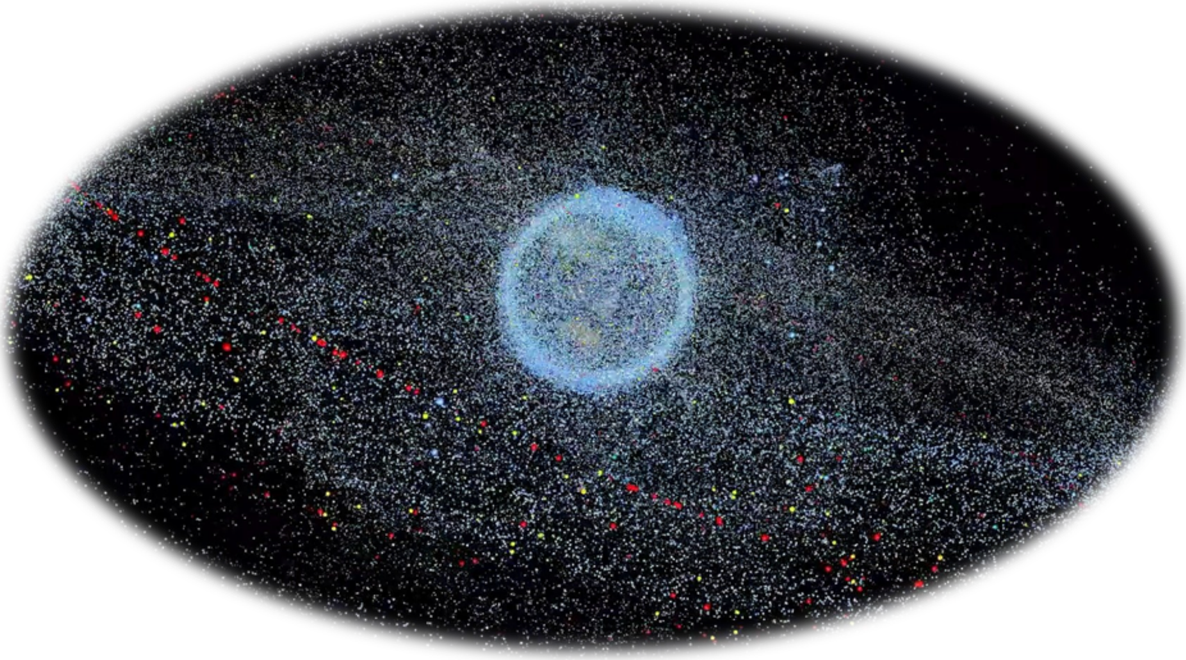

Image: ESA. Distribution of space debris in orbit around Earth, 01/02/2019, available at:
https://www.esa.int/ESA_Multimedia/Videos/2019/02/Distribution_of_space_debris_in_orbit_around_Earth

Future SST Markets Research: Final Report

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MAP Analytica

Inverse Quanta

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Glossary of Abbreviations

Abbreviation	Meaning
COLA	Collision on Launch Assessment
GEO	Geosynchronous (or Geostationary) Earth Orbit
GNOSIS	Global Network On Sustainability in Space
GNSS	Global Navigation Satellite System
ISAR	Inverse Synthetic Aperture Radar
JSpOC	Joint Space Operations Centre
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
OC	Operations Centre
RF	Radio Frequency
RQ	Research Question
RSO	Resident Space Object
SAR	Synthetic Aperture Radar
SPS	Stand-alone Prediction Services
SST	Space Surveillance and Tracking (this abbreviation is used throughout the report to encompass Space Surveillance and Awareness (SSA) and Space Domain Awareness (SDA))
STFC	Science and Technology Facilities Council
TLE	Two Line Element
TRL	Technical Readiness Level

1. Executive Overview

Over the coming decade, the number of operational satellites in orbit is set increase by an order of magnitude from around 2,300 to well over 20,000. The ability to detect smaller pieces of the debris population is also set to increase, resulting in the tracking of potentially a million objects in orbit. Low Earth Orbit will be particularly impacted as it faces the highest growth and the greatest risk of collision. As a result, the demand for products and services from a credible Space Surveillance and Tracking (SST) provider is projected to increase.

This project researched and described the global process for delivering SST products and services. Using this as the foundation, and informed by contextual factors, an analysis revealed that the UK industrial provision across this SST process is well founded although lacking clear demand signals. The associated SST-related academic research is broad and world-leading yet lacks the focus to provide the wider societal and economic impact. The output of the analysis points to opportunities in providing greater precision, accuracy and confidence in SST data and exploiting the UK's geographic 'uniqueness' and the strengths in small satellite manufacture that could contribute to much needed on-orbit SST. The biggest opportunity was found to be the provision of an SST operations focus to fully exploit and add value to existing sensor data, as well as develop the human capital essential to developing innovative future SST products and services.

The UK is well positioned to take commercial advantage of the opportunities if demand was stimulated. Given greater focus, the UK SST-related academic research could provide wider financial and social impact, especially within the SST sector. The UK is well placed to take advantage of all of these opportunities and take a global lead in the provision of SST products and services and if it did, would position itself as an informed and influential partner in the inevitable global discussion of space sustainability.

Please note: this report has been edited and abridged from the original for publication.

2. Executive Summary

2.1. Space Surveillance Context

The space environment is complex, congested and set to become more so in the near future. As more operators launch satellites into orbit, the need to better understand the orbital environment is greater than ever. The framework for undertaking space surveillance is also undergoing significant change. The US is in the process of bringing a hugely capable military sensor on-line, the new Space Fence, yet is nevertheless transferring responsibility for the space catalogue from the US Air Force to the Department of Commerce, reflecting the shift to the civil and commercial sectors as the dominant space actors.

Within this context, the study has looked at the existing process for conducting Space Surveillance and Tracking (SST) as a global opportunity and then conducted a review of provision of SST services and products from across that process to better understand where the dominant providers are and where there might be gaps for UK companies.

It is anticipated that the existing SST products and services will evolve as catalogue size increases (due to both mega-constellation launches and improved tracking of small debris), target object size decreases (Cubesats and Nanosats), the need for greater frequency of tracking of more nomadic satellites increases and new capabilities for debris removal and on-orbit servicing come to the market. Looking further into the future, an increased human presence in Earth orbit as a consequence of space tourism will place further demands on the SST systems to ensure their safety. These will all require more SST products and services and therefore more opportunities for UK firms offering them from across the SST process.

2.2. The SST Process

The extant SST process is illustrated in the diagram below:

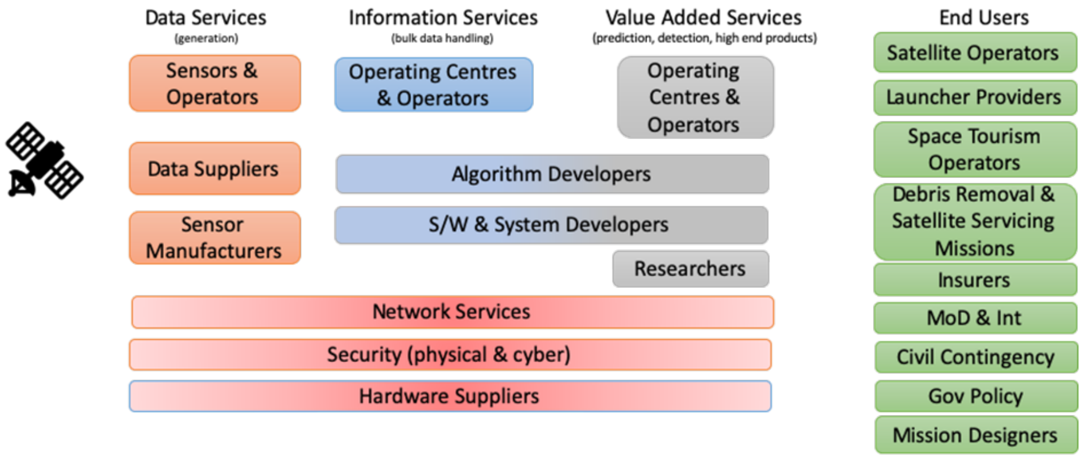

Figure 2-1. SST End-to-End Process Diagram

The foundation of this report was establishing the end-to-end SST process. This informed the subsequent consideration of the products and services that would comprise the opportunities both now and in the future. This also allowed the report to consider where gaps exist in the nominal process and what potential opportunities exist in the future.

2.3. Analysis of the UK SST Sector – Providers

The analysis undertaken for this report revealed an SST process that is set to expand as demand grows for more products and services in the future. The UK industrial provision across this process is well founded although lacking clear demand signals. The analysis of these factors and the broader context points to opportunities in providing greater precision, higher accuracy, lower latency and hence greater confidence in SST data. This is driven by the need to avoid smaller objects but manoeuvre less often and with greater certainty. Exploiting the UK's geographic 'uniqueness' and building an operations and customer focus to fully exploit the SST process and add value to existing sensor data, as well as develop the human capital essential to developing future SST products and services.

