COMMERCIAL SPACE SURVEILLANCE & TRACKING

Euroconsult for the UK Space Agency

Final Report

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LIST OF ACRONYMS

ADR	ACTIVE DEBRIS REMOVAL
AI	ARTIFICIAL INTELLIGENCE
AIS	AUTOMATIC IDENTIFICATION SYSTEM
ASAT	ANTI-SATELLITE MISSILE
ASI	AGENZIA SPAZIALE ITALIANA
BNSC	BRITISH NATIONAL SPACE CENTRE
BOOTES	SPANISH BURST OPTICAL OBSERVER AND TRANSIENT EXPLORING SYSTEM
CDTI	CENTRO PARA EL DESARROLLO TECNOLÓGICO INDUSTRIAL
CIS	COMMONWEALTH OF INDEPENDENT STATES
CNES	CENTRE NATIONAL D'ETUDES SPATIALES
COPUOS	COMMITTEE ON THE PEACEFUL USES OF OUTER SPACE
COSMOS	OPERATIONAL CENTRE FOR MILITARY SURVEILLANCE OF SPACE OBJECTS
CSPOC	COMBINED SPACE OPERATIONS CENTER
DARPA	DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
DLR	DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT
DOC	DEPARTMENT OF COMMERCE
DOD	DEPARTMENT OF DEFENSE
EC	EUROPEAN COMMISSION
ESA	EUROPEAN SPACE AGENCY
ESOC	EUROPEAN SPACE OPERATIONS CENTRE
EU	EUROPEAN UNION
EUSST	EUROPEAN UNION SPACE SURVEILLANCE AND TRACKING
FCC	FEDERAL COMMUNICATIONS COMMISSION
FHR	FRAUNHOFER INSTITUTE FOR HIGH FREQUENCY PHYSICS AND RADAR TECHNIQUES
FY	FISCAL YEAR
GEO	GEOSTATIONARY ORBIT
GEODSS	US GROUND-BASED ELECTRO-OPTICAL DEEP SPACE SURVEILLANCE
GESTRA	GERMAN EXPERIMENTAL SURVEILLANCE AND TRACKING RADAR
GPS	GLOBAL POSITIONING SYSTEM
GPSST	SPACE SURVEILLANCE AND TRACKING PROJECT GROUP
GRAVES	FRENCH LARGE NETWORK ADAPTED TO THE SURVEILLANCE OF SPACE
GSSAC	GERMANY'S SPACE SITUATIONAL AWARENESS CENTER
HEO	HIGHLY ELLIPTICAL ORBIT
IADC	INTER-AGENCY SPACE DEBRIS COORDINATION COMMITTEE
IOS	IN ORBIT SERVICING
ISO	INTERNATIONAL ORGANIZATION FOR STANDARDIZATION
ISOC	ITALIAN SPACE SURVEILLANCE AND TRACKING OPERATIONS CENTER
ITAR	INTERNATIONAL TRAFFIC IN ARMS REGULATIONS
ITU	INTERNATIONAL TELECOMMUNICATION UNION
JAPCC	JOINT AIR POWER COMPETENCE CENTRE
LEO	LOW EARTH ORBIT
LPM	MILITARY PROGRAMMING LAW
MEO	MEDIUM EARTH ORBIT
MFF	MULTIANNUAL FINANCIAL FRAMEWORK
MOD	MINISTRY OF DEFENSE
MS	MEMBER STATES
NASA	NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NEO	NEAR-EARTH OBJECT
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
POLSA	POLISH SPACE AGENCY
ROSA	ROMANIAN SPACE AGENCY
R&D	RESEARCH AND DEVELOPMENT
R&I	RESEARCH AND INNOVATION
SATCEN	EUROPEAN UNION SATELLITE CENTRE
SDA	SPACE DATA ASSOCIATION
SFS	SPACE FENCE SYSTEM
SPD-3	SPACE POLICY DIRECTIVE 3
SSA	SPACE SITUATIONAL AWARENESS
SSN	SPACE SURVEILLANCE NETWORK
SSO	SUN SYNCHRONOUS ORBIT
SST	SPACE SURVEILLANCE AND TRACKING
STM	SPACE TRAFFIC MANAGEMENT
SWE	SPACE WEATHER
S3T	SPANISH SPACE SURVEILLANCE AND TRACKING
S3TSN	SPANISH SPACE SURVEILLANCE AND TRACKING SENSOR NETWORK
TAROT	FRENCH RAPID ACTION TELESCOPE FOR TRANSIENT OBJECTS
TIRA	GERMAN TRACKING AND IMAGING RADAR
UK	UNITED KINGDOM
UKSA	UNITED KINGDOM SPACE AGENCY
UN	UNITED NATIONS
UNSW	UNIVERSITY OF NEW SOUTH WALES
USAF	UNITED STATES AIR FORCE
USSPACECOM	UNITED STATES SPACE COMMAND
USSR	UNION OF SOVIET SOCIALIST REPUBLICS
VHF	VERY HIGH FREQUENCY

Executive Summary

Study Scope and Key Inputs

The United Kingdom Space Agency (UKSA) has commissioned Euroconsult to assess the current and future market sizing for the supply and demand of commercial Space Surveillance and Tracking (SST) solutions. SST, usually known as Space Situational Awareness (SSA) outside Europe, is the 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. **Space debris is one of the principal threats to satellites and there are an estimated 750,000 debris objects larger than 1 cm in Earth orbit**. After launch and deployment into orbit, space debris is often the next highest risk to a mission.

The market sizing applies to the **commercialization of space object tracking and cataloguing and services directly linked to core SST activities** such as conjunction event alerts, collision on launch assessments, tracking of satellites during de-orbiting or orbit-raising, and so on.

In addition to dedicated desk research, this study relied extensively on an **SST stakeholder interview campaign** covering both the SST market supply side (commercial SST service providers) and the demand side (government and commercial satellite operators). The other key input was Euroconsult's proprietary satellite database, which tracks all satellites built and launched.

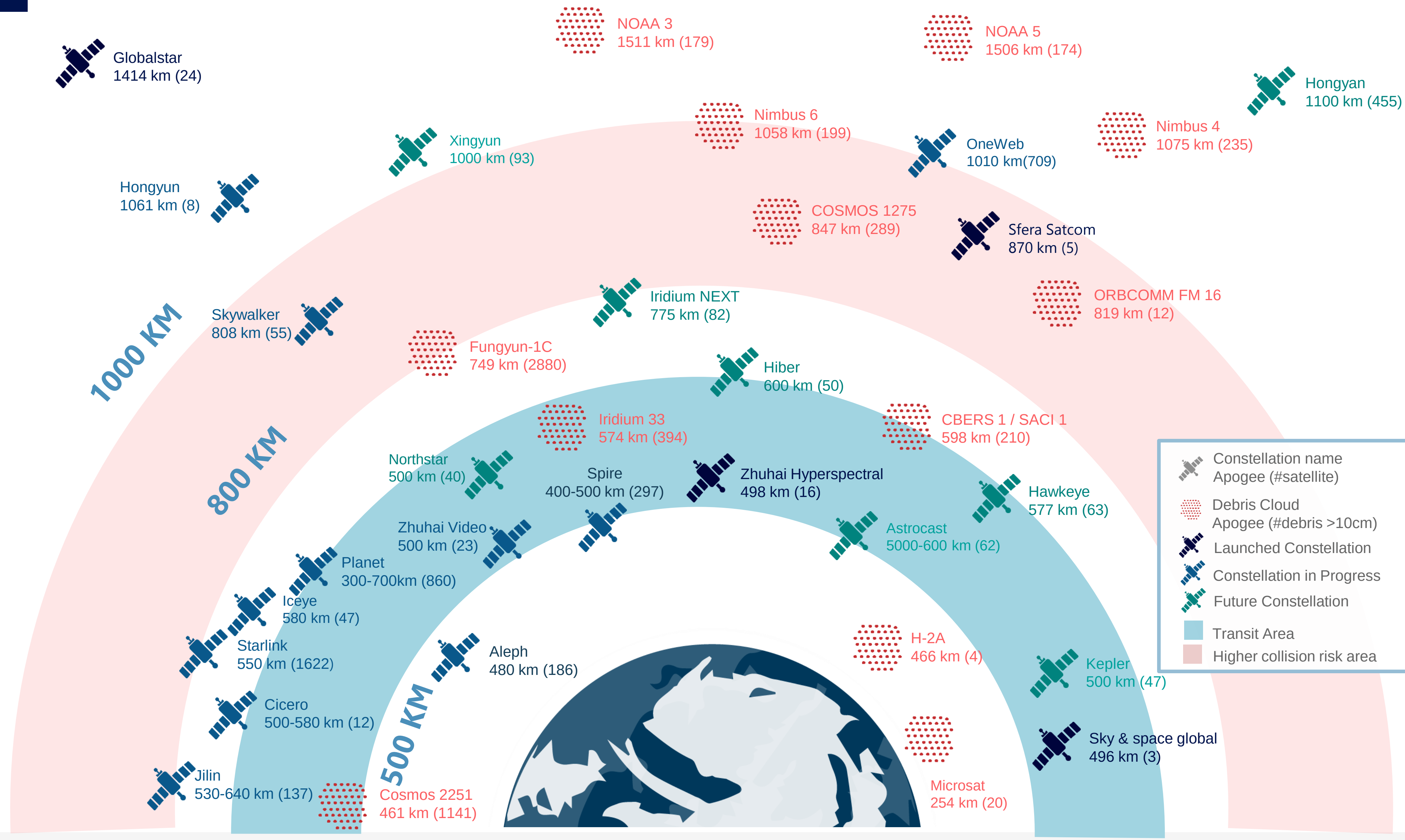
Space Debris Context

Space debris is an increasing concern amongst both public and private space actors as the space environment is becoming increasingly crowded. Human-made debris is largely composed of satellites which have reached end-of-life, space objects intentionally released as part of missions, rocket parts, frozen propellant from propulsion systems, as well as fragments which have broken off from space objects due to collisions and explosions. **As a result, there is a growing risk of collision for operational satellites and other space objects which may either impair the functionality of the satellite or result in catastrophic failure of the mission.**

In 2019, ESA's Space Debris Office estimated the number of space objects larger than 10 cm at 34 000, with 128 million objects under 1 cm. However, the debris which is tracked is far lower: **the US Space Surveillance Network catalogues less than 20,000 space objects.**

Debris are largely concentrated in Low Earth Orbit (LEO), the orbit most frequently used and with the highest satellite population as it is the easiest orbit to access. LEO offers many business opportunities in Earth Observation and new internet connectivity applications and is the future target of the mega-constellation projects proposed or already in the process of being launched, such as SpaceX's Starlink system. MEO is the least used orbit in terms of satellite populations, as it is home nearly exclusively to government navigation satellites such as Galileo, GPS and Glonass. GEO, the furthest of all orbits and the most technically-challenging to reach, is accessible only by the most advanced players, namely mature satellite communication providers and governments.

