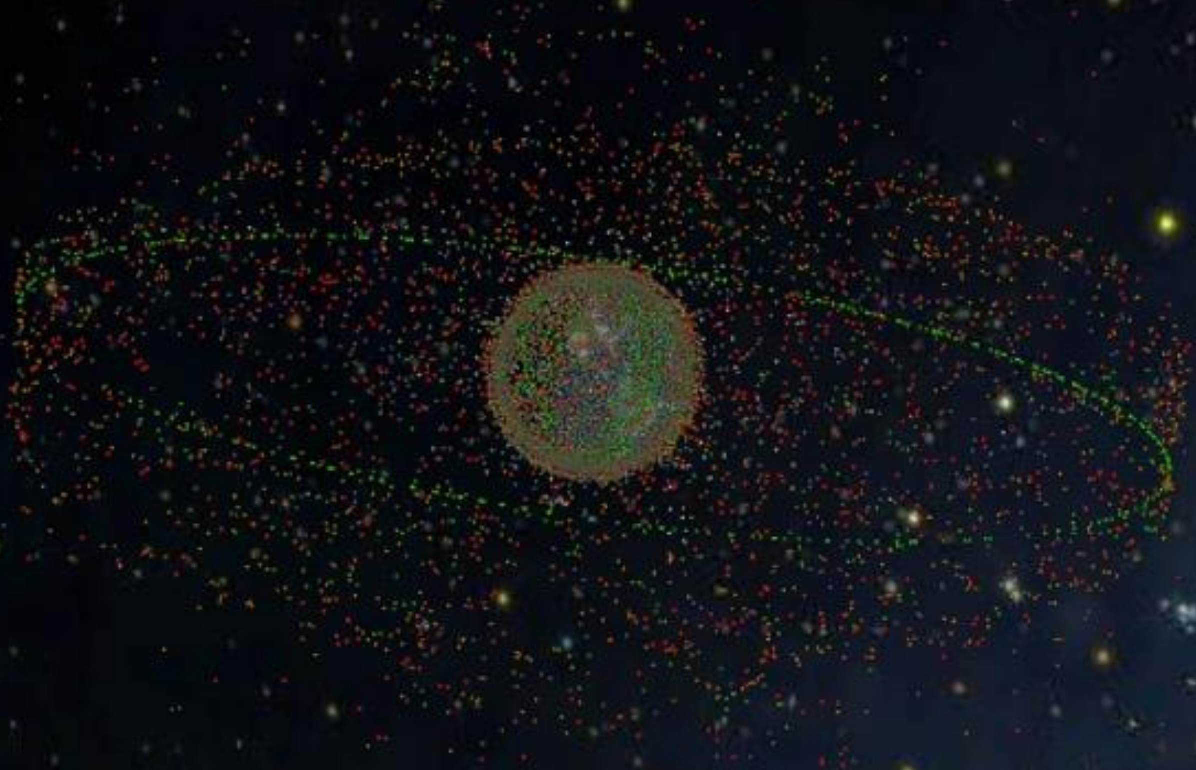

# Commercial Space Surveillance and Tracking Market Study

Full report

July 2020

LE London Economics

# Commercial Space Surveillance and Tracking Market Study

## A report for the UK Space Agency

FINAL REPORT

LE London Economics

July 2020

## About London Economics

London Economics is one of Europe's leading specialist economics and policy consultancies. Based in London and with offices and associate offices in five other European capitals, we advise an international client base throughout Europe and beyond on economic and financial analysis, litigation support, policy development and evaluation, business strategy, and regulatory and competition policy.

Our consultants are highly qualified economists who apply a wide range of analytical tools to tackle complex problems across the business and policy spheres. Our approach combines the use of economic theory and sophisticated quantitative methods, including the latest insights from behavioural economics, with practical know-how ranging from commonly used market research tools to advanced experimental methods at the frontier of applied social science.

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# Table of Contents

Page

# Executive Summary


London Economics was commissioned by the UK Space Agency (UKSA) to undertake a study investigating the current and future state of the commercial space surveillance and tracking market.

Space surveillance and tracking (SST) is defined as the activity for **detection**, **tracking** and **cataloguing** of space objects to **determine** their orbits and **predict** future collisions, fragmentations and re-entry events of satellites and/or debris. This is achieved using sensors, usually radars, telescopes and laser-ranging systems, to generate data on the position of space debris and a data centre to process and analyse the sensor data. The main objectives of this study are:

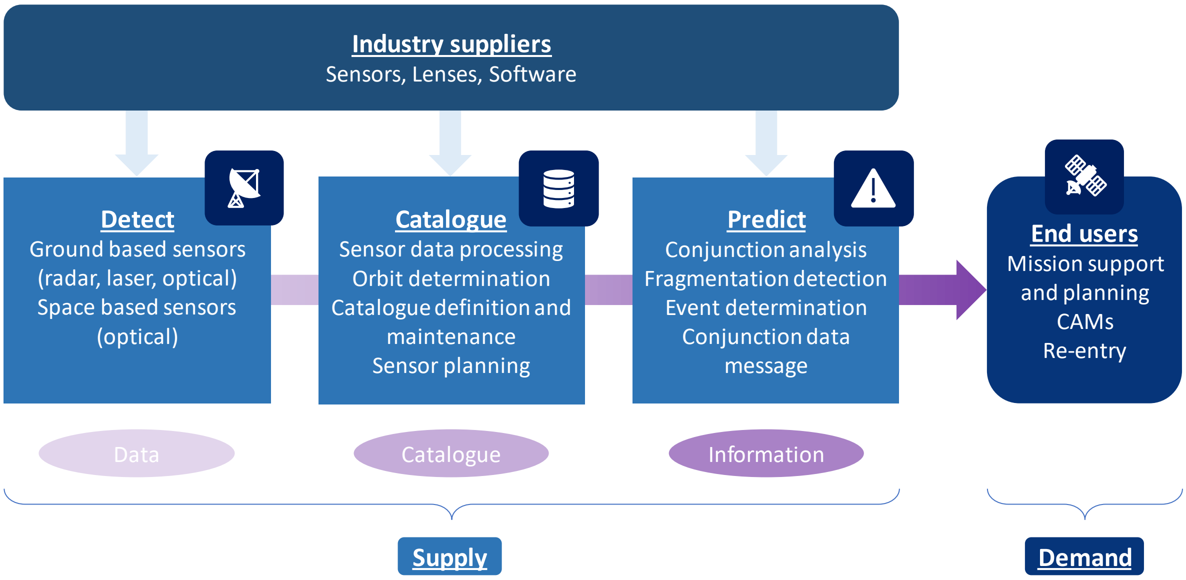
- Strengthen the UKSA understanding of the depth and breadth of the global commercial SST sector and the potential **value, opportunities** and **risks** associated with it.
- Develop a **model** for the **current** and **future** supply and demand for services in the global SST market.
- Identify future market segments enabled or impacted by SST.

This executive summary presents the **SST value chain** and **economic modelling**, which in turn feed into a 5, 10 and 20-year **market projection** and an analysis of the Political, Economic, Social, Technological, Legal and Environmental factors (PESTLE) which will shape the future of the SST market.

*NOTE: This report was written before OneWeb filed for Chapter 11 bankruptcy protection. The report considers OneWeb in a manner consistent with the company's published plans. The future of the company's assets (including in space) is currently uncertain, but for the purposes of this report it is assumed that another entity acquires the assets and continues with the published plans. All results should be interpreted with care, subject to business uncertainty attributed to constellation deployments.*

## Value chain

The wider SST value chain encompasses all stakeholders from component manufacturers and software developers to end users. This study focusses on **data**, **catalogue** and **information** providers, who are referred to as **the supply chain**, and **end users demand**. The figure below presents this value chain.




Note: CAM = Collision Avoidance Manoeuvre
***Source: London Economics analysis***

**Detect:** Ground station operators detect/capture data using ground or space-based sensors. Sensors can be optical, radar, laser or use radio frequencies. In GEO, **optical** detection is mostly used, but **radar** applications can contribute to the detection as well. **Radar** detection is preferred for tracking objects in LEO but **laser** ranging applications are a developing technology with a strong potential. In addition, active satellites are commonly detected via **radio frequency** surveying. Finally, an increasing number of **in-space sensors** add to the detection capability.

**Catalogue:** The **processing** and **storage** of observations. The raw data is linked to a known object and its orbital characteristics and is commonly stored in a Two-Line Element (TLE) identification format[1]. TLEs are then stored in a catalogue in a standardised format.

**Predict:** In prediction, the TLE and object characteristics are used to determine the trajectory of objects and assess collision and fragmentation risks in conjunction analyses. If a risk of collision is identified, a conjunction data message is sent to the operator/end user who will decide if action is required.

These three activities constitute the supply chain through which raw data is transformed into valuable **information** for end users.

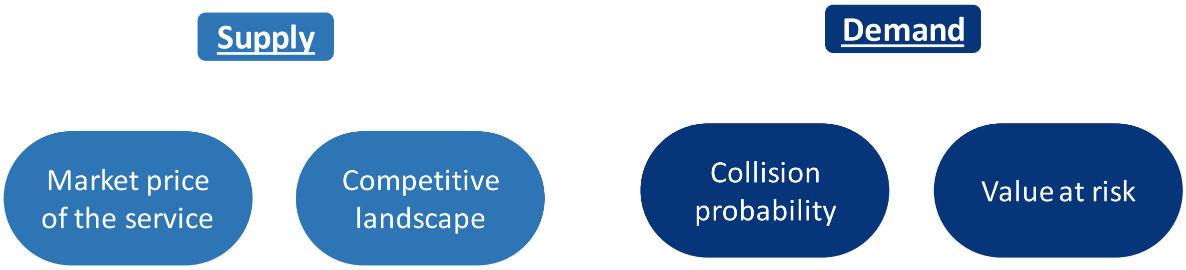
The **demand** is characterised by end users and more precisely, satellite operators. If a satellite is hit by debris, the damage will range from capability reduction (case of Sentinel 1A, 2016[2]) to complete annihilation (case of Iridium-Cosmos, 2009[3]). In the latter, this translates into a loss of the asset and a cancellation of any revenue stream from the data provision.

[1] TLE : http://spaceflight.nasa.gov/realdata/sightings/SSapplications/Post/JavaSSOP/SSOP_Help/tle_def.html
[2] https://sentinels.copernicus.eu/documents/247904/2142675/Sentinel-1A_Debris_Collision_August_2016_MPC.pdf
[3] http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100002023.pdf

## Economic modelling – Supply & demand

The economic model is structured as the demand and supply side of the SST market and the market product is **SST information**. The size of the market is determined by the quantity of information required to avoid a collision.

The components of demand can be combined to assess the expected loss of value. **We use the expected loss as a proxy to measure the addressable market**. It reflects (with limitations) what operators would be willing to pay to access information allowing them to determine when to execute a manoeuvre, potentially saving their asset from a disastrous ending.




***Source: London Economics Analysis***

The quantity of information is determined by the population of active satellites (**demand**) and the quantity of debris (**externality**). The presence of debris is distributed unevenly in orbit and some regions suffer from greater density (e.g. sun-synchronous orbit, SSO). Similarly, not all satellites are located within the same orbital plane and therefore are affected differently, proportionally to the local debris density.

The expected loss is estimated by combining the collision probability of each satellite, modelled with ESA software **MASTER** and **DRAMA**[4]**.** The value at risk is estimated using public data on manufacturing and launch costs which are combined to give the '**replacement value**' of a satellite. The model takes into account objects **greater than 10 cm** (for which the collision is assumed lethal) and **commercial** satellites, with **thrust capability**.

For future launches, we assume that the main market driver for SST services is led by the rapid rise of **constellation spacecraft**. We combine various market forecasts to determine likely launch patterns and estimate the proportion of non-constellation satellites. We assume these replacement satellites are of a similar mass and design to the satellites they replace and are positioned within the same orbital slot as vacated by the satellite they have replaced.

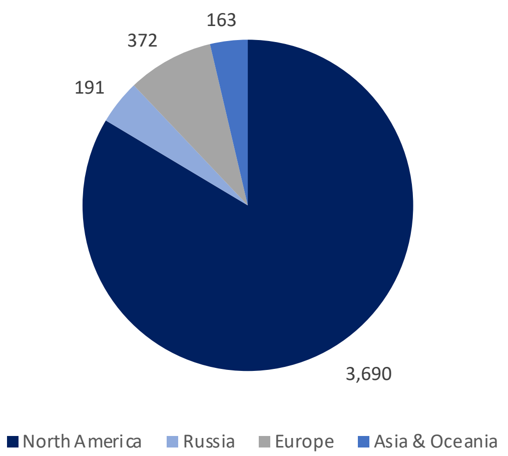
# Evolution of SST

For this study we assume that we can use the expected loss as a **proxy for estimating the value of services** which can be offered by SST providers. We only consider commercial satellites with a launch mass of 50 kg or above, as satellites below this are assumed to lack the propulsive capabilities required to respond to collision warnings. This is the case with many smaller satellites, such as CubeSats or nanosats, which tend to be designed on a low-cost basis. The first step towards calculating this loss is to determine the value at risk.

[4] MASTER = Meteoroid and Space Debris Terrestrial Environment Reference; DRAMA = Debris Risk Assessment and Mitigation Analysis

## Commercial value at risk in LEO

Based upon publicly available satellite data our analysis suggests that at present, the vast majority of commercial satellite value at risk in LEO is owned by organisations registered in **North America**. Next, **European operators** cumulatively have the greatest value at risk in LEO, which is around twice that of **Russian** and **Asia-Pacific operators.**

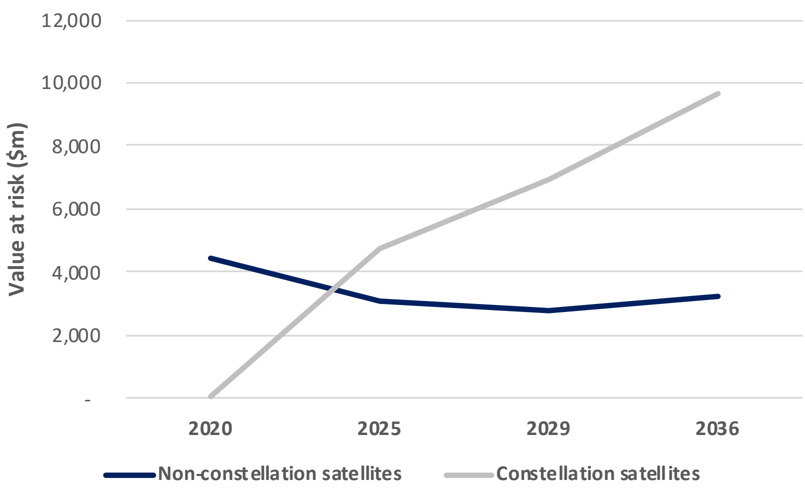



Note: Values adjusted for inflation and based on USD 2020 prices, inclusive of launch costs. Reflects satellites still within design life only.
***Source: London Economics analysis***

Based upon the definition of the addressable market above and the annual collision probabilities from the DRAMA simulation, we estimate the total expected loss annually to commercial satellite operators to be in the region of **$22.8m in 2020.** This is based upon a population of **216** commercial LEO satellites operating within their design lives at the start of 2020.

The distribution of satellite value is expected to change over time. Sizable **satellite constellation operators,** sometimes known as 'megaconstellations', began launching first generation spacecraft in 2019. These constellations are expected to increase the number of active satellites in LEO by several thousands, if not tens of thousands.

Individually, each constellation satellite is expected to be worth around $1m or less to manufacture, but cumulatively each constellation adds up to a sizable value at risk. Our projections informed by public release from constellation operators, shows that the total value of all constellation spacecraft is expected to exceed that of the cumulative value of all other LEO satellites during the early 2020's as shown in the figure below:

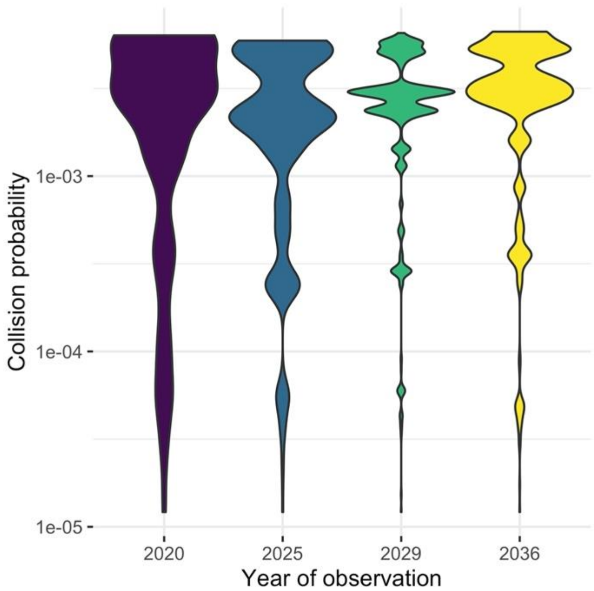



***Source: London Economics analysis***

**The total value at risk is expected to increase by a factor of 3.5 by 2036.**

## How does the collision risk in LEO change?

With the DRAMA software, we were able to estimate the collision probability for a subset of **216** non-constellation spacecraft and over **16,000** constellation satellites in 2020, 2025, 2029 and 2036.[5] The **violin plot** below shows the distribution of collision probabilities, for each year. A violin plot is simply a mirrored statistical distribution. It shows that in 2020, collision probabilities are concentrated at the upper end of the distribution (probabilities greater than 1 in 1000) with a long tail of low probabilities. This distribution changes over time showing an accumulation of higher probabilities towards the upper end of the distribution. This also shows that the maximum probability increases over time (after a small decrease from 2020 to 2025 owing to a peak in solar activity in 2025).




***Source: London Economics analysis***

[5] This time period was determined by the DRAMA software which had limitations in the years for which we could compute values.

The maximum annual collision probability in LEO in 2020, is around **1 in 157** (90 times higher than the GEO maximum) and the lowest is **around 1 in 85,000**. The average lies around **1 in 320**.

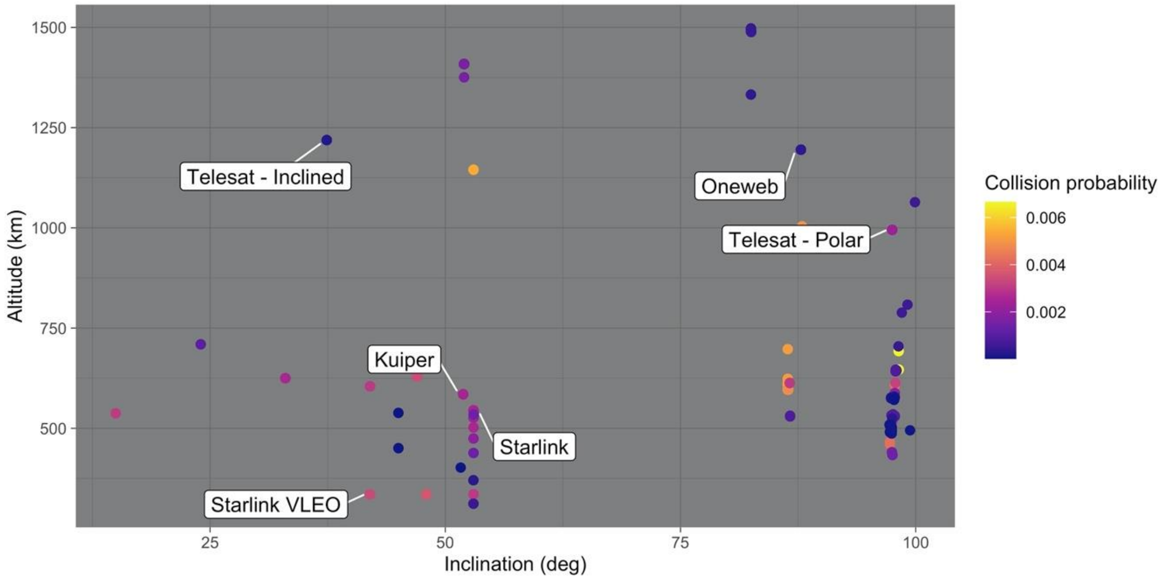
In 2025, the projected collision probabilities increase overall with an average collision probability of **1 in 370** and a maximum annual collision probability of **1 in 170**. The sun-synchronous and polar orbits are still the most densely populated and face the largest collision probabilities.

At this stage the deployment of constellations is well underway and has increased the number of active assets in orbit. Starlink should have completed its first phase and placed over 4,000 satellites into orbit, while OneWeb is finalising its deployment of 1,500 satellites.

In 2029, collision probabilities still increase, and the average is around **1 in 340**. The maximum annual collision probability is **1 in 153**. Constellations are almost all fully operational and Starlink numbers more than 11,000 satellites. OneWeb has 1,980 and Kuiper 1,180.

In 2036, constellations are complete and, assuming replenishment, the number of active spacecraft is constant over time. The maximum collision probability peaks at **1 in 150** and the average remains in the range of **1 in 290**. The greatest changes are localised in regions where the density has increased due to constellations.

The plot below shows satellites distributed over altitude and inclination and are coloured by collision probability. Brighter dots show higher collision probabilities. The number of visible satellites under-represents the real number of satellites as most of them are nested in constellations (not visible in 2D).




Note: collision probabilities simulated for the year 2036.

***Source: London Economics analysis***

## What additional demands will be placed upon operators?

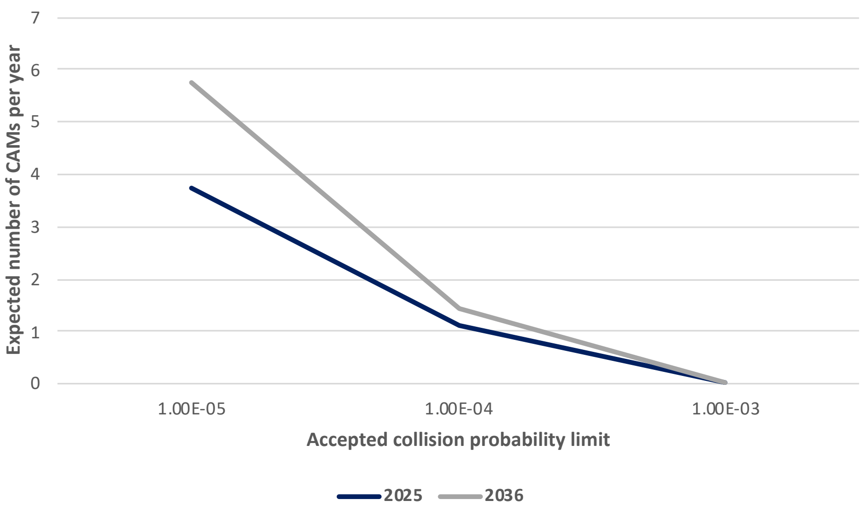
With the projected vast increase in the number of spacecraft in Earth orbit in the coming years, the amount of conjunction messages delivered annually to operators will undoubtedly increase. One can only imagine the amount of data required to assess all potential encounters in LEO once all megaconstellations are deployed. We know that currently on average in GEO, 450 conjunction messages are delivered per year per satellite of which a very small number results in a manoeuvre.

The density of debris in LEO is larger than in GEO. Logically then the number of conjunction data messages and manoeuvres will be higher. The analysis of future demand has also demonstrated that collision probabilities will increase alongside the density.

As a result, a growing demand is expected in the future. The supply chain will have to develop new enhanced methods and employ more skilled staff to process and analyse the data. The necessity for an increased workforce has been confirmed in interviews with industry stakeholders as a key resource for the treatment of the data.

The human brain however has its limits and it is likely that there will be a need for additional computational power in the future. The figure below shows the projected increase in frequency of collision avoidance manoeuvres (CAM) between 2025 – 2036 for each VLEO (Very Low Earth Orbit) satellite in the Starlink constellation. Dependant on how risk averse the operator is, by extrapolating the results below across the entire 11,000 modelled satellites in the entire constellation, the simulation suggests that by 2036 operators would need to process as many as **72,000 conjunction warnings**.

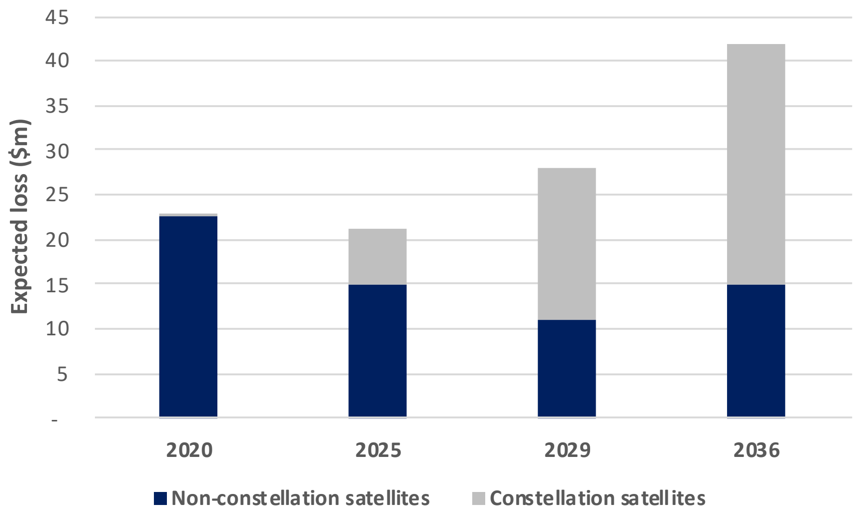
Clearly such volumes of data are beyond the abilities of human led analysis. The use of artificial intelligence techniques will be required to ensure that most (if not all) warnings are treated using reasonable capital and human resources.




***Source: London Economics analysis & DRAMA outputs***

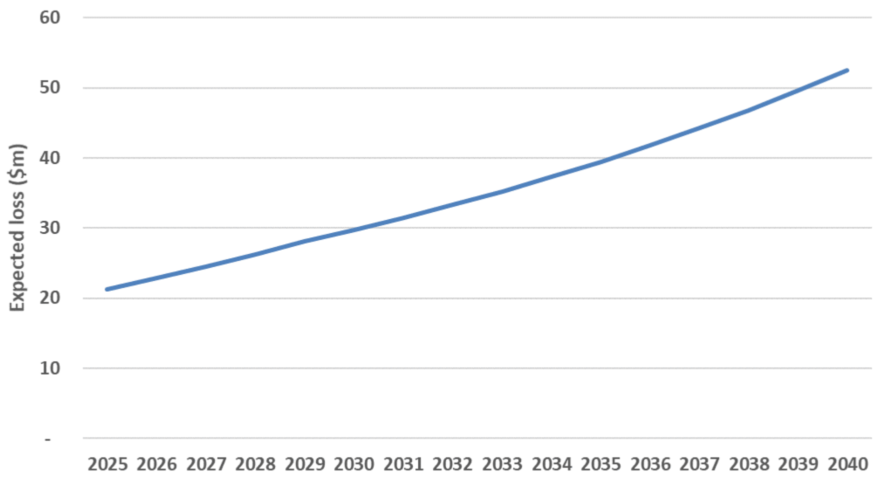
## How does the potential demand in LEO change?

As the value at risk in LEO shifts from non-constellation satellites to those forming the constellations, accordingly the primary source of demand from commercial operators also shifts. By 2025 approximately one third of demand is from constellation operators, which then overtakes the cumulative demand for services from non-constellation operators towards the end of the decade. By 2036 all the first-generation satellites from each of the four main constellation operators modelled have been launched and the majority of the expected loss is from constellation spacecraft operating in highly congested orbits.




***Source: London Economics analysis***

Examining the wider trend of growth in expected loss over a 5-20-year period shows an increasing curve as year on year growth begins to accelerate in the 2030's.




***Source: London Economics analysis***

## Overview of results

By 2040 our study estimates that the potential global market for LEO commercial SST conjunction warning services could be worth as much as **$52.5m (£41.6m)**[6]. It should be noted that with the progression of time, the percentage of users who opt for paid SST services should increase as LEO becomes ever more congested and the provision of timely, accurate SST data become ever more essential.

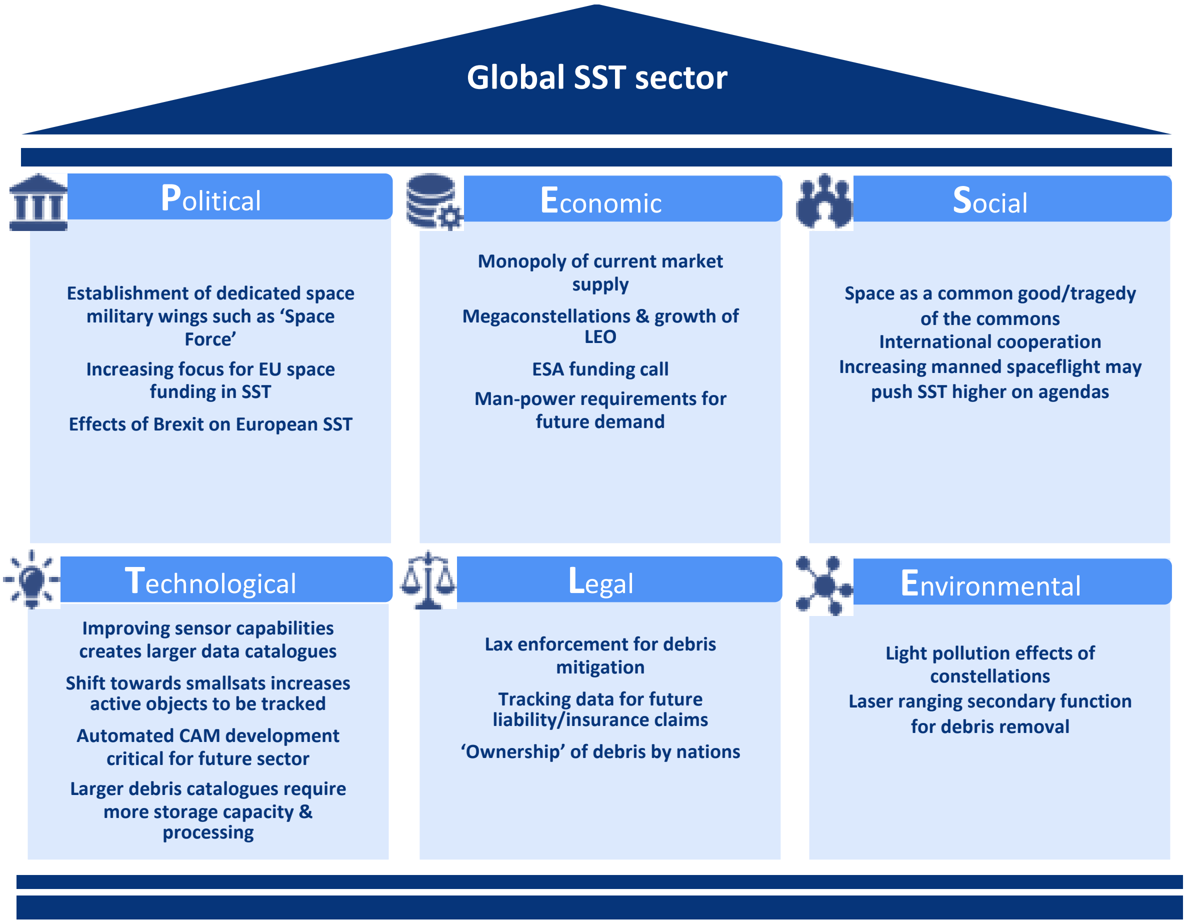
Additionally, we estimate that the current value of the GEO market is around **$1.2m (£0.93m)**, which is unlikely to fluctuate greatly in the next couple of decades without a major change in the risk factors to satellites in this orbit. Should for example a major fragmentation event take place, then

[6] Values in intervening years extrapolated assuming fixed CAGR, assumes USD/GBP xe.com exchange rate of 0.79254 (15/03/20)

historical analysis suggests the cumulative risk to satellites could increase by around 10%, with a corresponding increase in the annual expected loss.