2.4. Academic Research

The associated SST-related academic research is broad and world-leading yet lacks the focus to provide the wider societal and economic impact that the GNOSIS network is leading in.[1] The exploitation of novel ideas from concept to product is a traditionally difficult area for the UK.

2.5. Conclusion

The UK is well placed to exploit the existing and future SST markets. It has the entrepreneurial space industrial base, the conceptual thought leadership to best exploit the products and services and a strong academic base

[1] GNOSIS brings together scientists and industry to understand and solve problems related to the ever-growing problem of space debris and the challenges of safeguarding spacecraft set to launch into that environment.

3. Report Approach and Methodology

The approach and methodology interrogated each of the questions posed:

1. What are the key products or services needed to deliver SST offered globally by industry or government?
2. What products or services related to SST are currently offered by UK companies?
3. What academic research related to SST is currently underway or is confirmed by UK universities?

First the project considered the products and services that make up the delivery of SST globally. With this framework established, the project then concurrently undertook a review of the SST products and services offered by UK companies alongside a review of the SST-related academic research being undertaken in the UK (full review not included in this abridged version).

4. Key Products and Services for SST

This section considers the range of products and services that are possibly needed for SST. This is approached through a consideration of end users for such data and an assessment of their information needs. The range of products and services is agnostic to what is currently being offered and is developed form the position of what such users might "like" to have. The range of current products is then considered to identify the gaps.

To set the process into context and draw useful parallels, while avoiding pitfalls, some comparison is made with other emergent data services to illustrate the evolution of the process and how value-added services emerged.

4.1. Products and Services

SST is a unique environment and some distinction is drawn between different types of "product" delivery and includes:

1. Data – which comprises elements at the lowest practical level.
2. Services – which comprise an aggregation of data at a more of informational level.

But there is considerable overlap between them and the way they are delivered. All of these options create market opportunities for companies to offer existing information in new ways and even look to combine data sources to generate more sophisticated products. The differentiation between data and services is illustrated as a continuum in Figure 3-1 below.

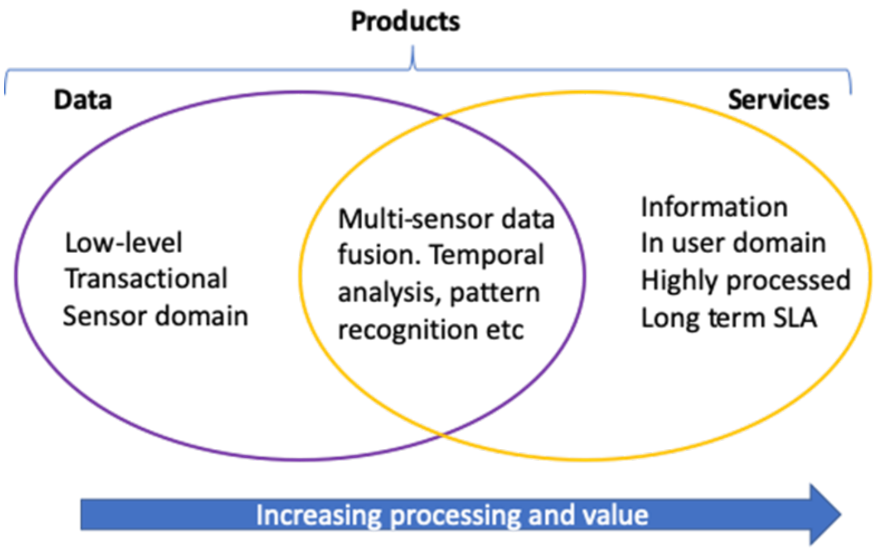

Figure 4-1. Data and Services occupy similar technical areas but often differ in their commercial delivery

The notion of an SST "product" can include a range of additional points that are unique to the SST domain, namely:

1. Geographic location in terms of terrestrial and in-orbit location.
2. Technical performance usually related to sensitivity or accuracy of prediction.
3. Latency in the detection of change and delivery of products.
4. An understanding of the space environment and the influences it exerts on objects.
5. Knowledge of the objects in the catalogue, and the intentions of the active satellites (derived from satellite operators).

The depth of the market comes from the expectation that if one end user has need of a particular type of information, then almost certainly that need is not unique. Hence others will have a similar need. Although such users might develop their own specialised solutions (a situation that occurs frequently in an emerging and immature market), it is more cost effective and tends to drive higher quality for a single provider to develop the required product (perhaps in several versions) and offer it as a service, drawing on the accumulated learning that is difficult for competitors to imitate.

Additionally, there are a range of products and services that underpin the provision of the core SST delivery (hardware for sensors, processing networks, software). These are dealt with as cross-cutting services.

4.1.1. Comparisons with Earth Observation Market

While not entirely similar there are useful comparison to be made with the Earth Observation data market. This market evolved in the late 70's as government-led organisations started to realise that data of scientific curiosity could be sold for commercial applications. Data was collected on a global basis using expensive space-based assets and downloaded to data centres for further processing. Users could then order (essentially) raw data. Much of this was photographic in its presentation, with later development in Synthetic Aperture Radar (SAR) that provided new sensor modalities. Even basic SAR data products required complex calibration and processing, and this was usually undertaken by the organisation that operated the spacecraft.

Earth Observation Product Levels: Internationally understood levels have been defined to indicate the amount of processing performed on data. Although the detailed definitions can vary between organisations.

Data Level	Description
0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artefacts (e.g., synchronization frames, communications headers, duplicate data) removed.
1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to Level 0 data.
1B	Level 1A data that have been processed to sensor units (not all instruments have Level 1B source data).
2	Derived geophysical variables at the same resolution and location as Level 1 source data.
3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency. May include additional data sources.
4	Model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Table 4-1. Earth Observation data levels (definition can vary between organisations)

A range of other specialist sensors were also developed (e.g. Radar altimeters for ice and ocean studies, multi-spectral imagers for crop detection, spectrometers for atmospheric chemistry etc). These were all driven by niche scientific needs and hence had initially limited commercial potential.

During the 80's governments strove to mature the market for Earth Observation data to make it self-sustaining as had been the case for the space telecoms market in the 60s. These initiatives struggled to gain traction as the technology was still evolving and the end-user segment was relatively small and did not understand the information that could be extracted from the data. The main change was the establishment of service companies that extracted "actionable information" from the data.

A classic example is crop-health, where a farmer could not usefully interpret a 4-band colour image of his field, but higher level products concerning crop stress and health could be extracted by algorithms and converted into detailed dosage instructions for fertilizer or pest treatments that added value to the data and made it marketable. This example is analogous to the current maturity of the SST market and there are similar opportunities for adding value to the data to make it more widely marketable.

The Earth Observation market has now matured with a wide range of products being offered by specialist companies, underpinned by technology development and capital investment in equipment. Although much of the equipment cost appears to be in the space segment, programme management guides suggest that ~ 50% of the mission costs should be devoted to the development of the ground segment including processing and its associated software.

Much of the development has been driven by major organisation (ESA) providing low-level data at low cost or free (for example the Sentinel programme), enabling researchers and specialist companies to focus on "value added products" that deliver value in the end-user domain without constrictive costs of data supply. Risks to commercial development have been the supply of similar products by research organisations based on preferential data costs and that has reduced the engagement of start-ups in the offering of new solutions. The key parallels with SST data services are:

1. Facilitating the development of value-added products in the domain of the user
2. Pump-priming with low cost or free low-level data to enable unique developments
3. Providing some confidence in the avoidance of undercutting (creating a level playing field)

4.1.2. Comparison with Weather Data Services

There have been other analogous market developments in the provision of terrestrial weather. The US government took a view that relatively complex and high level "information products", which were generally forecasts should be provided for free by the US Weather Service. This enabled US developers to create niche products and delivery methods where they could extract value.

Given that the US products were global (as is the nature of weather), it was hard for European companies to make a strong business case that required them to pay EUMETSAT for key data. Companies have developed specialised niche offerings often augmented by locally collected terrestrial data to improve accuracy and applicability to user groups who are prepared to pay for that service (e.g. rainfall at Wimbledon or F1 Circuits)

This further example displays similar issues to the Earth Observation data in the need to set clear boundaries for product development and look for niche value-adding opportunities.

4.2. Definition of End Users

The following broad categories of end users of SST data have been identified along with their information needs. These are not intended to be rigid definitions, as any user may have sudden interest in almost any aspect of SST data. However, these types help to define the sort of interests that users may have and helps define the information needs. Underpinning each of these needs in an as yet undetermined set of standards against which the threats and risks can be consistently established.