SST OVERVIEW – SELECTED CONSTELLATIONS AND DEBRIS CLUSTERS



SST Space Market Dynamics

The market for commercial SST is a challenge to assess. It is a developing commercial application with high interest across the stakeholder community. **Three main dynamics impact the commercial SST market:**

- The world is currently on the cusp of the **mega-constellation revolution**, with multiple projects in planning and at least two with first launches in 2019-2020. If all projects are realized, by the end of the decade the number of satellites in orbit will rise exponentially, with a **sustained launch rate of thousands of satellites per year.**
- The SST market is likely to exhibit **"S-curve"** characteristics, prevalent in **nascent, high-technology areas as they enter the mainstream commercial market**. SST technology and business adoption is currently in a preliminary phase, but as technology improves, a period of rapid growth with more significant service penetration is forecasted until market maturity is reached and penetration peaks, slowing further growth.
- A number of factors **currently suppress the commercial SST market**, most notably the fact that **commercial services must compete against free government solutions**, and that no legal framework exists to impose obligations on satellite operators to procure commercial SST services.

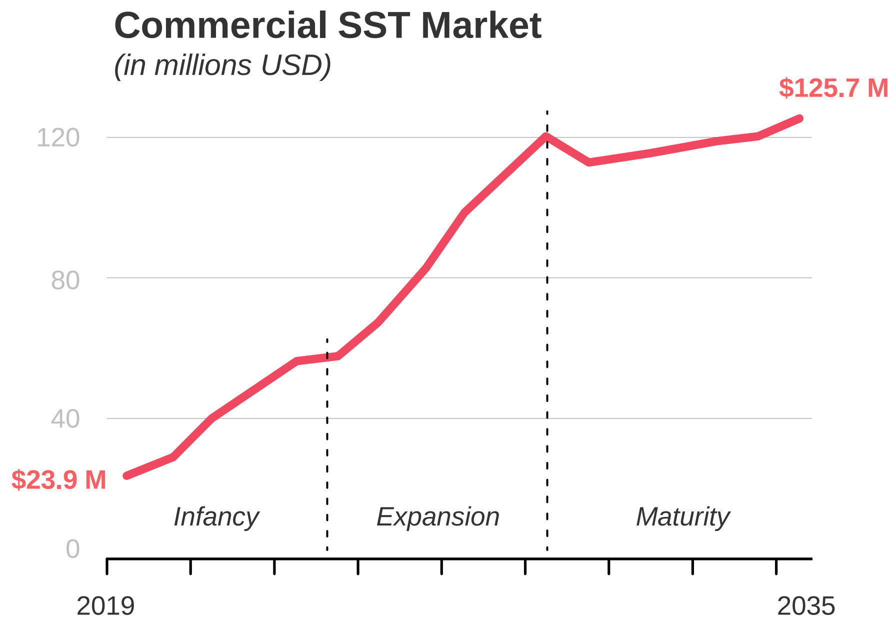
Quantifying the Commercial SST Market

Overview

In 2019, the addressable **SST commercial market is estimated to total US$23.9 million and forecasted to grow to approximately US$125.7 million by the end of the period in 2035**, of which 40% from commercial satellite operators.

The SST market is expected to undergo three distinct phases:

- **An infancy phase**, marked by pre-market characteristics and slow development and commercial uptake;
- **An expansion phase** with rapid technological development, growing market penetration, reduced costs and a larger commercial client base;
- **A maturity phase** characterised by slowing technological development and incremental advances, few new clients and a focus on operational cost reductions rather than investing in breakthrough technology.)



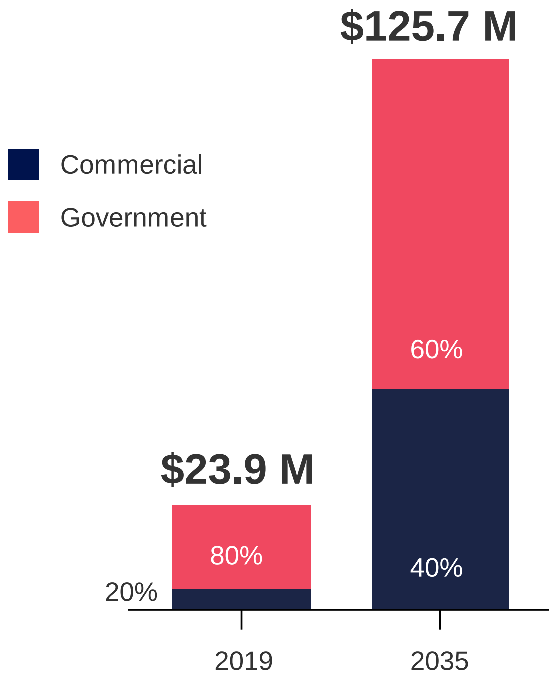
Quantifying the Commercial SST Market

By Client

Today, **commercial SST revenues are generated predominantly by governments**, who procure SST services or, more frequently, bulk-buy raw data from commercial SST service providers to incorporate into their own databases and models in order to augment and refine their catalogue of tracked space objects. Commercial SST providers indicated that **revenues from governments are about four times higher than SST services sales to private sector players.**

However, as the number of commercial satellites to be launched over the period dwarfs the number of government satellites, and as commercial SST service penetration with private sector players will increase over time, **the commercial market is forecasted to grow faster: 10x growth for the commercial market vs. less than 4x growth for the government market**. This will result in the government share of the commercial SST market shrinking to 60% of the total market by 2035, down from 80% today.

Market value by client
(millions USD)



Quantifying the Commercial SST Market

By Mission

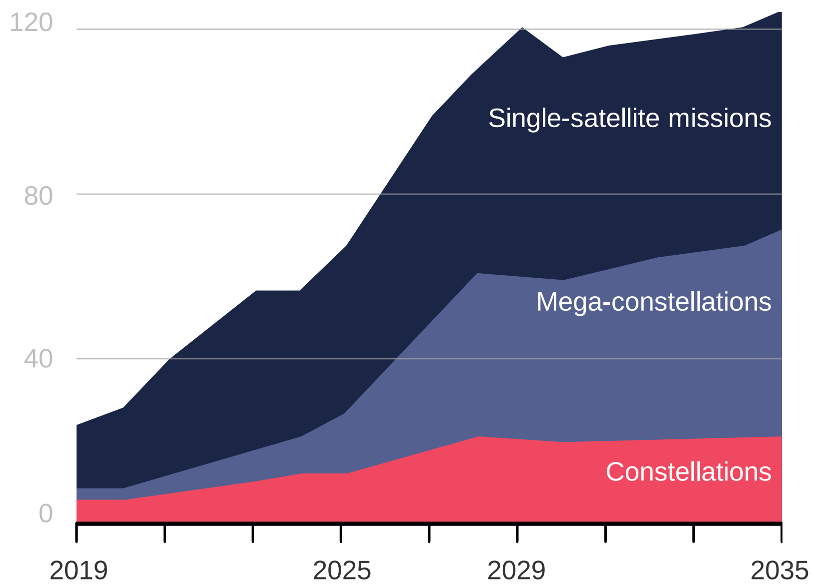
Despite their vast numbers, **mega-constellations (satellite systems with over 100 units) are forecasted to represent only $50.2 million of SST total revenues by 2035, approximately 40% of the total market of $125.7 million.** This is due to a number of factors, including a very low willingness to pay, a low price point tolerance due to the expendable nature of a single satellite within a mega-constellation architecture, unproven business cases, and the self-cleaning nature of LEO (to which most mega-constellation projects will launch).

Single-satellite missions are forecasted to generate $53.5 million in revenues by 2035, roughly the same market size as mega-constellations. Despite their lower numbers, it is typically governments who launch single-satellite missions, and as noted earlier governments generate the majority of commercial SST revenues.

Constellations (systems with less than 100 satellites) are forecasted to account for $21.8 million of the 2035 commercial SST market. Suffering from the same low willingness to pay for SST services as mega-constellations, they lack the sheer number of units to account for a significant portion of the market.

Market value by mission type

(in millions USD)



Quantifying the Commercial SST Market

By Orbit

A satellite's orbit is typically correlated to its size, complexity and value, as well as the satellite operator's business model.

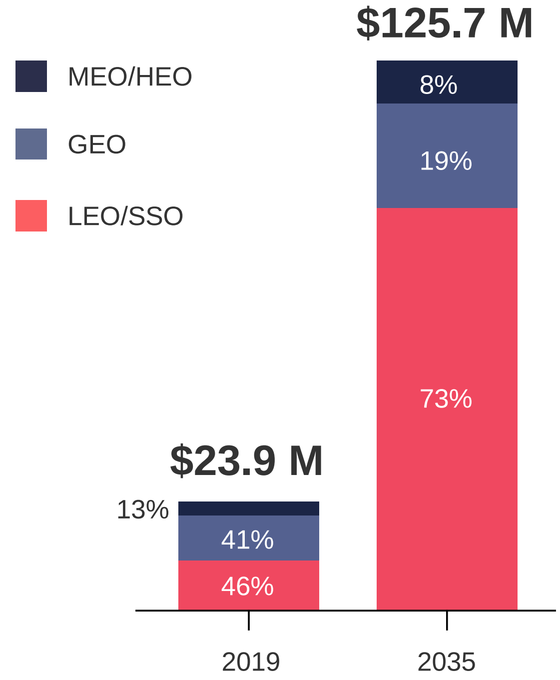
GEO orbit is dominated by governments and commercial satcom operators, both of which exhibit a high degree of SST maturity, including awareness of the issues, dedicated SST teams, and a willingness to invest time and resources into ensuring sustainability of the GEO environment. GEO operators report a relatively high degree of commercial SST service penetration but a low willingness to pay as they use other measures to mitigate risks, leading to a **41% share of the market today, but falling to under 20% in the future as GEO is not expected to become significantly more congested.**

MEO, as the least-used orbit, accounts for **13% of the $23.9 million commercial SST market in 2019, totalling $2.9 million**. MEO's share drops to 8% by 2035, but its values grows to $10.1 million.

LEO operators are in many cases start-ups more focused on short-term objectives and with some responsibility abdication since LEO is a "self-cleaning" orbit. Contrariwise to GEO, SST coverage costs are higher in LEO but penetration rates much lower. As a result in 2019 the LEO SST commercial market is only slightly larger than the GEO market, at 46% of the total, though **LEO is forecasted to capture 73% of the future commercial SST market, at $91.8 million.**

Market value by orbit

(in millions USD)



EXECUTIVE SUMMARY

PART 1 – SST SECTOR OVERVIEW

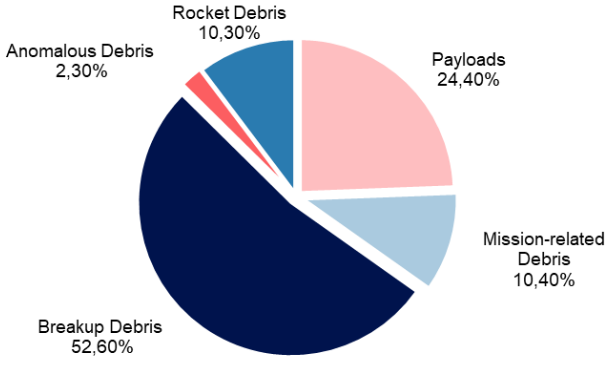
PART 2 – MARKET ASSESSMENT

SST OVERVIEW – CONTEXT

SPACE DEBRIS CONTEXT

Space debris is an increasing concern amongst both public and private space actors as the space environment is becoming increasingly crowded. Human-made debris is largely composed of satellites which have reached end-of-life, space objects intentionally released as part of missions, rocket parts, frozen propellant from satellite and rocket propulsion systems, as well as fragments which have broken off from space objects due to collisions and explosions. As a result, there is a growing risk of collision for operational satellites and other space objects which may either impair the functionality of the satellite or result in catastrophic failure of the mission. The chart below illustrates the composition of space debris as tracked and included in the US Catalogue.