## Factors which will the shape the future SST market

In order to understand the future developments within the SST market, a full and thorough analysis of the sector was undertaken using a '**PESTLE**' framework. The PESTLE analysis considers the Political, Economic, Social, Technological, Legal and Environmental factors that will impact upon the development of the sector in the coming years. The key findings of the analysis are summarised in the figure below.




***Source: London Economics analysis***

SST information will provide a vital role in the development of several nascent subsegments of the wider space industry. Many of the factors identified as part of the PESTLE analysis will have critical implications shaping how these subsegments develop in the future. The following services have been identified as industry enablers:

- **Satellite servicing** – docking activities for refuelling and repair of damaged or aging satellites rely upon accurate and timely information relating to the position of both servicer spacecraft and targets, as well as the location of hazardous debris in the vicinity.
- **Commercial space debris removal services** – initiatives to remove failed or defunct satellites from valuable orbital regions similarly rely upon the fidelity of SST data

- **Automation of collision avoidance** – with frequency of conjunction warnings for active satellites set to skyrocket in the near future, especially for constellation operators, satellite operations based upon human-led analysis are likely be insufficient. SST data will be required to feed into sophisticated autonomous 'Big Data' based or machine learning software to manage the vast increase in the number of objects in orbital space.
- **Manufacturing in space** – both commercial ventures and assembly of spacecraft in-orbit will need SST information to ensure the security of operations.
- **Space tourism/commercial space stations** – safety of astronauts is paramount for any manned spaceflight activities, and SST information will play a key role in safeguarding the lives of public and private sector efforts.

# 1 Introduction

The UK Space Agency (hereafter UKSA) have commissioned London Economics to undertake a study investigating the current state of the commercial space surveillance and tracking market. The study assesses the future developments of SST for the UK space sector the UK's position within the global market.

Space surveillance and tracking (SST), also known as space situational awareness (SSA) outside Europe, is defined as the activity for detection, tracking and cataloguing of space objects to determine their orbits and predict future collisions, fragmentations and re-entry events of satellites and/or debris. This is achieved using sensors, usually radars, telescopes and laser-ranging systems, to generate data on the position of space debris and a data centre to process and analyse the sensor data.

For the purposes of this study we assume that the terms 'space surveillance and tracking' and 'space situational awareness' are interchangeable.

## 1.1 Objectives

The study objectives are the following:

- Strengthen the UKSA understanding of the depth and breadth of the UK commercial SST sector and the potential **value, opportunities** and **risks** associated with the global SST industry.
- Develop a **model** for the both the current and future supply and demand for services in the global SST/SSA market.
- Identify future market segments enabled or impacted by SST/SSA
- Assess risks & barriers to UK firms in addressing commercial global demand
- Identify UK beneficiaries from future tracking/awareness activities
- **Benchmark UK government offering** in SST/SSA sector against support from other governments

## 1.2 Approach

In a first step, we establish the **SST value chain**, and identify **key players** currently active within the market. The value chain categorises the different types of organisations in the industry and is used as the starting point for the economic model of the SST sector. The value chain is divided into the demand and supply side of the SST market.

In the second step, we develop an economic model which provides quantitative estimates for both the current and future values of global SST market demand, from 2020 until 2036 (with extrapolation to 2040). These demand value estimates are segmented by the following criteria:

- Orbits of satellites (e.g. LEO & GEO)
- Commercial users of SSA services geographical regions
- Different SSA services where possible, though this study focuses primarily on the demand driven by the need for conjunction analysis

The above analysis then feeds into a 5, 10- and 20-year projection of the market. We also identify technology spillovers and externalities which SST activities may create or enable. In addition, the impacts of any potential changes in future legislation are considered.

With a specific focus on the UK, the study undertakes a strengths, weaknesses, opportunities and threats (SWOT) assessment of the UK SSA domain, which is complemented by a PESTLE analysis of the UK SSA industry. Both of these approaches support identification of the risks and barriers to the UK's participation in this market and provide a framework to understand the UK's position in the global marketplace.

## 1.3 Caveats and limitations

- The study focuses on the commercial demand for SST. It is recognised that non-commercial spacecraft operators also benefit from the use of SST. Information on the use and value of SST by government and military was not possible to obtain as part of this study and as such are not considered in this study.
- The value of SST to commercial operators is based on publicly available information. This includes satellite manufacturing costs, satellite technical data or SSA service fees. The collection of private information from companies was not available within the study scope.
- The study assumes that present information regarding developments in space technology such as megaconstellations proceed as currently planned. The concepts perceived to be the more likely to come to market have been modelled as being representative of this demand. We have assumed or approximated certain details such as orbital elements of satellites or mass and size of satellites where precise specifications are not currently known based upon the most representative data available.
- This study does not predict engineering related success or failure rates of satellite or rocket technology.
- Due to the nascent state of this market, detailed financial data relating to turnover of companies is not typically available, and as such no market share estimates are presented. The study does however identify some of the leading organisations based upon more qualitative data available at the time of writing.
- The valuation methodology for spacecraft exclude the commercial turnover associated with it. The data is not always publicly available and the attribution of a certain share of the revenue, to a specific satellite depends on multiple parameters such as the specific service or the penetration rate. This is out of the study scope.

The report proceeds in the following way, **chapter 2** defines the value chain and the value of information, **chapter 3** presents the methodology and assumptions for the economic valuation of the market, **chapters 4 and 5** present respectively the results for the GEO and LEO market. In **chapter 6** we look at the prospects of future markets and introduce the SWOT and PESTLE analyses centred around UK capabilities. **Chapter 7** draws the concluding remarks.

*NOTE: This report was written before OneWeb filed for Chapter 11 bankruptcy protection. The report considers OneWeb in a manner consistent with the company's published plans. The future of the company's assets (including in space) is currently uncertain, but for the purposes of this report it is assumed that another entity acquires the assets and continues with the published plans. All results should be interpreted with care, subject to business uncertainty attributed to constellation deployments.*

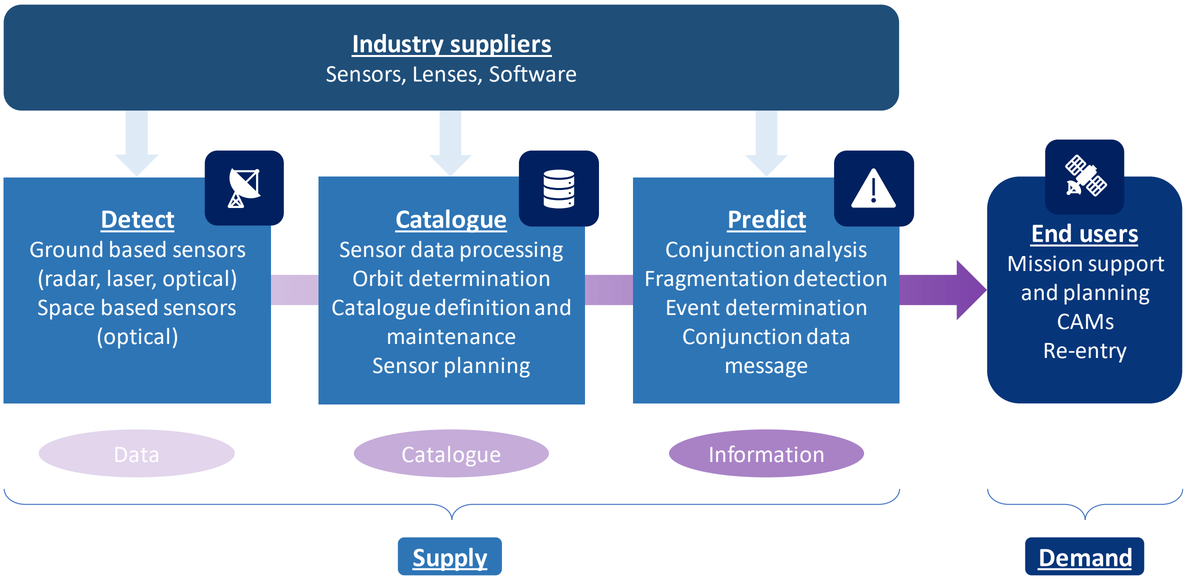
# 2 Value chain & associated considerations

In this section, we define the SST market by differentiating the supply and the demand. We also define the central product of the market as being **information** and the methodology used to estimate its value. The objective is to understand how the information flows throughout the value chain and what are the characteristics influencing its market value.

## 2.1 Definition of the value chain

The SST wider value chain encompasses all stakeholders starting from component manufacturers and software developers to the end users. The analysis focusses on data, catalogue and information providers, who are referred to as the supply chain, and end users, demand. The figure below presents this value chain.

**Figure 1 The wider SST value chain**

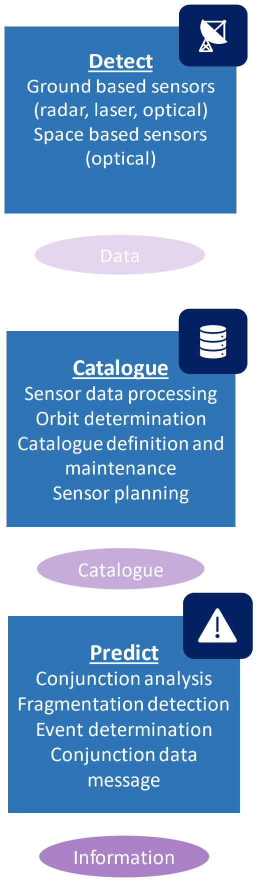



Note: CAM = Collision avoidance manoeuvre

***Source: London Economics analysis***

The supply side can be split into two categories: 1) industrial suppliers who manufacture sensors and spare parts and develop software for data storage and analytics; and 2) data and information providers who detect, catalogue and predict risks. The analysis focusses on the latter since the principal objective is to determine the value of information (VoI) and what end users are willing to pay for it. Industrial suppliers respond to the demand for inputs from the data, catalogue and information suppliers which influence the total production cost of data.

The **supply** can be split into 3 main activities.




**Detect:** The detection/capture of data is realised by ground station operators, using ground or space-based sensors. Sensors can be optical, radar, laser or even using radio frequencies. In GEO, **optical** detection is mostly used but **radar** applications can contribute to the detection as well. **Radar** detection is preferred for tracking objects in LEO but **laser** ranging applications are a developing technology with a strong potential. In addition, the detection of active satellites is commonly done via **radio frequency** surveying. Finally, an increasing number of **in-space sensors** add to the detection capability.

**Catalogue:** Once the raw data is captured, it needs to be processed and stored to be accessible to users. The raw data is linked to a known object and its orbital characteristics (orbit determination) and is commonly stored in a Two-Line Element (TLE) identification format[7]. This data format contains the NORAD and COSPAR identification numbers[8], the epoch and orbital characteristics. All TLEs are then stored in a catalogue, in a standardised format. The resulting catalogue(s) is the central product of the value chain.

**Predict:** In prediction the TLE and object characteristics are used to determine the trajectory of objects and assess collision and fragmentation risks in conjunction analyses. If a risk of collision is identified, a conjunction data message (CDM) is sent to the operator/end user who will decide if action is required. It is this information that has value to the satellite owner. This value depends on a range of factors.

These 3 activities constitute the supply chain through which raw data is transformed into valuable **information** for end users.

The **demand** is characterised by end users and more precisely, satellite operators. The core business of a satellite operator is the provision of data and applications using these data (EO, GNSS, satcoms). If a satellite is hit by debris, the damage will range from capability reduction (case of Sentinel 1A, 2016[9]) to complete annihilation (case of Iridium-Cosmos, 2009[10]). In the latter, this translates into a loss of the asset and a cancellation of any revenue stream from the data provision.

To avoid this situation, satellite operators rely on constant monitoring of the satellite's surroundings. They rely on the information provider who is sending a **conjunction data message** if the collision probability gets below a given threshold (the specific threshold may depend on the type of owner and the location of the satellite). The operator can then decide to carry out a collision avoidance manoeuvre or not.

Unnecessary manoeuvres can be avoided if operators are provided with a more precise and robust conjunction analysis, in which case the expected loss is minimised.

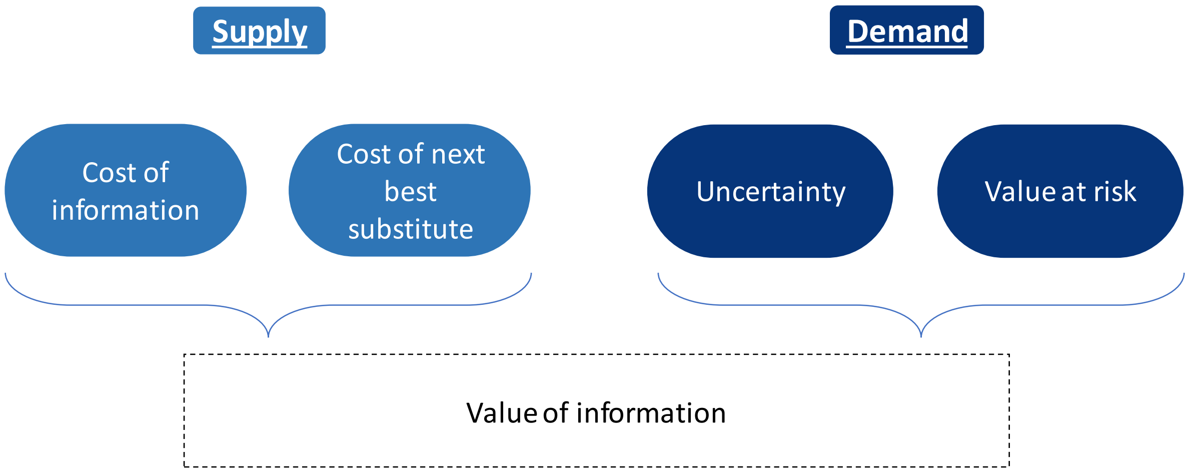
## 2.2 Definition of the value of information

The value of information defines the market price of the product under consideration. In this study, the product is SST information. The VoI can be split into several elements, each influencing its

[7] TLE : http://spaceflight.nasa.gov/realdata/sightings/SSapplications/Post/JavaSSOP/SSOP_Help/tle_def.html
[8] NORAD and COSPAR: http://celestrak.com/columns/v04n03/
[9] https://sentinels.copernicus.eu/documents/247904/2142675/Sentinel-1A_Debris_Collision_August_2016_MPC.pdf
[10] http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100002023.pdf

market value. Macauley (2006)[11] defined these elements as the uncertainty of the decision maker, the outcome at stake, the total cost to use/process the information and the price of the next-best substitute.

**Figure 2 The components of the value of information**




***Source: London economics analysis***

On the demand side, the **uncertainty of the decision maker** (the satellite operator) affects the risk of collision. It depends on the relative velocities of the colliding objects, the orbital location, the debris density and the size of the satellite. In the SST market, we model the uncertainty of the decision maker by the collision probability associated with a spacecraft.

The **outcome at stake** is the satellite and its associated revenue. If the satellite is active, it provides a constant flow of revenues. Any interruption or reduction of lifetime will reduce the revenue stream of the operator. Hence if the satellite collides with a large debris, the consequence is the termination of the mission and a loss of all future revenue. For the purpose of the study, we look at the replacement value of satellites.

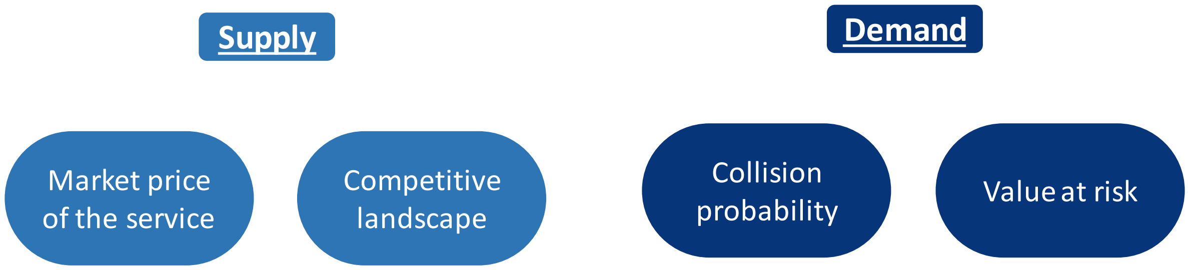
Looking at suppliers, the total **cost to process the information** is determined by the cost of producing the information in the supply chain. This encompasses the capital expenditures (e.g. sensors and computers) and operational expenditures (e.g. manpower). In this report, this information is proxied by the market price of services.

The last parameter described by Macauley is the **next-best substitute**. Substitutes are simply another source of information and in this case, it can be any other SST information supplier. The access to SST information can come from different sources but are constrained to the physical environment in which debris populations are evolving.

Figure 3 illustrates the components of the value of information applied to the SST market.

[11] Macauley. 2006. The Value of Information; Measuring the Contribution of Space-derived Earth Science Data to Resource Management

**Figure 3 The components of the value of SST information**




***Source: London Economics analysis***

The components of the demand can be combined to assess the expected loss of value. This loss is a key indicator for the market. **We use the expected loss as a proxy to measure the addressable market**. It reflects what operators would be willing to pay to access information allowing them to determine when to execute a manoeuvre, potentially saving their asset from a disastrous ending. This lies in the idea that consumers are willing to pay for information given that the expected benefit is greater with the information than without.

The components of the supply indicate the status of the market. If a small number of firms compete, the price of the service is likely to be higher than the consumer's willingness to pay for it and therefore will capture additional profit margin from the consumer. If the number of competitors is high enough however, consumers have a greater bargaining power and the price for service is lower.

In the following section, we present the methodology we use to quantify and qualify these parameters and how we use them to determine the value of the market.

# 3 Methodology

In this section we set out the approach to modelling the SST market and the value of information in this market. The economic model is structured as the demand and supply side of the SST market and the market product is **SST information**. The size of the market is determined by the quantity of information required to avoid a collision.

The section is split into **two parts**. In the **first** subsection we model the **demand for information**. In the **second** subsection, we look at the **supply chain** with a more qualitative approach, to analyse the structure of the supply chain.

While the demand side gives us an indication of the addressable market size and the value of information to operators. We model the value of information to operators as the **expected loss** if a satellite collides with debris. The analysis of the supply side will tell us more about the structure of the supply chain and what is the current structure of the SST market.

## 3.1 Modelling of the demand

This section sets out the approach to modelling the demand. First it describes how we estimate **space debris density and the risk of collision** at different orbits. Second it illustrates how we estimate **the value at risk**. Finally, the combination of both inputs gives the **expected loss** at a given date.

**Figure 4 Computation of the expected loss**


***Source: London Economics analysis***

### 3.1.1 Space debris density, risk of collision and uncertainty

The quantity of information is determined by the population of active satellites (**demand**) and the quantity of debris (**externality**[12]). The presence of debris is distributed unevenly in orbit and some regions suffer from greater density (e.g. sun-synchronous orbit, SSO). Similarly, not all satellites are located within the same orbital plane and therefore are affected differently, proportionally to the local debris density.

Spacecraft distribution depends on the mission. For instance, earth observation (EO) satellites are often placed in SSO so that the power provision from solar arrays is constant.

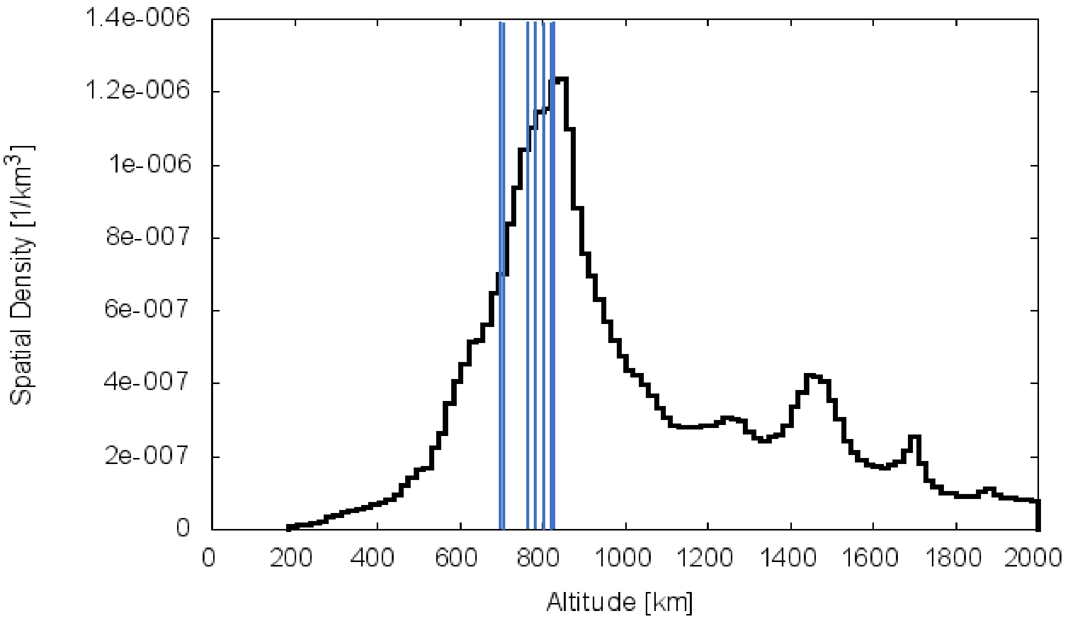
This uneven distribution means that the demand for information is different between orbital regions, specific missions and type of ownership.

[12] An externality occurs when the consumption of a good by one player affects activities of other players (e.g. pollution induced by consumption).

The density of debris imposes different threat to satellites and the most densely populated areas will have a greater **collision probability**. The density is computed using ESA software MASTER-2009. Figure 5 shows an output of the simulation of debris density in LEO, in 2019. It shows that the spatial density (objects per km$^3$) as a function of the altitude.

The spatial density peaks at an altitude between 800 km and 900 km. The blue lines show as an example where ESA's Sentinel satellites are located and illustrate that the risk of collision is different for each satellite.

**Figure 5 Spatial density as a function of altitude in LEO**




Note: MASTER-2009 simulation; 2019 population; Each blue line indicates (approximately) the location of a Sentinel satellite.

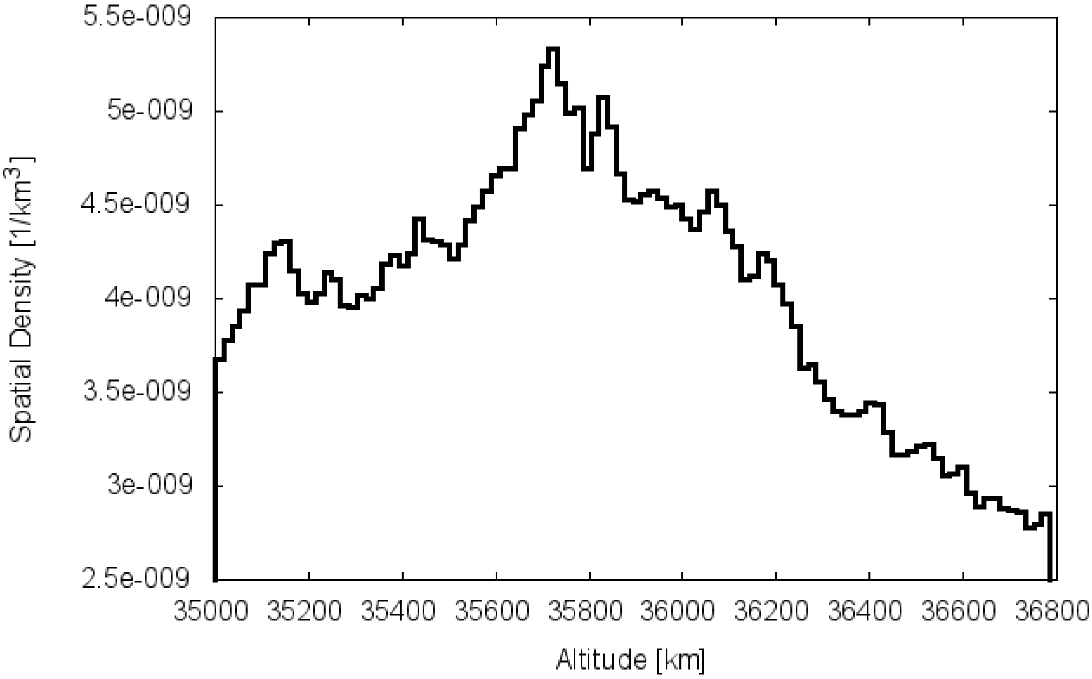
***Source: London Economics analysis***

This difference in risk translates into a difference in uncertainty which is the first parameter of the value of information, as defined by Macauley. If the collision probability increases, the decision maker becomes more uncertain. Therefore, information pertaining to denser zones is more valuable.

The collision probability takes into account additional parameters including spacecraft size (surface area / radius), precise orbital characteristics, and mass and orbit uncertainties. The latter accounts for potential simulation errors regarding satellite position.

In GEO, the density is much lower, as pictured in the following figure.

**Figure 6 Spatial density as a function of altitude around the GEO arc**




Note: MASTER-2009 simulation; 2019 population.

***Source: London Economics analysis***

The **size of the satellite** has a strong influence on the collision probability and larger objects occupying more space will have greater collision probabilities associated with them. The size of satellites is measured as the average cross-sectional area at risk of collisions. Our model uses the average cross-sectional area of satellites (computed by averaging n cross-sections taken from n different angles, see Annex 1 for details). This metric is provided by the DISCOS database[13] and proxied by nearest matching when the information was not available.

Using the DRAMA software, it is possible to simulate the collision probability of a spacecraft at a given point in space and time. The software uses the MASTER catalogue of debris and can simulate the collision probabilities, required change in orbital velocity (delta-V) and fuel requirements and annual expected number of collision avoidance manoeuvres (CAMs)[14].

The modelling assumes that a **collision leads to complete loss of the spacecraft,** and partial satellite failures due to smaller debris collisions are out of scope. This is owing to the DRAMA simulation only considering debris greater or equal to 10 cm in diameter, with the capabilities of the software limited to the expected number of collisions per year without differentiating whether the collision is lethal or not. The lethality depends on the size of the debris but also the location where the debris hits the satellite. An impact on a solar array will limit the energy provision without necessarily ending in a total failure. If the bus is hit however and a critical component such as motherboard or battery is damaged, then the failure is total.

[13] https://discosweb.esoc.esa.int/

[14] Mathematical specifications behind the simulations can be found in Sanchez-Ortiz et al. (2006). CAM during spacecraft mission lifetime.

To compute the **collision probability**, we use the TLE (two-line elements) of individual satellites as of 22nd January 2020[15]. We have retrieved the data from the Celestrak database[16] which publicly provides the orbital characteristics for all man-made objects greater than 10 cm in diameter. The TLE then feeds into the DRAMA calibration pane to which we add the size of the spacecraft (from DISCOS).

The output of the computation is a **cumulative annual collision probability (ACP)**.

### 3.1.2 Values at risk

The second component required to compute the expected loss is the **value at risk**. To determine the value of the satellite population at risk, we use publicly available data regarding the asset value of each spacecraft.

This is defined as the **manufacturing cost** of the satellite at launch, which is typically reflected by the insured value of the satellite, plus the **cost of launching** the satellite. These figures do not take into account the revenues generated by the spacecraft during its lifetime, as this information is not typically available publicly and varies considerably based upon the satellite's purpose and corresponding region covered by its ground track.

The sum of manufacturing and launch costs is defined as the total **replacement value** or **value at risk**.

#### Satellite bus values

When a commercial satellite suffers from a failure in-orbit, or when a launch failure occurs, resulting in the termination of the mission, it is common for the industry media to report the **insured value** of the satellite. Such values are also sometimes revealed in the **annual public filings** required by large satellite operators in certain countries, as well as in **pre-launch media articles**. We used this information to estimate the value of reference spacecraft at the beginning of their life.

For bookkeeping purposes, satellites are assumed to **depreciate linearly** over time. They start their mission at maximum value and achieve a net value of zero upon reaching the end of their design life. Whilst in practice a satellite may continue to be a revenue generating asset beyond its design life provided it has enough reserves of fuel onboard, valuing a spacecraft during this period is problematic owing to the lack of commercially available information.

Once the original satellite value at the **beginning of life** (BOL) is known, we can then estimate the value of a satellite at any point during its design life. Conversely, if the value of a satellite at the point of total failure is known, we can then determine the original value at BOL.