Group	Interests							
	Position (self)	Position (other objects)	Threats	Risks	COLA	Characteristics	Status	Anomaly Resolution
Satellite Operators	✓	✓	✓					✓
Launch Providers	✓	✓	✓	✓	✓			✓
Space Tourism Operators	✓	✓	✓	✓	✓			
Debris Removal Satellite Servicing Missions	✓	✓				✓	✓	
Insurers			✓	✓			✓	
MoD and Agencies	✓	✓	✓	✓		✓	✓	
Civil Contingency			✓	✓				
Mission Designers			✓	✓				
Researchers	✓	✓	✓	✓	✓	✓	✓	✓

Table 4-2. End user and information types

4.3. Information Needs

From the information needs perspective there are three main types of user: military, civil and commercial. Modern approaches to government services now recognise that commercial suppliers can provide military and security products to government as well as their indigenous internal agencies (e.g. Airbus Space & Defence Secure Communications that operates Skynet for UK MoD). The three main user groups do have some variation in their needs due to different concerns, but also have much in common.

4.3.1. Civil Users

Civil users are a broad category of information clients that encompass functional operations, commercial support, regulation, development and research.

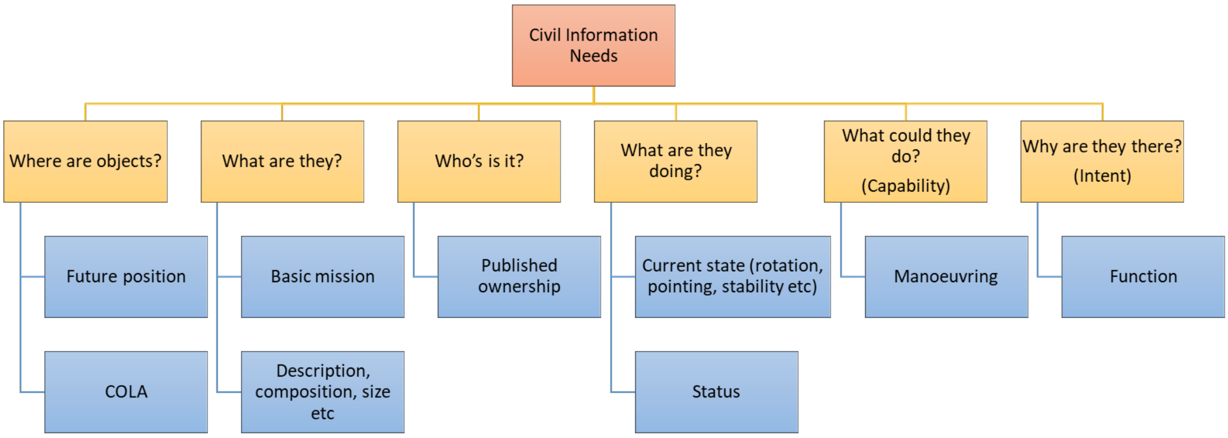

Figure 4-2. Civil information needs: less detail about more objects

4.3.2. Commercial Users

Commercial users have similar needs to the civil users and will increasingly need more detailed information services and products on the relative position of other objects to ensure uninterrupted service from their satellites.

4.4. Current SST Products and Services

The overarching need is for a range of offerings (covering data products to information services) to deliver effective SST for operators across all three sectors and for other users.

4.4.1. Specific terms

SST data uses a range of specific terms and these are clarified to ensure common understanding:

- Epoch – Time reference for a specific set of parameters, usually the start of a prediction
- TLE – Two Line Element. A compact (and constraining) data format that dates from the 1950's listing the key orbital element values at a given epoch.
- State Vector – The 3D position and velocity of an object at a given epoch. From that place and with known speeds, it will move under gravity and other forces such as drag and solar

radiation pressure following the predicted future path, unless caused to do otherwise by a manoeuvre or a collision.

- Propagator – A method to predict the future motion of the object. The most accurate estimate a range of forces on the object including gravity (Earth, Sun, moon, Jupiter and other solar system objects), atmospheric drag, solar wind etc. There are other smaller forces that can be significant over time.

4.4.2. Product Types

While a data processing export can create almost any revised data set or information product from observational data, there are several main types of SST product that are currently used within the global markets.

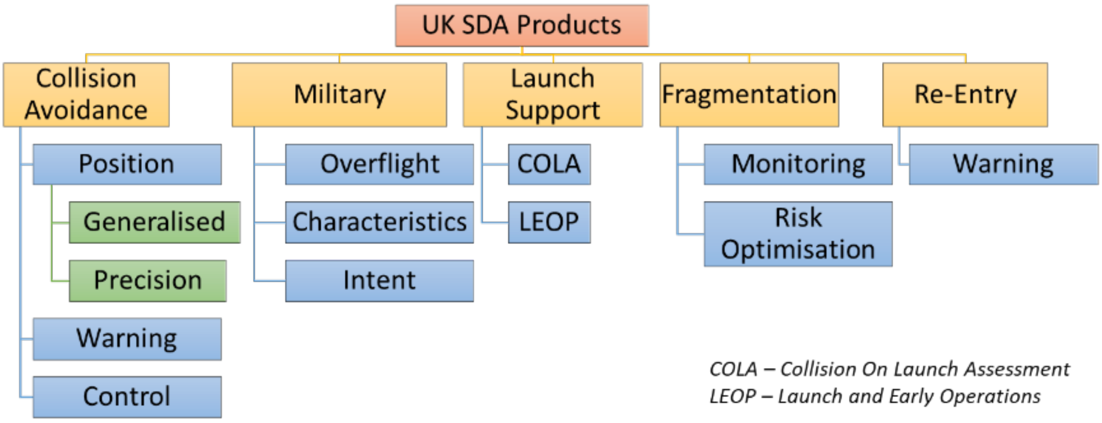

Table 4-3. Summary of current product types

These products and services represent current requirements. These will evolve as catalogue size increases, target object size decreases, the need for greater frequency of tracking of more nomadic satellites[2] increases etc. It is anticipated that there will be more SST requirements and therefore more opportunities for UK firms offering SST products and services.

Of the products considered above, 2 are worthy of additional explanation:

- **Control**: represents information products that provide directives to operators to reduce the probability of collisions. Such directives may be based on commercial arrangements (i.e. outsourcing the astrodynamics of a mission and hence collision avoidance) or required by national statue, or agreed as part of international regulation, much the same as air control. Although not an element of current operations, such products are expected to become necessary as LEO becomes increasingly crowded by mega-constellations over the coming decade. Mandatory international regulations exist in the Maritime and Air domains, and there is increasing evidence to suggest that the Space domain will need to follow suit.[3]

[2] The term 'nomadic' is used to refer to satellites that manoeuvre more frequently, often as part of new missions such as debris removal, on-orbit servicing or refuelling. The term may also refer to satellites that are designed to move for other more nefarious reasons. The wider use of ion-based propulsion allows such objects great choice in non-Keplerian orbits.

[3] Within the military domain, 'Space Control' has a different definition. UK Joint Doctrine Publication 0-30, UK Air and Space Power (2nd Edition, dated December 2017), defines Space Control as: the use of defensive and offensive capabilities to assure access and freedom of action in space.

- **Risk Optimisation**: seeks to optimise the risk outcomes for a spacecraft or groups of spacecraft after a fragmentation event. It should be emphasised here that the optimisation of a constellation may well change following a major fragmentation event, and an operator may seek to modify the orbital parameters of their spacecraft to lessen the probability of subsequent collisions. It has been suggested, (McKnight, 2019), that a collision between two large, multi-tonne Russian rocket bodies could “double the tracked catalogue overnight”. In such a scenario, many constellation operators could simultaneously wish to conduct risk minimising manoeuvres to optimise the level of risk.

4.4.3. Geographical Dimension

The visibility of sections of the GEO region are practically limited to around ±50° longitude from the longitude of the terrestrial observation site (usually placed equatorially to optimise visibility). Although ±60° is technically feasible, low elevation angles make for poor “seeing” through telescopes. Hence the GEO data is limited to those longitudes visible from that site. Thus, a supplier looking to offer a new product type will need a more geographically dispersed installed capability. The main constraint is Sun angle to enable observations, with the site selected for clear weather as most observations of GEO are optical. As the objects move very little relative to the sensor site, almost continual observation is possible. It is worth making the general point that range constraints on radars limit their utility to LEO, so that most MEO and GEO tracking is done optically.

In planning for the generation of LEO SST products, many studies have spent considerable time and effort seeking the optimal location for sensor sites. Since many of the objects are associated with polar orbits, northern (or southern) latitudes allow increased observation opportunities, while equatorial sites will see objects less frequently. However, if the sensor site is too far north, objects in low inclination orbits will not be seen. Several studies have looked at how networks of sensors can be linked and optimised for coverage and accuracy. This has proved to be a complex question. The main constraints are the time before the object is once again within the Field of Regard of the senor leading to extended latency issues.