Debris are largely concentrated in Low Earth Orbit (LEO), the orbit most frequently used in terms of number of satellites, and the future target of the mega constellation projects proposed or already in the process of being launched, such as SpaceX's Starlink system. Due to LEO's closer proximity to Earth, resulting in a smaller circumference, the same number of space objects results in a higher density of objects and thus greater congestion, thereby significantly increasing the risk of collision.



Anomalous debris are the result of unplanned separations of space objects from the parent body.

Mission-related debris are space objects intentionally released as part of nominal on-orbit operations.

Source: *NASA History of On-orbit Satellite Fragmentation, 15th Ed., July 2018*

ESTIMATING THE COST OF SPACE DEBRIS

It is difficult to accurately estimate the true cost of satellite collisions or near-misses in space, as it is not always possible to ascertain the true cause of the incident – was a satellite malfunction caused by a collision or a failing component of the satellite? Estimating the cost is challenging, especially in cases of only partial destruction or reduced capabilities of a satellite. Three approaches are presented here.

An ESA paper* estimates each emergency maneuver in LEO to cost €25,000 – a 300-satellite constellation would receive about 580 alerts per year requiring either human intervention or a satellite maneuver, costing €14 million per year in staff costs, analysis work, infrastructure, and more.

Calculating operator revenue losses is another way. An Iridium satellite was involved in a collision in 2009, leading to complete satellite loss. A replacement satellite was in orbit, but when two Iridium satellites were damaged in 2014, the full constellation was not operating at full capacity for over 400 days, resulting in over $8 million in revenues being lost**.

Finally, the table below illustrates select recent incidents whose likely cause was space debris collision, including only the cost of the satellite in order to provide an approximate idea of the financial cost of space debris.

SATELLITE	DATE	IMPACT TO SATELLITE	SATELLITE COST
Aura	2010	Reduced Capability	$785M
BLITS	2013	Failure	$10M
Iridium-47	2014	Reduced capability	$40M
Iridium-91	2014	Reduced capability	$40M
WorldView-2	2016	Nine pieces hit, still functioning	$400M
Sentinel-1A	2016	6-8 pieces hit, still functioning	$300M
Orbcomm FM 16	2018	Break-up of the spacecraft	$5M
		TOTAL	**$1,580M**

Table adapted from "*How satellite constellations impact space risk*", Swiss Re, 2018 and ODQN, NASA, 2019. Additional satellite costings based on Euroconsult estimates

* "Ground-based Laser for Tracking and Remediation", ESA/ESOC, 69th IAC, October 2018.

** Interview with Iridium's Mission Planning and Orbital Analyst / SSA Lead, 7 February 2020

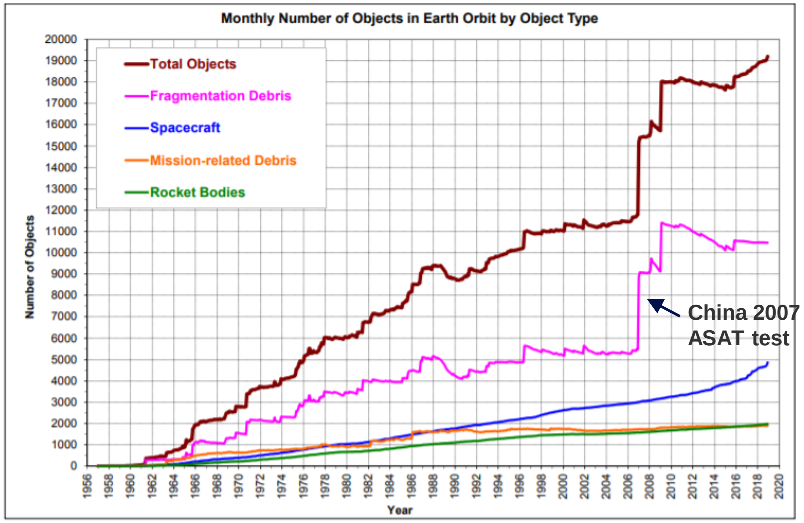
SPACE DEBRIS BY THE NUMBERS

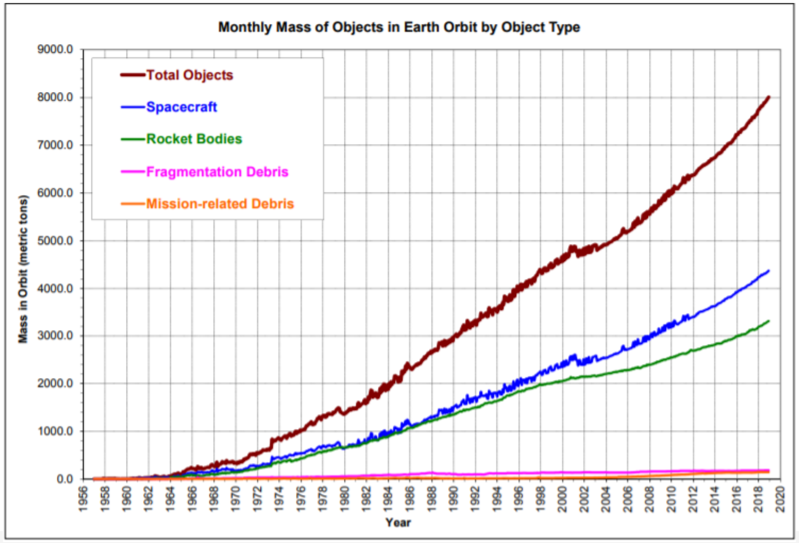
In 2019, ESA's Space Debris Office estimated the number of space objects to be 34 000 objects >10 cm, 900 000 objects between 1 and 10 cm and 128 million objects from 1mm to 1cm. However, the debris which is tracked is far lower. According to the NASA Orbital Debris Program Office, the US Space Surveillance Network, as of November 2019, has catalogued 19,779 space objects – see table below. Due to their extensive legacies conducting space activities, including Anti-Satellite Tests (ASAT), the US and Russia (CIS) have contributed the largest amount of space debris in orbit, followed by China – its 2007 ASAT test alone is estimated to have created approximately 3,000 pieces of debris.

The charts on the right show the growth over time of the space debris tracked by the US Space Surveillance Network. The catalogue includes only objects 10cm or larger. The top graph includes the number of objects, whereas the bottom graph shows total mass. Spacecraft and rockets contribute the most by mass, but fragmentation debris are the largest by far in terms of number.

COUNTRY / ORG.	SPACECRAFT	ROCKET BODIES AND DEBRIS	TOTAL
China	369	3,720	**4,089**
CIS	1536	5,099	**6,635**
ESA	90	57	**147**
France	66	507	**573**
India	96	163	**259**
Japan	180	115	**295**
US	1,878	4,815	**6,693**
Other	966	122	**1,088**
TOTAL	**5,181**	**14,598**	**19,779**

Source*: NASA, Orbital Debris Quarterly News, Volume 23 – Issue 4, extracted from the US Space Surveillance Network Catalogue*





Source*: the US Space Surveillance Network Catalogue*

SST OVERVIEW – CONTEXT

THE CAUSES OF SPACE DEBRIS

The coming decade is likely to introduce a paradigm shift for orbital debris. As human activity in space has increased, so too has the number of space objects left in orbit. Apart from a number of deliberate collision events to test anti-satellite weapons such as China's 2007 and India's 2019 tests (see box below), the quantity of space debris has increased in lockstep with the intensity of human space activities. Over the coming decade, Euroconsult estimates the number of satellites to be launched to increase exponentially, thereby contributing to in-orbit congestion and increasing the likelihood of a collision. A few key trends explain the exponential increase.

The emergence of commercial mega-constellations (defined as constellations with >100 units), all of which will be situated in LEO, will exacerbate the already-critical situation. Indeed, a number of mega-constellations are currently being launched, including SpaceX's Starlink (12,000 units), Planet (860) and Oneweb (700). This accelerating growth of space activities will exponentially increase the risk of collision.

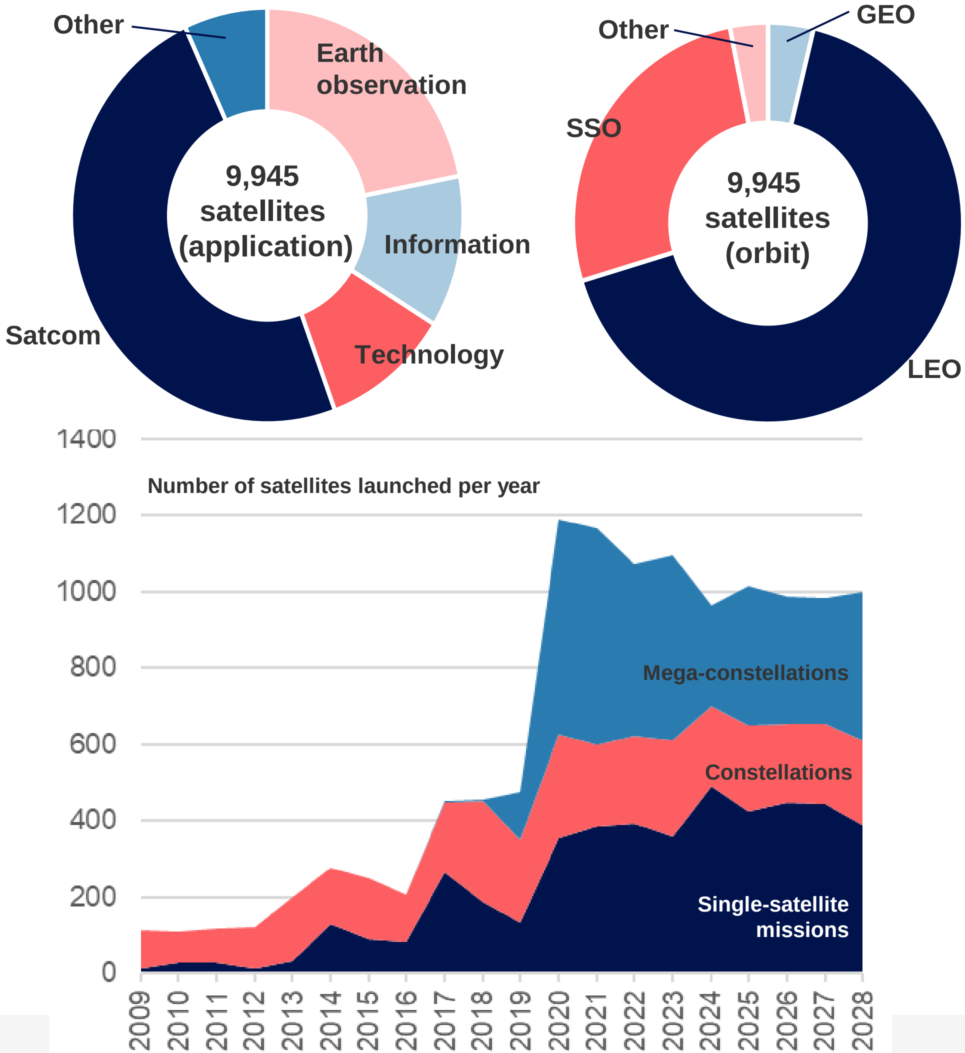
Decommissioned satellites also contribute to the problem. Although mitigation guidelines state that satellites should be disposed of after end of life, ESA estimates that more than two thirds of satellites in orbit are non-operational. Satellite explosions also increase the number of space debris. These explosions are mainly due to residual fuel that remains in the spacecraft

THE INDIAN ASAT: MISSION SHAKTI

Anti-satellite weapons and their testing, consisting of destroying a spacecraft with a ground-launched missile, worsen the space debris situation. The most recent example of an ASAT was in March 2019, when India tested an anti-satellite weapon in an operation called Mission Shakti to destroy its own satellite, Microsat-R. The test generated more than 250 pieces of debris with apogees up to 2000km. Although India claimed that the orientation and low altitude of the test would ensure that almost all the debris generated would disintegrate less than 50 days after the test, around 20 pieces of debris over 10cm were still being tracked at the end of 2019.