Many spacecraft are typically based on the same generic base platform or satellite bus, with customisations depending on the intended mission or operating environment. This allows for **economies of scale** during the manufacturing process, as well as ease of manufacture and assembly, plus the use of heritage components proven to operate in the harsh environment of space.

Larger, more expensive satellites such as those found in GEO or MEO tend to be built by a **small number of satellite manufacturers globally**, which account for most of spacecraft in-orbit. Whilst

[15] Date when we extracted the TLE from the Celestrak database.
[16] https://celestrak.com/

the complexity of design or customisations at a subsystem level may introduce a range of manufacturing values for satellites based on the same bus type, for the purposes of this study we assume that the manufacturing cost per kilogram is constant for spacecraft produced by the same manufacturer. Thus, by multiplying this value by the known launch mass of the satellite we can estimate the BOL value on a per satellite basis.

For the smallest of satellites which are commonly found in LEO, such spacecraft often conform to sizing form factors based upon the standard 1U cubesat unit, meaning that for example any two 3U cubesats are of approximately the same size and mass. Additionally, values of such spacecraft are comparatively low versus the larger satellites described above, such that the absolute difference in value between two cubesats is typically an order of magnitude lower than the difference between two GEO satellites produced by the same manufacturer.

As such we make the simplifying assumption that reference manufacturing costs per kilo for satellites of a certain size or mass are broadly similar, and can be used to approximate the asset value of other smallsats manufactured by different organisations. This only is relevant for satellites with a mass greater than or equal to 50 kg, as we assume that lower mass spacecraft lack propulsive capability to benefit from conjunction warnings and are excluded from the population.

Satellites are **primarily** matched to the closest representative cost per kilo value based on the following factors:

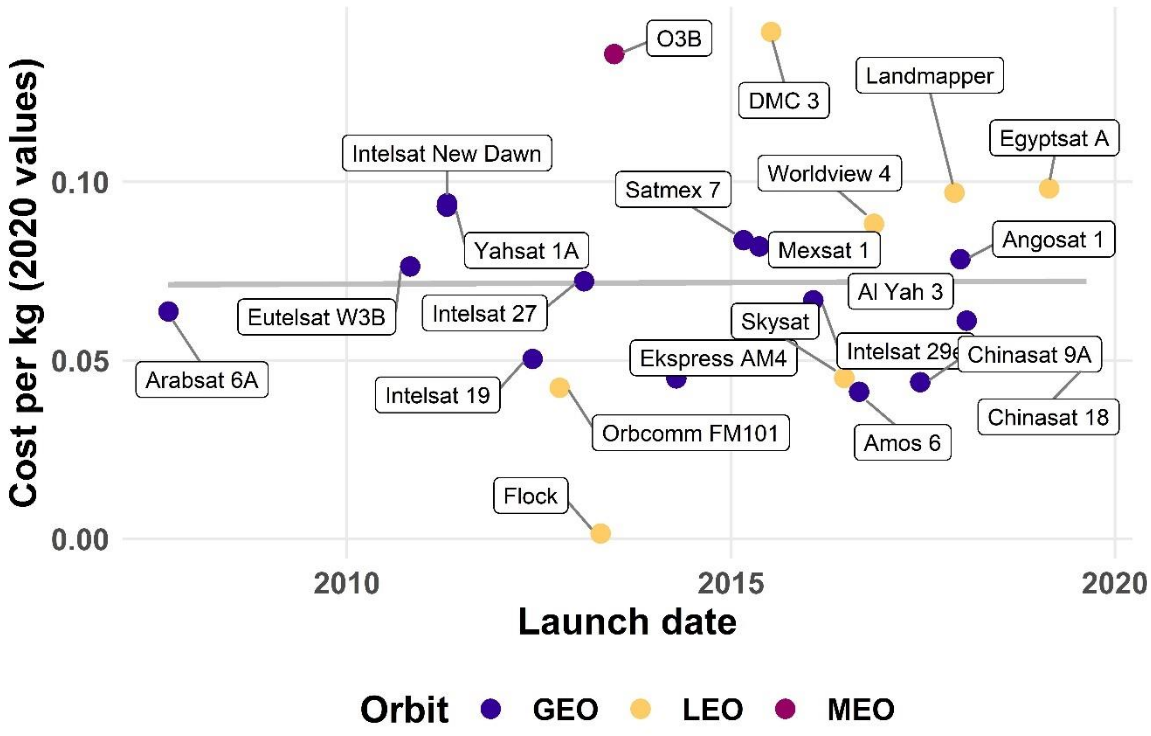
- Orbit;
- Manufacturer; and
- Year of launch.

If a suitable match is not available, then the criteria is **expanded** to include:

- Propulsion type;
- Geographical locality of manufacturer; and
- Mass of satellite.

Finally, if a close enough match is not available, then we use the **average cost per kg of spacecraft** with similar characteristics. The figure below displays a selection of the reference data values derived from asset value and launch mass data, coloured by orbit. The grey line represents the trend over time and shows constant manufacturing cost per kg in real terms.

**Figure 7 Cost of satellites (USDm per kg, 2020 prices)**




***Source: London Economics analysis***

## Launch costs

Recognising that the launch costs represent a sizable proportion of an operator's expenditure, this study also attempts to capture the value at risk from this sunk cost for satellites in-orbit. To achieve this, a similar methodology to the satellite asset valuation is used, whereby a simplifying assumption is made that all satellites can be grouped based on the following criteria:

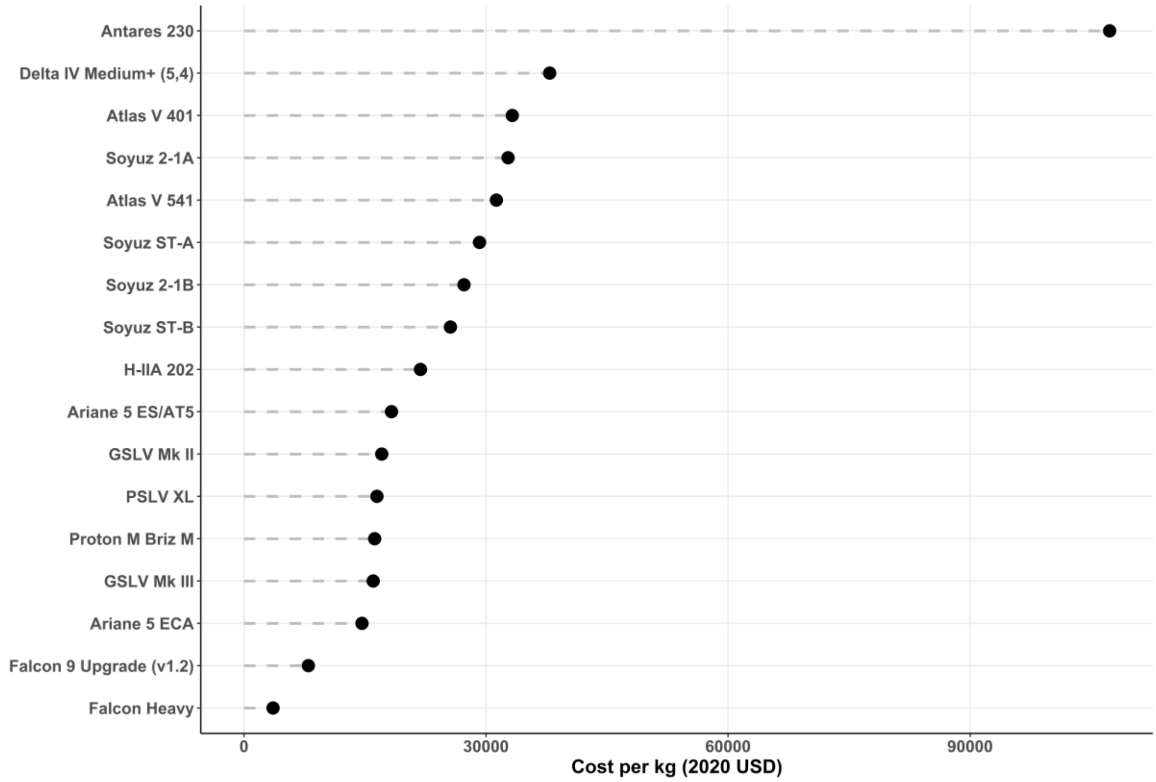
- Target orbit – GTO, LEO (sun synchronous), LEO (polar)
- Mass of satellite (LEO only); and
- Constellation satellites where launch provider has the same parent company.

We use the estimated **launch costs** from 'The Space Report 2018'[17] (adjusted for inflation to 2020 values, see figures below) to calculate the **average cost per kilogram launched** (based on the appropriate launch vehicle performance criteria). We simply multiply the launch mass of the satellite by the launch cost per kilogram to obtain an approximation of the original launch cost at 2020 prices.

Given the assumption taken on the depreciation of the value of the satellite bus and for consistency, we apply the same depreciation rule to the launch costs.

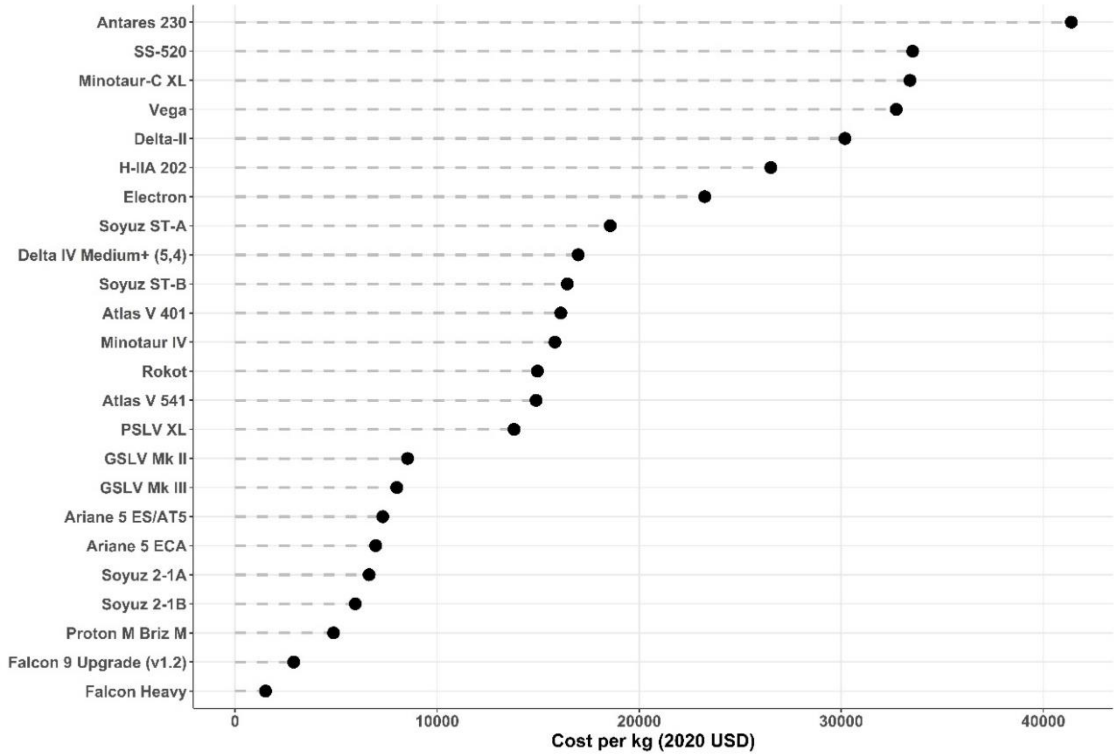
[17] Holst J. & Yukman B. (2018), 'The Space Report 2018', The Space Foundation

## Figure 8 Launch cost per kg to GTO (Geostationary Transfer Orbit)




*Source: London Economics analysis & 'The Space Report 2018' data*

## Figure 9 Launch cost per kg to LEO




*Source: London Economics analysis & 'The Space Report 2018' data*

### Valuing future satellites

Predicting the launch of future satellites is a difficult task. This is because launch schedules are frequently subject to change and funding and business cases behind satellite ventures can collapse at any point prior to launch. In light of these many uncertainties, we make the following simplifying assumptions.

For **LEO** we assume that the main market driver for SST services is led by the rapid rise of **constellation spacecraft**. We combine market forecasts from sources such as Euroconsult[18], SpaceWorks[19] and Nanosats.eu to determine likely launch patterns, and estimate the proportion of non-constellation satellites. Based upon the latest information available in the media, the 20 most likely satellite constellations to be launched into LEO were identified.

This identification was based on published orbital parameters for satellites, funding information and reported satellite launches into orbit prior to the end of 2019. This information forms the foundation of the future LEO model, both in terms of values at risk and active spacecraft modelled for collision frequency assessment within MASTER.

For **GEO** we base our assessment upon the current trends of satellite procurement. Over the course of the last three years global orders of GEO satellites have been lower than in the previous decade,[20] which suggests many GEO operators are monitoring the developments in LEO with respect to communications constellations before committing to orders of expensive new satellites. As such we make the assumption that the **overall population of GEO satellites remains relatively constant throughout the duration of the time period chosen for the study**, with only replacements launched for existing satellites once they exceed their design life and are graveyarded (retired) at end of life, or fail on orbit.

We assume these replacement satellites are of a similar mass and design to the satellites they replace and are positioned within the same orbital slot as vacated by the satellite they have replaced. As such this may represent an overestimation of the GEO demand, as potential future trends such as satellite miniaturisation and digitisation of payloads become more commonplace. The overall figure should however remain within a reasonable margin of error of the true value.

## 3.2 Modelling of the supply

This section sets out the approach to modelling market supply. First, the section summarises our findings on the current **status of the market** and **describes the organisations**, their **characteristics**, the different **services** they provide and defines the **competitive landscape**. Second, we look at the available information about **pricing**.

As mentioned earlier, the approach is more qualitative than for the demand since commercial information is rarely available. We provide quantitative estimates where possible however, which enables provision of an overview of the **status of the market** and also feeds into **future market analysis**. Knowledge about the number of companies and their activities indicates how the **market**

[18] Euroconsult (2019). 'Prospects for the small satellite market 5th Edition', available online at http://www.euroconsult-ec.com/shop/index.php?id_product=116&controller=product

[19] SpaceWorks Enterprises, Inc (2019). 'Nano/Micro satellite market forecast, 9th edition', available online at https://www.spaceworks.aero/wp-content/uploads/Nano-Microsatellite-Market-Forecast-9th-Edition-2019.pdf

[20] Henry, C. (10/09/19). 'GEO satellite orders are up, but full rebound remains to be seen', available at https://spacenews.com/geo-satellite-orders-are-up-but-full-rebound-remains-to-be-seen/

**is concentrated**. It also indicates its **structure** (monopoly, oligopoly) from which it is possible to make assumptions on the ability to address the demand.

**Figure 10 Analysis of the supply chain**


***Source: London Economics***

### 3.2.1 Competitive landscape

The value of information also depends on two other market parameters which are the **market price** of the service, and the extent of **competition**. The cost of information depends on the type of service and the needs of the operator.

There are different services in the SST market:

- Conjunction analysis and collision predictions
- Launch tracking
- Re-entry analysis
- Fragmentation detection and tracking.

The launch tracking is ad-hoc and necessary for the launch phase, and orbit-raising of satellites. As at least one major commercial launch operator is known to operate its own sensors (ArianeGroup)[21] this is expected to be a market which offers limited opportunities for commercial operators. Re-entry analysis is usually needed to detect when satellites are at a low enough altitude to re-enter the Earth's orbit. The need for surveillance comes from the requirement for safety on the ground (humans and material). Prior to a launch, and for the acquisition of a licence, mission agendas must include specifications of the management of re-entries.

Fragmentation detection is also a small subsegment of the market. Fragmentation detection is mostly used for monitoring the proliferation of debris and cataloguing of new debris pieces due to fragmentation events in orbit.

This study focusses on **conjunction analysis and collision prediction**. We focus on this service as it is the most relevant segment of the SST market due to its ubiquity and importance to the survival of assets. Most satellite operators require constant tracking of their surroundings and rely on this service to ensure the survival of their asset.

Table 1, overleaf, presents the commercial companies that have been identified as relevant to the study. It shows which segments of the value chain companies are active. A tick (✓) indicates that the company is active in either data provision, cataloguing and / or information provision.

[21] Lal B. et al (2018), IDA Science & Technology Policy Institute. "Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)"

Of the 20 commercial companies identified, **ten** own sensors and are actively tracking objects, **13** manage a catalogue of objects and **17** provide information about potential collisions. **Nine** companies are fully integrated and active in the three areas.

## Data collection

We distinguish two types of tracking methods: 1) the **continuous collection** of data which is provided by a set of sensors scanning the sky and providing general observations and relative location of space objects, which usually feeds into a catalogue and 2) **ad-hoc tracking** which allows an operator to "rent" a dedicated sensor for a given period and target a specific (or multiple) object(s).[22]

Ad-hoc tracking is particularly important for operators when a collision is expected. The dedicated tracking updates data for conjunction analyses and should reduce the uncertainty vis-à-vis the decision to perform a collision avoidance manoeuvre (CAM) or not.

Companies may also differentiate by target orbits. In the list of identified companies, nine publicly publish information regarding which orbits they service. Three focus on LEO, three on GEO and three have capacity in both GEO and LEO. For the remaining companies, no information was publicly available.

Table 1 also shows most companies are headquartered in North America (14/20), five are in Europe and one in Australia. This does not necessarily reflect the presence of sensors in other locations however (LeoLabs for instance is building a radar array in New Zealand). Since LEO objects do not have a fixed orbital trajectory as with GEO satellites, there is a clear need to have sensors all around the globe to be able to provide a quasi-constant tracking service.

## Cataloguing and maintenance of catalogues

Data catalogues are a key product of the supply chain. They contain the data about objects and feed into applications. Most companies (13/20) possess their own catalogue (to which access is only granted via a subscription process) which is updated with public data or by the company's own capacity if it operates sensors.

Catalogues need to be up to date with the orbital characteristics of objects because they are the foundation of information provision. Conjunction analysis for instance is based on heavy computations that feed into the orbital characteristics of all space objects.

## Information provision

The last step in the supply chain is the service provision. Once the data has been captured and stored, algorithms and software process it and procure different services. 17 companies are active in this segment making it the most active of the supply chain.

A (✓) indicates the companies provides different services including conjunction analysis on which we focus our attention.

[22] Note that we do not include routine telemetry and tracking of satellites performed by ground stations as part of our value chain.

**Table 1 List of commercial organisations active in the SST market as of 2020**

| Company | Data | Catalogue | Information | HQ Location | Target orbit | Type of company |
|---|---|---|---|---|---|---|
| Lockheed Martin | ✓ | ✓ | ✓ | USA | LEO | VL |
| INDRA | ✓ | ✓ | ✓ | Spain | LEO | L |
| AGI | ✗ | ✗ | ✓ | USA | | M |
| Deimos Space | ✓ | ✓ | ✓ | Spain | | M |
| GMV | ✗ | ✗ | ✓ | Spain | | M |
| L3 – ADS | ✗ | ✓ | ✓ | USA | | M |
| Centauri | ✗ | ✗ | ✓ | USA | | S |
| EOS | ✓ | ✓ | ✓ | Australia | LEO/GEO | S |
| Etamax Space | ✗ | ✗ | ✓ | Germany | | S |
| ExoAnalytics | ✓ | ✓ | ✓ | USA | GEO | S |
| Gauss SRL | ✓ | ✗ | ✗ | Italy | LEO/GEO | S |
| Launchspace Technologies | (✓) | ✗ | ✗ | USA | | S |
| LEO LABS | ✓ | ✓ | ✓ | USA | LEO | S |
| Northstar | (✓) | ✓ | ✓ | Canada | | S |
| Numerica Corporation | ✓ | ✓ | ✓ | USA | GEO | S |
| Orbit Logic | ✓ | ✓ | ✗ | USA | GEO | S |
| Polaris Alpha | ✗ | ✗ | ✓ | USA | | S |
| Schafer | ✗ | ✓ | ✓ | USA | | S |
| SpaceNav | ✗ | ✓ | ✓ | USA | | S |
| Vision Engineering | ✓ | ✓ | ✓ | USA | LEO/GEO | S |
| **Total** | 10 | 13 | 17 | | | |

Notes: Type of company; VL = very large, L = Large, M = Medium, S = Small. A ✓ indicates the company is providing this solution, a (✓) shows that the company is developing this capability and a ✗ determines the company does not provide the solutions.

Blank cells for target orbit mean no public data available

***Source: London Economics analysis***

The market however is not only populated by commercial actors. Public organisations such as space agencies and universities also take part in the collection, cataloguing and service provision. The main difference compared to commercial entities is that the data is provided for free.

The reference catalogue space-track.org is a freely available catalogue of all debris and active satellites and is maintained by the $18^{th}$ SPCS (SPace Control Squadron).

Initiatives like EUSST (EU Space Surveillance and Tracking Programme)[23] are built on the need for resilient activities in space. As the EU economy relies on a growing use of space data and because the space environment is becoming more crowded, in 2015 the EU built a consortium of eight member states (France, Germany, Italy, Poland, Portugal, Romania, Spain and the UK) to lead activities for resilient use of space and develop a European SST capacity.

To date, the EUSST provides information to 47 organisations (from 16 different EU member states) and operates 34 sensors.

[23] https://www.eusst.eu/

Larger space agencies like ESA and NASA also possess their own capabilities and provide conjunction alerts to registered users.

### 3.2.2 Segmentation of the market

**Market prices of SST services**

A couple of companies provide public information about their tariffs, such as ExoAnalytics, who provide data for GEO, and LeoLabs, who provide data for LEO. Table 2 summarises the costs information from the two public sources. The only price available from LeoLabs corresponds to a monthly subscription fee of $2,500 per month and per satellite with a discount for constellations.

ExoAnalytics has a broader range of prices, depending on the service, sensors and need of the operator. Their data subscription ranges from $90,000 per month for up to 28 dedicated sensors. The highest value for a monthly subscription is more than $1.1m and offers up to 320 sensors. The tasking of sensors however is an additional expense which depends on the type of telescope and the timing required for receiving the information (faster response is more expensive).

**Table 2 SST Price list (public data)**

| Orbit | Periodicity | Application | Cost | Source |
|---|---|---|---|---|
| GEO | Monthly | Per operator | $90,000 to $1,100,000 | ExoAnalytics |
| GEO | Ad-hoc | Per telescope | $1,850 to $17,725 | ExoAnalytics |
| LEO | Monthly | Per spacecraft | $2,500 | LeoLabs |

Note: The costs for GEO are a gross average and only take into account the range of prices publicly available

***Source: London Economics analysis***

**Orbital region characteristics**

As characterised later in chapters 4 & 5, the LEO and GEO orbital environments have a number of differentiating characteristics. In summary, LEO has a higher density of debris objects per squared km than GEO, with active satellites operating within the sphere it encloses. GEO satellites are spread across the extent of the geostationary arc and are within a few degrees of inclination of the equatorial plane. GEO satellites typically are fixed within their orbital 'box', unless being relocated or operating without inclination control or stationkeeping, whereas LEO satellites typically have a shorter orbital period, with imaging satellites frequently relocated if required to scan ground targets of interest.

In the coming years, LEO looks set to become an even more densely packed region of orbital space owing to the number of proposed spacecraft to be launched. Additionally, the risk profiles of the types of satellite operators actively utilising each orbit is already markedly different. GEO features a greater proportion of traditional space operators, who have larger satellites and tend to be more risk adverse. Increasing numbers of 'NewSpace' operators with disruptive design philosophies are launching satellites into LEO; these operators generally favour more disposable use of satellites, and more rapid replacement of spacecraft. As the trend characteristics of the two regions appear to be heading in ever more divergent directions, for the purposes of the economic analysis we model the two regions separately before combining the results of each analysis to obtain an estimation of the overall SST market.

In sections 4 and 5 we proceed to the analysis of the GEO and LEO regions respectively. For each, we compute the annual expected loss and we analyse the specific structure of the market. The objective is to gauge the addressable market.

# 4 Economic analysis of the GEO market

In this section we consider the GEO market and apply the methodology defined earlier to assess the market specificities and estimate its current value.

## 4.1 Analysis of the demand

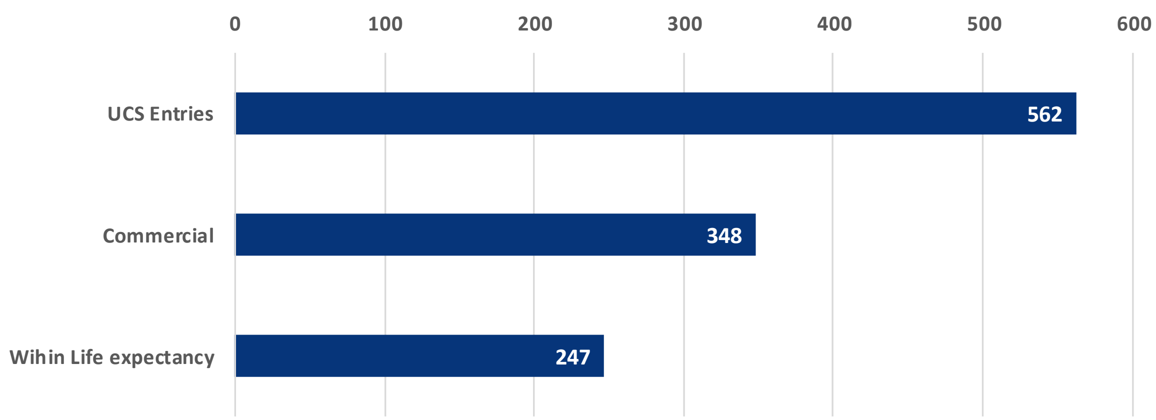
The present geostationary (GEO) orbit consists primarily of large communications satellites which remain in a fixed orbital slot relative to the Earth. As a result, satellites tend to be clustered in groups above continental land masses, with some large operators purposefully collocating spacecraft above regions with high population density.

The UCS database[24] represents the basis of our analysis. We apply a selection filters before running our analysis. We assess the relevance of satellites as follow:

- We select only commercial satellites. We assume commercial actors would value their satellites as a tangible commodity, whereas the value of non-commercial assets extends well beyond such considerations and cannot be valued in this way.
- Satellites must be within their life expectancy. As mentioned earlier, we apply a linear depreciation to the value of the satellites from launch to end of designed lifetime. Therefore, all satellites beyond this threshold are excluded as their asset replacement value is zero.

The figure below shows the selection process. The total number of satellites under the scope of our analysis is 247.

**Figure 11 GEO satellites in scope**




***Source: London Economics analysis (data from UCS)***

### 4.1.1 The value at risk

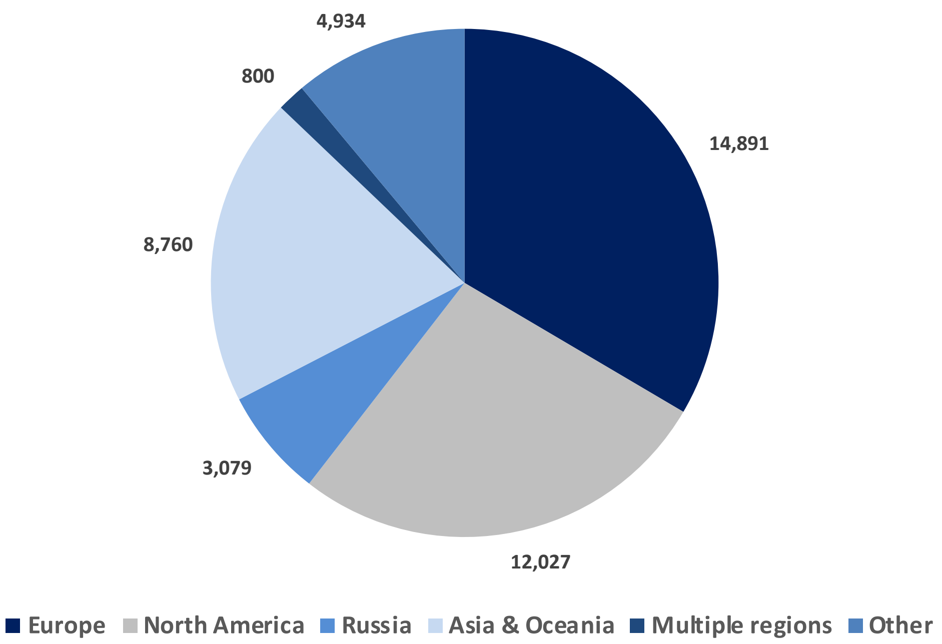
The GEO belt represents the orbital region with the highest cumulative value of satellites. Larger satellites tend to be designed to operate for at least fifteen years, which comes at a considerable

[24] https://www.ucsusa.org/resources/satellite-database; contains details on both commercial and non-commercial satellites

cost. Launch costs for this type of satellite are correspondingly large due to the greater mass that is needed to be lifted, plus the greater orbital altitude.

The figures below depict the breakdown of the value of satellites by geographical region of the **registered owner**, which shows that in terms of current asset value, European operators have the highest value satellites in-orbit, with North American operators also owning a considerable portion of total GEO assets. This is partly due to the satellites registered in Europe being launched more recently than those registered in North America.

**Figure 12 Cumulative total in-orbit GEO commercial satellite value by region of owner/operator (USD m, 2020 prices)**




Note: Values adjusted for inflation and based upon 2020 prices, inclusive of launch costs. Reflects satellites still within design life only.
***Source: London Economics analysis***

Owing to the large commercial asset values concentrated in the GEO belt, which is estimated to total over **$45.9 bn globally in 2020**, the risk posed by space debris is of some considerable importance to GEO satellite operators.