MEO objects are generally visible from all locations – eventually. Most studies have focussed on the general SST provision have considered the LEO or GEO optimisation cases, as these have the highest collision risk or equipment and service value respectively. The designs are optimised for LEO and GEO, while MEO coverage is considered an outcome of such system designs, rather than a design driver. That is, they are designed for LEO & GEO, with MEO performance simply accepted. Since most of the satellites in MEO perform navigation functions, where high precision orbital data is important, laser rangefinders make an important contribution to MEO tracking and orbit determination.

Any sensor type will have a list of installation requirements (power, data connectivity, weather etc), but there are clear opportunities to use existing UK territories to extend the geographical locations and provide enhanced data collection opportunities, some of which offer significant comparative advantage. One potential example of this is the Falkland Islands.

4.4.4. Data Products

As discussed earlier, “data” is taken to be the least processed area of the market. This is the provision of data from sensors (perhaps corrected for engineering units) to a recognisable standard that the end user will perform further processing on. Sources of such data include:

- Radars (24/7 coverage mainly LEO)
  - Tracklets (range data, processed to estimate current orbit)
  - ISAR imagery, from wide-bandwidth systems
- Optical telescopes (coverage constrained by Sun angles, mainly MEO and GEO – some LEO)
  - Astrometric (angular position relative to the station to estimate current orbit)
  - Photometric (time series brightness curves)
  - Imaging (2D image, pan or 3-band colour)
  - Video (2D time series brightness, usually panchromatic)
- Laser ranging stations - range data, processed to estimate current orbit (of a limited group of objects) with high accuracy. Mainly LEO and MEO
- Other sensors – varies with sensor type, but might include RF monitoring, radar emissions monitoring (Power, Characteristics, Content, Direction), thermal imaging, spectral characteristics, polarimetry

At a technical level these all come in a variety of file sizes covering different durations, with a range of resolutions, accuracies, colours, wavelengths, frequencies, bandwidths, latencies and coverage. These lower level data sets can be summarised in the following table:

Title	Description	Application
Sensor data	Data from the sensor in its basic form	Research and specialist processing
Historical Object Position	Usually processed to provide a TLE or State Vector for a given Epoch which smooths the historic observations	Analysis of past position, prediction of future position using own propagator
Predicted Object Position	Created using local propagator. Various formats, time series data file	Expected future position
Historical Object Photometry	Apparent brightness of a tracked object	Estimates and change monitoring of pointing stability, condition, size
Image (optical)	2D resolved image of the space object (LEO) few cm resolution	Size, disposition, orientation, deployment
ISAR Image	Inverse SAR image of object, few cm resolution (LEO)	
Video	2D unresolved [100m pixel] (GEO)	As for image – stability and change
Other	Will depend on the sensor modality	

Table 4-4. Summary of basic data products

Low level data of the types described here is usually associated with two specific types of user:

- Those who wish to conduct specialist work on such data. Their algorithms being highly specialised to extract the niche information that they require.
- Operators who have specific needs (usually historic and predicted position) to enable their underlying mission and conduct their own conjunction warning analysis.

4.4.5. Information Products (Services)

As discussed in section 4.1, the derivation of "information" from the underlying data is key to its use by the end user. Information products are usually offered as "services" due to the on-going nature of the information need. This also allows the service provider some options in terms of sourcing data. It is quite common for such products to utilise additional sources of data to improve the offering. A key example is the use of space weather data to better estimate atmospheric drag in LEO and hence improve the accuracy of object location in future predictions.

In assessing possible "information" products or services, almost any combination of data sets is possible for even the most obscure end-user applications. This analysis will not try to list every possible information product but will focus on those commonly required by end users.

A distinction should be drawn between the delivery of such information products and further processing within the end user organisation. In many cases, the end user will make decisions based on that information, sometimes mixing with internal information sources or company policies. Two illustrative examples would include the following:

- In 2009: Iridium[4] received a collision warning about possible conjunction of the active commercial Iridium 33 and the derelict Russian military Kosmos-2251 but decided not to act upon it as it had received many warnings before without incident and was unwilling to use precious mission manoeuvring fuel. The result was a collision.
    - The "service" provided by US Joint Space Operations Centre (JSpOC) was free but was modified by internal policies and attitudes that often ignored such warnings (probably to minimise operating costs and fuel expenditure) and hence no action was taken. This shows the distinction between information services and the provision of directive instructions.
- A spacecraft operator managing a constellation may receive regular data provision (as a service) to understand the disposition of its spacecraft. But its internal policies will decide which spacecraft to adjust in order to maintain the required constellation dispersions. This would often be strongly influenced by the fuel state of each spacecraft.
    - Providing a directive service would be very difficult for a 3rd party intermediary as they would need to know much more about the status of each spacecraft and associated mission management policies.

A table illustrating the range of information products is provided below.

[4] https://en.wikipedia.org/wiki/2009_satellite_collision

Title	Description	Application
Conjunction Warning	Warning message that the “monitored” spacecraft may pass within a critical distance of another object.	Daily operations of spacecraft (where it has a manoeuvring capability)
High accuracy future position	Use of specialist modelling to create a more accurate estimate of future position	Collision avoidance monitoring, rendezvous operations
Re-entry warning[5]	Estimate of time/date/location of re-entering object	Civil contingencies
High accuracy post-processed position	Highly accurate orbit predicted for modest number of selected objects	International Laser Ranging Service and GNSS systems
Collision On Launch Assessment (COLA)	Determination of collision risk during given launch windows	Launch service providers and mission design[6]
Fragmentation Warning	Warning that a given object has fragmented	Space safety and re-assessment of associated conjunction warnings
Satellite warning service	Overpass of satellites to avoid observation of sensitive activity	Military forces, commercial advantage

Table 4-5. Summary of common information products

	Noted EU-SST product

More specific and specialised services (e.g. regular condition assessments or high-end military and intelligence products) are not in the commercial domain and will not be considered further.

Specialised research information products (e.g. density assessments for insurance estimation) are considered very low volume at this time.

Highly accurate observations and services are likely to be required in the near future although are not currently available.

4.4.6. Value Added Offerings

At the moment there are no additional individual products or services that add more value beyond those listed above. However, there are no organisations that offer additional value through integrating the whole SST process and providing expert interpretation of the data or providing bespoke services that can be extracted from the significant range of available data. For example, using expert operators to intelligently exploit available sensor data to fill gaps in the space catalogue to deliver a product or service to a satellite operator they know is lacking information or providing it to insurers based on relationships with regulators and operators. This gap is similar to the gap described in the early evolution of the Earth Observation market. It is also assessed that some of the future SST products and services listed at Table 4-7 could be met if an operation centre, integrating across the SST process, existed.

[5] These tend to be ***very*** inaccurate even a few days before re-entry, due to the highly variable nature of the atmosphere.
[6] This is less applicable to space tourism services operating around 110km (as only large debris will survive below 200km, with most large units breaking up around 80km)

4.4.7. Cross Cutting Offerings

The implementation of an SST system requires some additional and specialised offerings. In many cases these are proprietary equipment or software that is simply dedicated to this task. Some are highly specialised, although with very low sales volumes (i.e. one-off bespoke designs).

4.4.7.1. Software

The core of any system is a wide range of software installed in the sensor's out-stations and processing centre. Almost all aspects of these systems are managed by commercial software and include, but not limited to, the following:

- SST data processing algorithms and software
- Data base management software
- Server farm (processing) load management software
- Network management software
- Individual computer operating systems
- "Office" facilities for control and management
- Hardware controllers
- Condition monitoring (including power)
- Sensor control (at the pointing and data collection level)
- Building management and security

Recent studies have looked at using cloud services to enable flexible dynamic scaling of processing capability in processing centres and high-reliability distributed storage. For some scenarios these offer significant advantages.

4.4.7.2. Network Services

SST Sensors, processing centres, spacecraft operators and other end users will usually require specialised high-reliability (and enhanced security) network services to enable them to generate data and control their spacecraft. Such networks are "mission critical" to both the SST organisation and spacecraft operator, hence the need for high reliability and alternative sources.

Depending on the SST system architecture model, large data volumes are usually shipped from the sensors to the processing centres, with much smaller volumes exported to users as products and services.

4.4.7.3. Physical Security

For an SST system, physical security is required at the sensor sites and processing centre. The exact threat will vary from site to site and the requirements will be no more onerous than other remote facilities, ground stations or commercial data centres.

Within the consideration of security and resilience, additional requirements may arise for back-up sites and inter-site connectivity.

4.4.7.4. Cyber Security

The cyber security of an SST system is complex, with remote (often un-attended) sensor sites and complex data centres sometimes spread over different continents. This analysis is focussed on commercial and civil systems (perhaps operating at Official-Sensitive) rather than then more sensitive military levels of security.