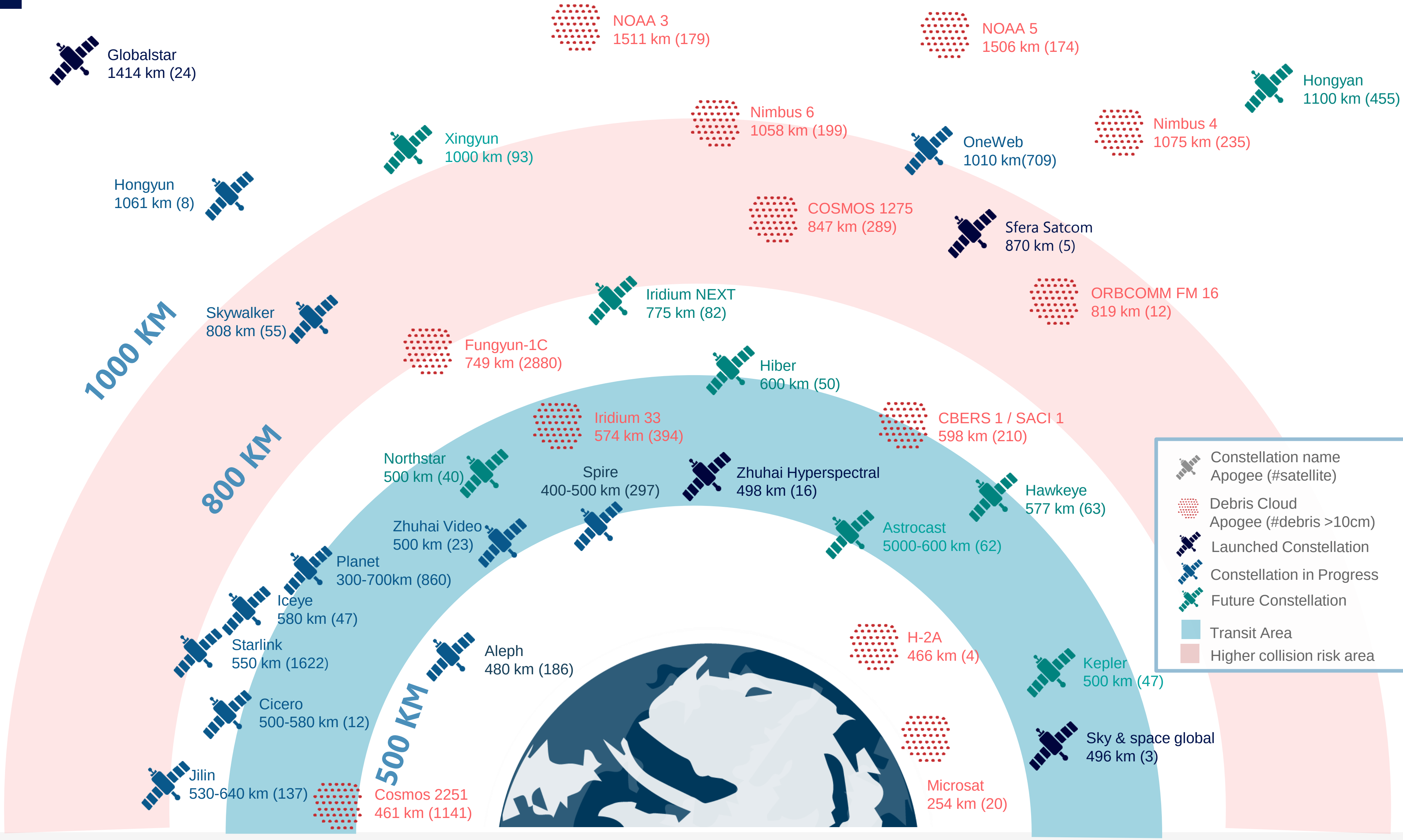
SATELLITES LAUNCHED TO ORBIT

Launches by Application and Orbit, 2019-2028



***Source**: Euroconsult database & "Satellites to be Built and Launched" report*

SST OVERVIEW – SELECTED CONSTELLATIONS AND DEBRIS CLUSTERS



SST OVERVIEW – CONTEXT

SPACE DEBRIS MITIGATION

As of today, no legally-binding international regime has been adopted regarding space debris mitigation. However, important international guidelines were developed in the 2000s by several actors including the Inter-Agency Space Debris Coordination Committee (IADC), European national space agencies and ESA, the UN COPUOS, ITU and the International Organization for Standardization (ISO). More recently, the COPUOS member states agreed on 21 new Guidelines for the long-term sustainability of outer space activities.

The IADC guidelines notably detailed end of mission disposal measures in GEO and LEO and recommended a 25-year lifetime limit for post-mission debris. The 2004 European Code of Conduct adopted by ASI, BNSC (now UKSA), CNES, DLR and ESA recommends several measures such as forbidding intentional destruction of a space system, considering de-orbiting measures in the design of the space system and eliminating all its stored energy at the end of its disposal phase to reduce the chance of break-up. The Code of Conduct attempted to find practical means of applying the guidelines such as appointing a "space debris manager" for each space project who would have the authority and responsibility to enforce a debris mitigation plan. The UN COPUOS 2007 guidelines are in line with previous recommendations, notably recommending disposal and passivation measures. Concerning ITU, its guidelines mostly aim at limiting space debris in GEO and avoiding radio frequency interference when transferring satellites to the graveyard orbit. Last year, the COPUOS adopted space sustainability guidelines which urge States to adopt, revise and amend national regulatory frameworks, to supervise space activities and to share information on space objects and orbital events in order to satisfy sustainability goals. All these international guidelines adopted over the past two decades (and represented below) advocate for a more careful consideration of the space debris issue. Although some recommendations are vague, this plethora of instruments still gives several concrete and consistent measures. It should be noted that these guidelines concern debris mitigation and not debris remediation. Practically no guidelines recommend active debris removal measures yet.

At national level, numerous countries considered space safety and debris mitigation in their national laws such as the UK (1986), Japan (1996) and France (2008). Although binding on nationals, these provisions are often too general to effectively ensure the long-term sustainability of space operations. An important national instrument are the US 2001 guidelines as they inspired subsequent recommendations. The document aims at limiting the amount of debris generated during normal operations and by accidental explosions and minimizing the probability of operational space systems becoming a source of debris via collisions. It encourages satellite disposal and lists three options for doing so: atmospheric reentry, maneuvering to a storage orbit, or direct retrieval of the spacecraft. The guidelines were updated in 2019 and now cover additional issues, such as Cubesats, satellite servicing and mega-constellations (>100 satellites). For the latter issue, the guidelines call for each satellite to have at least a 90% chance of successful disposal at the end of the mission.

2002: *IADC*
Space Debris Mitigation Guidelines

2004: *European Code of Conduct for Space Debris Mitigation*

2007: *COPUOS*
Space Debris Mitigation Guidelines

2010: *ITU*
Recommendation ITU-R S.1003.E

2010: *ISO*
Space Debris Mitigation Requirements (1st edition)

2014: *ESA*
Space Debris Mitigation Policy for Agency Projects

2019: *COPUOS*
Guidelines for the Long-term Sustainability of Outer Space Activities

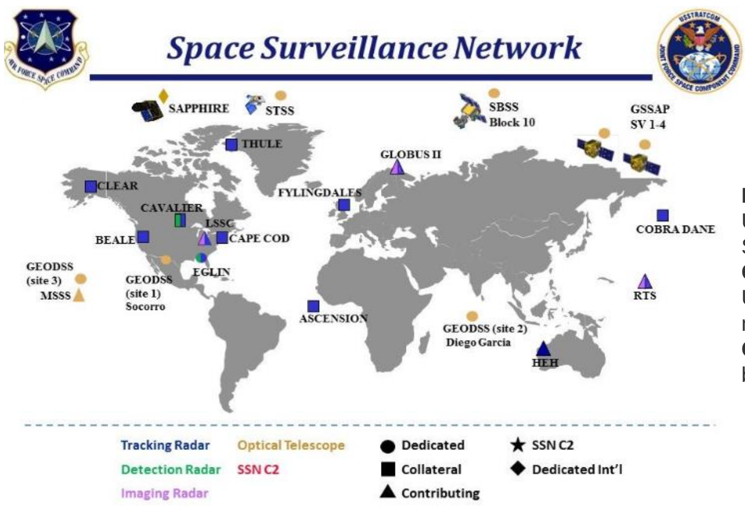
SST OVERVIEW – SST IN THE US (GOVERNMENT)

US GOVERNMENT SST CAPABILITIES

As US military, civil governmental and non-governmental entities rely on and benefit from the use of outer space, SST is considered a key element to mitigate against significant risks threatening space systems and to ensure global freedom of action in space.

Initially, US SST relied on Minitrack, a system which tracked every satellite launched in respect with the international agreement on satellite transmitting frequencies. However, a major limitation regarding uncooperative satellites, such as those of the USSR, lead to the development of the the Spacetrack network in the 1950s, which eventually developed into what is known today as the current US Space Surveillance Network (SSN).

Managed by the Combined Space Operations Center (CSpOC), this global network is composed of more than 30 ground-based optical telescopes and radars supplemented by six in-orbit satellites. This wide range of sensors allows the country to track more than 23,000 space objects orbiting around the Earth.



Dedicated sensors: Operated by USSPACECOM and designed for SST

Collateral sensors Operated by USSPACECOM but primary mission different from SST

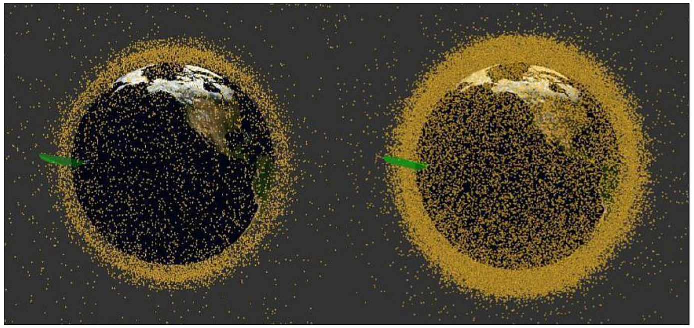
Contributing sensors: Operated by other agencies

Source: *18th Space Control Squadron*

The CSpOC is co-located with the 18th Space Control Squadron whose mission is to use the data collected to maintain the Space Catalog divided into two databases. One is used internally by the 18th Space Control Squadron and the other is publicly available and provides data for the entire space community (registration is required). However, there are some limitations to the current SSN as the system can only track space objects bigger than 10 cm, with little coverage over some regions such as Asia or South America.