### 4.1.2 Collision probability

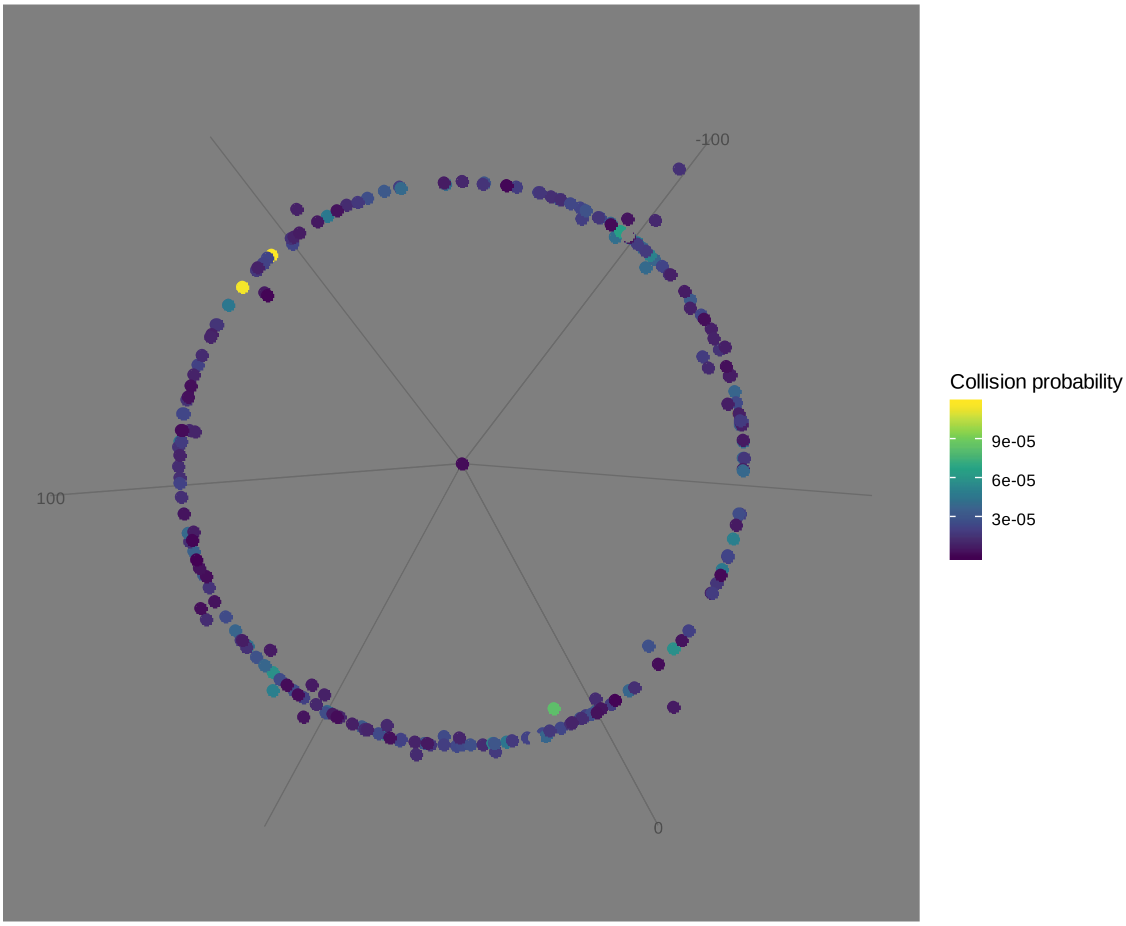
With the DRAMA software, we were able to estimate the collision probability for all 247 satellite in GEO. The probabilities range from around **1 in 10,000** to **1 in 1,000,000**, with the average annual collision probability for a typical GEO satellite around **1 in 50,000**. These numbers have been cross checked with experts from ESOC and from a study published in Acta Astronautica, looking at several studies of GEO orbit collision probabilities[25]. In all cases, the results yield similar probabilities and we are confident our estimations are realistic.

Most of the debris crossing the orbital slots are highly elliptical objects such as rocket boosters or residual objects from past fragmentations. In GEO, the size of spacecraft also has a strong influence

[25] Oltrogge et al. 2018. A comprehensive Assessment of collision Likelihood in Geosynchronous Earth Orbit.

on the collision probability. By plotting the collision probabilities against the orbital location, we see that the precise location has limited influence on the collision probability. Figure 13 shows the distribution of satellites in GEO, by longitude (position on the ring) and altitude (distance from the centre) and coloured by collision probability. The darker the colour, the lower the probability.

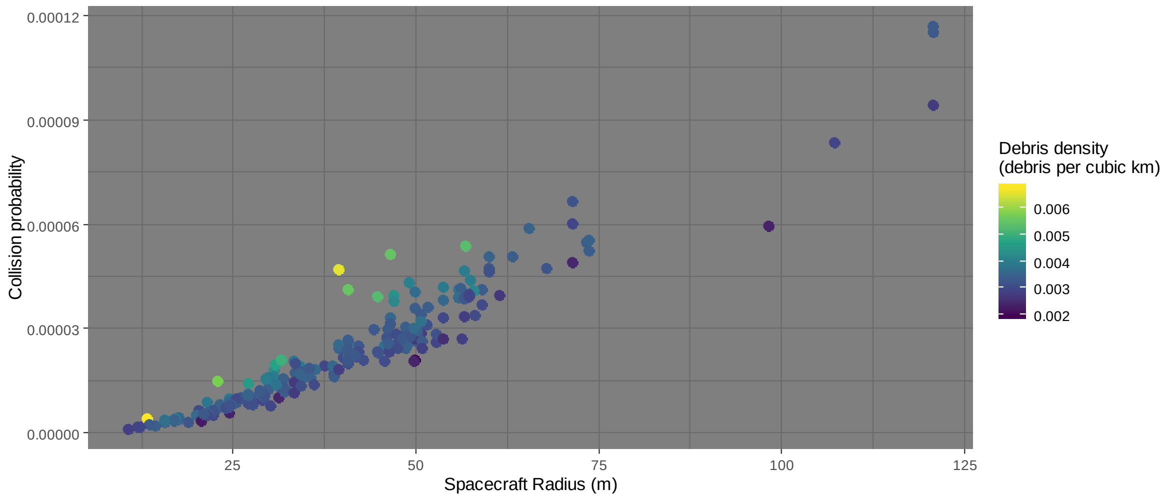
**Figure 13 Collision probabilities in GEO**




***Source: London Economics analysis***

Spacecraft size and the respectively collision probability can be shown to be correlated as per the figure below:

**Figure 14 Collision probability as a function of the size**




***Source: London Economics analysis***

### 4.1.3 Computation of the expected loss

We assume the **addressable market** for SST services to be commercial GEO satellites within their design life. Whilst GEO satellites are often still operated beyond their design life, provided they are still in a working condition and possess sufficient reserves of fuel to ensure responsible operations, they no longer possess a quantifiable asset value and are omitted from the addressable market.

By combining the **replacement value of** spacecraft and the **annual collision probabilities** from the DRAMA simulation, we estimate the total expected loss annually to satellite operators to be around **$1.2m in 2020 (£0.93m)**[26]. This is based upon a population of **247** commercial satellites. Note that this estimation omits the annual turnover generated from these satellites.

The probability of collision is lower compared to LEO (see section 5) but the high value of an operational asset means that the absolute value of expected loss values in GEO are non-trivial. Additionally, as the GEO telecoms market represents a well-established community of risk adverse operators, the financial services industry for products catering to financial risk transfer needs (i.e. insurance) is highly mature, and typically includes coverage for debris related damage to spacecraft.

The SSA market therefore currently is better suited to appeal to GEO operators who typically would have a higher level of interest in SSA products and services combined with the ability to purchase more sophisticated products. Firms such as ExoAnalytic Solutions currently cater to the needs of GEO operators, and this represents the most mature market in relation to SSA servicing of demand.

## 4.2 Future GEO market

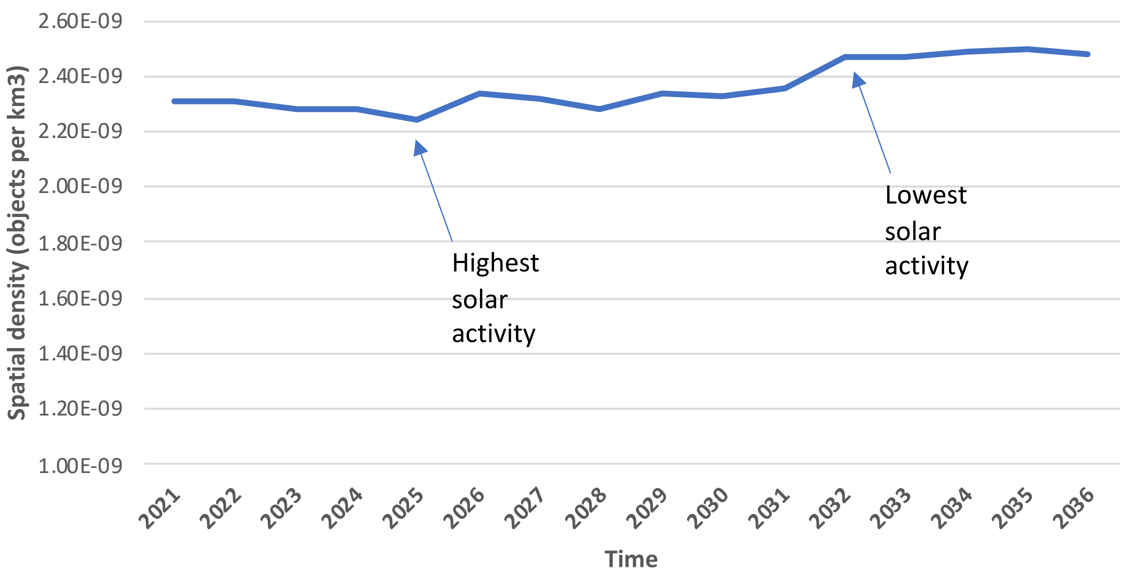
The starting point for the analysis of the GEO market was to examine the model for the propagation of debris within the MASTER software to characterise the predicted trends for future years. We also considered the model outputs for historical years, which is based on actual data and reflects events

[26] Assuming xe.com USD/GBP exchange rate of 0.79254

which have already occurred in GEO. This was to understand how the debris population in GEO evolves over time, and to evaluate how valid the ESA model is likely to be.

To do this we looked at the cumulative flux of debris for all spacecraft located in the GEO belt for each year from 2000 through to 2036 (which represents the end limit of the simulation). The flux of debris is defined as the number of objects which pass through a 2d plate located at a particular point in orbit. Effectively then this calculates the average number of collisions per year which would occur per square kilometre for a satellite located within the GEO belt. The results of this are depicted in the chart below:

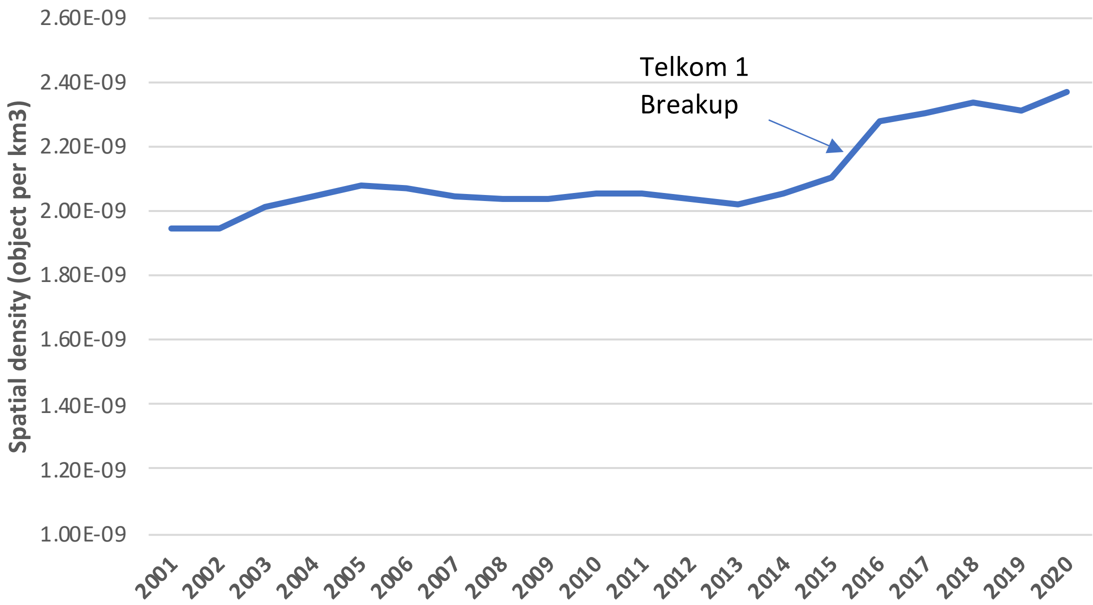
**Figure 15 Future annual debris flux in GEO**




***Source: London Economics analysis & MASTER model***

The line in the chart demonstrates that the flux within GEO is predicted to be largely static in the coming years. This is because the debris population in GEO is less dynamic than populations of debris at lower altitudes, and so debris generated from standard mission events such as small flakes of paint or layers of multi-layer insulation (MLI) which detach from satellites tend to remain in-situ. They are low velocity particles and generally do not travel to other regions of the GEO ring unless acted upon by an external force. The same however cannot be said for debris generated during high energy events, and so we examined the past history of GEO to determine how common such events are.

**Figure 16 Annual historical debris flux in GEO**




***Source: London Economics analysis & MASTER model***

From the figure we can see that during the last two decades of activities in GEO, there was one notable event that led to a significant increase in the annual debris flux, which is marked upon the chart above. These events correspond to explosive high energy events which generated significant populations of debris within the GEO belt. A high portion of the debris generated from each event tended to be high velocity particles which erupted in several different directions dependent upon the nature of the event. As the GEO belt is closest geometrically to a two dimensional ring situated around the equatorial plane of the Earth, some particles would radiate outwards to the north of the equator, and some to the south in a mostly harmless fashion as these particles would not remain within the belt. Some debris however would remain within the orbital plane and pose a risk to operational satellites, or even interact with other debris objects to create even more debris. Such fragmentation events can be tracked via ground based optical telescopes, with the larger pieces of debris catalogued so future conjunction events with active satellites can be monitored.

We also considered other factors likely to affect the debris population in GEO in the coming years.

### 4.2.1 In-orbit servicing

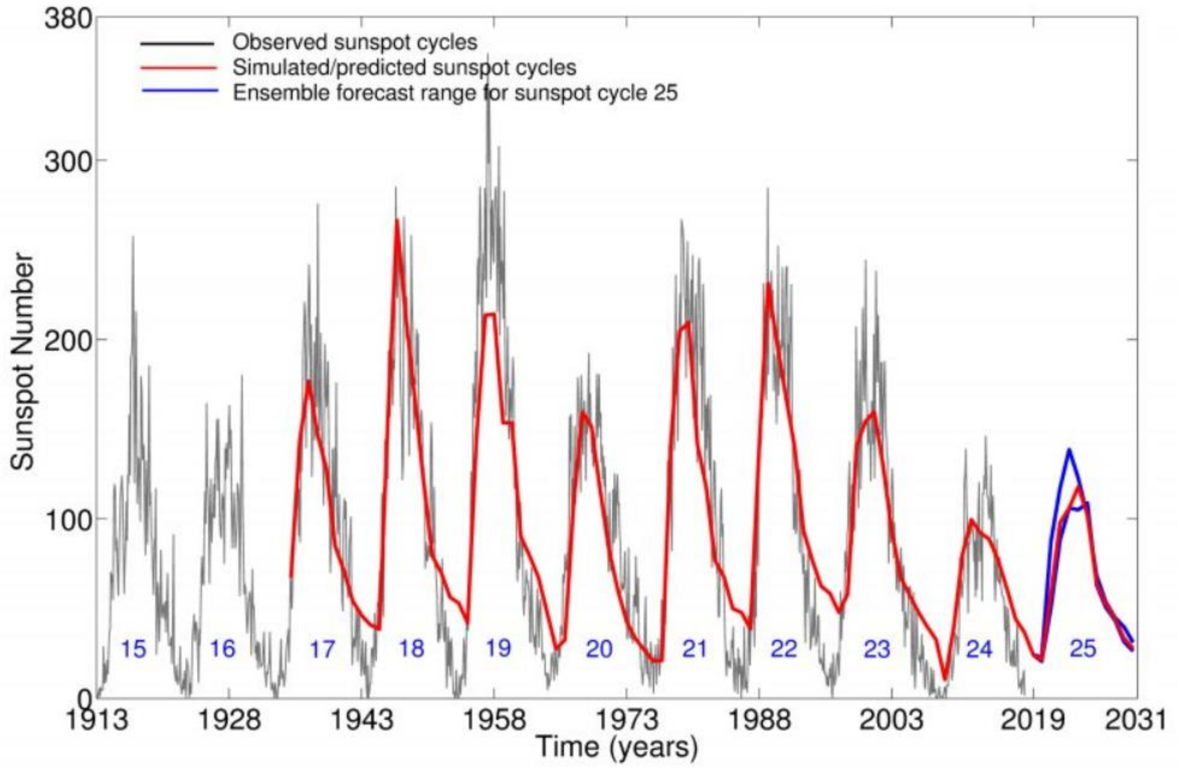
On 25th February 2020 an historic first occurred some 36,000 km above the Earth. The MEV-1 spacecraft designed by Northrop Grumman docked with an Intelsat geostationary spacecraft which was running out of fuel. This represented the first occasion where a robotic servicing spacecraft successfully docked with an active satellite in GEO. The result of the mission, aside from demonstrating this capture and docking capability, was to allow the Intelsat satellite to operate for an additional five years by transferring propellant from MEV-1 to the satellite. MEV-1 is one of a number of in-orbit servicing solutions currently in development, and this event marks the herald of a new era for operations in space.

The potential for in-orbit servicing missions is not solely for refuelling satellites which are low on fuel. Robotic servicers are expected to be used to repair ailing or damaged spacecraft, or to act as a tug to remove failed satellites from the GEO belt, allowing new satellites to take their place and mitigating the risk of debris generating events. As such, aside from the inherent risk involved in such a complex type of mission, i.e. docking two large objects in GEO or lower orbits is not straightforward by any means, the potential to remove failed or damaged satellites should help to **prevent an increase in the average flux in GEO in the future,** or even help to lower the risk. This development then would seem to support the overall prediction of the ESA model, though it has not been factored into the simulation explicitly.

### 4.2.2 Solar cycles

The sun is known to undergo regular cycles of intensity, which typically span around 11-year periods. In 2019 the current solar cycle was thought to be entering a period of minimal intensity, which means that the number of solar weather events will be lower than the typical average. By the mid 2020's the cycle will have reversed, leading to a solar maximum or a period of above average solar activity. The significance of space weather is particularly of importance in GEO more so than for lower altitude orbits such as LEO, which are offered some levels of protection by the Earth's magnetic field which is more prominent at lower orbits. Radiation from the Sun can also be trapped by the Van Allen belts located around the Earth, the lower of which protects some regions of LEO from the solar wind. The effects of the solar cycles are counterbalanced by correspondingly higher levels of galactic radiation during solar minima, and lower levels during solar maxima, which has different and yet not entirely dissimilar effects to solar radiation.

**Figure 17 Solar cycles**




***Source: Byrd, D, (2018) https://earthsky.org/space/solar-cycle-24-25-sunspot-predictions***

The effects of the solar wind in GEO are twofold. Firstly, the solar wind represents highly charged particles which can bombard satellites in GEO, leading to satellite anomalies. A prominent example of this occurred in 2010 when Intelsat's Galaxy 15 satellite was rendered uncommunicative with ground operators following an intense solar flare. The satellite then proceeded to drift uncontrolled throughout the GEO belt, generating a number of conjunction warnings with other active satellites. Aside from the clear need for SST data to avoid potential collisions in GEO, this incident demonstrated the heightened risk of debris generating events arising from periods of high or low solar activity.

Secondly, the solar wind also exerts a solar radiation pressure upon objects in orbit, which acts as a perturbing force. The effects of this upon debris then can be to nudge such objects out of the GEO orbit and **reduce the debris flux.** Periods of high solar activity could then actually lower the risk of collisions in GEO orbit, and this has been factored into the results of the ESA model shown in Figure 15. As Figure 17 shows, during the twentieth century the solar maxima have been relatively mild by historical standards. Were higher levels of solar activity observed in the coming years then this could markedly change the annual orbital debris flux during those years and in subsequent years. The progression of such natural phenomenon is impossible to predict but is noted as a potential factor which could impact on the need for SST services in GEO in the future.

### 4.2.3 Natural space debris

Another natural phenomenon relates to the effects of natural space debris, or meteoroid showers which may interact with the debris population and lead to increasing levels of SST demand. The MASTER simulation provides users with the capability to factor in predictions of meteoroid activity based on astronomical observations and is not taken into account in the figure above. As this is a random factor which could change significantly with further astronomical discoveries, this could potentially increase the risk in GEO and increase the value of the GEO SST market.

### 4.2.4 Future fragmentation events

In early 2020 a major issue was detected for the Spaceway-1 satellite which was then occupying the GEO belt. Spaceway-1 was a Boeing built satellite which was operating well beyond its design life. Its operator DirecTV had identified an issue whereby the battery onboard the satellite could potentially explode if used operationally. For GEO spacecraft the need to rely on battery power only occurs during regular predictable intervals during each year. As this was due to occur in the coming weeks, the race was on to safely graveyard the satellite at a safe distance outside the GEO belt. Fortunately, as Spaceway-1's battery was not currently in use and the issue was identified early enough, sufficient time was available for the operator to safely deorbit the satellite and avoid a potential catastrophic fragmentation event.[27]

This near miss demonstrates the potential for large scale debris generating events to occur randomly in GEO, similar to the Telkom 1 break up event depicted in Figure 16. This event **increased the cumulative debris flux across GEO by around 10%,** and a similar event in the future could increase the value of the GEO SST market considerably. The occurrence of such an event is impossible to forecast however and is not included within the ESA model.

### 4.2.5 Summary

Notwithstanding some of the factors discussed above, the risk to spacecraft in GEO appears to be relatively stable. Indeed, the value of the future SST market in terms of servicing demand for GEO services are likely to be primarily influenced by the **change in values at risk** rather than changes occurring within the environment itself. As recent trends for the GEO market suggest no great

[27] Henry, C. (2020), SpaceNews. 'DirecTV's defunct Spaceway-1 reaches high graveyard orbit in one piece', available at https://spacenews.com/directvs-defunct-spaceway-1-reaches-high-graveyard-orbit-in-one-piece/

increase in terms of the numbers of satellites, or to an increase in the values of individual satellites, we conclude that the growth prospects of the GEO SST market are **bound by the current estimation of expected loss in the region of $1.2m**. As such GEO does not represent an area of potential growth for the global SST industry, unless there is a significant unforeseen trend or event(s) occurring within the next twenty years.

## 4.3 Analysis of the supply

### 4.3.1 Competitive landscape

The information available about the supply chain is scarce as most stakeholders are commercial entities. A handful of them however provide pricing and detailed information about their activities.

We have split the suppliers into three categories but some of them overlap between more than one (see Table 1, page 27).

The current situation shows that a small number of firms are present in the supply chain. The market competition has yet to mature and we identified six companies providing services to the GEO orbit (note that blank cells indicates that no information was available to precisely state whether the company is servicing GEO or LEO). All companies servicing the GEO orbit are small companies.

We have also noted in this table that most companies are providing information services. While these services can be of a different nature, we will focus on the one most relevant to the study which is conjunction analysis.

The conjunction analysis process can be simplified to three steps. The first step is the receipt of information stemming from observational data, which triggered an alert to the operator. These alerts indicate that an object could make a close approach to the satellite and threaten its existence. The second step is the filtering of messages. A high number of messages are received every year (approximately 450 per satellite per year[28]). Satellite operators need to filter out the false alarms and retain the potential threats. Lastly, once a threat is confirmed, the object needs to be tracked over time in order to assess its trajectory and reduce the uncertainty of its position. Ultimately, if the threat persists and the accepted miss distance or collision probability are below operator's thresholds, the decision is taken whether to move the asset or not.

These conjunction analyses are provided primarily by private companies, and publicly available catalogues allow operators to do the analyses in-house. For large companies with the capacity, it may be more cost effective to employ an engineer whose job is to survey and filter and process the conjunction messages. The existence of free sources distorts the market and companies with higher capacity can easily internalise the service. Therefore, the demand is reduced.

### 4.3.2 Market pricing

Price data from companies such as ExoAnalytics for instance are higher than the modelled average expected loss of the satellite from collisions. This owes to the presence of a small number of suppliers on the market, which drives the market prices up. The consequence being that market prices will be higher than the expected loss.

[28] Oltrogge et al. 2018. A comprehensive assessment of collision likelihood in Geosynchronous Earth Orbit.

It is also likely that private companies supply their services to governments, space agencies and defence bodies. We are not able to certify that due to the lack of information, but a data point has shown that one company's revenue is mostly attributable to public clients.

### 4.3.3 Summary

The level of supply available to the commercial GEO industry appears to be adequate at present. The value of the commercial supply market can be obtained by multiplying the cost of services provided by companies such as ExoAnalytics against the number of GEO operators globally. As per the UCS data, this would appear to be around 70 companies. Based upon the data in Table 2 (page 28), this would suggest a potential market between **$6.3m - $77m for global SST supply,** although in practice the actual number will be significantly lower than this estimate due to lack of appetite from GEO operators, reliance on freely available data, and in-house capabilities.

# 5 Economic analysis of the LEO market

In this section we consider the LEO market and apply the methodology defined earlier to assess the market specificities and estimate its current value.

## 5.1 Analysis of the demand

The region of Earth's orbit designated as Low Earth Orbit (LEO) is home to satellites representing a diverse range of applications and based upon several different design philosophes. Masses of in-orbit satellites range from enormous 18 tonne US military satellites down to satellites weighing just a few kilos. In terms of ownership type of LEO satellites, there is an approximately 50-50 split between those owned by commercial organisations and those owned by non-commercial organisations.

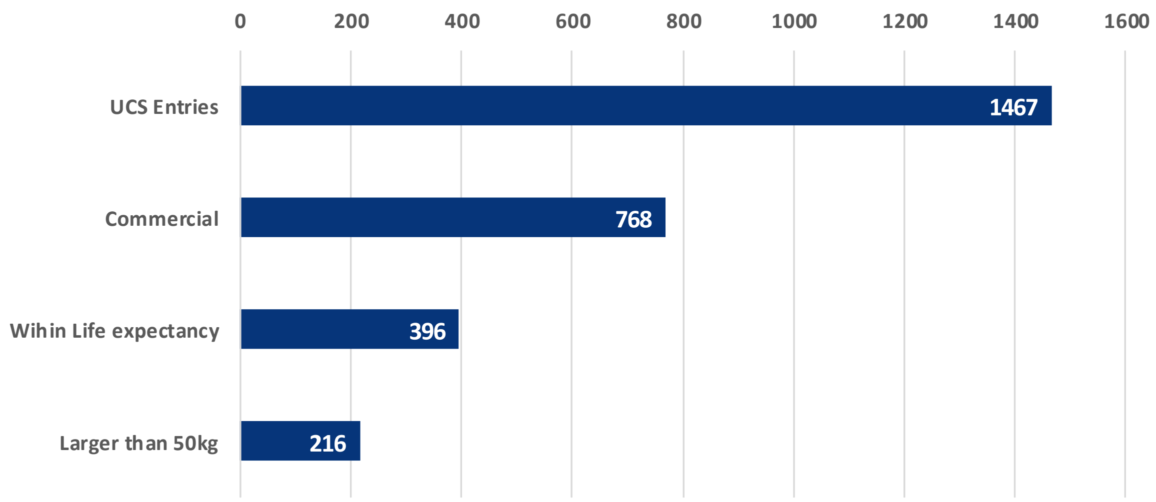
Using the same starting point as that used for GEO, we identify LEO satellites from the UCS database.[29] We apply the same selection filters as we did for GEO plus an additional condition on the satellite mass. We assess the relevance of satellites as follows:

- We select only commercial satellites. We assume commercial actors would value their satellites as a tangible commodity, whereas the value of non-commercial assets extends well beyond such considerations and cannot be valued in this way.
- Satellites must be within their life expectancy. As mentioned before, we apply a linear depreciation to the value of the satellites from launch to end of designed lifetime. Therefore, all satellites beyond this threshold are discarded since their replacement value is zero.
- Satellites must be heavier than 50 kg. Based on our findings, satellites smaller than this threshold are unlikely to carry thrust capacity. Therefore, the use of SST data for collision avoidance manoeuvre is useless to the operator and does not constitute a commercially valid case.

The figure below shows the selection process, which first removes all non-commercial satellites, then all satellites beyond original design life, and finally satellites of mass less than 50 kg from the original population of 1467. The total number of satellites remaining within the scope of our analysis is **216**.

[29] https://www.ucsusa.org/resources/satellite-database; contains details on both commercial and non-commercial satellites

**Figure 18 LEO satellite in scope**

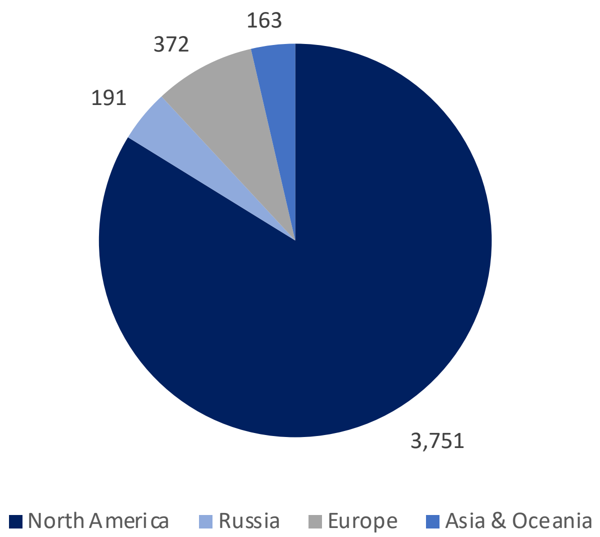



***Source: London Economics analysis (data from UCS)***

### 5.1.1 The value at risk

The sizes and applications of satellites operating in LEO varies considerably, as such, so does the range of values of individual spacecraft. This range spans tiny nanosats costing in the order of thousands of dollars, right the way up to larger imaging satellites worth hundreds of millions. The cumulative commercial LEO satellite assets currently in-orbit (and within design life & over 50 kg in mass) are skewed heavily by several fleets of comparatively higher valued US commercial operators, as shown in the figure below.