The data being manged at the sensor level is generally of limited security, espionage or commercial interest as it quickly ages and requires specialised processing to extract useful information. As the data is processed and can be associated with specific (sensitive) space objects, then the risk increases. However whole systems are vulnerable to spoofing and Denial of Service (DoS) attacks although it is somewhat mitigated by the relative slow on-set of conjunction crisis (order of days). Ransomware and similar destructive effects would render the systems useless.

All of this implies the need for well-considered and high-quality cyber security products and procedures built into the system. These are likely to be propriety, with the value added during careful installation and configuration.

4.4.7.5. Hardware

The hardware products fall into two main groups:

- Propriety – which will include computers, servers, and building systems etc.
- Bespoke – which will include sensors (optical, radar or laser among other potential sensors)

These represent almost the extremes of the possible products. The propriety hardware is very generic and outside of the office services, is mainly focussed on data, database management and processing. The bespoke hardware is highly specialised towards its role, usually designed as a "one off" piece of equipment optimised for its work.

4.5. Use of Information Products (Collision Avoidance)

One the main areas of regular use of SST data is in collision avoidance. It is worth noting the generalised process involved in collision avoidance in order to better understand the opportunities and benefits of more precise, dispersed sensors and of an integrated SST process able to generate innovative products or services.

Once an initial collision warning is issued, with a large inherent error ellipsoid that is a function of the warning extending across a 5-day window, the operator will need to start considering a manoeuvre to assure the safety of their satellite. The inputs to such a decision are complex and will include perceived risk, manoeuvre capability, operational customer demands, fuel state, and data access opportunities among some considerations. Typically, this is performed by a day-shift team and checked by others, leading to an approved command that can be uploaded[7]. Most manoeuvres consist of at least 2 burns to satisfy the Hohmann criteria to minimise errors by circularising the adjusted orbit. However, more complex burn strategies are also adopted to slowly nudge the spacecraft back to the desired orbit with multiple smaller burns based on intervening SST data.

The example is based on the LEO case, where drag effects and access are key issues. But similar opportunities exist in GEO. With all options, there is a key issue related to the outsourcing of trust and responsibility for the information.

[7] In LEO the opportunities for upload can be spread over time with only 2-3 access opportunities per day.

The diagram below illustrates the inputs and considerations that play a part in the process of any collision warning.

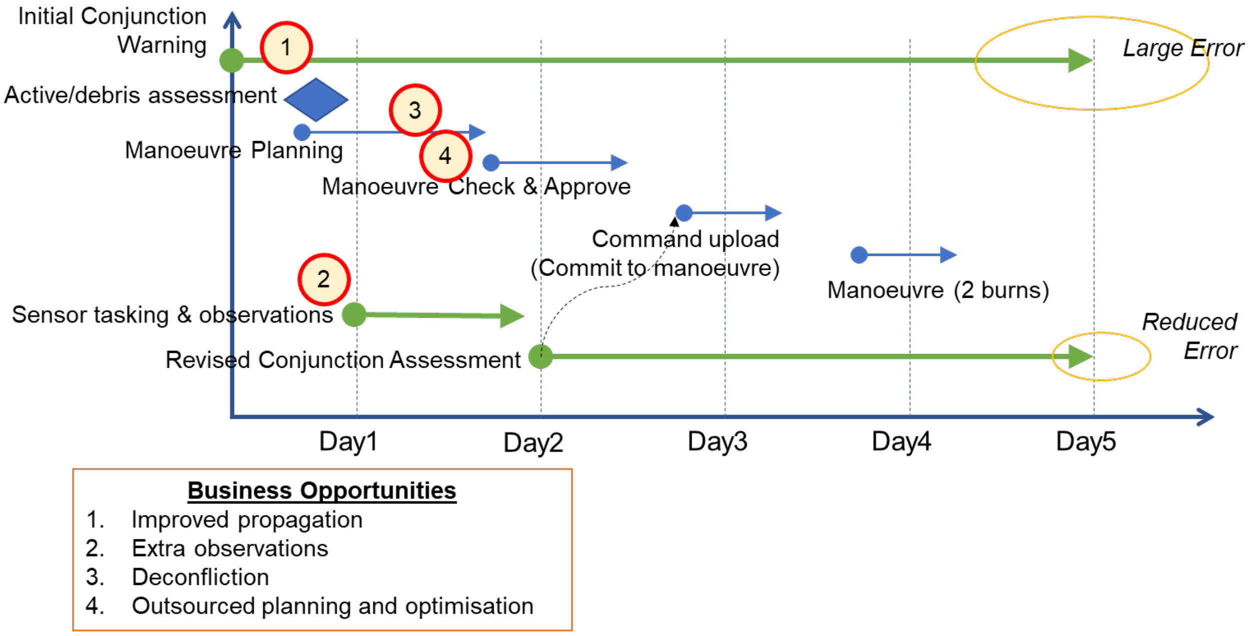

Figure 4-3. Collision avoidance process and SST data business opportunities

The SST information provider will repeat observations and produce a more accurate product in the intervening days between the original conjunction warning message and the anticipated conjunction window. The quandary for the operator is that the manoeuvre must be planned and uploaded well before the potential conjunction. Many of the options are essentially the desire to “buy a better estimate”. Detail on the noted points of the diagram are expanded below:

1. **Improved Propagation for greater Precision**: An initial option for the operator is to order higher accuracy propagation products, perhaps drawing in more detail (e.g. shape, rotation state etc) for the other objects and their own spacecraft.

2. **Extra Observations to increase Precision**: The opportunities for an SST operator to offer specific tasking of key sensors to reduce the error ellipse at an earlier time are obvious. Provided this generates an improved product before the operator must commit to a manoeuvre, the disturbance to the orbits (and planned operations – especially observations) can be minimised. However, for maximal value, the improved collision avoidance product is required before the operator commits resources to planning the manoeuvre.

3. **Deconfliction**: Further enhancements are possible: a key question is whether the “other” object is debris or an active spacecraft? While the case above assumes that the other object is debris and hence uncontrolled, the case of an active spacecraft raises further questions about “who moves?” assuming the other party can be reliably contacted in the limited time available. Services could be offered to contact the other party and broker such manoeuvres, as there are (currently) no

internationally agreed processes[8]. Such a service might be provided by an Operations Centre.

4. **Outsourced Optimisation**: At the more strategic mission level manoeuvre planning could involve "propellant minimisation", "miss distance maximisation", "non-functional time minimisation" or some compromise between these objectives.

4.6. Future SST Products and Services

The existing SST process is still immature, and it is anticipated that future demand for SST products and services will expand. The gaps revealed in the notional case study looking at collision avoidance revealed some of those gaps, namely the requirement for greater precision, a wider dispersion of sensors to reduce latency, and an operations centre able to better exploit the existing data that is available and generate a wider range of innovative products and services.

This next section addresses some of the extensive range of potential SST products and services that such an operations centre could offer end users. A summary of the extensive range of products and services that emerged during the research for this report are highlighted in the table below:

Product/Service	Associated Product/Service	Sensor/Resource	Potential end-user
Mega constellation planning	Orbital inclination and optimal altitude	Radar	Satellite operators
	Choice of right ascension values	SST expertise	Satellite operators
	An assessment of the debris population in the chosen orbit	SST expertise	Satellite operators
	Assessment of the radiation environment	SST expertise	Satellite operators
	Assessment of gravitational perturbations	SST expertise	Satellite operators
	Physical and RF interference	RF sensors	Satellite operators Regulators
Mega constellation deployment and replenishment		Radar	Satellite operators Regulators
Mega constellation operations (manoeuvre planning operations)		Radar SST expertise	Satellite operators (own and neighbouring) Regulators

[8] Space Traffic Control has been discussed at length in space-related media and implies a neutral broker to ensure participants are not disadvantaged by strategic manoeuvring (using the agreed rules force excessive changes from a targeted spacecraft).