To enhance the SSN system, the Air Force initiated the Space Fence System (SFS) in 2005 consisting of a ground-based system of dispersed S-band array radars tracking small objects in LEO. Construction of the system was awarded to Lockheed Martin and is underway on Kwajalein Atoll in the Marshall Islands. Testing of the system started in March 2019 with success. A second Space Fence is currently under study in Western Australia by Lockheed Martin. Even though no public documentation specifies the size of debris detected, the Program might enable the DoD to identify objects down to 2-3cm. Once operational, the system will increase the number of space objects tracked by the Space Command to an estimated 200,000 items – as shown by the illustration below.

Evolution of the Space Catalog in LEO with SFS



Source: *USAF, Lockheed Martin*

SST OVERVIEW – SST IN THE US (GOVERNMENT)

ADOPTION OF SPD-3: A SHIFT TO A CIVIL-ORIENTED MISSION

Prior to the adoption of the Space Policy Directive-3 in June 2018, the Department of Defense (DoD) was in charge of tracking over 20,000 space objects and published a sub-section of these in a catalogue free of direct fees for users, including also basic alert notifications of potential conjunctions. However, this limited STM activity and architecture became inadequate due to the increasing number of space objects.

Echoing the Obama administration's space policy, the 2018 National Space Strategy emphasizes the need to improve global spaceflight safety by increasing the quantity and quality of SST information the US has access to, leading to the adoption of the directive. Through SPD-3, the US recognizes the importance and benefits stemming from space technologies (enabling space-based capabilities for communications, navigation and more) and the need to protect these assets from the increasing congestion of outer space. Reaffirming the fact that access to and freedom to operate in space is of vital interest to advance security, economic prosperity and scientific knowledge, SPD-3 sets new priorities for SSA and STM innovations.

It notably introduces several structural and substantial changes. One major structural reform consists in the shift of SSA and STM responsibilities from the military (the DoD) to a civil authority (the Department of Commerce or DoC). This shift enables the DoD to focus solely on national security-related issues while designating the DoC as the new civil lead for SSA and STM in charge of providing free basic data to civil and commercial stakeholders. The DoD will continue maintaining the "authoritative catalog" of space objects and military-to-military SSA and STM engagement, while the DoC will publish the publicly releasable portion of the DoD's catalogue and encourage growth of the commercial space sector by administering an Open Data Repository. The repository will aim at improving SSA data interoperability and enabling greater SSA data sharing and will consider the technical and economic feasibility of options involving partnerships with industry and academia. The DoC will cooperate with the DoD to provide basic SSA data and should be the focal point for the delivery of an On-Orbit Collision Avoidance Support Service (providing warning of potential collisions and other related data free of direct user fees).

Apart from the reorganization of SST governance, SPD-3 introduces several substantial changes aimed at maintaining US leadership in the space sector. To achieve this goal and enhance US capabilities, a new approach for SST was needed relying on the existing expertise of the commercial sector.

Through SPD-3, the country commits itself to establish an Open Architecture SST Data Repository to continue providing basic free data to various users. The US also seeks to minimize deficiencies in SST capability by providing new sensors, sharing SSA data and most notably by multiplying its SST data sources. SPD-3 introduces the possibility of purchasing and incorporating information collected by commercial, civil and international players creating new business opportunities for the private sector.

Moreover, SPD-3 encourages the development of STM standards and best practices and the strengthening of the US' international influence. It provides that the US regulatory agencies should develop and adopt such standards and practices in domestic regulatory frameworks to promote safe and responsible behaviour in space and inform and shape international consensus practices and standards.

SPD-3 – KEY TAKEAWAYS

A number of the reforms introduced by the Space Policy Directive-3 aim to transform the US' SST activities into a civil and commercially-oriented mission. The main points extracted from the policy include:

- Addressing SST activities **within a civil framework** by shifting responsibility for providing basic SSA data to private players from the DoD to the DoC.
- Continuing to provide basic SST data and STM services to US commercial and civil entities and international partners **free of direct user fees**.
- Improving SST data interoperability by **purchasing and incorporating data collected by private players** into the open architecture.

SST OVERVIEW – SST IN THE US (COMMERCIAL)

INCREASED SUPPORT TO US SST SERVICE PROVIDERS VIA GOVERNMENT SERVICE CONTRACTS

Recent developments of the US space strategy support the growth of the country's SST commercial sector. SPD-3 reaffirms that a basic level of SST data will continue to be provided free of direct user fees to users, promoting the rise of the private sector in the field. Using the open architecture, SST companies will be able to leverage available government assets and provide commercial value-added SST services. In addition, the US government is also seeking to augment the quality of its own catalogue's data, notably through the purchase of data from the private sector, thus offering new business opportunities to companies which have their own tracking system. US government support to commercial SST companies is via the direct purchase of SST data, rather than R&D grants or other funding types. As such, the government acts as both provider and client of high-quality SST data.

As a result, a significant portion of satellite operators are registered with the government's data-sharing scheme, increasing awareness of the impact of collisions and encouraging the sustainable use of space. Currently, the US Air Force has agreements with more than 450 organizations including private stakeholders, operating more than 2,200 spacecraft.

Contrary to the European situation, a number of US commercial companies operate their own tracking systems allowing them to maintain an independent catalogue of satellites and debris. Nearly all systems are ground-based systems able to detect a large range of space objects, with optical telescopes used for GEO and radar systems for LEO. The ExoAnalytic Global Telescope Network is composed of more than 300 telescopes installed worldwide which fuse data in real-time to satisfy the space industry needs. LeoLabs supplies commercial radar tracking services in LEO. Thanks to its phased array radar currently under construction in New Zealand, the company will be able to detect objects down to 2cm, rivalling the US' new Space Fence capabilities. The company is also developing a tool to help New Zealand monitor satellites in LEO.

US SST companies all leverage the US government as an anchor client, while also servicing contracts to commercial satellite operators. Euroconsult estimates that the US government represents 50% of revenues. Some companies such as SpaceNav commercialize their SST services based on data collected by other entities, without their own tracking capabilities.

MAIN US COMMERCIAL SST SERVICE PROVIDERS

COMPANY	OWN TRACKING SYSTEM	OPTICAL	RADAR	LEO	GEO	SMALLEST SIZE TRACKED
ExoAnalytic	✓	✓			✓	10cm
AGI	✓	✓	✓	✓	✓	N/A
LeoLabs	✓		✓	✓		0.25U/2cm
SpaceNav		✓			✓	N/A
L3	✓	✓			✓	20cm

The table above describes the capabilities of the main US commercial SST service providers including whether or not they operate their own tracking system, the nature of the data they collect, their ability to independently track space objects, and other data characterizations.

SST OVERVIEW – SST IN THE EU (GOVERNMENT)

REGIONAL EUROPEAN SST CAPABILITIES

In Europe, SST is being simultaneously developed at national and European levels.

The EU SST program, born in 2014, is a dual civil-defence initiative. It has received funding from EU programs such as Horizon2020, Copernicus and Galileo programs and is implemented by the SST Consortium working in collaboration with the European Commission and EU SatCen. The Consortium is composed of several Member States represented by their national agencies. The initial participating States were France (CNES), Germany (DLR), Italy (ASI), Spain (CDTI), and the UK (UKSA), and were then joined by Poland (POLSA), Portugal (GPSST), and Romania (ROSA). The EU SST program aims at coordinating national sensor resources (radar, telescopes, laser stations), processing SST data and enabling the provision of services related to this data. Currently, the system offers a Re-entry Analysis service, a Fragmentation Analysis service, and a Collision Avoidance service. EU SST allows Member States to benefit from a more comprehensive SST network and reduces reliance on US sensors and its catalogue. This initiative is funded by the EU budget up to €70 million for the 2015-2020 period. In order to enhance the protection of its space assets, the EU is looking to include the EU SST initiative and improve its SST capabilities to monitor space debris in the context of its new space program as part of the next Multi-Annual Financial Framework, covering 2021-2028. If the regulation establishing the new EU space program is adopted, Member States' participation in such an initiative and the EU budget allocated will increase, as the Commission has proposed a €250 million budget for SST activities. However, negotiations are ongoing.

SST projects being inherently dual-use with an important military component, ESA has a limited SST segment since the organization's activities shall be *for exclusively peaceful purposes*. Excluding Space Weather and NEOs, ESA's SST segment consists in combining and promoting R&D activities related to SST (hardware, software, networking in support of SST) and aims at providing an independent ability to acquire prompt and precise information regarding space objects (such as up-to-date orbit information for all objects over a certain size threshold) by developing a catalogue containing this data.

NATIONAL SST CAPABILITIES

Several EU countries have developed independent SST capabilities, with the most significant capabilities developed by France, Germany and the UK (See table for Germany and France). Italy and Spain also have SST Operation Centres and a set of ground-based SST sensors, which includes radar, electro-optical and laser facilities. SST is now set as a priority in several national space strategies. Recently, The French MoD has announced the creation of a new arms program focusing on space surveillance and active defence to which will be allocated €700 million by 2025. Nonetheless, national SST capabilities in the EU still lack budget and suffer from the duplication capabilities across Europe, which is a factor fuelling the pooling of national SST resources in the EU SST initiative.

SELECT EUROPEAN NATIONAL SST CAPABILITIES

COUNTRY	MAIN SST CAPABILITIES
France	• **COSMOS** (Operational Centre for Military Surveillance of Space Objects), run by the Ministry of the Armed Forces: collects SST data to support military operations, protects the national territory • **GRAVES** bi-static VHF radar: tracks 3000 objects of 1m or larger in LEO, is complemented by 3 SATAM radars used for trajectography purposes in LEO (for objects between 400km and 1000km altitude) • **TAROT** (optical telescope): detects objects in GEO with visual magnitude of +17 • **OSCEGEANE** & project Tavel: SST capabilities in GEO* • **GeoPOLARSAT**: telescope equipped with a polarimeter capable of determining the shape and size of space objects*
Germany	• **German SSA Centre**, run by MoD, generates SSA status reports based on diverse inputs (sensors, open sources, etc.) • TIRA sensor, owned by Fraunhofer Institute: detection threshold of 2cm at 1000km • The **GESTRA** (German Experimental Surveillance and Tracking Radar) system: a quasi-monostatic, pulsed, phased array radar operating in L-band*

*Equipment currently being developed
Table adapted from "*Command and Control of a Multinational Space Surveillance and Tracking Network*", JAPCC, June 2019.

SST OVERVIEW – SST IN THE EU (COMMERCIAL)

THE RISE OF EUROPEAN SST SYSTEMS AND SERVICE PROVIDERS

Europe's commercial SST sector is less mature than the US, though there are a growing number of established companies and new startups entering the space and offering services. However, apart from one exception (ESA's ADRIOS mission), European governments typically do not directly purchase data or services from industry in large quantities, which has slowed growth compared to the US. However, the financing landscape appears likely to improve.

The new EU space programme constitutes new opportunities for commercial actors as it will require their participation in its implementation, with the new MFF budget proposal including €250 million for SSA. The EC has also proposed a €94.1 billion budget for Horizon Europe to finance R&I projects which may include SST projects. For example, the EU's previous R&I framework program helped finance the Italian company D-Orbit's D3 project consisting in a customizable decommissioning device. In December 2019, the company raised additional funding following investments by Seraphim Capital and Noosphere Ventures. At the national level, the Luxembourg government also took actions to promote its commercial sector by signing in 2019 a Letter of Intent with Northstar, a Canadian SST company, to create a Centre for Excellence for Clean Space to strengthen collaboration between public and private SST stakeholders.