**Figure 19 Cumulative total in-orbit LEO commercial satellite value by region of owner/operator (USD m)**




Note: Values adjusted for inflation and based upon 2020 prices, inclusive of launch costs. Reflects satellites still within design life only.

***Source: London Economics analysis***

The total value at risk sums up to **$4.6bn**, in 2020 prices.

### 5.1.2 Collision probability

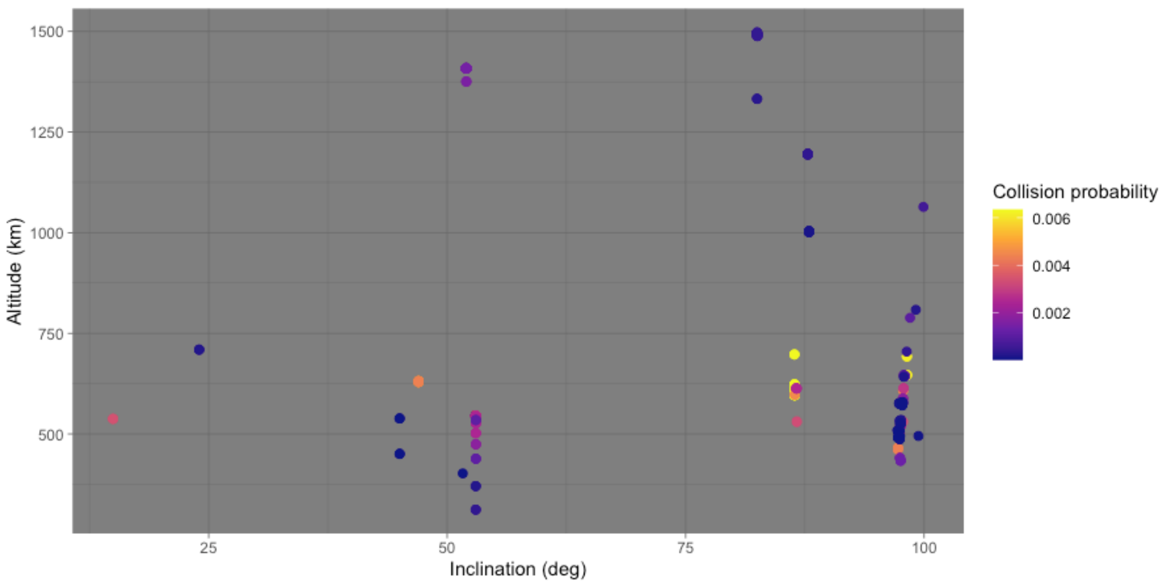
With the DRAMA software, we were able to estimate the collision probability for all **216** spacecraft.

In LEO the density of debris is much higher than in GEO, yielding higher collision probabilities. The maximum annual collision probability is **around 1 in 157** (more than 60 times higher than the GEO maximum) and the lowest is **around 1 in 85,000**.

At lower altitudes the scenario is more dynamic, many objects cross the orbital plane of multiple satellites, and therefore the density of objects is increased. The consequence is that, even with lower value at risk, the average number of collision probability per year is more than **150 times higher**, with the potential for a collision of **1 in 320 chance**.

While the size of spacecraft is of relevance, the location of spacecraft is more important in LEO compared to GEO.

**Figure 20 Collision probabilities in LEO, in 2020 (inclination vs altitude)**

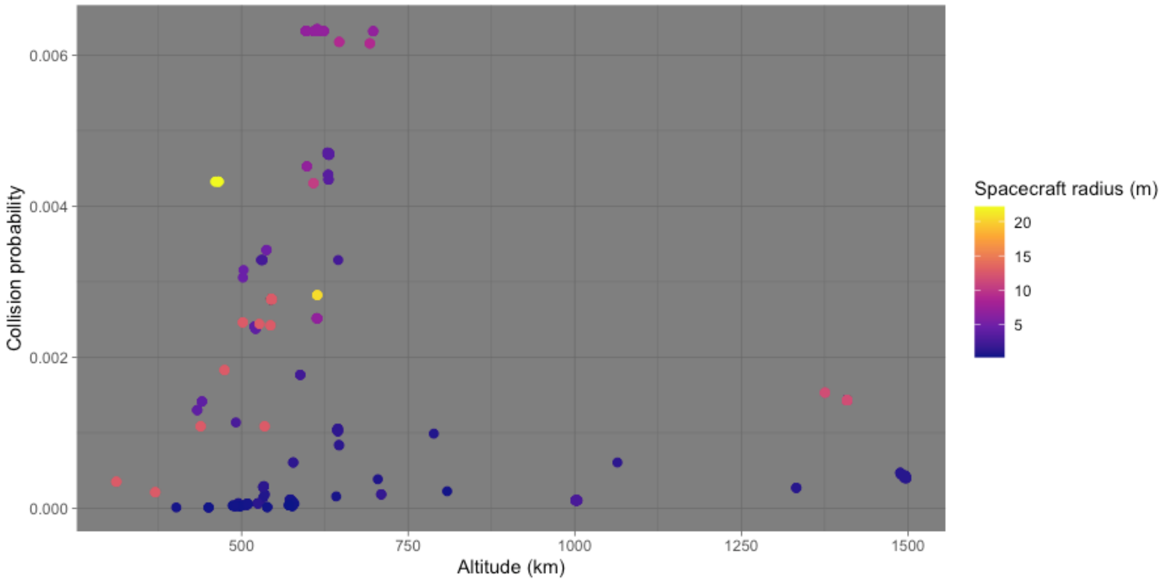



Note: Many satellites are shown as nested into constellations in the above

***Source: London Economics analysis***

The figure shows that the collision probabilities are higher for an altitude between 600 and 700 km and an inclination around 80 degrees and 98 degrees. These are the polar and sun-synchronous orbits.

**Figure 21 Collision probability as a function of the altitude and coloured by satellite size**




***Source: London Economics analysis***

### 5.1.3 Computation of the expected loss

In terms of the current demand for LEO SST services, only a relatively small number of well-established operators have the means to purchase SST services beyond the freely available information provided by the 18th SPCS. These operators are the large US fleet operators referred to above, plus a small number who own high value satellites. Other operators with sizable fleets by number of spacecraft such as US based fleet operators Planet or Spire Global, which combined contribute over a quarter of all commercial LEO satellites, largely lack the propulsive capabilities to make use of real-time SST information in any case. As such the commercial LEO SST market is virtually non-existent at present.

The potential first signs of change are already present within the market however, as large megaconstellation operators have in 2019 begun the first phases of their constellation launch programmes and already represent over 10% of the commercial total above.

In terms of the addressable market demand for SST services in LEO, only satellites with the ability to perform collision avoidance manoeuvres (CAMs) have the means to benefit directly from the availability of real-time information. As typically satellites below 50 kg do not feature propulsive systems, we have assumed that these spacecraft are not part of the addressable market for SST services.

Based upon the definition of the addressable market above and the annual collision probabilities from the DRAMA simulation, we estimate the total expected loss annually to commercial satellite operators to be in the region of **$22.8m per year.** This is based upon an assumed population of 216 commercial LEO satellites operating within their design lives at the start of 2020.

#### Lloyd's RDS value

Based upon the identification of the satellite values at present in LEO, we can adopt a similar methodology used by UK insurance institution Lloyd's of London in their 'Realistic Disaster

Scenarios: Scenario Specification'[30] (RDS) publication, to estimate the value of a catastrophic chain effect debris collision event in LEO. This figure is included to provide the worst case expected loss in the event of a major fragmentation event occurring in-orbit.

The publication provides insurance syndicates with a framework to calculate a worst-case cumulative loss value to aid contingencies with respect to financial reserving of funds to pay insurance claims.

Here we assume the expected loss value for the entire population of commercial satellites within the Lloyd' criteria of:

- Orbital altitude 400 km – 800 km
  or
- Orbital altitude 1200 km – 1600 km

assuming the magnitude of loss per satellite ranges between 20% - 40%. This results in an estimate of **$903m - $1.8bn** in cumulative losses in asset value to global satellite operators from a catastrophic event in LEO at the start of 2020. This would provide a rough estimate for the upper bounds of a one of fragmentation type event in LEO in terms of expected loss, though within the context of this study we are unable to refine this range based upon our analysis.

## 5.2 Future LEO market

The LEO market is expected to grow substantially in the next decades. With the introduction of large constellations, the reduction of cost of access to space and the emergence of new space faring nations, the population of active spacecraft will change substantially.

Here we analyse this evolution from different angles. We look at the evolution of active populations and then we take a closer look at the impact on the collision probabilities. We have selected three key years in the development of the analysis of LEO, namely 2025, 2029 and 2036. The 2025 analysis provides a snapshot of the state of LEO five years into the future, with 2029 representing the year in which our model predicts all three current known major constellations (Starlink, OneWeb and Telesat) will have completed the launch of their first generation systems, and the first phase of a fourth future constellation (nominally modelled on Amazon's proposed Kuiper constellation) has been launched. 2036 represents the finite limit of the ESA software simulation, and so provides the furthest modelled estimate which we are able to provide.

### 5.2.1 The future LEO population

The future population is two-fold. On the one hand there are the current active satellites that are still not beyond design life. On the other hand, there are also completely original satellites forming the megaconstellations.

We assume that non-constellation LEO satellites which are beyond design life are replaced following end-of-life with satellites which have identical characteristics to those being replaced (size, mass, orbital elements, manufacturing cost at 2020 prices etc). In practice many LEO satellites tend to exceed their original design life by an average factor of 2.4x, based upon UCS data, as pre-launch

[30] Lloyd's (January 2020), 'Realistic Disaster Scenarios: Scenario Specification', available at https://www.lloyds.com/market-resources/underwriting/realistic-disaster-scenarios-rds

fuel loading often considerably exceeds design life. We conservatively assume that a satellite is replaced after a period of twice its original design life has passed since it was launched. We do not use the figure of 2.4x design life for the relaunch date in order to account for satellites which fail much earlier than this and do not form part of the UCS data. We again assume that satellites less than 50 kg in mass are out of scope, this specifically includes cubesats and below. These satellites therefore will not require future SST services, and we do not model any future launches.

The major change in the landscape is expected to be from the megaconstellations. As some operators have already deployed some satellites, doubts about this development are minimised. To reflect that, we have selected what we believe to be the most credible future constellations to be launched before 2040. We also researched any evidence of spectrum attribution from the FCC and use this as the baseline for the estimation of the orbital parameters and launch scheduling. The table below shows the constellations, the number of spacecraft and the date of first launch. Note that constellations like Starlink are planned around multiple orbital planes. The table distinguishes these planes as well.

### Table 3 List of commercial organisations active in the SST market as of 2020

| Name | Number of satellites | First Launch |
|---|---|---|
| OneWeb Phase 1 | 720 | 2019 |
| OneWeb Phase 2 | 1260 | 2023 |
| Starlink Phase 1a | 1584 | 2019 |
| Starlink Phase 1b | 2822 | 2022 |
| Starlink Phase 2a | 2490 | 2025 |
| Starlink Phase 2b | 2490 | 2026 |
| Starlink Phase 2c | 2490 | 2027 |
| Kuiper Phase 1 | 784 | 2025 |
| Kuiper Phase 2 | 1296 | 2031 |
| Telesat Polar | 72 | 2022 |
| Telesat Inclined | 45 | 2023 |
| Kepler | 140 | 2020 |

***Source: London Economics analysis & various online sources***

A total of over 16,000 first generation satellites are modelled as being launched by the end of 2032 and we assume a regular launch schedule between the planned date of first launch and the expected full operability of the constellation. Similar to the non-constellation satellites we assume that constellation spacecraft reaching the end of their useful life are replaced by new identical satellites which take their place in the constellation. In terms of when they are replaced however, we use the example of the existing Iridium and Iridium Next constellation[31]. The original Iridium satellites were used operationally well beyond original design life, and for Iridium Next the operator has stated a design lifetime of 10 years, with an expected usage life of 15 years.[32] We therefore assume that future constellation satellites are replaced in orbit after 1.5x their original design life has elapsed since launch.

Overall, the value in orbit will increase substantially between 2020 and the completion of all constellations, bearing in mind that the value of satellites is still assumed to depreciate linearly between beginning of operations and end of design lifetime. The chart below shows the value at risk by year of analysis. We can see the progressive evolution of the value at risk in Figure 22 below,

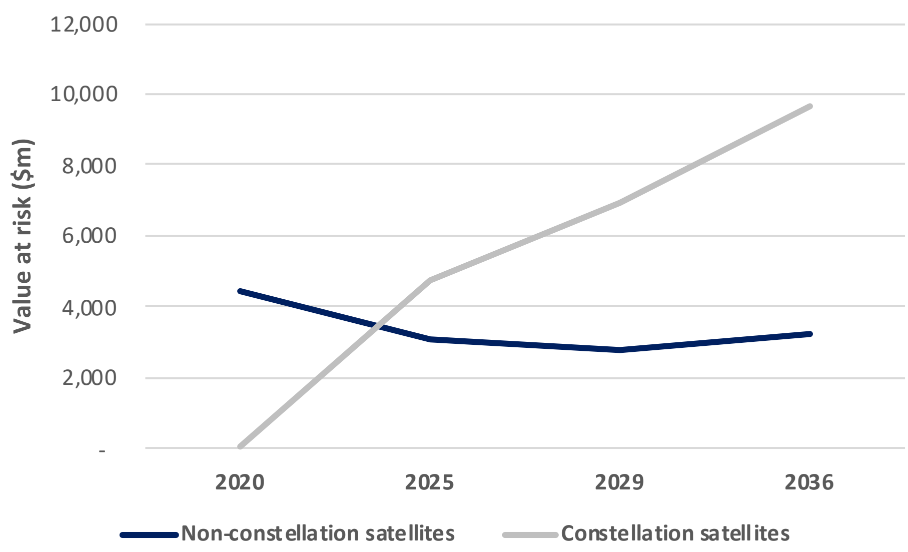
[31] Note that for the purposes of this section, we consider a 'constellation' to be a constellation of spacecraft yet to be fully realised, i.e. we do not include already launched constellations such as Iridium Next or Globalstar

[32] https://directory.eoportal.org/web/eoportal/satellite-missions/i/iridium-next

which remains fairly flat between 2025 and 2029 owing to depreciation of the first generation satellites, but climbs steadily into the 2030's as replacement satellites are launched.

**The total value at risk is expected to grow 3.5 times higher by 2036.**

**Figure 22 Cumulative value at risk for (mega)constellations**



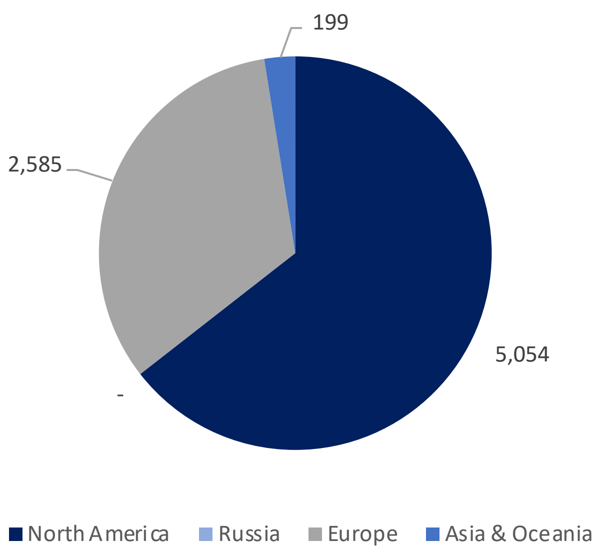

*Source: London Economics analysis*

## 5.2.2 LEO in 2025

### Value at risk

As the figure below demonstrates, in five years' time we expect the vast majority of value in orbit to be from recently launched spacecraft from North America.

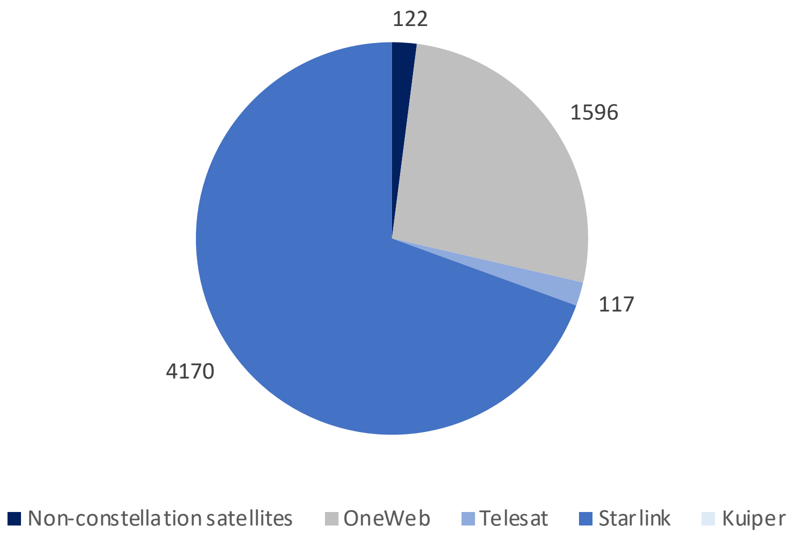
**Figure 23 Commercial value at risk in LEO in 2025 by region (USD m)**



***Source: London Economics analysis***

The main reason for this shift in value is the huge numbers of constellation satellites launched by North American operators, plus three large, high value replacement satellites for the existing Digitalglobe fleet.

### Figure 24 Types of satellite in LEO in 2025




***Source: London Economics analysis***

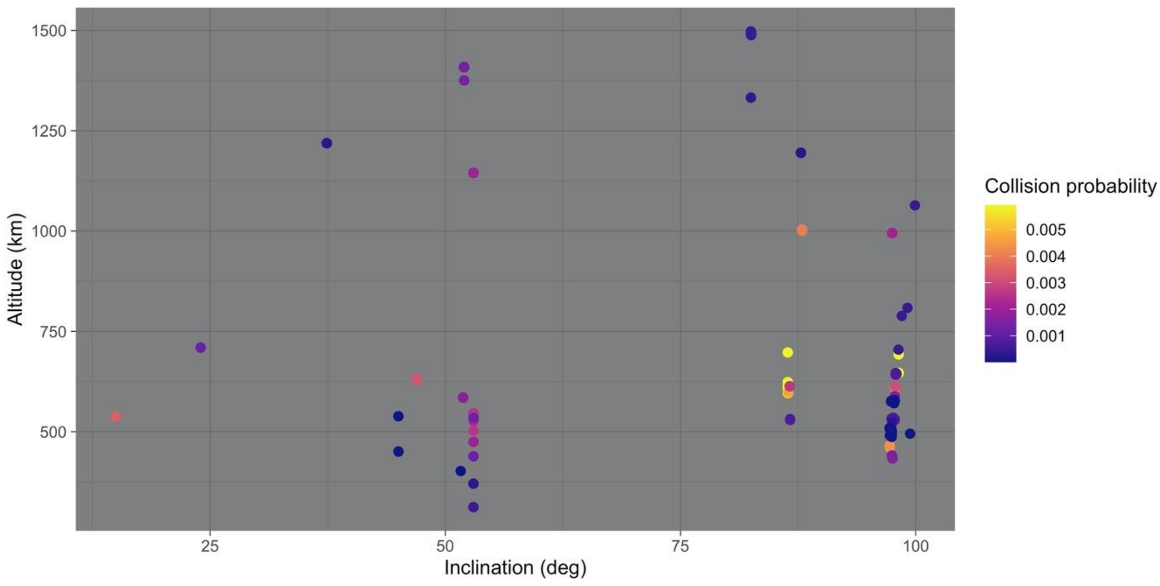
### Expected loss

In 2025, the projected collision probabilities increase overall with an average collision probability of **1 in 370** and a maximum annual collision probability of **1 in 170**. The sun-synchronous and polar orbits are still the most densely populated and face the largest collision probabilities.

At this stage the deployment of constellations is well underway and has increased the number of active assets in orbit. Starlink should have completed its first phase and placed over 4,000 satellites into orbit, while OneWeb is finalising its deployment with 1,500 satellites.

Other satellites crossing these orbital planes will have an increased collision probability.

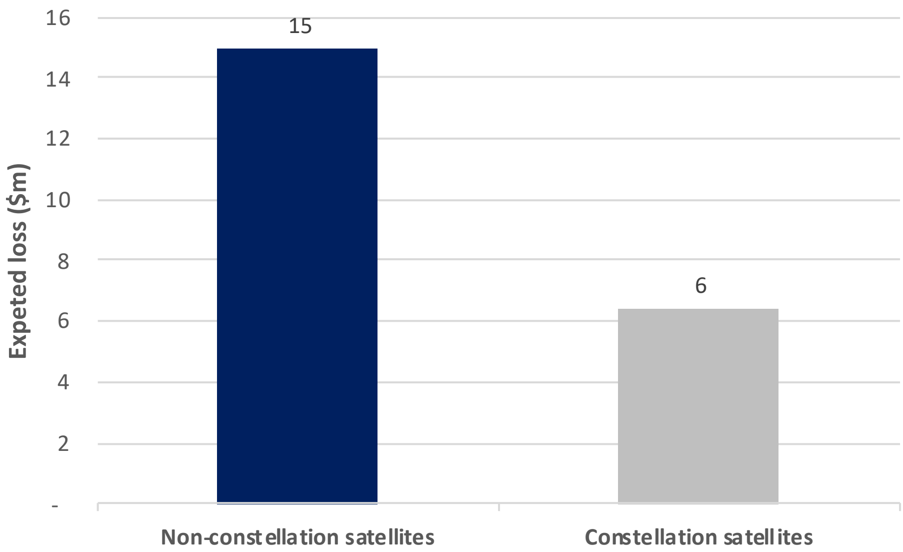
## Figure 25 Collision probabilities in LEO in 2025




***Source: London Economics analysis***

As the figure below shows, although expected losses from constellation spacecraft are sizable, in 2025 the losses from non-constellation satellites is cumulatively 3.5x greater and thus the bulk of the SST market is still focused on non-constellation or legacy constellation operators.

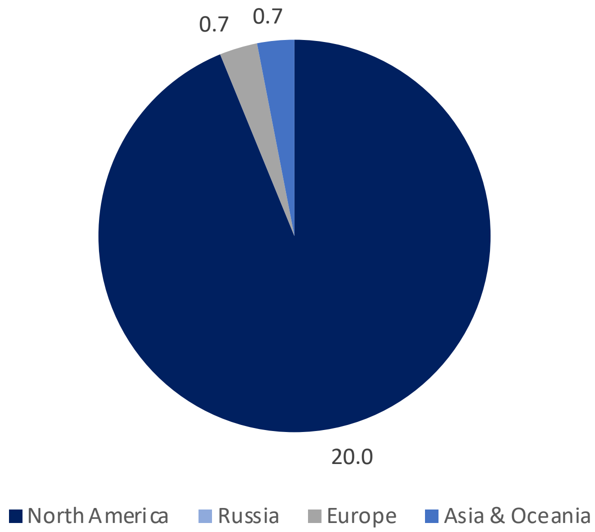
## Figure 26 Expected loss in LEO in 2025 by type of satellite




***Source: London Economics analysis***

Despite the overwhelming value in orbit being from North American satellites, European and Asian operators have a greater representation within the expected loss. This suggests that some European and Asian satellites are operating in orbits that are more risky than typical for LEO orbits.

**Figure 27 Expected loss in LEO in 2025 by region**




***Source: London Economics analysis***

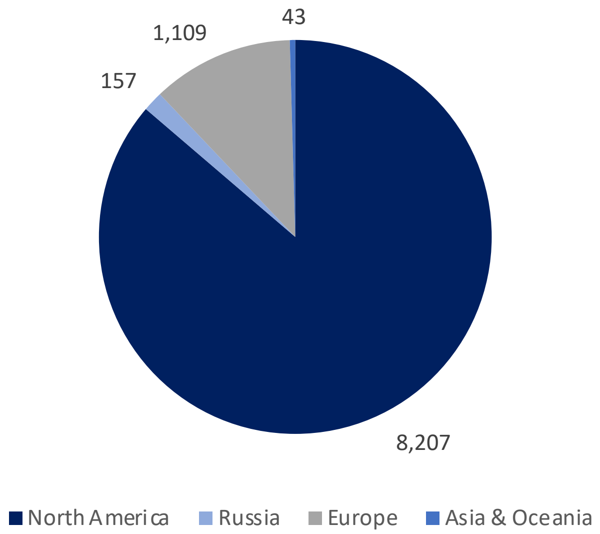
### 5.2.3 LEO in 2029

**Value at risk**

By 2029 the split between regions in terms of value at risk in orbit has a more even look. In particular, Russian satellites now have a greater value as several of the Gonets fleet of communications spacecraft have been replaced.

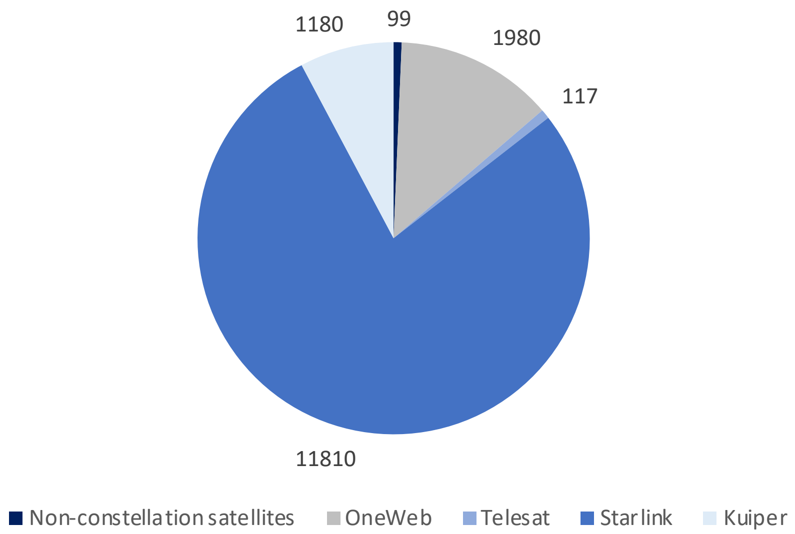
Another contributing factor is the relatively short lifetimes of the North American constellation satellites, as although the entire first generation Starlink satellites have launched, the depreciation effects mean that many earlier spacecraft now have a net book value of zero. The same can be said of the first launches of the Kuiper constellation, as we have assumed short lifetimes for this initial batch of spacecraft as failure rates will be considerably higher for the earlier generation of satellites, particularly as the company has no history of building spacecraft. By comparison, European operator OneWeb opted for established manufacturer Thales Alenia as the prime contractor for its satellites, and correspondingly they have a longer design life and retain some of the value across the constellation.

**Figure 28 Commercial value at risk in LEO in 2029 by region (USD m)**




***Source: London Economics analysis***

**Figure 29 Types of satellite in LEO in 2029**



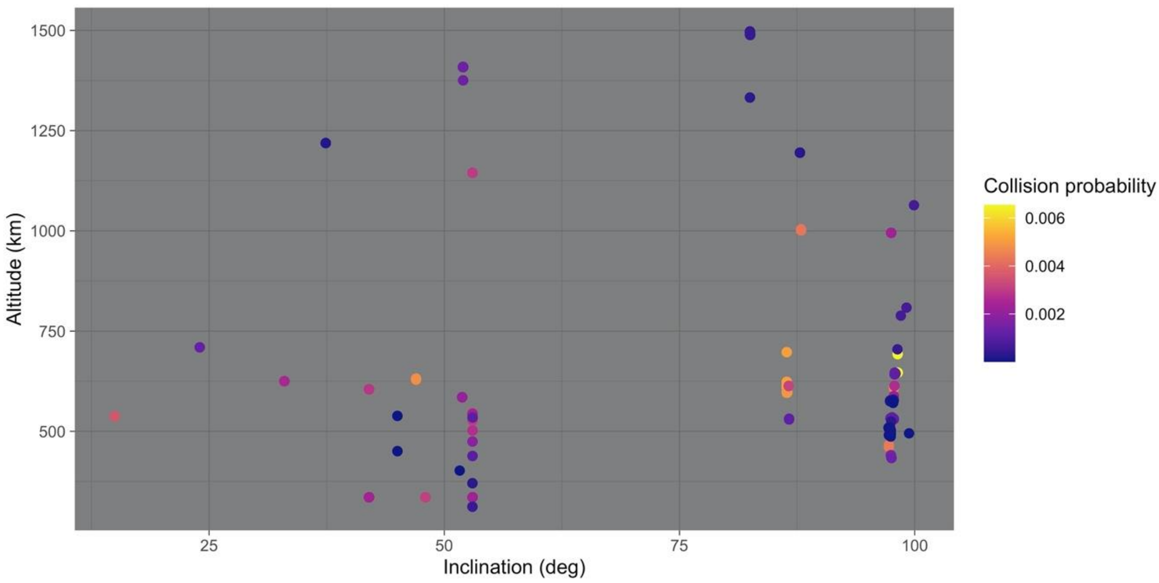

***Source: London Economics analysis***

### Expected loss

In 2029, collision probabilities still increase, and the average is around **1 in 340**. The maximum annual collision probability is **1 in 153**. Constellations are almost all fully operation and Starlink numbers more than 11,000 satellites. OneWeb adds 1,980 and Kuiper 1,180.

Despite a substantial change in the number of objects compared to 2025, collision probabilities do not vary too much. Most of additional satellites are in orbits crossed by very few satellites. In addition, the largest contributor to the number of satellites is Starlink in VLEO, which previously did not feature a large number of objects.