Mega constellation disposal		Radar	Satellite operators Regulators Government
Space licence compliance		Radar, RF, Optical SST expertise	Regulators
Manoeuvre and altitude change detection and characterisation		Radar, RF, Optical SST expertise	Regulators Neighbouring satellite operators
RF activity monitoring		RF	Satellite operators Regulators
RF interference monitoring		RF	Satellite operators Regulators
Space sustainability index and space traffic footprint assessment		Radar, RF, Optical SST expertise	Regulators
Debris characterisation		Radar, RF, Optical SST expertise	Satellite operators Regulators Security agencies
Debris removal/re-orbiting		Radar, RF, Optical SST expertise	Satellite operators Regulators Security agencies
Large debris traffic management		Radar, RF, Optical SST expertise	Satellite operators Regulators Security agencies
Debris capture and reprocessing		Radar, RF, Optical SST expertise	Satellite operators Regulators
Satellite servicing		Radar, RF, Optical SST expertise	Satellite operators Regulators Security agencies
On-orbit assembly		Radar, RF, Optical SST expertise	Satellite operators Regulators Security agencies
Precision SST *(to deliver the majority of these products and services an enhancement of the existing sensor capability would be advantageous, and these might include on-orbit sensors and RF sensors)*	Navigation	RF	Satellite operators Regulators
	Surveillance	Radar, RF, Optical SST expertise	Satellite operators Regulators
	Proximity operations	Radar, RF, Optical SST expertise	Satellite operators Regulators Security agencies
	High precision conjunction warnings and efficient collision avoidance manoeuvres	Radar, RF, Optical, laser SST expertise	Satellite operators
	Small object detection	Radar, RF, Optical SST expertise	Satellite operators

	Small object tracking	Radar, RF, Optical SST expertise	Satellite operators
	Calibration	laser	Satellite operators
	Targeting	Radar, RF, Optical SST expertise	Satellite operators
	Damage assessment	Radar, RF, Optical SST expertise	Satellite operators Regulators
	Debris population assessments	Radar, RF, Optical SST expertise	Satellite operators Regulators Insurers Security agencies
Space tourism		Radar, optical	Satellite operators ATC agencies Regulators
Collision on launch assessment		Radar, RF, Optical	Launch agencies Satellite operators Regulators
Fragmentation risk monitoring		Radar, RF, Optical SST expertise	Satellite operators Regulators Insurers Security agencies
Custody maintenance		Radar, RF, Optical, on-orbit sensors SST expertise	Satellite operators Space catalogue agencies
Size/shape and mass/ballistic coefficient determination		Radar, RF, Optical, on-orbit sensors SST expertise	Space catalogue agencies Security agencies
Space weather forecasting		On-orbit research satellites Machine learning for prediction of solar flux	Satellite operators Security agencies
Meteor flux determination and prediction			Satellite operators Security agencies
Celestial orbit data ingest and exploitation			Satellite operators Security agencies
Satellite operator data ingest and exploitation			Space catalogue agencies Regulators
In-situ space weather data ingest and exploitation			Satellite operators Space catalogue agencies Regulators

Table 4-6. Summary of common information products

4.7. Value Proposition Derived from Future SST Products and Services

Having established the SST process value chain and then added the potential future products and services that these may offer, this report then takes this value proposition one step further and offers suggested exploitation routes. The following table is a consideration of those potential routes of exploitation for the future SST products and services:

No.	Product	Customers	Value Proposition
Data Products			
1.	Sensor data	Operations Centres (OCs), standalone prediction services (SPS)	Building and operating a large series of sensors is complex and expensive, buying data is more cost effective. Can be enhanced by responsive tasking agreements.
2.	Historical object position	Operators, OCs, SPS	Need access to accurate historical data to inform algorithms, can only be obtained from those currently holding it.
3.	Predicted Object Position	Operators, OCs	Customer base could do this themselves but paying an external entity allows external expertise to offer more advanced services. Economies of scale in clustered expertise and shift patterns. Could include "current" estimate of position to assist inter-satellite links and sensor pointing.
4.	Historical Object Photometry	Operators, OCs, SPS	Such data can only be obtained from those currently holding it.
5.	Image (optical)	Operators, MoD/Gov, OCs, SPS	Will be occasional images of objects of interest, not economic for a customer to develop capability to provide this.
6.	ISAR Image		
7.	Video imagery		
Information Products			
8.	Conjunction Warning	Operators, OCs	Avoid catastrophic damage to expensive spacecraft and comply with licence conditions. Enable focus on conjunctions of interest or value
9.	High accuracy future position	Operators	Minimise size and frequency of avoidance manoeuvres for minimum operational disruption, maximum fuel economy and other efficiencies. "Buy a better estimate"
10.	Responsive high precision conjunction estimate	Operators	
11.	Re-entry warning	OCs, MoD/Gov, civil sec, Researchers (Rs)	Needs regular late stage tracking to provide accurate result, avoid interpretation as aggressive act, post-impact preparations
12.	High accuracy post-processed position	Operators, Rs	Occasional or highly specialised requirement makes establishing own capability expensive and less effective.
13.	Collision On Launch Assessment (COLA)	Launchers	To ensure safe launch

No.	Product	Customers	Value Proposition
14.	Fragmentation Warning	Operators, MoD/Gov, OCs, SPS, Rs	Infrequent events with high consequences imply specialist capability – not economic to create multiple instances. Can focus expertise.
15.	Fragmentation characterisation	MoD/Gov, OCs, SPS, Rs	
16.	Satellite warning service	MoD/Gov, commercial	Understand nature of over-flying sensor to optimise what has to be hidden, changed or camouflaged.
Advanced Products			
17.	Mega Constellation Planning	Operators, Gov	Economies of scale, focus of expertise and specialist tools is more economic than separate developments. Issues with commercial sensitivity
18.	Debris risk minimisation planning	Operators, Gov	
19.	Mega-constellation deployment planning	Operators, OCs	
20.	Mega-constellation operations support	Operators	
21.	Mega-constellation disposal	Operators, Gov	Economies of scale, focus of expertise, group insurance and specialist tools is more economic than separate developments. Might include specialist services to reduce re-entry times or achieve designated locations.
22.	Space licence compliance	Gov	Access to specialist services and equipment to confirm compliance with licence conditions.
23.	Manoeuvre and attitude change detection and characterisation	Operators, OCs, MoD/Gov, SPS	Early understanding of probably future position of objects avoids unnecessary manoeuvres.
24.	RF Activity monitor	Operators, MoD/Gov	To avoid non-compliance with licence conditions, to buy additional information about threat objects
25.	RF interference monitor	Operators, MoD/Gov	
26.	Space Sustainability Index and Space Traffic Footprint assessments	Operators, Gov, Rs	To comply with (possible) future licence conditions, fines or other penalties
27.	Debris characterisation	Operators, MoD/Gov, OCs, SPS, Rs	To buy additional information about the object to enable better predictions of future motion or current condition.
28.	Large Debris Traffic Management	Operators, Gov, Rs	Reduced risk of major collision triggering Kessler densities, making some altitude shells un-usable.
29.	Proximity operations & warnings	Operators, MoD/Gov	Purchase of more information understand options and risks.
30.	Small object detection & tracking	Operators, MoD/Gov, OCs, SPS, Rs	Purchase of more information understand and reduce risk (need to track and predict to enable avoidance)

No.	Product	Customers	Value Proposition
31.	Space tourism flight coordination	Operators, Gov	Purchase information to minimise risk.
32.	Day time tracking product	Operators, MoD/Gov, OCs, SPS, Rs	Increased quality and cadence of information to ensure surety of tracking.
33.	Basic object characterisation (mass, BC, etc)	Gov, OCs, SPS, Rs	Purchase of more information to make better predictions (to improve accuracy and reduce manoeuvring needs) and inform servicing and recovery options.
34.	Enhanced object characterisation (shape, rotation, materials)	MoD/Gov, OCs, SPS, Rs	
35.	Integrated Space Weather nowcast and forecast	Operators, MoD/Gov, OCs, SPS, Rs	Delivery of more targeted information that is limited to that which is most limited to the object/location. Buying less of more focussed data.
36.	Near Earth Object risk product	Operators, MoD/Gov, OCs, SPS, Rs	Specialist occasional product to mitigate effects of NEOs (done once, used by many).

Table 4-7. Value Proposition Derived from Current and Future SST Products and Services.

4.8. SST Process Diagram

Based on the analysis of the SST process and with an eye to potential future SST products and services, the following SST process diagram captures the key components of a viable SST process.