Moving away from R&D, in terms of operational European SST capabilities, there have been promising developments here too.

In late 2019, the Swiss company Clearspace offering tracking, capture and removal services for non-functioning spacecraft was awarded a debris-removal contract by ESA as part of the agency's Active Debris Removal/In-Orbit Servicing (ADRIOS) mission. Under this scheme, Clearspace will build a spacecraft to capture a 100kg piece of Vega launcher and deorbit it. The Spanish company GMV is a world leader in satellite ground control systems and participates in ESA's SSA and SST programs. Amongst other projects, GMV runs Spain's SST center and leads ESA's space fragmentation and analysis service which consists in monitoring and forecasting the evolution of catalogued space debris. GMV does not have any autonomous tracking facilities; rather, it acquires SST data and provides additional services. Finally, Elecnor Deimos has developed a series of SST products and services including sensor systems, space object catalogue generation, collision avoidance warnings to satellite operators and more.

MAIN EUROPEAN COMMERCIAL SST SERVICE PROVIDERS

COMPANY	OWN TRACKING SYSTEM	OPTICAL	RADAR	LEO	GEO	SMALLEST SIZE TRACKED
GMV		✓			✓	10cm
Elecnor Deimos*	✓	✓	✓	✓	✓	10-15cm
ClearSpace		✓	✓	✓	✓	10cm
D-Orbit		✓				

The table above describes the capabilities of the main European commercial SST service providers including whether or not they own their own tracking system and the nature of data, independently collected or not, they use to provide their services.

COMMERCIAL SPACE SURVEILLANCE AND TRACKING

EXECUTIVE SUMMARY

PART 1 – SST SECTOR OVERVIEW

PART 2 – MARKET ASSESSMENT

MARKET ASSESSMENT – STAKEHOLDER CONSULTATION CAMPAIGN

SST STAKEHOLDER INTERVIEWS

One of the primary inputs for this study was an **SST stakeholder consultation**. The consultation was carried out between **mid-January to early February 2020**. We conducted phone interviews with government and commercial SST service providers to understand the **supply side of the market**, as well as with government and commercial satellite operators to capture the **demand side**. The interviews were fairly representative of the space industry as a whole, in terms of operator space applications, orbits, and other characteristics. A number of key statistics are included in the boxes below.

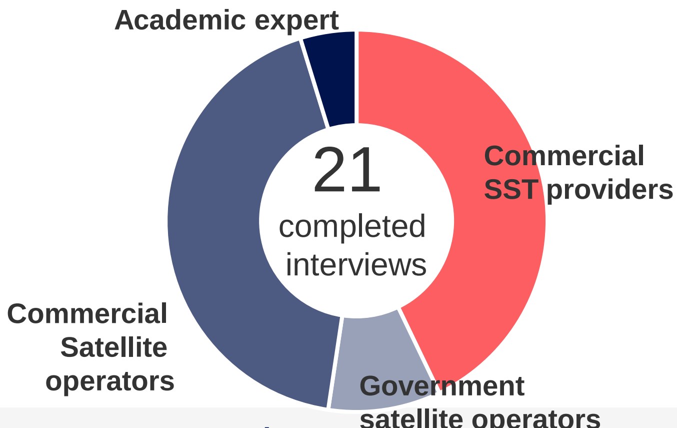
A complete **Stakeholder Target List** with all relevant details as well as completed **Stakeholder Questionnaires** are included as part of the project deliverables.

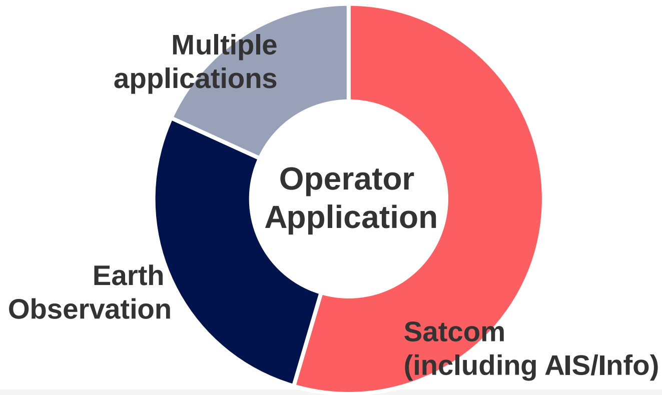
SST STAKEHOLDERS AND RESPONSE RATE

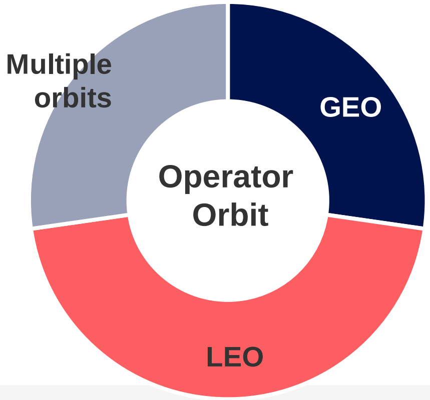
- **40 targets identified and contacted**
  - 11 Commercial SST service providers
  - 7 Government satellite operators
  - 22 Commercial satellite operators
- **Response rate: 21 / 40 (52.5%)**
  - 9 Commercial SST service providers
  - 2 Government satellite operators
  - 9 Commercial satellite operators
  - 1 Academic expert

SST STAKEHOLDERS BREAKDOWN

- **By region:**
  - 9 North America
  - 12 Europe
- **By Operator orbit:**
  - 3 GEO
  - 5 LEO
  - 3 multiple orbits
- **By Operator application:**
  - 6 Satcom (including AIS/Information)
  - 3 Earth Observation
  - 2 Multiple Applications







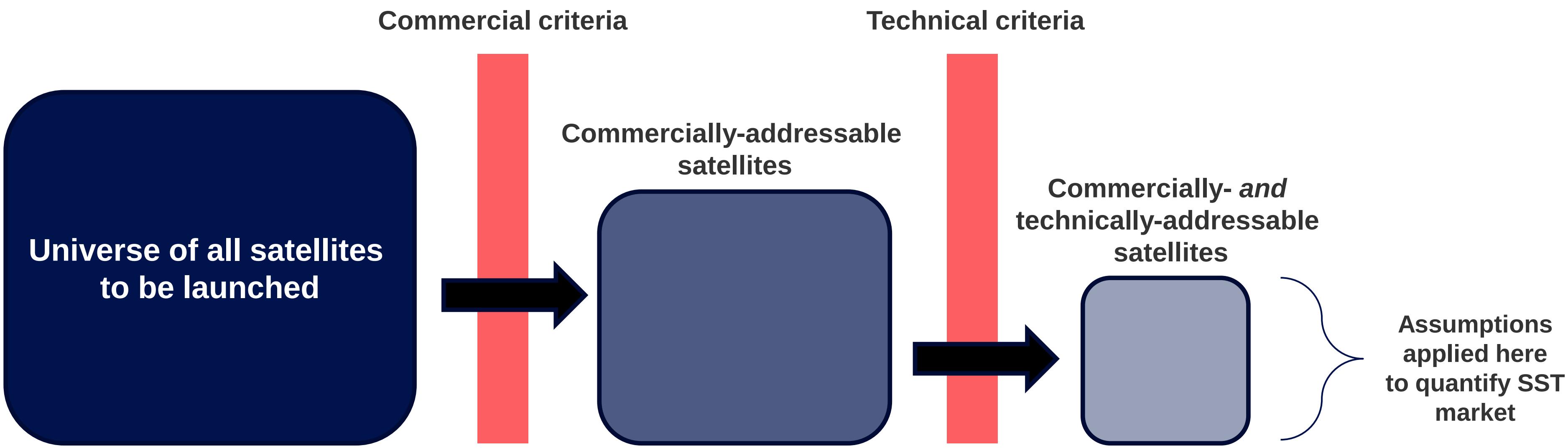
MARKET ASSESSMENT – MARKET ASSESSMENT MODEL AND ASSUMPTIONS

BUILDING THE MARKET MODEL

The methodology used in order to quantify the commercial SST market is as follows:

1. We start with the entire Euroconsult proprietary database of satellites launched, and apply a number of preliminary parameters, to include all satellites in orbit between the period in question (2020 to 2035), with the following info for each: satellite name, orbit (apogee / perigee), operator name and type (commercial, government civil or military), region and country, launch date, End of Life, application, constellation, and other relevant satellite characteristics.
2. To determine the **addressable market**, we take the total universe of satellites and apply a number of **commercial and technical addressability criteria** in order to arrive at the addressable market. The addressability criteria are laid out in the following slide.
3. The remaining satellites are considered the **commercial SST Addressable Market**. A number of **assumptions** are applied to these satellites (pricing structure, willingness to pay, market and technology trends, and so on) and **each satellite is assigned a US Dollar value per year in order to derive the commercial SST market sizing.** The market can be analysed in terms of commercial vs. government market share, market per orbit, per application, and so on. All the assumptions applied to the commercial SST Addressable Market are detailed in the following slides.

The market model and all corresponding elements (database of all satellites to be launched, market assumptions, pricing model, willingness to pay, etc.) are included in the separate **Market Model Excel document**, submitted as a Deliverable to the UKSA.



MARKET ASSESSMENT – MARKET ASSESSMENT MODEL AND ASSUMPTIONS

COMMERCIAL AND TECHNICAL ADDRESSABILITY CRITERIA

Type of Addressability	Satellite category / Type	Exclusion Case	Rationale
Commercial	Government (civil and defense), Commercial	China	Limited / unreliable public information, security reasons
	Government (civil and defense), Commercial	Russia	Limited / unreliable public information, security reasons
	Academia	Academic satellites	Short lifetime, low budget

Type of Addressability	Satellite category / Type	Exclusion Case	Rationale
Technical	Satellite mass	Microsatellites (<50kg)	Unlikely to pay for SST services
	Satellite lifetime	1 year or less lifetime	In self-cleaning orbit
	Satellite orbit	Escape orbit	Incompatible with SST services
	Mission type – human spaceflight	Manned spaceflight missions	Incompatible with SST services

ASSUMPTIONS APPLIED TO THE COMMERCIAL SST ADDRESSABLE MARKET

The excel document **"UKSA Commercial SST Database and Model"** lists in detail the methodology and assumptions used to quantify the commercial SST market – a high-level summary is included here. All prices are in Constant 2020 US dollars. The assumptions permit the **conversion** of the number of satellites in the **Commercial SST Addressable Market** into a dollar figure representing the **Commercial SST Market Sizing.**

The Commercial SST Addressable Market is composed of two types of satellites: those operated by **governments** (civil / military), and those operated by **commercial companies**.

- **Commercial entities** pay for SST services on **a per-satellite basis**; as a result, the commercial market model is **bottom-up**: a price is assigned to each satellite, and the SST market total is calculated by **aggregating the total**.
- **Governments** do not pay per satellite, but typically buy **data and services via large contracts**; as a result, the government market model is **top-down**: the total market size is estimated then divided by the number of gov. satellites to derive a per-satellite cost.