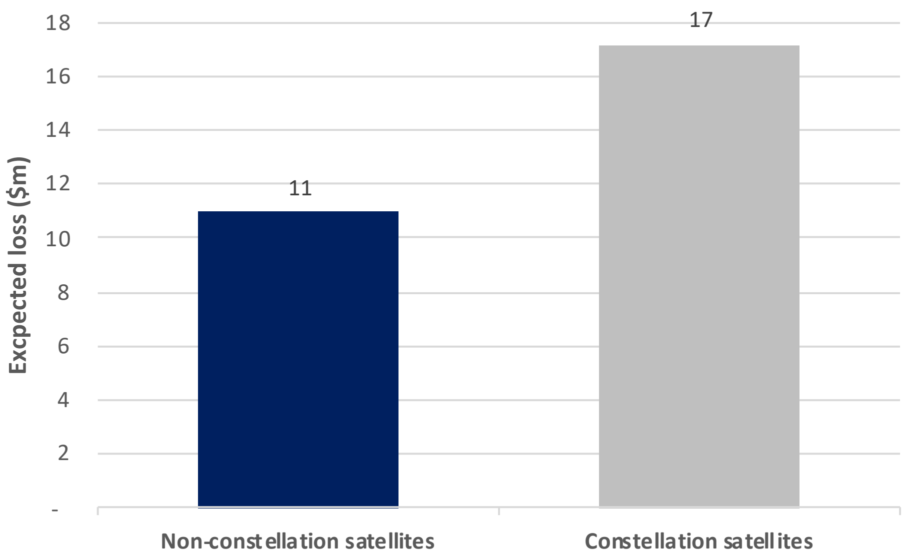
## Figure 30 Collision probabilities in LEO in 2029




***Source: London Economics analysis***

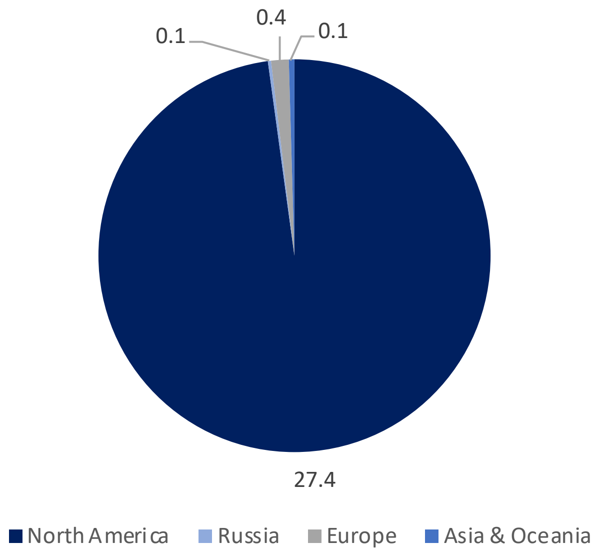
Constellation expected losses now exceed those of the rest of the LEO population by around 50%, indicating the shift in demand for commercial SST services which is now accounted for by a handful of constellation operators.

## Figure 31 Expected loss in LEO in 2029 by type of satellite




***Source: London Economics analysis***

**Figure 32 Expected loss in LEO in 2029 by region**



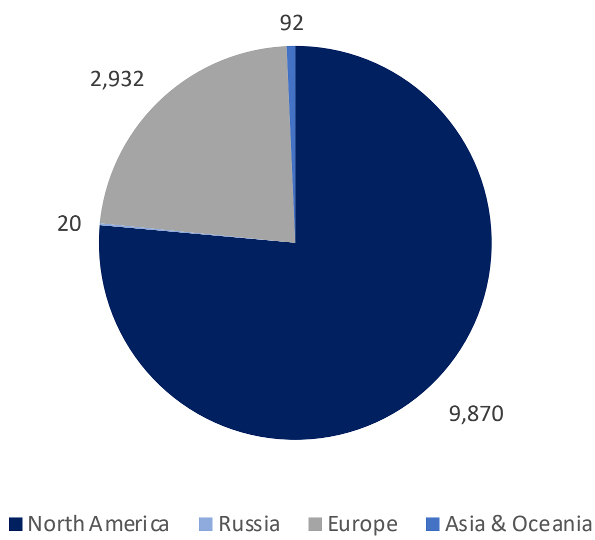

***Source: London Economics analysis***

### 5.2.4 LEO in 2036

**Value at risk**

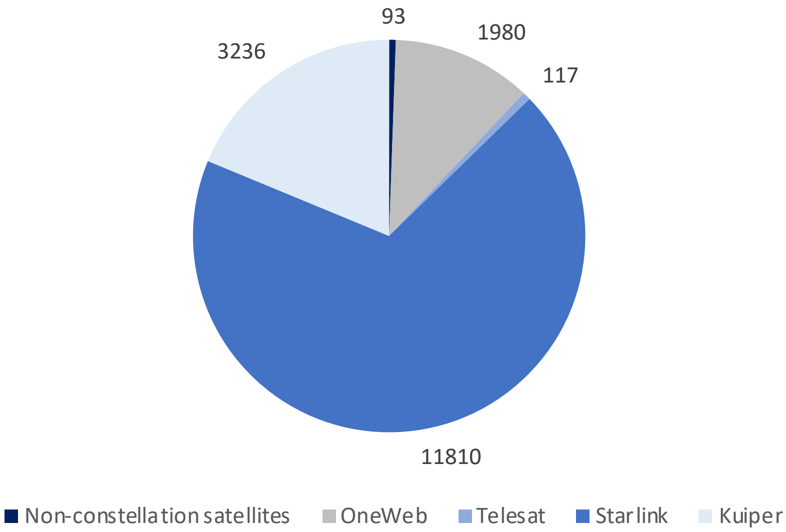
Replenishment of the initial constellations is well underway and slightly more of the value now resides with North America compared with 2029. As well as replacement Starlink and Kuiper spacecraft, long time operator Iridium has also replaced its fleet of satellites. OneWeb have replaced many of their first-generation satellites and account for a sizable portion of the value of the European spacecraft.

**Figure 33 Commercial value at risk in LEO in 2036 by region (USD m)**




***Source: London Economics analysis***

### Figure 34 Types of satellite in LEO in 2036

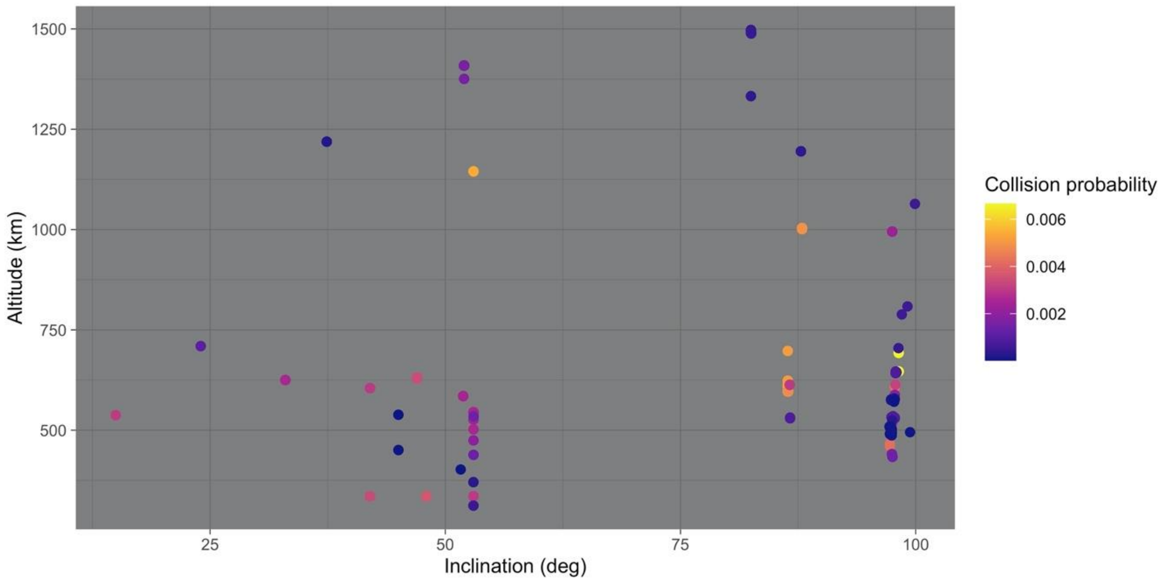



***Source: London Economics analysis***

### Expected loss

The constellations are complete and, assuming replenishment, the number of active spacecraft is constant over time. The maximum collision probability peaks at **1 in 150** and the average remains in the range of **1 in 290**. The strongest changes are localised in regions where the density has increased due to constellation. Overall, the collision probabilities fluctuate at minor rates, illustrated by a quasi-constant average in the long run.

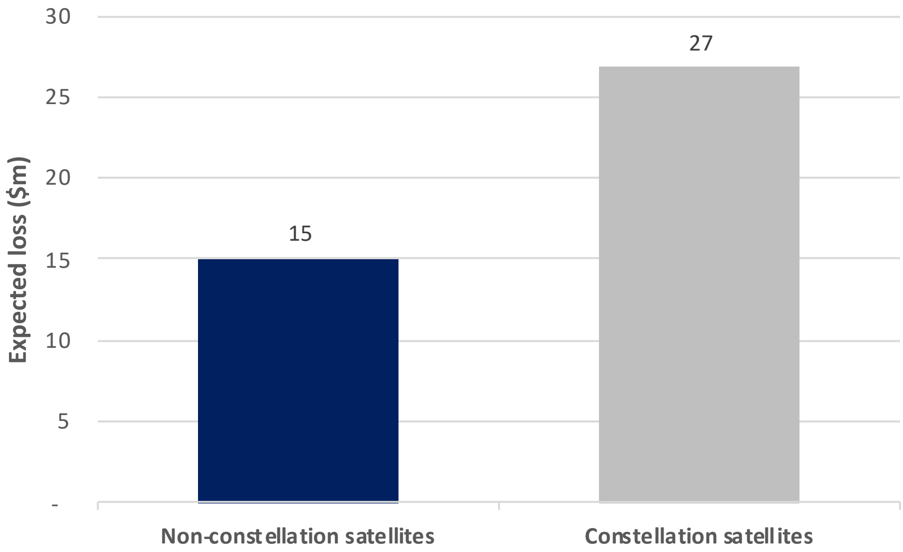
### Figure 35 Collision probabilities in LEO in 2036




***Source: London Economics analysis***

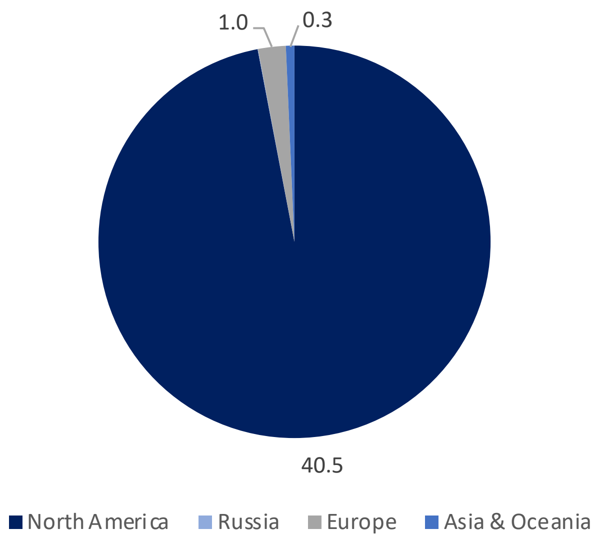
Constellation expected losses now tower over those of non-constellation spacecraft, which are nearly double the rest of all satellites combined. LEO is heavily congested with four fully deployed newer generation constellations, plus a fifth in Iridium (which still forms part of the spacecraft which has replaced current satellites in the UCS database). Starlink alone accounts for around 60% of the total demand for SST services, as it operates its constellation of around 12,000 satellites across three different altitudes and hundreds of orbital planes.

**Figure 36 Expected loss in LEO in 2036 by type of satellite**




***Source: London Economics analysis***

**Figure 37 Expected loss in LEO in 2036 by region**

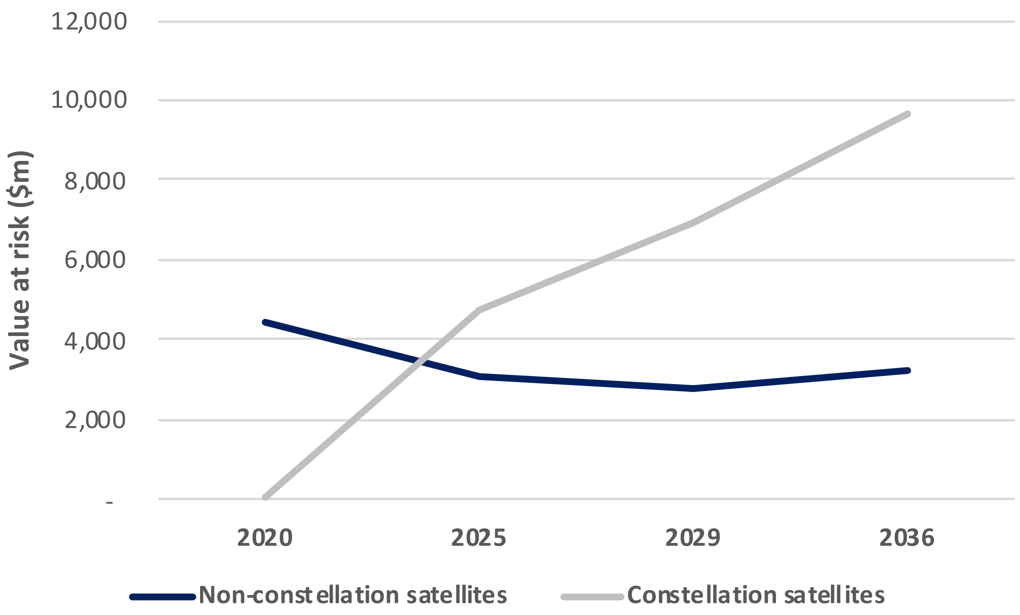



***Source: London Economics analysis***

## 5.3 Summary of results

Our model estimates that constellation spacecraft will exceed the aggregate sum of all other satellites in LEO in terms of net book value during the mid-2020's. This difference is further exacerbated by a shift towards smaller spacecraft for some operators who currently operate larger satellites (>50 kg).

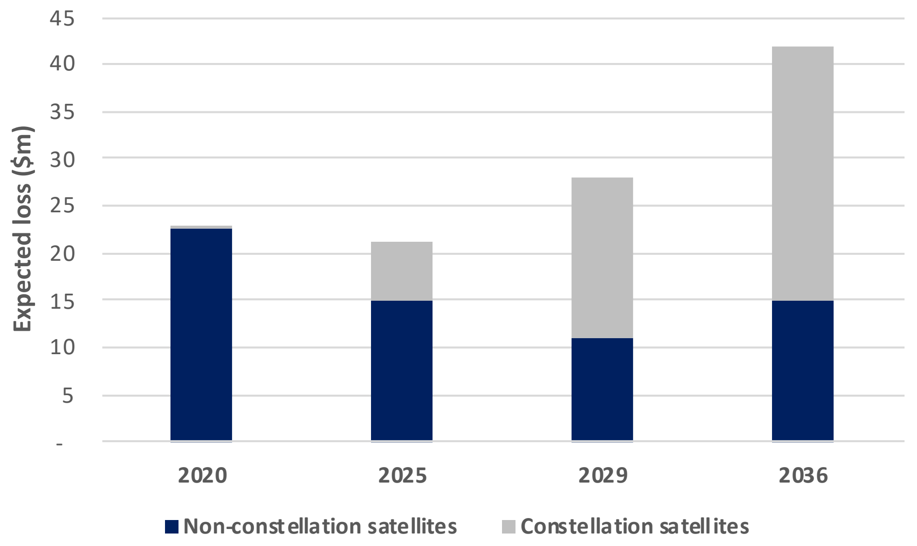
**Figure 38 Evolution of value in LEO by type**




***Source: London Economics analysis***

As can be seen in Figure 39 below, the primary source of expected loss becomes constellation spacecraft during the early 2020's. By 2029, the expected loss from constellations is more than double that from the rest of the LEO satellites combined. By 2036, it is nearly three times the size from non-constellation satellites and consequently represents a key market for SST service providers. Were any further constellations to be added to the huge numbers of spacecraft in orbit (e.g. any potentially emerging from China, Russia or elsewhere), then market dynamics would shift even further in this direction.

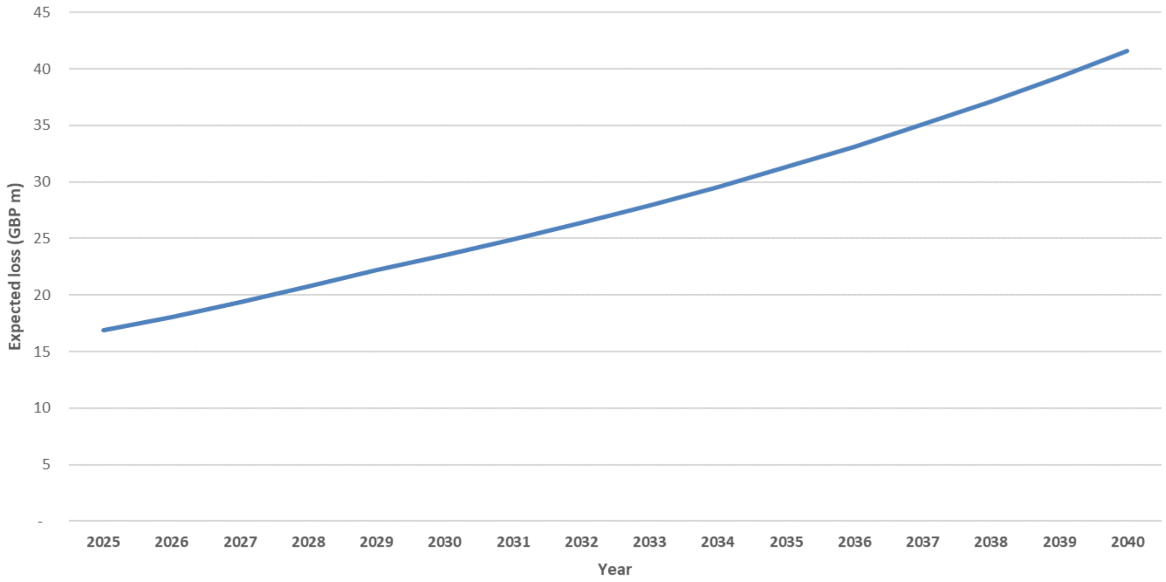
## Figure 39 Future expected loss in LEO in by type of satellite




***Source: London Economics analysis***

By extrapolating between the reference years discussed above, we can see that the global market for commercial SST conjunction services exhibits a gradual upwards curve over the next two decades from 2025 onwards.

## Figure 40 Cumulative annual future expected loss in LEO




Note: Values in intervening years extrapolated assuming fixed CAGR, assumes USD/GBP xe.com exchange rate of 0.79254 (15/03/20)

***Source: London Economics analysis***

## 5.4 Analysis of the supply

In LEO, we still focus on the same level of services from the supply. Conjunction analyses use similar methodologies but face a greater challenge due to a greater density of objects.

In LEO, we have identified six companies providing data, catalogues and services to operators. Two of them are large companies and four are small. Interestingly, five of the six are fully integrated. As with GEO the total number of companies actively providing services is still low, and the publicly available data would allow larger companies to internalise services rather than use an external supplier.

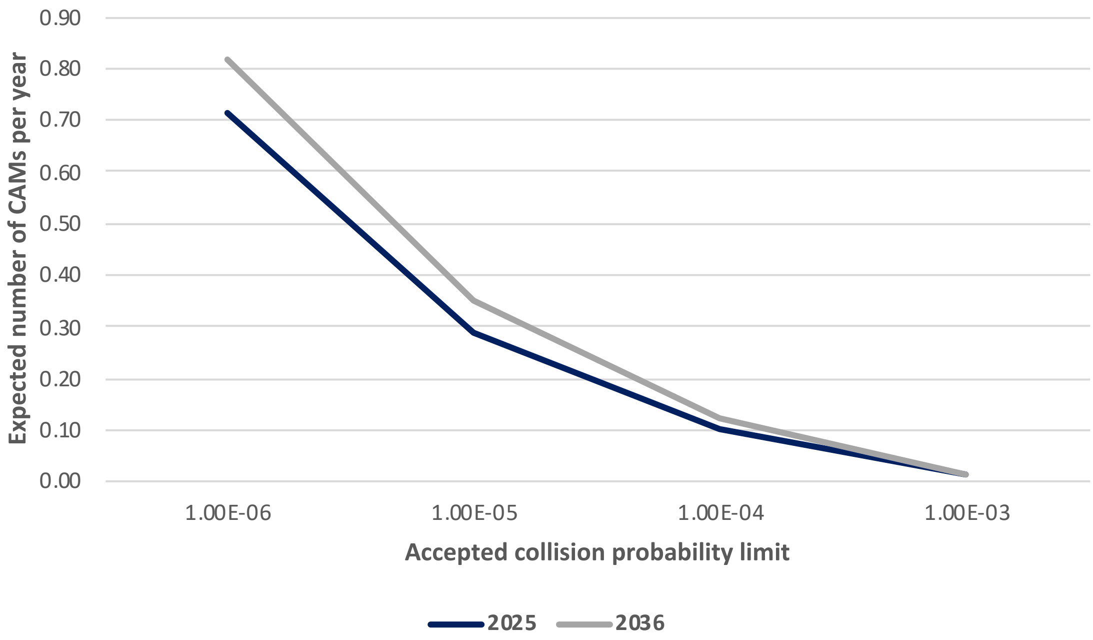
LeoLabs publicly provide a price range for satellite tracking, specifically an annual cost of $30,000 per satellite per year. This is much lower than the current estimated expected loss per satellite ($100,000).

The DRAMA software allows the user to compute the expected number of collision avoidance manoeuvres required per year. This illustrates the interdependence on the need to perform a CAM and the density of objects. This depends upon the location of the spacecraft and the denser the debris population in the orbit, the greater the need for CAM.

The figure below shows the expected number of CAMs per year for the OneWeb constellation, in 2025 and 2036. The number of CAMs is a function of the accepted collision probability threshold. Note that the density of debris is higher in 2036.

This graph illustrates two ideas. Firstly, the more risk averse agents are, the more CAMs they will have to perform. If the risk aversion increases, the number of CAMs will be higher and the supply/demand dynamic of the marketplace for tracking services shifts towards the suppliers. Secondly, as mentioned before an increase in objects (active and passive) increases the need for CAMs.

**Figure 41 Annual CAMs per OneWeb satellite**



***Source: London Economics analysis***

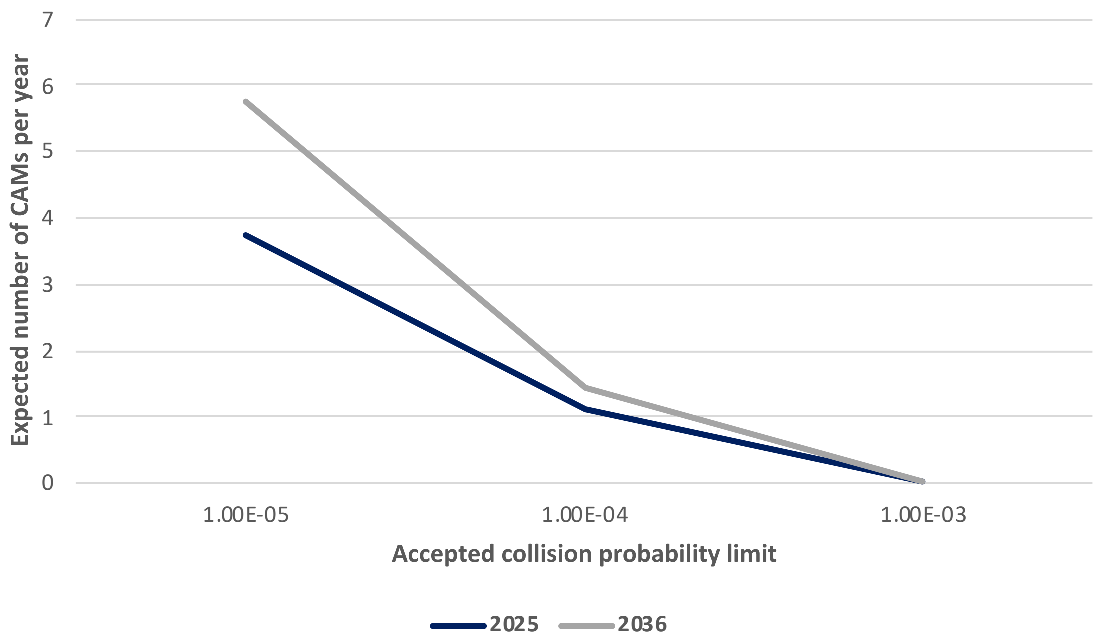
The number of conjunction messages delivered annually will undoubtedly increase. One can only imagine the amount of data required to assess all potential encounters in LEO once all mega constellations are deployed. We know that currently on average in GEO, 450 conjunction messages are delivered per year per satellite, of which a very small amount result in a manoeuvre. Despite a lack of data for LEO, we can project the situation.

We already know that the density of debris in LEO is 80 times larger than in GEO. Logically then the number of conjunction data messages (CDMs) and manoeuvres will be higher. The analysis of the future demand has also demonstrated that the collision probabilities will increase alongside the density.

As a result, a growing demand is expected in the future. The supply chain will have to develop new enhanced methods and employ more skilled staff to process and analyse the data. The necessity for an increased workforce has been confirmed in interviews with industry stakeholders as a key resource for the treatment of the data.

The human brain however has its limits and it is likely that there will be a need for additional computational power in the future. For the Starlink constellation for example, simulations we performed (see figure below) suggested that by 2036 operators would need to process as many as 72,000 conjunction warnings across the entire constellation, which is clearly beyond the abilities of human led analysis.

**Figure 42 Annual CAMs per Starlink satellite by year**

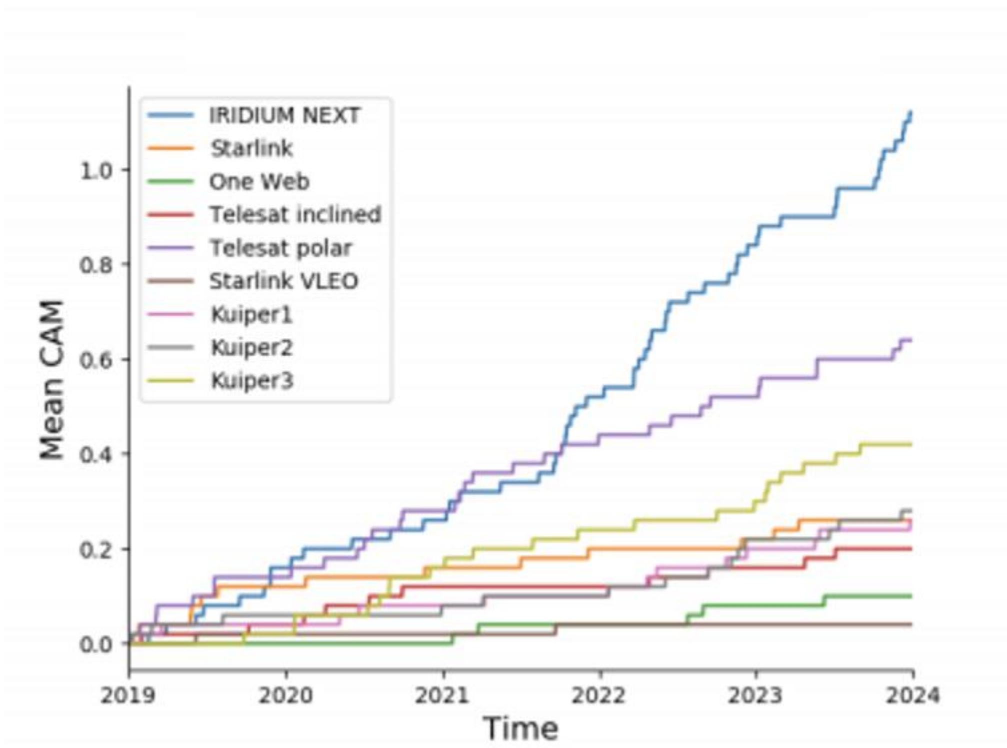



***Source: London Economics analysis & DRAMA outputs***

Another recent study simulated the number of CAMs from 2019 to 2024[33], and shows that the trend is accelerating with the full deployment of constellations. The figure below represents the evolution of the number of CAMs for different constellations, over time. It is clear that the increase in mean CAM will be different with respect to the constellation. This owes to the different orbital planes, constellation will sit in.

Note that the time scale on this chart is different than ours in our assessment of the evolution of the mean number of CAMs.

**Figure 43 Average CAMs for various constellations between 2019 & 2024**




***Source: Petit et al (2019)***

The paper shows that over a five-year period, more than 2600 CAMs are expected in total across these five constellations which provides a reasonable comparator for our estimates.