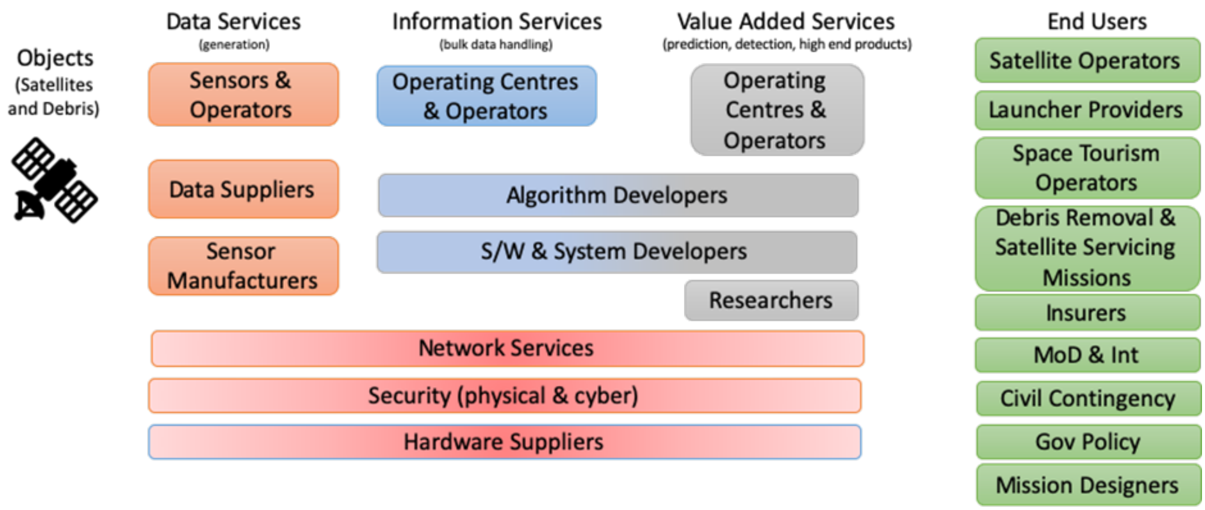

Figure 4-4. End-to-end SST process from space objects through to end users

4.9. Mapping of Companies to SST Process

The range of organisations in the UK that offer a contribution to the SST process illustrated above is wide-ranging. The following diagram overlays groups of organisations alongside the part of the process to which they contribute. While there is significant overlap, the illustration does indicate where the bulk of the contribution resides. It also reveals that all the organisations integrate vertically, but no organisations integrate horizontally across the whole SST value chain process.

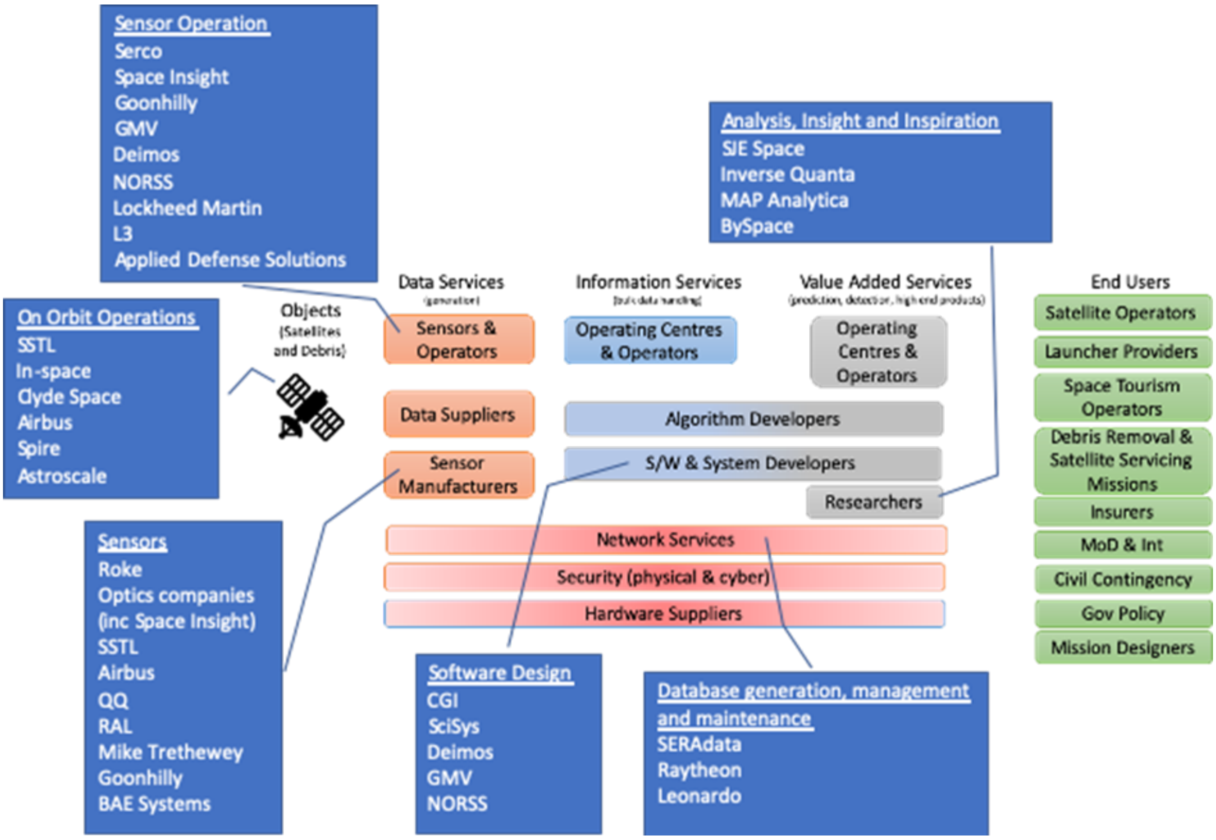

Figure 4-5. End-to-end SST process from space objects through to end users

4.10. Gaps

4.10.1. Gaps in the Existing SST Market

Within the current SST market, gaps are limited to what ***could*** be provided with existing technologies and sensors. However, as the environment becomes more congested, the number of objects increase and the more nomadic nature of operations expands, the demand for SST products and services are anticipated to increase significantly.

ID	Gap	Discussion
1	Higher accuracy prediction	Has benefits for all users as false conjunctions are reduced (especially with growing numbers in the catalogue due to debris events and increasingly sensitive system providing more objects).
2	Low latency products	Reactions to events and better manoeuvre planning, implies some direct tasking of sensors.
3	Integrated space weather	Provision of "one stop shop" for all environment risk needs
4	Condition & risk assessments	To understand the risk posed by close neighbours and to inform the emerging satellite servicing and debris removal markets.

5	Outsourced services	Enabling a specialist entity to provide astrodynamics, avoidance and related services to the operator.
6	Post Collision Assessment	Following recent collisions, there has been a considerable effort to understand the behaviour, manoeuvres and ownership of some of the objects involved. An independent service (similar to aircraft accident investigation) would reduce investigation costs.
7	Prox-Ops Warning	To search the catalogue for objects that will ***not*** form a close conjunction with the one being projected but may take station some distance away.

Table 4-8. Existing SST market gaps

4.10.2. Anticipated Future Gaps in the SST Market

The scope of the future SST markets is informed by:

- New sensors (offering more data of existing types)
- New technologies and modalities (offering new information products)
- New end user systems requiring new types of information products
- New service offerings and mission types (space tourism, debris removal/servicing)
- Less specialist operators who buy in the component of an information generation system (e.g. spacecraft and ground segment) and hence will not wish to develop comprehensive SST capabilities.

The SST product & service market offers several areas where gaps arise. These can be commercial or technical.

Within the ***technical*** Areas:

- Sensor performance is closely linked to minimum object size. By tracking smaller objects, a provider can offer protection to the end-user client to avoid more objects, however, this will create more conjunction warnings, unless accuracy through precision is improved.
- Lower Latency
- Accuracy and precision
- Object Characterisation
- Object behaviour
- Integrated space weather products
- RF interference monitoring

Within the ***Commercial*** areas:

- SST as a service, offering products that are marketed to end-users and products that are demanded from end-users.
- Interfaces to other systems

Some of the more information-centric (quasi “intelligence”) products originate from the military and security domain. While the military and security users will still have a valid interest in such information. There is a growing realisation that similar products should be considered by commercial operators. These can provide information on the threat to economic activity. Globally there is an increase in such sub-threshold warfare against economic targets and the situation cannot be effectively monitored by government organisations.

Additional gaps may be created within the market as government focus more on the sustainability of the space environment. Terrestrial global initiatives associated with Carbon trading have become widely accepted in recent years, despite significant international barriers to enablement. A similar approach may be considered in space, mainly linked to debris creation and ownership to encourage sustainable behaviours and minimisation of footprint. Any such initiative will need highly capable SST to track (at evidential levels of certainty) objects and associate them with launcher states and companies.

ID	Gap	Discussion
1	Smaller objects	Trackable debris is currently around 10cm, while that which causes damage is above 1cm. Hence interest in smaller objects.
2	Low Latency product	Responsive SST, high precision tracking of objects on-demand. This could not be applied to all objects, all of the time without significant investment, the opportunity is to purchase faster products when the user needs them.
3	Object Shape & Rotation	Characterisation to inform higher precision product (LEO & GEO), could include a pointing estimation.
4	Emission Detection	To determine whether a satellite is active or not. This would signal the start of the 25 years before the object should de-orbit.
5	Condition Assessment	A similar function, although requiring greater sensor fidelity. This may also include determination of 'passivation', that is the non-operational nature of the satellite.
6	Manoeuvre monitoring & warning product	Shared information (for those who buy into the service) to know when others in their area of space are manoeuvring.
7	Large constellation planning & support	Large constellation operators will not be keen to also be large SST system operators and hence would need data from a federation of sensors. While constellation spacecraft might know their own position while working, old/dead spacecraft or debris (from launch of collision) would become of great interest for tracking.
8	Space Sustainability Index and Footprint assessments	Measurements at evidential levels to ascribe the "harm" caused by a particular mission and quantify those effects.
9	Re-entry warning	Expanded low altitude tracking to deal with possible re-entry rates of ~1 defunct spacecraft per day from the mega constellations.