There are two main types of assumptions which act as variables:

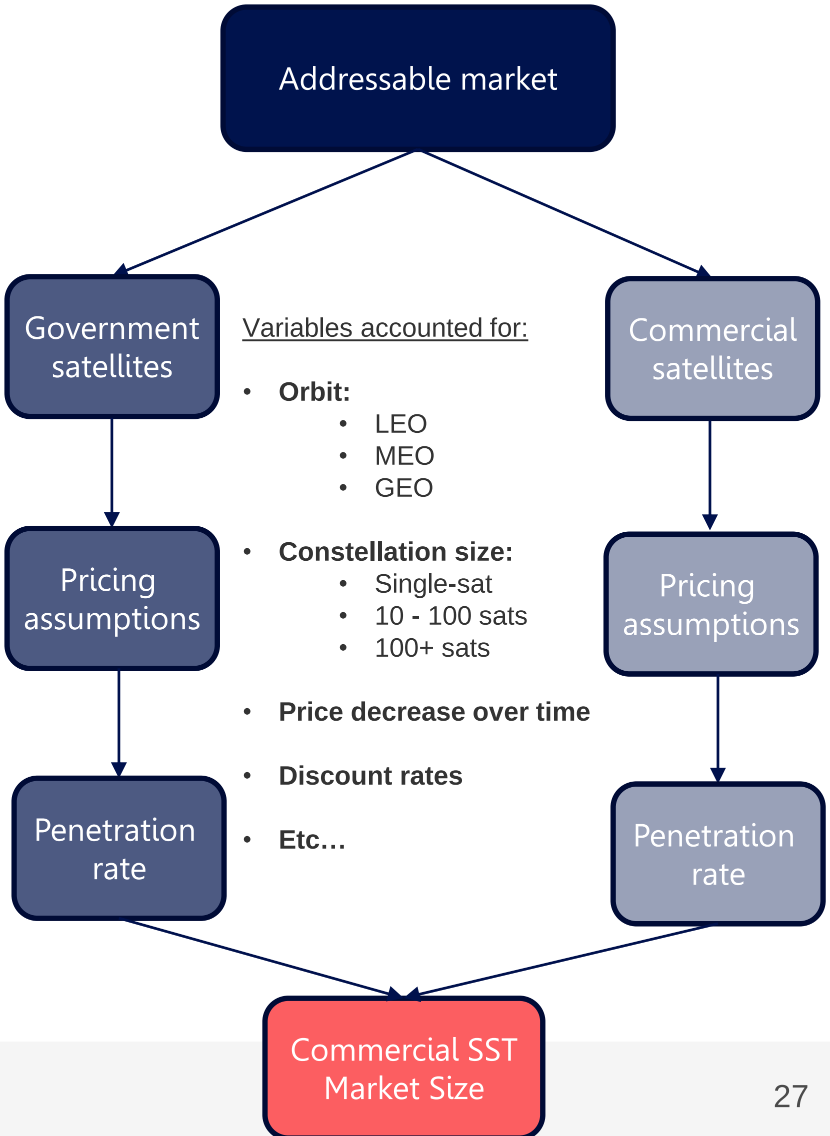
1. **Pricing Assumptions**, which affect the **value assigned to each satellite** over the period, including growth trends, discounts, variations for orbit or client type, and so on;
2. **SST Service Penetration rate**, which affect the **proportion of satellite operators willing to pay for commercial SST services**, today and in the future.

A number of additional variables affect how each satellite is priced. These variables include:

- **By satellite operator**: commercial / government (civil and defense)
- **By orbit**: LEO / MEO / GEO
- **By constellation size**: single-satellite missions / constellations with 10 to 100 satellites / constellations with over 100 satellites (so-called mega-constellations).

The tables in the **Annex** lay out all of the individual assumptions used to build the model, how that assumption affects the pricing, and finally the assumption justification or rationale.

The justification column is colour-coded: **green** signifies **empirical data** or **direct interview inputs**; **yellow** represents **hypotheses based on market trends**, and which therefore inherently have a lower level of confidence.



MARKET ASSESSMENT – MARKET ASSESSMENT MODEL AND ASSUMPTIONS

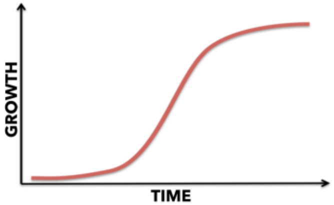
UNDERSTANDING SPACE MARKET DYNAMICS RELATED TO SST

Before the report proceeds to a deep dive analysis of the SST commercial market over the next 15 years, it is useful to provide some context and to understand some of the basic market, business and technology forces at play which will heavily influence the SST commercial market.

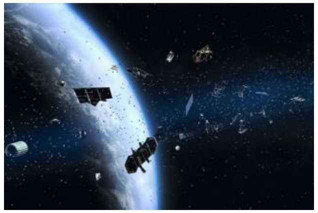
1. The world is currently on the cusp of the **mega-constellation revolution**, with multiple mega-constellation projects in planning, and at least two of these (Starlink and OneWeb) having entered the constellation build-up phase with first launches in 2019-2020. If all projects are realized, by the end of the decade the number of satellites in orbit will rise exponentially, with a sustained launch rate of thousands of satellites launched per year over a decade. As such, we expect to the next 15 years to be characterized by two major phases:

- **Phase 1: Constellation Build-up** (2019 – 2028) → an exponential increase in the number of launches as the mega-constellations are constructed, resulting in an extremely rapid increase in the number of satellites in space.
- **Phase 2: Constellation Replenishment** (2028 – 2035) → as the mega-constellations reach maturity, the number of launches (and therefore of satellites in space) will slow down, until they reach levels required to sustain the constellations in space, but not grow them further.

However, it remains to be seen if all the proposed projects will come to fruition. Compared with the exponential growth in the commercial mega-constellation sub-sector, we expect more modest and linear growth in other sectors, such as government operators and single-satellite missions.



2. **S-curve market dynamics**: SST technology and business adoption is currently in a **preliminary phase**, in terms of technological maturity and commercial uptake. However, as the technology improves and more companies begin to offer SST services, in conjunction with the launch of mega-constellations, we expect a period of rapid growth, with **more significant SST service penetration** into the space sector. Finally, as the market reaches its **full maturity stage and penetration peaks**, growth will begin to slow. This is in effect the so-called "S-curve" which is prevalent in **nascent, high-technology areas as they enter the mainstream commercial market**.



3. Finally, concerning the commercial SST market specifically, it should be noted that fee-based, commercial services must compete against a free, government-provided solution, which **currently serves to suppress the market**. In addition, **no legal framework exists to impose obligations** on satellite operators to procure commercial SST services or take any other significant actions to **ensure the sustainable use of space**. Apart from submitting debris mitigation and deorbit plans in order to receive a launch license, there is no regulatory regime which works to **continually ensure and/or enforce the responsible and sustainable use of space by operators**. As such, commercial uptake is estimated to remain low until either there is a mandatory obligation to ensure the sustainable use of space, there is a wide-scale, large-impact collision or debris cloud heavily impacting operations, or the space environment becomes very congested and the cost-benefit assessment of operators changes in the balance of paying for SST services to avoid a collision.

MARKET ASSESSMENT – COMMERCIAL SST MARKET SIZING

COMMERCIAL SST MARKET SIZING – OVERVIEW

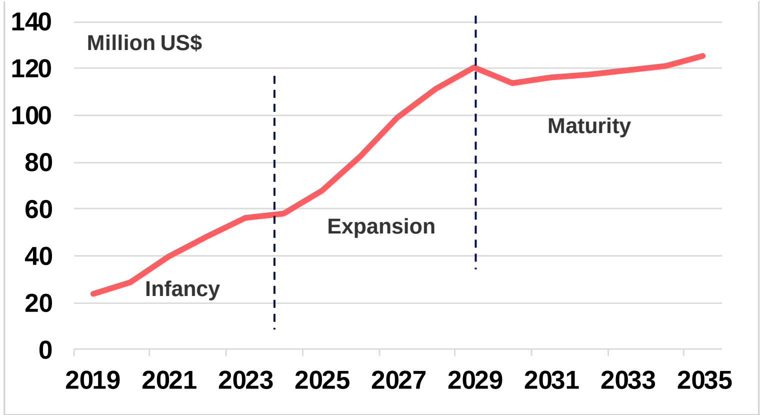
The market sizing covers the period 2019 to 2035. In 2019, the addressable SST commercial market is estimated to total **US$23.9 million** and forecasted to grow to approximately **US$125.7 million** by the end of the period in 2035.

The SST market is expected to undergo three distinct phases:

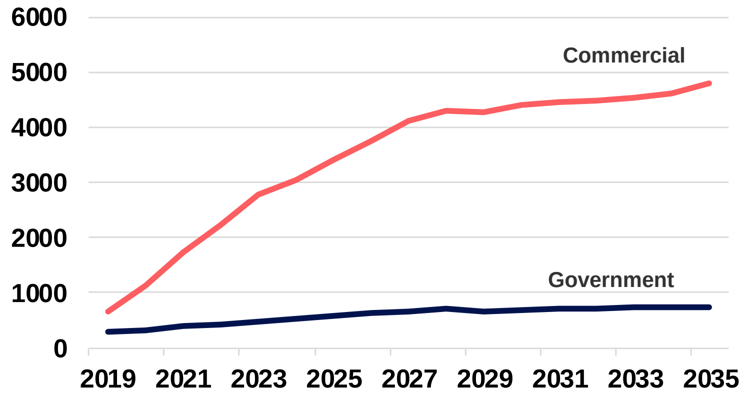
- **An infancy phase**, marked by pre-market characteristics and slow development and commercial uptake with governments representing the bulk of demand;
- **An expansion phase** in which there is rapid technological development and advances, growing market penetration rates, reduced costs and a larger commercial client base;
- **A maturity phase** characterised by slowing technological development as it approaches physical limits, incremental advances, few new clients and a focus on operational cost reductions rather than investing in breakthrough technology.

The above assumes the growth trend of **ground-based SST solutions only** (optical telescopes and radar systems). It's possible that the next breakthrough SST technology will emerge in the coming decade and result in a second S-curve growth dynamic, possibly by in-space SST sensors and solutions.

COMMERCIAL SST MARKET VALUE



COMMERCIAL SST ADDRESSABLE SATELLITES



There are three main variables which significantly affect the market pricing:

1. **Client type**: government (both civil and defence) and commercial;
2. **Satellite mission type:** single-satellite mission, constellation (defined as a system with 10 to 99 100 satellites), or mega-constellation (any system with more than 100 satellites);
3. **Orbit type**: Low Earth Orbit (LEO), including Sun Synchronous Orbit (SSO), Medium Earth orbit (MEO) including Highly Elliptical Orbit (HEO), and Geosynchronous Earth Orbit (GEO)

Each of these variables are discussed in turn in the following slides.

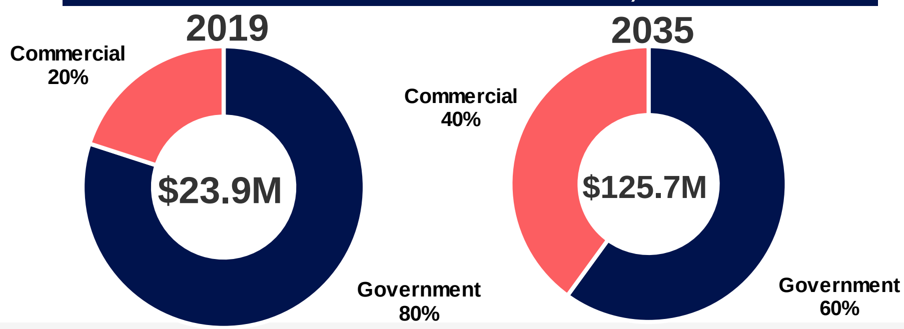
COMMERCIAL SST MARKET SIZING – BY CLIENT

Today, commercial SST revenues are generated predominantly by governments, who procure SST services or, more frequently, bulk-buy raw data from commercial SST service providers to incorporate into their own databases and models in order to augment and refine their catalogue of tracked space objects. For example, in 2015, the US Air Force awarded a $8.4 million contract to commercial SST service provider AGI for a one-year subscription service for the company's orbital tracking data. In an interview with Euroconsult, AGI said that their total revenues was approximately $10 million – meaning that their government revenues were four times larger than their commercial revenues. In Europe, Elecnor Deimos echoed this ratio of government vs commercial revenues: posting SST-related revenues of €5 million, they estimated that purely commercial sales equalled to approximately €1 million, with the rest from government.