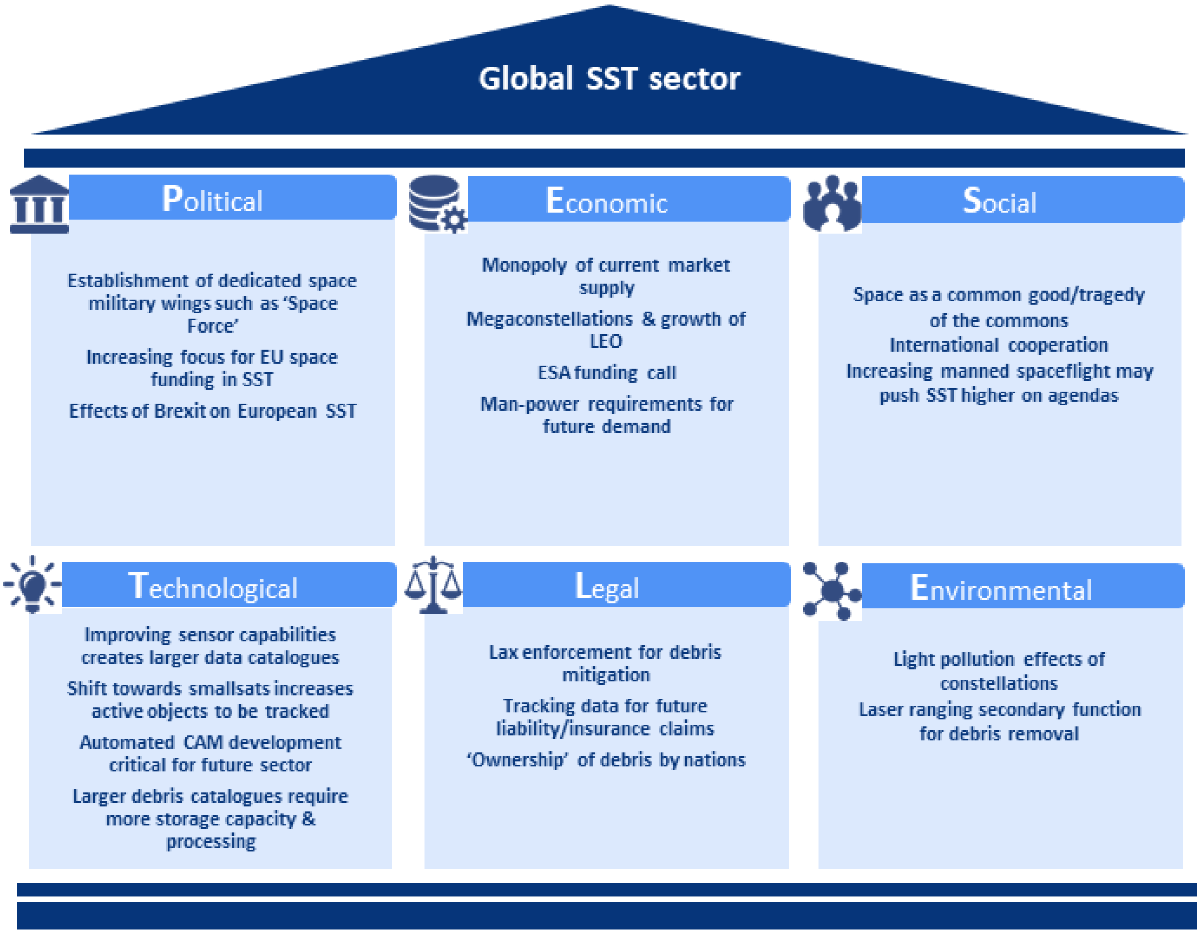
The supply chain will certainly need a growing number of sensors as well. In fact, once potential collisions are detected, it is important to focus on the target and the chaser to analyse their relative positions and reduce the uncertainty in order to provide the best information to the operator. An increase in the number of CDM will induce an increase in the need for ad-hoc tracking which would then put a pressure on the supply chain to build more sensors and maintain and operate them.

[33] Petit et al. 2019. Risk of collision for satellites in configuration of mega constellation

# 6 Future market development

The orbital space landscape looks set to change dramatically in the coming years based upon developments such as the emergence of megaconstellations and in-orbit servicing. This chapter considers some of the major implications, both for the SST market as a whole and for the UK in particular.

## 6.1 PESTLE analysis of the global SST industry




***Source: London Economics analysis***

**Political**

The **establishment of the US 'Space Force' in combination with Space Policy Directive-3 (SPD-3)** will likely stimulate further debate and discussion around the area of SST. In establishing a dedicated space arm of the military, considerations relating to SST are brought sharply into focus, and adoption of similar military branches by other national governments is certain to increase the funding and prominence of SST activities for both civil and military applications.

In terms of the European SST landscape, a major potential shift relates to the withdrawal of the UK from the European Union. In terms of direct effects, given the potential military applications of SST data this may introduce some complications into existing agreements such as the EUSST programme. As issues have already been seen relating to the UK's continued involvement with the Galileo programme, it would seem these issues are unlikely to be resolved in a straightforward manner. There may also be secondary implications in terms of willingness to participate in data sharing agreements with European peers, however presumably UK membership of organisations such as NATO would preclude any serious concerns in this regard.

The transition may also encourage more direct foreign investment into UK SST facilities, as UK know how in scientific and engineering disciplines may become more appealing for overseas investors given the potentially more favourable currency exchange rates, plus the UK's ability to negotiate new trade deals directly with other nations.

**Economic**

The **growth in the proliferation of LEO** can be seen as a major economic growth driver for the space sector. This has occurred as a result of increasing ease of access to orbit in recent years, with the advent of wider use of small satellites removing some of the barriers to entry cost in terms of launching spacecraft into orbit. Whilst many of the smallest satellites lack the propulsive systems to benefit from SST information in real-time, the same cannot be said for the emergence of **large-scale constellations** which have already begun rolling out early generation satellites in-orbit. As SpaceX's Starlink constellation plans alone have the potential to more than double the number of objects launched into orbit throughout the entire history of human spaceflight, this rapid expansion in the number of satellites to be launched into orbit represents a huge potential economic stimulus for the industry. From an SST standpoint, there are many potential opportunities for commercial companies to provide products and services to the constellation operators, whilst at the same time the developments will create additional difficulties which will also need to be addressed.

As discussed in section 5.4, with the frequency of conjunction warnings set to increase markedly in years to come, this will necessitate **increased levels of man-power and processing** to determine which alerts are actionable and which are not, and in the case where a collision avoidance manoeuvre (CAM) is required, the optimal method by which to execute the manoeuvre. In the short-term at least, this will require more trained personnel at satellite ground stations who are able to deal with such alerts. Whilst future developments such as improved accuracy of data or potential automation of tasks may reduce the volume of alerts received, the requirement for skilled personnel will place increased demands upon the labour market, which in itself may create more jobs and opportunities within this subsector.

**Social**

SPD-3 sets out the intention of the current administration to "maintain U.S. leadership in space" and "Provide U.S. Government-supported basic SSA data and basic space traffic management (STM) services to the public" and notes that this should be "free of direct user fees".[34] Whilst this is a laudable commitment on the part of the US government and is assumed to include non-domestic SSA users as part of this service offering, it cannot be assumed that this provision in its current form will continue indefinitely, and the build-up of complementary SSA/SST capabilities should be maintained and enhanced by other sovereign nations. The directive also states a commitment to "Establishing an Open Architecture SSA Data Repository […]. As additional sources of space tracking data become available, the United States has the opportunity to incorporate civil, commercial, international, and other available data to allow users to enhance and refine this service", which provides some reassurance that levels of international collaboration are anticipated in the future so

[34] Trump, D.J. (2018). 'Space Policy Directive-3, National Space Traffic Management Policy', available at https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/

as to avoid a potential '**tragedy of the commons**' type scenario where tracts of orbital space are rendered unusable.

Currently, actual human presence in space is limited to astronauts travelling to and from the International Space Station (ISS), and spells onboard the orbiting habitat for scientific purposes. In years to come however it would appear that this is about to change, as commercial human spaceflight efforts are expected to come to fruition. These developments could potentially open up a wide range of human activities in space, ranging from traditional professional astronauts in space employed by space agencies, to affluent 'tourists' seeking the thrill of an experience in space (see section below). An **increasing involvement of humans in space** could lead to a sharper focus on the safety aspects of orbital space, with the subject increasingly higher on the international agenda. Certainly, any commercial operation would be expected to have a firm grasp of any risks posed by orbital debris or potential collisions, and SST information will be pivotal to these undertakings.

**Technological**

Current technology trends point towards **vastly expanded debris or object catalogues compared with today's standards**. There are several drivers behind this. Firstly, to understand these drivers we must first categorise the main types of sensor currently in use today, which are as follows:

- Optical – useful for observations in GEO.
- Radar – classical technology typically inherited or repurposed from non-space related military applications. Primarily useful for tracking LEO objects, but can be used as far out as GEO.

Other types of sensor which are becoming more commonplace are:

- Radio Frequency (RF) – i.e. scan the sky in various frequencies within the electromagnetic spectrum. Only useful for tracking active objects, i.e. satellites.
- Laser ranging - whereby laser beam reflections off satellites in LEO can be used to measure their distance and velocity. Whilst some active sensor installations already exist in this class, research and development (R&D) efforts are still underway to refine the use of the technology.
- In addition, sensors can be situated either on the ground or increasingly within space itself, such as the US 'Space-Based Space Surveillance' (SBSS) programme, or Canada's Sapphire satellite.

Aside from ongoing R&D for laser ranging all types of sensor are subject to continual upgrade in capabilities, particularly in light of more recent focus on SST measures. A specific development which may impact on the imaging capacity available for the growing LEO market is noted in a recent study,[35] and relates to the potential for combining optical and RF sensors with software solutions to widen the field of objects which would be trackable by these means. The same study also notes the potential for use of artificial vision systems based upon biological processes to augment sensor capabilities so that they can be used continuously at all times of day. This technology is currently thought to be 10-15 years away from operational usage.

[35] Lal, B. et al (2018), Science & Technology Institute. 'Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)'

The growing number of sensors will also impact the volume of data to be processed. The Russian ISON network is known to have expanded in number by 3.5x since 2008, with a corresponding increase in the number of measurements taken. Japan and Poland are also known to be considering repurposing some of their existing optical sensors for SST data collection, and China appears to be augmenting its existing capabilities with sensor installations around the globe and in space.[36]

On the commercial side, companies such as ExoAnalytics are known to possess the largest sensor network in the world. LeoLabs are known to be in the process of expanding their sensor network, which will enable tracking of up to 250,000 objects (up from 13,000 today) and enhance capabilities from the current level of tracking down to 10 cm sized objects to being able to track particles as small as 2 cm.

Whilst the US currently provides free two-line element (TLE) data to the world, the opaqueness of the processing of this data means that other entities, both commercial and non-commercial, have begun to develop their own software to process SST data. This in itself has driven innovation within the software industry and looks set to continue into the future, as techniques such as data-fusion allow the free US DoD data to be combined with other sources of SST data (both domestic and from international sharing agreements) to augment and enhance this information. This has led to a wider range of more sophisticated products to be developed for users, both at a national level and at an international level for commercial operators. With wider technology trends such as improvements in processing power and access to low-cost cloud storage solutions set to continue, these benefits look set to flow into the future SST domain and help to meet the needs of this burgeoning market.

**Legal**

The Outer Space Treaty of 1967 still represents the framework which underpins the foundation of the modern legal system with respect to space. This and subsequent UN resolutions form the basis of the multilateral agreements regarding the use of space. Given the passage of time since agreements made around the dawn of the space era set against the backdrop of the Cold War, it is evident that the various treatises are not entirely fit for purpose when viewed through a modern lens, and with a future usage of space far removed from the perspective of the time of signature.

The treaty has as one of its core principles **ownership of debris**, namely that 'States shall be liable for damage caused by their space objects'. This appears to infer that if damage to another's spacecraft is caused by orbital debris, then the party 'at fault' will be responsible for damage. In practice, in many instances it will no doubt be difficult to prove where the fault for a collision lies, and indeed if the debris is a miniscule piece of mission related debris then it may be impossible to trace the origins of the debris in any case. SST data in the future however may be able to form part of the solution to such issues, which will no doubt become more prevalent in the coming years. A test case for such incidents occurred in 2009 when the operational Iridium 33 satellite and the derelict Russian military Kosmos-2251 collided in LEO, destroying both objects and creating a resultant debris cloud. A follow on from the Outer Space Treaty was the Space Liability Convention of 1972, which allows one state to claim for damages in the situation where an object launches from State A's territory or registered by State A causes damage to the property of State B. When Iridium

[36] Lal, B. et al (2018), Science & Technology Institute. 'Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)'

attempted to seek recompense from the Russian state via the US government, reportedly one of the factors which prevent the establishment of 'fault' was the lack of SST data to support the claim.[37]

The 1975 Registration Convention requires signatories to register all newly launched space objects to the United Nations. The limitation which arises from this convention however is that only 63 nations were signatories to the original treaty, and therefore with many more nations participating in space activities there is no obligation for all space launches to be registered at a central repository. Increased levels of global observation and data catalogues should increase the level of identification of new space objects and can potentially act as a 'gap filler' at least until new legislation is created.

**Environmental**

In recent times, several astronomers have raised complaints stemming from **negative light pollution effects caused by satellite constellation spacecraft**. Specifically, the launch of the first iterations of SpaceX's Starlink constellation have impacted the field of view of various telescopes across the globe, as reflections or glare from multiple satellites in an orbital plane have spoiled imagery carried out whilst satellites are passing overhead. As the number of constellation satellites is set to rise markedly, the issue could pose a grave threat to the future of ground-based astronomy. Indeed, a recent study by the European Southern Observatory has concluded that up to 3% of long exposures could be threatened, and for one US facility up to 30% to 50% of exposures could be "severely affected".[38]

Whilst satellite manufacturers are said to be in discussions with the astronomical community to find ways to mitigate some of the impacts via modified satellite design, at least as a short-term solution it would appear that SST information may hold the key. If astronomers have advance warning of the orbital track of constellation spacecraft, then they can avoid targeting specific regions of the sky which would be subject to light pollution. This would avoid wasting telescope time, which can be highly valued particularly for large sensors prioritised for scientific research which permit dedicated time allocations split across multiple users.

## 6.2 Future services enabled by SST

**Satellite servicing**

An important future market is satellite servicing in GEO, and potentially also in LEO and MEO. Robotic servicing satellites in development at present are expected to undertake a variety of in-orbit servicing missions in the coming years, including refuelling and damage repair of active satellites. Indeed, proof of concept was illustrated in February 2020 with the successful refuelling of the Intelsat-901 satellite by Northrop Grumman's Mission Extension Vehicle-1.[39]

For such missions, SST information will be **vital** for informing servicing operators of the condition of target satellites, and for rendezvous and docking activities. Another satellite servicing type endeavour occurring at the end of the useful life of spacecraft with particular implications for SST is discussed in greater detail below.

[37] Listner, M. (2012), The Space Review. 'Iridium 33 and Cosmos 2251 three years later: where are we now?', available at https://www.thespacereview.com/article/2023/1

[38] Hainnaut, O.R. & Williams, A.P. (2020). 'Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains', Astronomy & Astrophysics, *to be published Q1 2020*

[39] Henry, C. (2020). 'Northrop Grumman's MEV-1 servicer docks with Intelsat satellite', available at https://spacenews.com/northrop-grummans-mev-1-servicer-docks-with-intelsat-satellite/

**Commercial space debris removal services**

A potential future market identified during industry interviews relates to one of the key growth drivers of the LEO market, satellite communications constellations. The architecture of these initiatives typically involves a design to ensure global coverage, or at least a sizable portion of the globe.

The total number of satellites involved are split into groups and situated within several orbital planes which are spaced at regular intervals around the equatorial planes. Each of these orbital planes represents a region of orbital space where the operators have been granted approval to operate, based upon regulatory authorisations from appropriate bodies (e.g. the International Telecommunications Union, or the US Federal Communications Commission).

As such the viability of these orbital planes for safe satellite operations is key for constellation owners. Whilst satellite operators are currently expected to comply with the 25-year guideline for disposal of satellites, in practice on some occasions this may not be feasible as satellites may fail unexpectedly before passivation activities can occur, or even run out of fuel in exceptional cases.

In fact, a recent ESA study estimated that for satellites in higher altitude orbits that will not deorbit naturally because of atmospheric drag, only 15–25% of satellites will attempt to comply with the 25-year de-orbit guideline.[40]

Accumulations of failed or defunct constellation satellites within these regions may lead to the build-up of debris clouds from fragmentation events. It is paramount to the interests of operators looking to make use of these regions to keep them as free of debris as physically possible. In terms of their own activities, they should be looking to remove any non-controllable satellites as soon as possible to reduce the threat posed to their other functional spacecraft.

This is where commercial debris removal services available in the future may provide a valuable offering to the space community. Operations such as Astroscale, an enterprise headquartered in Japan but with a UK presence, and a separate commercial initiative by ESA, appear well positioned to cater to this potential market demand.

An interview conducted in relation to these activities confirmed that commercial operations will require the availability of SST data to assess the location of the target deactivated spacecraft (or fragments of), plus to build up a picture of both the target object and debris in the vicinity of any operation to assist with assessment of the situation and safe operation of the servicing vehicle.

**Automation of collision avoidance**

A need for automation of conjunction analysis and collision avoidance manoeuvres has been identified as a key enabler of future satellite operations. Firstly in the commercial world, where SpaceX have suggested that their constellation will feature autonomous collisions avoidance techniques.[41] ESA have also published a proposal for a system known as CREAM (Collision Risk

[40] ESA (2019). 'ESA's Annual Space Environment Report', available at https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[41] Fernholz, T. (2019). 'SpaceX's new satellites will dodge collisions autonomously (and they'd better)', available at https://qz.com/1627570/how-autonomous-are-spacexs-starlink-satellites/

Estimation and Automated Mitigation) which is intended to reduce the required human workload for such situations.[42]

In the report, ESA state that with debris catalogues set to expand in future years owing to improved sensor precision and data processing, the task of committing to 'classical' human led assessments will prove to be unmanageable due to increasing workload demands. As such, development of autonomous systems is critical for the operations of satellite constellations.

The systems will rely on the accuracy of SST data to avoid the need for false alerts leading to unnecessary CAMs, in addition to developments in machine learning techniques. In summary, provision of accurate and reliable SST data can be seen as a key enabler for preventing damage to constellation spacecraft and their operational viability.

**Manufacturing in space**

Initiatives to make use of some of the unique characteristics of the space environment and utilise technology such as 3D printing means that in future, manufacturing in-orbit on a sizable scale could become a reality. A recent study suggests that these developments could gather pace and come to fruition within the next decade,[43] although the potential size of any commercial market is unclear at this juncture. Any in-orbit manufacturing facilities would presumably need to safeguard against any debris related damage occurring to both manufacturing devices and products.

SST information could be used both as a guide for location of such facilities in terms of avoiding heavily trafficked regions of orbital space, or regions with known populations of debris which could prove hazardous. Real-time operation would also require SST data, particularly if sizable facilities are required, as the greater the cross-sectional area of an orbiting satellite, the greater the risk of conjunctions.

**Space tourism/commercial space stations**

Also referenced within the study mentioned above are activities relating space tourism. As much of the immediate developments are anticipated to occur at sub-orbital altitudes, the need for SST products and services is less clear, other than perhaps the need for re-entry notifications to avoid the unlikely event of collisions occurring within the Earth's atmosphere.

Should longer term ambitions come to fruition such as commercial journeys into space, lunar tourism or extended stays onboard commercial orbiting space stations, then SST information will form an important component of ensuring passenger safety. In fact, it is conceivable that in the event of commercial manned spaceflight coming into focus, the need for strict regulation to ensure passenger safety could include stipulations regarding quality of SST information baring some resemblance to current legislation around aviation passenger safety.

High volumes of commercial travel into orbital space and beyond are unlikely to come into reality within the next decade, however it is conceivable that they occur during the time horizon covered by this study.

[42] Virgilli et al (2019). 'CREAM - ESA's Proposal for Collision Risk Estimation and Automated Mitigation', First Int'l Debris Conf. (2019)
[43] Flytkjaer, Oswald, Sadlier & Stanbrough (2019). 'NewSpace Bringing the new frontier closer to home', available at 'https://www.lloyds.com/news-and-risk-insight/risk-reports/library/understanding-risk/newspace-bringing-the-new-frontier-closer-to-home'

### 6.2.1 Technology spillovers and externalities

At present, owing to the highly distinctive nature of the space industry it is difficult to forecast where technology used for SST purposes can be repurposed or adapted for use in other domains. Also, whilst developments impacting upon the SST landscape such as megaconstellations have implications for many other industries and normal everyday life on Earth, it is difficult to attribute specific externalities which arise from growing use of SST.

One possible exception to this may be in relation to laser ranging techniques discussed earlier in the chapter. Such techniques can also be used to 'nudge' small fragments of debris into a re-entry orbit, in addition to providing valuable SST information. At present such techniques are largely experimental, however with further R&D efforts in coming years the sensors used to track debris could also be used as one method for solving some of the issues caused by build-up of debris.

Another may be in the area of liability and insurance claims. Whilst this application is not a direct beneficiary of SST data as presumably the original purpose of SST data for a satellite mission would be to ensure the safety of operations in space, in the event of a collision then SST data could be used to support any liability or insurance claims for a party 'not at fault'. The aftermath of an earlier collision would appear to highlight the importance of SST for such purposes (see 'Legal' in section 6.1).

## 6.3 UK SST market focus

### 6.3.1 Peer comparison of UK SST capabilities

The table below summarises some of the current primary civil and military sensor capabilities of six of the major NATO powers. Unsurprisingly, the US has the strongest network of sensors and capabilities as it distributes its key 18 SPCS data to global partners.

In Europe, France, Spain and Italy have strong sensor networks in terms of optical and non-optical systems, operating from different strategic locations around the globe. All three also have national centres of excellence dedicated to provision of SST products and services for civil, military and commercial domestic operators. Germany by contrast began building its programme from 2009, with an extension to 24/7 operations in 2016 to satisfy EU SST programme requirements.

The UK's SSA efforts have previously been coordinated by the UK Space Operations Centre (SpOC), however in 2018 plans were announced for a restructuring of the service, with a doubling of personnel at SpOC and plans to merge operations with the National Air Defence Operations Centre to create the National Air & Space Operations Centre.[44] The extent of the services provided for military users in the MoD, other civil services and commercial operators is also understood to be under review. At present, it does not appear that the UK provides a UK maintained object catalogue to either commercial operators or academia. This has been highlighted as a key desirable based upon survey responses,[45] and represents a difference in the way other peer governments support commercial activities.

Based upon data reported by Joint Air Power Competence Centre, the UK appears to lack the variety of sensor network some of its peer nations possess and does not appear to operate any facilities

[44] Robinson, T. (2018), Royal Aeronautical Society. 'UK MoD goes more boldly into space', available at https://www.aerosociety.com/news/uk-mod-goes-more-boldly-into-space/
[45] UK National Operations/Analysis Centre, Customer Engagement Survey Result, SCISYS

outside the UK in its overseas territories (other than a single optical sensor in the Mediterranean), nor has it established any partnerships to operate in strategic geographical locations (e.g. southern hemisphere). The greatest non-UK asset the nation possesses is the close ties with the US as part of the 'Five Eyes' alliance, and from data sharing agreements such as the USUKA, although the other leading European powers also leverage the US data within their national strategies to some extent. Currently the UK also participates in the EU Space Surveillance and Tracking Programme (EUSST), however ongoing participation is subject to negotiations as part of the discussions relating to the UK's withdrawal from the EU.[46]

[46] Charity, N. (2018), Evening Standard. 'Britain less likely to be warned of space debris heading towards Earth in event of no-deal Brexit', available at https://www.standard.co.uk/news/uk/uk-less-likely-to-be-warned-of-space-debris-heading-towards-earth-in-event-of-nodeal-brexit-a3935401.html

## Table 4 Known SST capabilities of selected NATO powers

| Nation | Major optical sensor programmes | Major non-optical sensor programmes | Other |
|---|---|---|---|
| **UK** | **Two:**<br>- **PIMS (Passive Imaging Metric Sensor) telescope: Three 40 cm Cassegrain telescopes covering 165° of GEO**<br>- **Starbrook telescope: 10 cm telescope located in Cyprus for GEO surveillance** | **Two:**<br>- **CASTR (Chilbolton Advanced Satellite Tracking Radar): 25 m antenna currently being upgraded**<br>- **Fylingdales radar: Three phased array 22 m UHF radars primarily for ballistic missile early warning** | **UK Space Operations Centre (SpOC) provides limited SST services for military and civil users. Data sharing agreement with the US means the UK has virtually unrestricted access to the world's largest SST database. Disclosure of data to third parties is limited however.** |
| USA | Three:<br>- GEODSS System: Three 1 m telescopes for deep space observation<br>- Space Surveillance Telescope: 3.5 m telescope located in Australia for southern hemisphere coverage<br>- Maui Space Surveillance System: One 3.67 m telescope plus several other sensors (IR, photometric) | Nine:<br>- Three dedicated radar, including a UHF sensor in Florida, GLOBUS II in Norway, and a new VHF system replacing 'Space Fence' in 2021<br>- Four collateral sensors across a range of EM frequencies; the Haystack Radars in Massachusetts, and four island sites in the pacific and south Atlantic<br>- Two auxiliary sensors across multiple sites in the US | 18 SPCS is a world leading centre for SSA information<br><br>Two space-based sensors in SBSS-1 and the Canadian Sapphire satellite |
| France | Two:<br>- The SPOC telescope for initial orbit determinations<br>- The TAROT System: two 25 cm telescopes + one 50cm telescope operated in partnership with CNES. Based in Chile, with a secondary use for GEO observations | Three:<br>- GRAVES, a VHF radar capable of tracking 1 sq m objects<br>- SATAM radars: comprised of three tracking sensors also used for management of collision risks and re-entry<br>- BEM tracking ship: three tracking radars also used for SST | Spectral analysis of debris from OSCEGEANE<br><br>COSMOS centre responsible for civilian and military SSA<br><br>CNES CAESAR (Conjunction Analysis and Evaluation Service: Alert and Recommendations) public service, which fuses 18 SPCS data with French domestic data |

| Nation | Major optical sensor programmes | Major non-optical sensor programmes | Other |
|---|---|---|---|
| Germany | None known | Two:<br>- TIRA radar & Effelsberg Radio Telescope: capable of tracking particles as small as 1 cm<br>- GESTRA system: phased array antennas currently undergoing commissioning | The German SSA Centre (GSSAC) fuses data from international and domestic sources to provide CAs, re-entry warnings and space weather forecasts to users, with full operational 24/7 capability from 2020 |
| Italy | Two:<br>- PdM-MITE 'fast' telescope<br>- VdV-CAS telescope: used for surveillance and tracking GEO | Four:<br>- RAT-31 radars: phased array radar with secondary purposes for SSA<br>- BIRALES: UHF radar capable of tracking sub-metre objects<br>- BIRALET: LEO tracking radar<br>- MLRO: laser ranging station capable of measuring orbital parameters for satellites fitted with laser reflectors | Italian SST Operations Centre (ISOC) is the national SST centre which merges data from national sensors, US military data and in future, ESA to deliver SST products and services to military users |
| Spain | Six:<br>- Centu-1 & Tracker-1 telescopes: sensors owned by Deimos Electron capable of monitoring debris in Geo& MEO<br>- TFRM: 50 cm tracking & surveillance telescope<br>- TJO: 1 m class tracking telescope<br>- IAC-80: 80 cm sensor in Tenerife<br>- BOOTES network: four telescopes spread around the globe for tracking & surveillance of GEO | Three:<br>- MSSR: military L-band radar<br>- S3TSR: phased array radar expected to be fully commissioned shortly, also used by ESA<br>- SFEL: dedicated to tracking laser reflective spacecraft in LEO | The Spanish Space Surveillance and Tracking (S3T) system combines US 18 SPCS data with its domestic sensor network and ephemerides from satellite operators to create the S3T catalogue. Based on this it can provide CDMs, fragmentation alerts and re-entry surveillance |

***Source: Joint Air Power Competence Centre (2019). 'Command and Control of a Multinational Space Surveillance and Tracking Network'***

### 6.3.2 UK SWOT analysis

**STRENGTHS**

- Data sharing agreement with the US
- Academic institutions
- Regional hubs provide useful concentrations of access to supply chain
- UK funding environment conducive to supporting SST developments
- Regulatory environment for commercial SST enterprises
- UK based optical sensors useful for imaging GEO
- Funding of ESA SST focused programmes

**WEAKNESSES**

- Lack of clarity over UK SpOC at present
- Fewer dedicated sensors than some peer nations
- Limited non-UK based sensor capability in other regions
- Dependency on US-UK relationship
- Limitations for growth in LEO market from types of sensors
- Limited involvement in SST commercial services

**OPPORTUNITIES**

- Major constellation operator based in the UK
- UK exports currently in favourable position owing to competitive exchange rates
- Future UK spaceport operators may need SST services
- Commercial satellite servicing operations based in the UK

**THREATS**

- Potential loss of participation in EUSST due to Brexit
- Potential loss of EU funding sources for UK based initiatives
- Lack of manpower to process high volumes of future data
- Changes to regulation relating to global debris

***Source: London Economics analysis***

**Strengths**

The **data sharing agreement with the US** provides the UK government with almost unrestricted access to the most comprehensive SSA dataset in the world and represents a key asset for UK SST capabilities. Agreements such as the USUKA agreement have established a strong relationship with what is undoubtedly one of the world's leading players in the SST domain, in terms of both its role in leading the global SST agenda and in terms of the depth and extent of its sensor network. Potentially this gives the UK a slight competitive advantage compared with some peer nations, who may not benefit from such close ties with the US.

The **UK funding environment**, combined with the capabilities of some of its **academic institutions**, can also strengthen the UK's position in the global SST stakes. Public sector collaborations such as DSTL's Defence And Security Accelerator (DASA) competition, which will invest £1.5m into improving 'resilience, awareness and capability in space' demonstrates how the UK can leverage its scientific and technological expertise on the world stage. The University of Warwick and the University of Strathclyde have both benefited from funding awarded from the competition[47], and in addition to

[47] Lye, H. (2019). 'UK to invest £1.5m in space defence technology', available at https://www.airforce-technology.com/news/uk-to-invest-1-5m-in-space-defence-technology/

centres of excellence at the University of Southampton and UCL amongst others, the UK is well positioned to make a key contribution to SST research and development over the coming years.

Some of the political uncertainty surround the UK leaving the European Union in 2020 has been mitigated in SST terms by the UK's **continued membership of the European Space Agency**, which in the latest funding round in late 2019 announced considerable budget allocation for SST programmes. As a result the UK can still benefit from this pooling of resources with other European nations, and potentially claim some of the 'juste retour' benefits underlying the principles of ESA participation by attracting both contracts and services for the UK, in a similar manner to how commercial companies in peer nations such as Spain manage ESA SST ground facilities.