Table 4-9. Future SST market gaps

All of these products can be offered as a service. It makes good commercial sense to group these functions within a single entity as the underlying data is often common and the need to directly manage the sensors in response to tasking is also shared. By grouping 24/7 staffing support at a single location and enabling operators to simply buy the time they need has huge implications for economies of scale. The challenge is the management of IP and commercial sensitivity. But such issues have been overcome in the banking, communications and network provider sectors.

5. SST Products or Services Currently offered by UK companies

An overview of companies, together with an indication of the products and services they offer is indicated in the diagram below (full list not included in this abridged report):

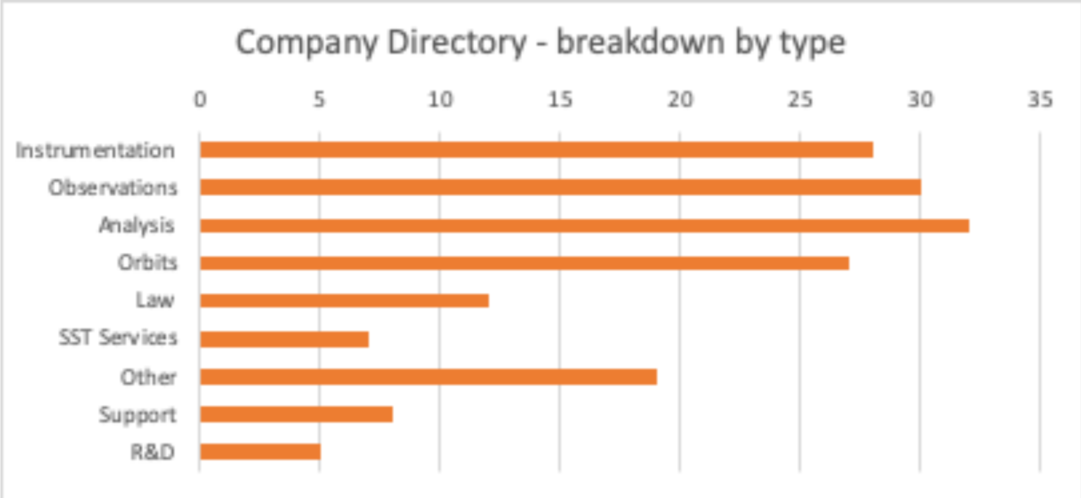

Table 5-1. UK SST Companies and the Products and Services they offer

6. UK Academic research related to SST

The UK SST-related research base is wide and deep. There are a range of research disciplines that cover areas from the highly technical exploitation of sensors, understanding of the orbital domain, to mining the catalogue of data compiled from sensors to space law and regulatory frameworks. Below is a table highlighting the key research types and an indication of the thematic research areas (full list not included in this abridged report):

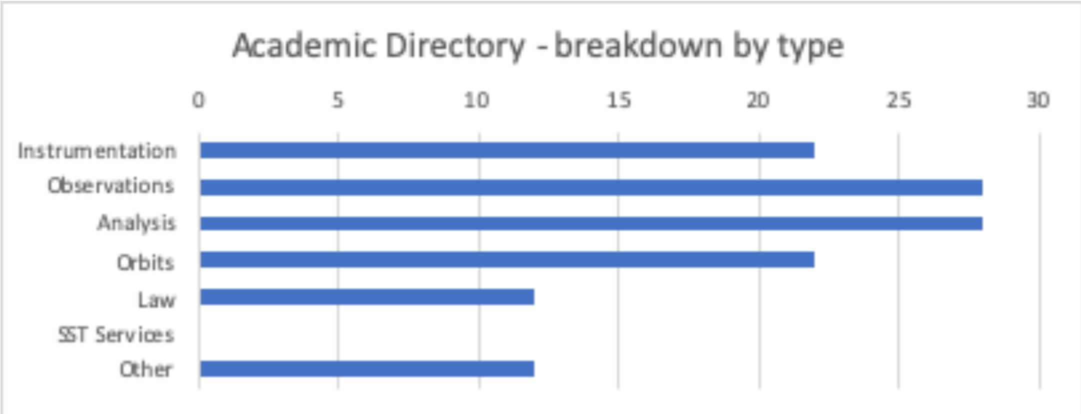

Table 6-1. UK SST Companies and the Products and Services they offer

7. Conclusions

In conducting this short study, there emerged some interesting findings.

7.1. The SST Process

The continuum from data to services within the SST domain offers some unique opportunities, for example the geographic location of the sensors that provide the data which forms the basis for subsequent value-added services. There were useful comparisons to be drawn with the early Earth Observation market, which developed from offering the raw data to agencies developing which took the data and added knowledge and expertise to offer value-added services. This also had the effect of facilitating the further development of value-added products and services for the users as well as pump-priming the research and development of yet further products and services. The SST sector is at a comparable point with the majority of the market offering data and very few offering value-added information services.

The SST sector has three main user communities: military, civil and commercial. Each has overlapping requirements although the research revealed that the military and security sector tended to focus on a small number of objects in great detail, while the civil and commercial sectors were more concerned with the wider environment and the natural or accidental threats to their assets. When all sectors were considered, a common group of products and services emerged, which were used to inform the development of the SST end-to-end process. Compiling the list of products and services revealed **the importance of geography**. To deliver the required products and services required a sensor to observe each of the main orbital domains (LEO, MEO and GEO) and the geographic location of these sensors determined the coverage they could achieve and also exposed the gaps in coverage due to lack of sensors in some difficult to access geographic areas. The geography also contributed to a reduced overall latency in SST sensor data.

In exploring the range of products and services offered, the list was clear and comprehensive, yet it did reveal that, at the moment, there are no additional individual products or services that add more value beyond those produced by the sensors. However, there are no organisations that offer **additional value through integrating the whole SST process** and providing expert interpretation of the data or providing bespoke services that can be extracted from the data. This gap is similar to the gap described in the early evolution of the Earth Observation market.

Supporting the SST process are a number of generic cross-cutting functions that include software, hardware, physical security, cyber security and network providers. The SST process itself was illustrated through a notional case study of a key product, that of collision avoidance. The intention was to explore potential gaps in the provision of products and services within the existing SST process. While there were a number of gaps revealed, the key gap was the requirement for **greater precision**.

A number of other gaps were assessed to exist, yet they could all be grouped as a single entity as the underlying data product was often common and it was the service offered that varied. Consequently, the deduction is that by grouping SST expertise at a single location or within a single agency, it would enable operators to simply deliver **a range of value-added services with economies of scale**.

7.2. UK SST Providers

Research into the range of UK SST providers was challenging. The global nature of space as an industry sector and the geographic dispersion of space surveillance sensors, make identifying what comprises the UK portion of the market almost a moot point. That said, the broad metric adopted was a company that is registered in the UK and can be found in a search on Companies House. This included any UK branches or subsidiaries of foreign companies as well as, of course, companies that are headquartered, founded, and/or only operate in the UK.

With this baseline assumption adopted, the search revealed a significant range of companies that contributed to various functions of the SST process. What the research also revealed was that there were **no companies that contributed across the SST process**, integrating the process from end-to-end.

7.3. UK SST-Related Academic Research

The UK SST-related research base is wide and deep. There are a range of research disciplines that cover areas from the highly technical exploitation of sensors, understanding of the orbital domain, to mining the catalogue of data compiled from sensors to space law and regulatory frameworks.

Alongside the range of UK SST-related research, there exists a range of companies, public institutions and other organisations that contribute to the rich vein of research available in the UK. The combination of academic and other bodies undertaking this research have a varied source of funding, although the diffused nature of this funding does not provide the catalyst for SST-specific research, nor do the companies that operate in the sector pull-through a significant portion of that research.

There is room for greater focus to be provided to the research sector to encourage and to pull through the innovative studies underway or being considered.

7.4. Summary

The analysis undertaken for this report revealed an SST process that is set to expand as demand grows for more products and services in the future. The UK industrial provision across this process is well found although lacking clear demand signals. The associated SST-related academic research is broad and world-leading yet lacks the focus to provide the wider societal and economic impact that the GNOSIS network is leading in. The analysis of these factors and the broader context points to opportunities in providing greater precision, accuracy and confidence in SST data, exploiting the UK's geographic 'uniqueness' and building an operations focus to fully exploit the SST process and add value to existing sensor data, as well as develop the human capital essential to developing future SST products and services.

<Ends>