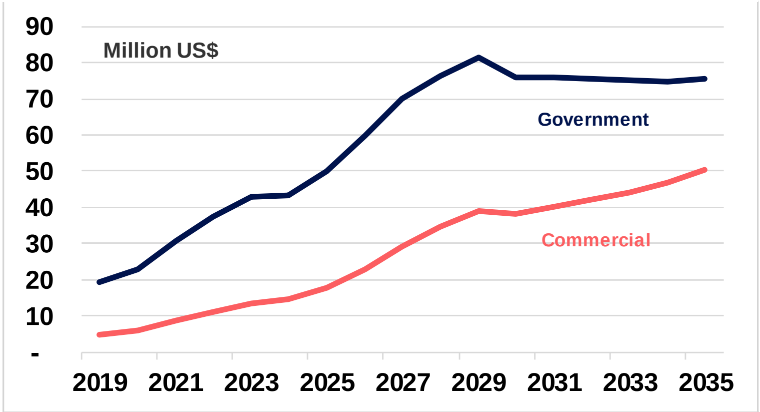
However, it should be noted that the total number of addressable commercial satellites dwarfs the number of addressable government satellites (see chart, lower right). Governments launch far fewer satellites than commercial operators, but the latter have a lower willingness to pay for SST services, and have a much lower service penetration rate. Over the period however, the commercial market is forecasted to grow faster: 10x growth for the commercial market vs. less than 4x growth for the government market.

Another key cleavage is that governments without exception expressed a strong concern for the sustainable use of space and the importance of debris mitigation, whereas commercial operators were more ambivalent, with cost considerations coming first.

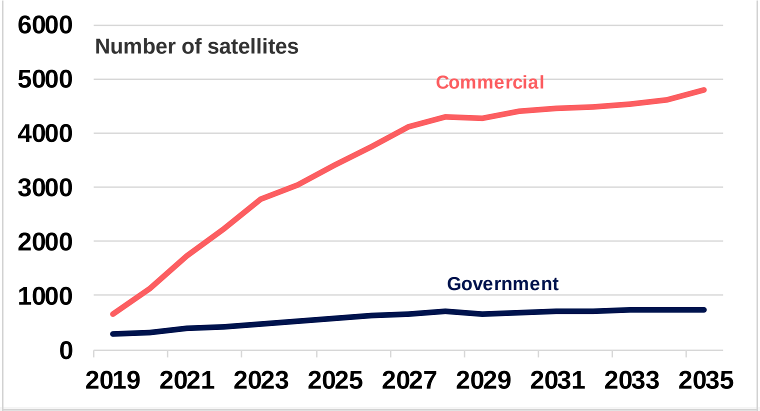
ADDRESSABLE MARKET BY CLIENT, 2019 VS 2035



SST MARKET VALUE BY CLIENT TYPE



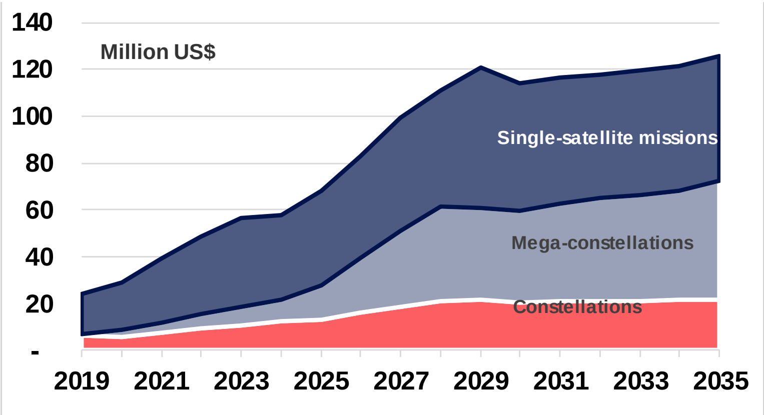
ADDRESSABLE SATELLITES BY CLIENT TYPE



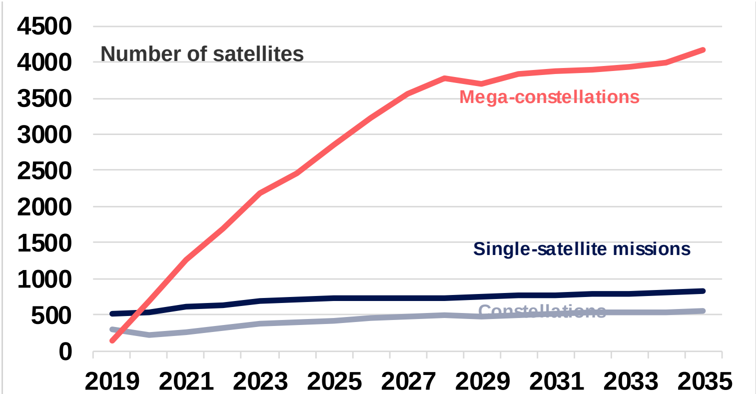
MARKET ASSESSMENT – COMMERCIAL SST MARKET SIZING

COMMERCIAL SST MARKET SIZING – BY SATELLITE MISSION

MARKET VALUE BY SATELLITE TYPE



ADDRESSABLE SATELLITES BY MISSION TYPE



A second key variable for the SST market is the satellite mission type: whether a single satellite is launched, or if that satellite is part of a constellation. It is clear that future launch trends will be overwhelmingly dominated by commercial mega-constellations launching to LEO. Euroconsult forecasts that already-announced and future mega-constellation projects in the pipelines (Euroconsult discounts certain projects which have a low probability of materializing) will reach a peak launch rate of over 3,500 satellites launched per year, before the constellations enter into replenishment phases with sustained, rather than increasing, launch rates.

However, despite the vast numbers of satellites, mega-constellations are forecasted to represent only $50.2 million of SST total revenues by 2035, approximately 40% of the total market of $125.7 million. This is due to a number of factors, including a very low willingness to pay, a low price point tolerance due to the expendable nature of a single satellite within a mega-constellation architecture, unproven business cases and lack of revenues today forcing these operators to minimize all superfluous expenses, and the self-cleaning nature of LEO to which most mega-constellation projects will launch to. In addition, many mega-constellation satellite designs lack any type of propulsion, so even in the case of a conjunction alert, the operator would have no way of moving the satellite. In the case of SpaceX’s Starlink system, the operator has stated that their satellites are equipped with onboard sensors and the ability to manoeuvre based on automated processes, and have not publicly expressed any interest in procuring commercial SST services.

Single-satellite missions are forecasted to generate $53.5 million in revenues by 2035, compared to the $50.4 million by mega-constellations and $21.8 million for constellations. Despite their lower numbers, it is typically governments who launch single-satellite missions, and as noted earlier governments are expected to continue to generate the majority of commercial SST revenues.

MARKET ASSESSMENT – COMMERCIAL SST MARKET SIZING

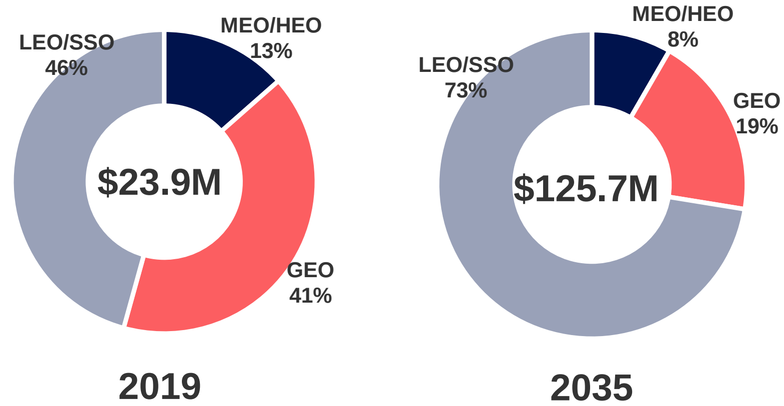
COMMERCIAL SST MARKET SIZING – BY ORBIT

The final main variable which significantly affects the SST market pricing is the orbit of the satellite using the service. The satellite's orbit will typically impact its size, complexity and value, as well as the satellite operator's business model.

GEO orbit, due to its extreme distance from the Earth and the technical challenges of successfully placing a satellite in orbit, is dominated by advanced and sophisticated players: governments and mature commercial satellite communication operators, the latter being robust, long-standing businesses generating tens or hundreds of millions in revenues annually. These companies in the stakeholder consultation indicated a high degree of SST maturity, including awareness of the issues, dedicated SST teams, and a willingness to invest significant sums of time and resources into ensuring the long-term viability of the GEO environment. Indeed, satcom operators are typically well-organized, fee-paying members in data-sharing associations such as the Space Data Association (which costs about $7,500 per satellite per year), and overall take pains to act responsibly in space, such as deorbiting satellites as they approach end of life, taking proactive measures for at-risk satellites, and more. Due to the relative low level of risk (compared to LEO) of a collision in GEO, as well as the self-regulating and highly organized nature of GEO operators, there was a relatively high degree of SST service penetration, with about half investing money into SST services. However, the willingness to pay per satellite was very low, as they relied mostly on free services from CSpOC and their data-sharing measures (membership fees of the Space Data Association), which they deemed sufficient to meet their present and future needs, since GEO is not expected to become significantly more congested than today.

In contrast, LEO has been called by more than one respondent as the "Wild West." Operators launching to LEO are in many cases nascent start-ups, with unproven business cases and no steady revenues. They are more focused on short-term objectives and in nearly all cases do not have dedicated SST personnel. There is also some degree of responsibility abdication, since LEO is perceived to be a "self-cleaning" orbit, and therefore no mitigating action needs to be taken. While SST coverage costs per satellite are much higher in LEO than in GEO—commercial SST providers charge around $4,000 per month per satellite in LEO—SST penetration rates are much lower. As a result, despite there being far more satellites in LEO than GEO, in 2019, the LEO SST commercial market is only slightly larger than the GEO market, at 46% and 41% of the total, respectively.

MARKET VALUE BY ORBIT



However, over the forecast period, while in constant revenues both MEO and GEO markets are expected to remain roughly stable, with little pricing or market penetration increases, by 2035 both orbital markets will decrease by about half from their 2019 market share, ceding ground to a rapidly-expanding LEO market. Even if all else remained equal, the sheer number of satellites to be launched into LEO would grow the market, but adding to this are a number of other factors fuelling growth and higher market penetration rates.

LEO operators have without exception noted the rise of mega-constellations and the rapid rise of congestion in LEO as strongly contributing to increasing the risk of collision, and thus driving up their use of SST services. Other contributing factors include increasing awareness of the space debris problem and growing maturity in LEO operators' space activities.