systems, Tech. Rep., 2020. [Online]. Available: https://sdup.esoc.esa.int/master/downloads/documentation/8.0.2/MASTER-8-Final-Report.pdf

[32] Space Exploration Technologies Corp., "Capabilities & services," May 2020. [Online]. Available: https://www.spacex.com/media/Capabilities&Services.pdf

[33] S. Clark, "SpaceX launches 60 more Starlink spacecraft; FCC clears SpaceX to fly satellites at lower altitudes ," *Spaceflight Now*, Apr 2021. [Online]. Available: https://spaceflightnow.com/2021/04/29/spacex-launches-60-more-starlink-spacecraft-fcc-clears-spacex-to-fly-satellites-at-low

[34] ——, "SpaceX launches its first mission for the U.S. Space Force," Jun 2020. [Online]. Available: https://spaceflightnow.com/2020/06/30/spacex-launches-its-first-mission-for-u-s-space-force/

[35] C. Henry, "Boeing unveils small GEO product as part of new 702X satellite lineup," *Space News*, Sep 2019. [Online]. Available: https://spacenews.com/boeing-unveils-small-geo-product-as-part-of-new-702x-satellite-lineup/

[36] D. W. Miller, J. Keesee, and C. Jilla, "16.851 satellite engineering. fall 2003. massachusetts institute of technology: Mit opencourseware," 2003. [Online]. Available: https://ocw.mit.edu/courses/aeronautics-and-astronautics/16-851-satellite-engineering-fall-2003/lecture-notes/l15_costmodellec.pdf

[37] J. Bui, N. I. Om, J. K. Roth, M. L. Corso, and J. A. Titus, "Functional cost-estimating relationships for spacecraft," 1996. [Online]. Available: https://apps.dtic.mil/sti/pdfs/ADA308665.pdf

[38] Alioth Finance, "$1 in 1992 → 2022 — inflation calculator." Feb 2022. [Online]. Available: https://www.in2013dollars.com/us/inflation/1992?amount=1

[39] O. AB, "Rights issue 2020," 2020. [Online]. Available: https://www.ovzon.com/en/wp-content/uploads/sites/4/2020/10/ovzon-ab-publ-prospekt-slutlig-version-fi-1-juni-2020.pdf

[40] P. Blau, "Iridium-next," 2022. [Online]. Available: https://spaceflight101.com/spacecraft/iridium-next/

[41] I. del Portillo, B. G. Cameron, and E. F. Crawley, "A technical comparison of three low earth orbit satellite constellation systems to provide global broadband," *Acta astronautica*, vol. 159, pp. 123–135, 2019.

TRITA – XXX-XXX 20XX:XX