**Weaknesses**

In terms of sensor capabilities, these can be categorised by different types of sensor (optical, RF or radio frequency, radar and laser ranging) and by location (i.e. ground-based or space-based). At present, **the UK is only known to possess ground-based sensors in the optical and radar categories.** This could be construed as a weakness in the overall SST strategy, as if these sensors were not available for some reason then the UK could be left without sufficient real-time SST information. At present this is mitigated by international information sharing agreements, however consideration could be given to whether more redundancy could be added for overall capability levels, as issues such as the Starlink constellation impacting ground-based astronomy demonstrate the potential for unforeseen disruption.

In terms of the types of sensor the UK possesses, as demonstrated in chapter 5 the major future growth markets from an SST perspective in terms of anticipated demand is in LEO. With only one dedicated radar sensor at present, the UK is not well placed to cater for this anticipated boom in demand for LEO tracking services in future years, which is of relevance for **servicing commercial markets**. As such further funding of enhancing sensor capabilities should perhaps add more weight towards non-optical systems suited for LEO applications. Additionally, as some types of sensor such as laser ranging systems require compatibility in terms of the materials used to construct satellites (i.e. so the satellites are able to reflect laser beams), with no capabilities in this area the UK is not positioned to take an active role in leading technology development for such systems.

Coordination of central UK SSA initiatives are known to be in a state of transition at present, with **uncertainty regarding the ongoing review of services to be offered by a UK Space Operations Centre (SpOC)**. As summarised in 0, all peer NATO nations have a clearly defined SST service strategy for both commercial and non-commercial users, or are in the process of executing a clearly defined strategy. In this sense the UK could be seen to be lagging behind some of its peers, although as it appears this has been identified to some extent already with the current review process underway, it is a positive sign that thoughts at a governmental level are being crystallised as to implementing measures to improve the UK's capabilities in this area.

**Opportunities**

A key market driver for SST services that has been identified stems from **SST requirements of sizable future satellite constellations.** With OneWeb being one such operator legally based in the UK, the geographical proximity of the OneWeb operations centre naturally provides opportunities for commercial companies to provide services in relation to SST. Also, with a major player in the future development of the LEO ecosystem being based in the UK, this provides UK regulatory bodies concerned with SST and space debris mitigation a pathway to participate in global discussions to reflect the concerns of operators situated in the UK. This allows UK advisory bodies to help **shape**

**the future direction of initiatives** relating to legislation, debris mitigation efforts, development of best practice standards and space traffic management within the framework of global collaboration and coordination efforts.

**Threats**

A key concern repeatedly mentioned by stakeholders within the space community relates to the potential **additional manpower required to process satellite conjunction data**. As detailed in section 5.4, with simulations suggesting a marked increase in the number of conjunction warnings which operators will have to process, at least in the short term there will be a need for additional trained staff to be available as part of satellite ground control operations to cope with the demand. As such levels of conjunction warnings are not commonplace within the industry at present, it is unknown as to whether there will be sufficient skilled capability available within the local and global labour markets to meet the increased demand. If not, then this could result in disastrous consequences for the viability of orbital space, as a small number of severe collision events could render large tracts of orbital space unviable for space operations.

### 6.3.3 Risks and barriers to UK firms

In terms of addressing global demand for SST, based upon the results of the SWOT analysis it would appear that the primary potential barriers to addressing global demand for SST relate to **lacking sensor capability to service the growing LEO market** and **insufficient manpower to process available data.**

In terms of sensor capability, firstly ground based radar and RF systems are needed to characterise debris in LEO. Whilst the UK has plans to upgrade the CASTR system, this currently represents the only dedicated sensor in this class, although increasing usage of the Fylingdales radar may help in this regard. Laser based ranging systems are an emerging technology which other nations such as Spain and Italy already have operational systems. These systems also have the potential for extension of purpose to nudging debris in-orbit so that it burns up via entry. At present, there are no known plans for the UK to install this technology.

A lack of sensor capability in different geographical regions may also hinder UK efforts to service global needs. Maintaining a catalogue of objects in relation purely to UK considerations limits the potential market for services, however initiatives in the academic and non-profit sectors in terms of data sharing arrangements may show the way forward. The Square Kilometre Array (SKA) projects links institutions in Australia, Canada, China, India, Italy, New Zealand, South Africa, Sweden, the Netherlands and the UK and would provide UK institutions with data from southern hemisphere locations.

Space based sensors may also represent a way for the UK to supplement its catalogue of objects in-orbit. Body mounted cameras fitted onboard in-orbit satellites as secondary payloads could provide additional data relating to tracking of objects in-situ.

With the likelihood of an ever-increasing need for manpower to process conjunction data, UK firms are at risk of lacking sufficient manpower to process the sheer volume of data available in the near future. As both sensor capabilities in terms of size of trackable debris and numbers of satellites increase, the size of catalogues of object data are set to greatly increase. The potential solution outlined in section 6.2 appears to be automation and CAMs and application of Big Data and machine learning techniques. Via its ESA membership, the UK can endeavour to remain at the forefront of projects such as CREAM and facilitate public-private technology transfer to aid commercial efforts.

# 7 Conclusion

Table 5 shows a selection of values of expected loss as forecasted by the model. Aside from a slight decrease from 2020 to 2025 as a result of the trend of a general shift towards lower value small satellites across the industry, it can be seen that there is a **trend of increasing market value over the next twenty year period for the global commercial SST conjunction market in LEO**. It should be noted that with the progression of time, the percentage of users who opt for paid SST services should increase as LEO becomes ever more congested and the provision of timely, accurate SST data become ever more essential.

### Table 5 Summary of potential value of LEO SST market

| Year | Expected loss (USD m) | Expected loss (GBP m)* | Cumulative value at risk (USD bn) | Cumulative value at risk (GBP bn)* |
|---|---|---|---|---|
| 2020 | 23.0 | 18.2 | 4.5 | 3.6 |
| 2025 | 21.3 | 16.9 | 7.8 | 6.2 |
| 2029 | 28.1 | 22.2 | 9.7 | 7.7 |
| 2036 | 41.8 | 33.1 | 12.9 | 10.2 |
| 2040** | 52.5 | 41.6 | | |

Notes: * Assuming USD/GBP exchange rate of 0.79254 as per xe.com (15/03/20)

** Projected growth based upon CAGR between 2029-2036

***Source: London Economics analysis***

We also estimate that the current value of the GEO market is around **$1.2m (£0.93m)**, which is unlikely to fluctuate greatly in the next couple of decades without a major change in the risk factors to satellites in this orbit.

**Comparative studies**

As comparisons for our study, we note that Markets&Markets predict that the space situational awareness market is estimated to be USD 1.00 billion in 2017 and is projected to reach USD 1.44 billion by 2023, at a CAGR of 4.54% during the forecast period. The base year considered for the study is 2017 and the forecast period is from 2018 to 2023. Additionally the Markets&Markets report considers the space situational awareness market on the basis of offering, services (Space Weather Services, Near-Earth Object Detection Services, Space Surveillance and Tracking Services), object (mission-related debris, rocket bodies, fragmentation debris, functional spacecraft, non-functional spacecraft), end user (government & military and commercial).[48]

Additionally, Market Research Engine value the Global Space Situational Awareness Market at more than US$ 1.5 billion by 2025, at a CAGR of 4.50% during the forecast period. The Market Research Engine report considers the Space Situational Awareness (SSA) Market by Object (Functional Spacecraft, Non Functional Spacecraft, Rocket Bodies, Fragmentation Debris, Mission Related Debris), by Offering (Software and Services) and by End User (Commercial or Government).[49]

We note that both of the above studies incorporate estimates for segments and services which we do not attempt to estimate the value of in this study. For example, we do not attempt to value non-commercial markets as the modelling methodology we have used is not commensurate with the intangible value of space assets for governmental and military users. In reality this is likely to be a

[48] https://www.marketsandmarkets.com/Market-Reports/space-situational-awareness-market-150269456.html
[49] https://www.marketresearchengine.com/space-situational-awareness-ssa-market

sizable number, however as we are not privy to sensitive information in this regard, we do not attempt to address this market. We also do not attempt to quantify the value of **services** derived from commercial satellites as this varies considerably by geographical region of target market, type of satellite, future demand for services etc. which is infeasible to quantify within the bounds of this study.

We also do not attempt specific valuations of submarkets such as re-entry, fragmentation events or launch service tracking as our research indicates they are of much lower importance compared with conjunction analysis.

It should be noted that given the availability of free US derived space data at present, our results have shown the uptake of paid services within the next five years will be limited and a longer-term view for the development of the market is required.

**Areas for further study**

In terms of the specific value of SST services for UK commercial operators, it should be noted that whilst we are theoretically able to extract a year-on-year estimate of the demand from our data, in practice it is highly dependent upon the asset value of the spacecraft owned by each operator at that point in time. This is due to the fact that this represents a relatively small subset of the overall data, and such fluctuations at a micro level may provide an unrealistic estimate of the true demand. Further study could customise the modelling to provide more tailored analysis for these organisations.

Also within the DRAMA model, it is possible to select whether constellation satellites and both current and future rocket upper stages are deorbited in line with industry guidelines. As a default we assumed no deorbiting of upper stages, and deorbiting of satellites. It would be interesting to analyse the effects that post-mission disposal have upon the overall debris risk in orbit to help to assess whether current deorbiting guidelines are sufficient, or whether tighter industry regulation is required.

**Closing remarks**

We believe however that our estimates provide a reasonably robust and conservative estimation of the potential commercial SST market for conjunction services in the coming years and highlights the impact of major factors affecting the shape of the market. These factors include the launch of sizable new satellite constellations, increasingly higher number of objects in space and the required sensor capability needed to track them, and the need for increasing levels of international cooperation to facilitate market growth, which more importantly will facilitate the safe and sustainable use of the Earth’s orbit for the common good of all humanity.

# INDICES

# Index of Tables, Figures and Boxes

## Tables



## Figures

# ANNEXES

# Annex 1 Description of ESA software

## 7.1 MASTER

MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) allows to assess the debris or meteoroid flux imparted on a spacecraft on an arbitrary orbit. The software hosts the data source (object populations) necessary to all simulations.

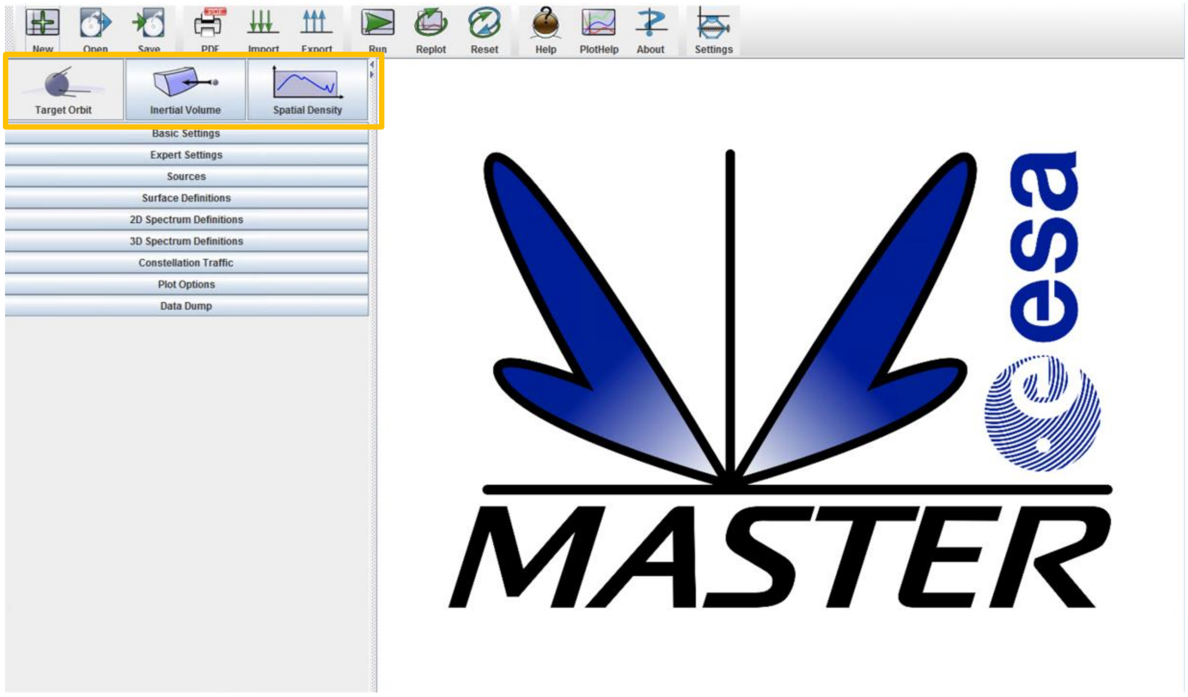
MASTER is ESA's reference model for the space debris and meteoroid environment and has gained international acceptance over the years. The purpose of the model is the realistic description of the natural and the man-made particulate environment of the Earth and the risk assessment via flux predictions on user defined target orbits.

The incident flux due to the particulate environment of the Earth on user-defined target orbits is described down to impactor diameters of 1 micrometre. Predictions for the historic space debris evolution from the start of the space era to a reference epoch on November 1st, 2016. All population files are date from November 2019, and future simulated population available until 2036.

We calibrate the model such as the population of objects reflect only the deadly impactors (>10cm in diameter).

MASTER comes with 3 simulation options. Target orbit allows to compute the spatial flux for a given orbital slot, inertial volume allows to compute the 3D density of objects and the spatial density allows to compute the spatial density for all orbital regions.

**Figure 44 MASTER environment**

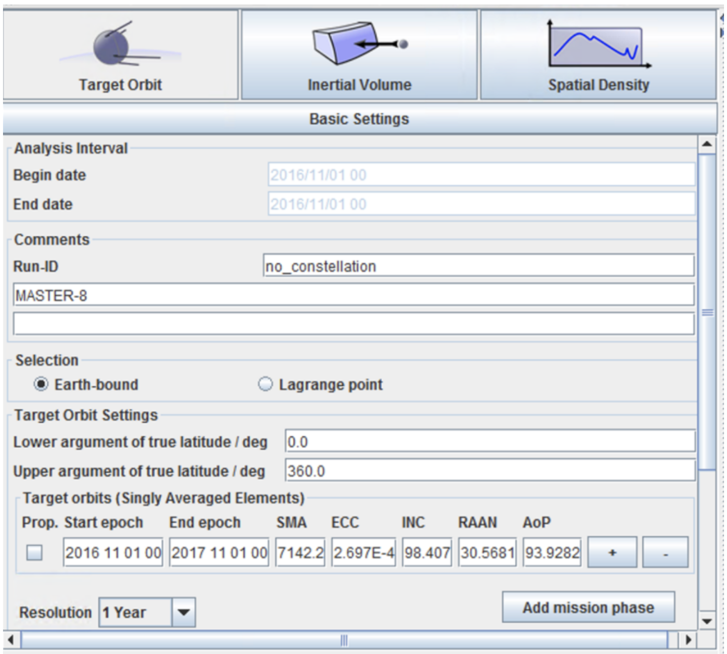



***Source: London Economics (screenshot from MASTER)***

The initial analysis of the spatial density was done through the Spatial Density option. This allow to draw the quantity of objects over all the orbit. This can also be restricted to specific orbital regions as well as over time.

To compute the impact of constellation satellites we used the Target Orbit Option. We start by referencing the orbital characteristics that we are looking to study. The references of orbital characteristics depend on the given orbit and the epoch is set to the time of reference we want to study.

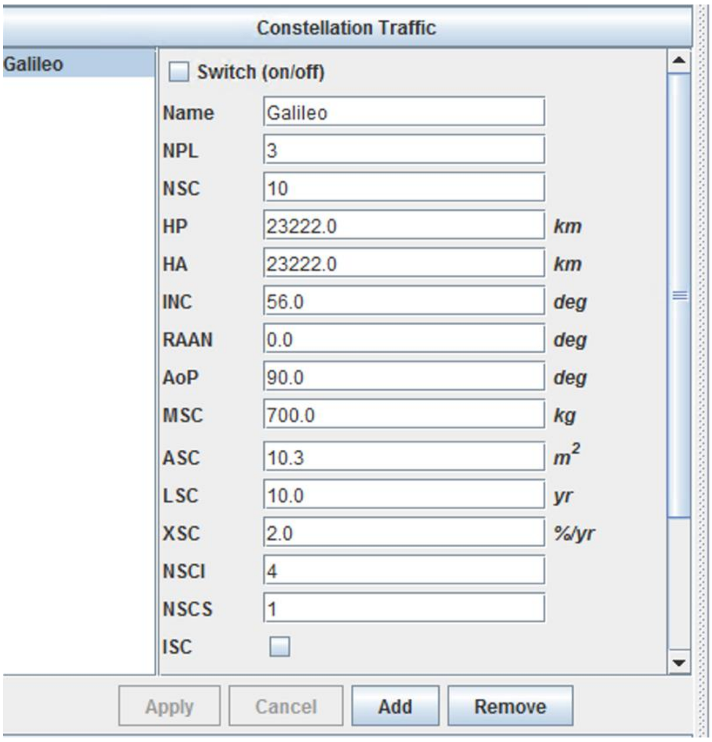
### Figure 45 Target orbit environment - settings




***Source: London Economics (screenshot from MASTER)***

The second step was to include the constellation satellites, and this was done in the constellation traffic tab. The underlying data includes the number of orbital planes, number of satellites per plane, their orbital specifications (perigee and apogee, right ascension node, inclination, argument of perigee), satellite size, mass, and dates of launch and full deployment. The number of satellites in orbit is split evenly between the debut and end date and the replenishment rate is taken into account based on the expected lifetime of the satellite.

**Figure 46 Target orbit environment – Constellation traffic settings**




***Source: London Economics (screenshot from MASTER)***

The software needs a tweak to take into account the constellation. The population files contain two type of information: 1) the condensed population includes every type of object without distinction, and 2) the detailed population which split objects with respect of their origin (mission related, explosions, fragmentation, droplets, and more). In order to capture the effect of constellation satellites, we need to simulate the evolution of the density using only the launch and mission related object (LMRO) density file. This owe to a limitation of the software which does not factor in constellation on the overall population.

We then run 3 different simulation, for each constellation, for each year of analysis. First, we run the overall population flux to get the overall picture at a given date. Second, we select the sub-population (launch and mission related objects) only and simulate the flux without the constellation input. Finally, we estimate the flux with the constellation in it.

We build a flux variation estimator as follow:

$$\Delta_{flux} = Flux_{all\ objects} + \left(Flux_{(\text{LMRO with constellation})} - Flux_{(\text{LMRO without constellation})}\right)$$

This formula late feeds into the scaling factor we describe in annex 2.

**Historical population files**

The historical population in MASTER is a fusion of published object data and simulated objects. The main data basis for the non-simulated population share are the two-line elements. For the simulated untracked objects, the use of an ESA algorithm is required. The algorithm is called POEM (Program for Orbital Debris Environment Modelling) simulates the generation and propagation of orbital debris objects larger than 1 µm. The output of POEM represents the basis for the debris population of the MASTER model.

**Future population files**

The future populations are simulated via statistical projection algorithm. It simulates the space debris environment down to 1 mm. In order to provide the full spectrum of diameters down to 1 µm, the event lists produced by the algorithm are used as input for the POEM algorithm which is then used to re-simulate the entire future population using the same debris models which are also applied to the historical time frame.

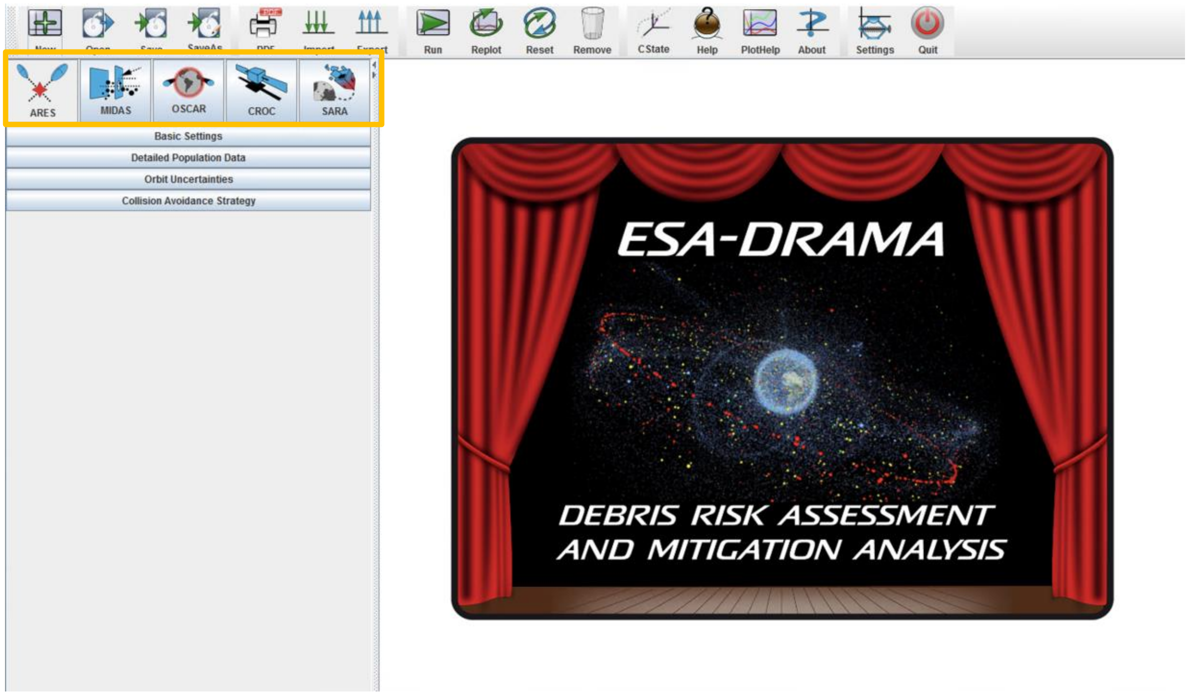
## 7.2 DRAMA

Initially, the aim of the DRAMA tool suite as a whole is to enable space programs to assess their compliance with international requirements related to space debris, providing current mitigation measures that represent best practice.

For this report, we have used the drama software as a data source for the estimation of the collision probabilities in different orbits. The software has 5 options, but we focused on ARES (Assessment of Risk Event Statistics) which allows the computation of collision probabilities, collision avoidance manoeuvre requirement and fuel and thrust requirements for CAMs.

Our analysis was split between GEO and LEO as we have identified them as being the most relevant. For the GEO analysis, the software limitations did not allow us to compute the future expected collision probabilities. Alternatively, we have simulated the density with MASTER and found almost no evolution of the flux of debris in the GEO orbit.

**Figure 47 DRAMA environment**




***Source: London Economics (screenshot from DRAMA)***

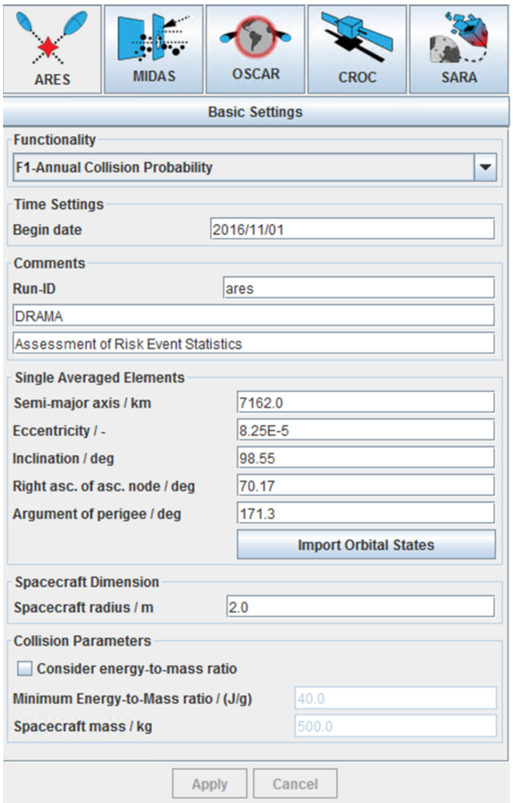
The ARES interface is similar to the MASTER's. Inputs required include epoch date, orbital characteristics, spacecraft size and collision parameters including the mass of the satellite and the energy to mass ratio which can be used to assess the criticality of collision damages.

In our analysis, we used the two-line element orbital specifications in order to compute the collision probabilities. The TLE was retrieved via CelesTrack.

Due to a large number of computations and a substantial computational time, we looped the simulations with a Python package, provided with the software.

The inputs from constellations are not factored in ARES. Therefore, we computed a scaling factor based on the MASTER specification above and the mathematical specification of the collision probability computation (see annex 2).

### Figure 48 ARES environment




*Source: London Economics (screenshot from DRAMA)*

# Annex 2 Description of modelling

## Scaling factor for constellations

The introduction of constellations has a sizeable impact on the spatial density in space. However, the computation of collision probabilities in the DRAMA software does not take into account these, as they are not part of the underlying database.

Instead, we used the MASTER software as a complimentary input and built a scaling factor based on the impact on spatial density of constellations.

The collision probability can be approximated by the following formula:

$$p = 1 - e^{-C}$$

$$with: C = \Phi_{\mathrm{r}} \times A_t \times \Delta_t$$

The equation defining $C$ is based on the kinetic gas theory50 and depends on $\Phi$ which defines the flux of objects in the targeted region $r$, $A_t$ defines the cross sectional area of the target object (in our case, a satellite) and $\Delta_t$ the time considered in the analysis.

To measure the impact of a constellation we first compute the differential flux $\Delta_\Phi$ of the given region:

$$\Delta_\Phi = \Phi_{with\ constellation} - \Phi_{without\ constellation}$$

This is then inserted in the collision probability formula and yields:

$$p_{with\ constellation} = 1 - e^{-(\Delta_\Phi \times A_t \times \Delta_t)}$$

Finally, we compute the scaling factor as being the percentage change in the collision probability:

$$\Delta_p = \frac{p_{with\ constellation}}{p_{without\ constellation}} - 1$$

## Future Collisions

The direct consequence of an increase in the number of man-made objects in space is the creation of more traffic also known as flux. The flux of debris is measured as the number of objects which trajectory go through an imaginary 2d plate which can be measured in squared metre or squared kilometre. The resulting collision probability depends on the flux as well as the size of spacecraft and the time period of measurement.

[50] https://www.grc.nasa.gov/www/k-12/airplane/kinth.html

The collision probabilities can be directly computed with the DRAMA software as it was done for the current LEO market. However, a limitation of the software is that the population of objects is fixed and do not take into account the future launches, even though the number of future debris is already integrated in the software population files.

Alternatively, we used the MASTER software to estimate the spatial density at a given point in time. The software also allows to specify new objects, and more precisely, new constellations. With that option, we were able to assess, the variation of density induced by constellations, over time.

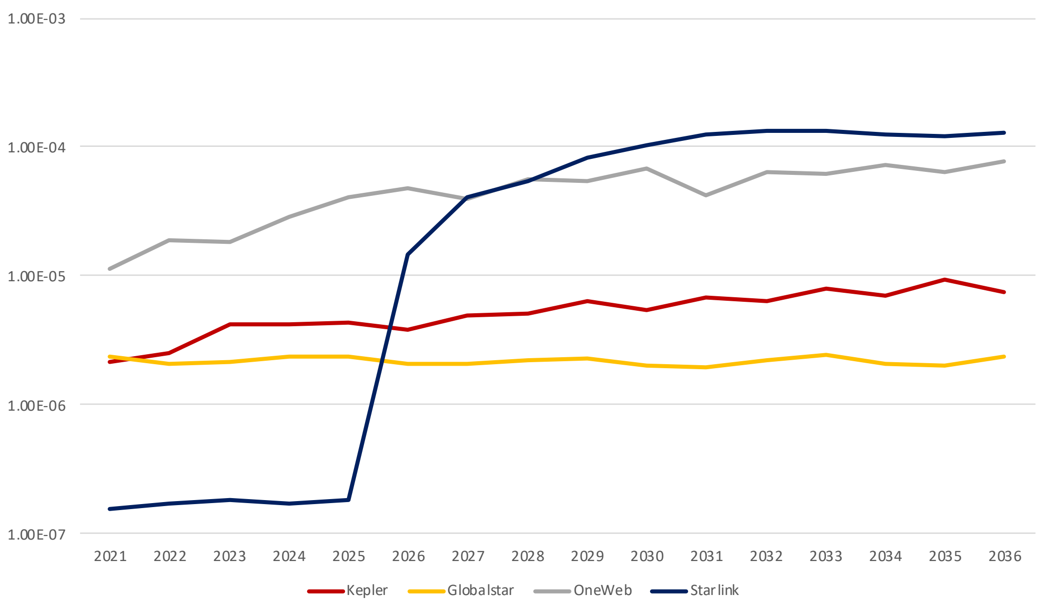
For this, we use the 'specific target scenario' in MASTER and compare the density with and without each constellation. The number of objects has an influence on that density variation, however, the altitude does as well. We have seen before that some regions were already more densely populated and lower altitude have a higher 'cleaning' rate due to a higher atmospheric density.

All that taken into account, we compute a scaling factor which is the percentage change in collision probabilities, induced by a given constellation.

This scaling factor is applied to any satellites that crosses the 'extended' orbital plane of the constellation. And we define and extended orbital plane to be represented by the semi-major axis plus or minus 20km (10km for VLEO) and the inclination plus or minus 1 degree.

The scaling factor varies with respect to the orbital plane and time. The chart below illustrates a few examples of the evolution of the spatial density of launch and mission related objects51. It shows how impactful very large constellation can be. Kuiper and OneWeb have a non-negligible impact on the density. However, the impact of the fully deployed Starlink VLEO will be very substantial.

**Figure 49 Variation of spatial with respect to constellation deployment flux over time**




***Source: London Economics analysis (data from MASTER simulations)***

[51] The total population of objects includes more that mission related objects. It also includes fragments from explosions, collisions, droplets, paint flakes and more.

Over time, the collision probability oscillates. There are multiple factors for this and one of them is the solar activity cycles. Every 11 years, the Sun reaches a peak (or pit) of activity and matter and ions bombarded in the atmosphere cases it to swell and increase its density of particles. This affects positively the orbit by increasing the erosion of debris. In 2020, the Sun is within its lowest activity levels which will increase progressively in the next six years.

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