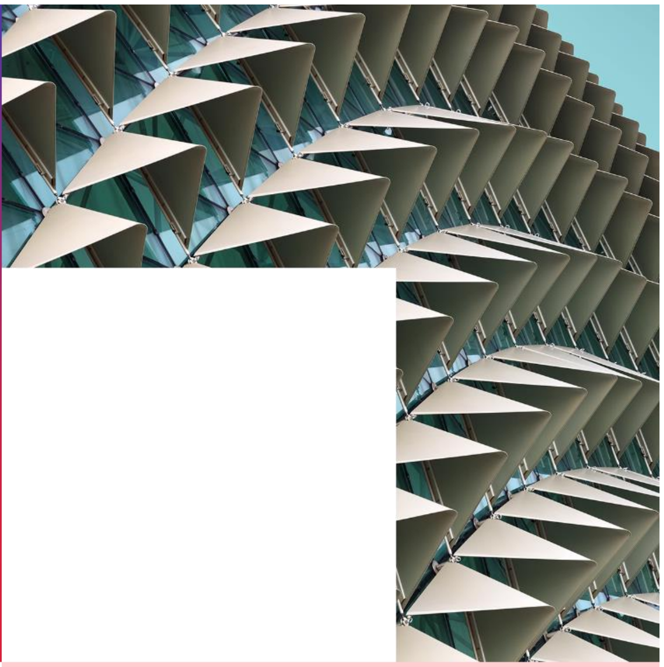

UKSA SDA Study

V2.4

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Acronyms

AI	Artificial Intelligence
CASTR	Chilbolton Advanced Satellite Tracking Radar
CNI	Critical National Infrastructure
COATS	Chilbolton Optical Advanced Tracking System
COLA	Collision on Launch Assessment
CSpO	Combined Space Operations Initiative
DSS	UK Defence Space Strategy
EGNOS	European Geostationary Navigation Overlay Service
EoL	End of Life
ESA	European Space Agency
ESG	Environmental, Social, and Governance
EUSST	European Space Surveillance and Tracking
GEO	Geostationary Orbit
GNOSIS	Global Network On Sustainability In Space
GNSS	Global Navigation Satellite System
IADC	Inter-Agency Space Debris Coordination Committee
ICAO	International Civil Aviation Organization
ICT	Information Communication Technology
IOSM	In Orbit Servicing and Manufacturing
ISR	Intelligence, Surveillance and Reconnaissance
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MOSWOC	Met Office Space Weather Operations Centre
MoD	UK Ministry of Defence
NSpOC	National Space Operations Centre
NSS	UK National Space Strategy
PIMS	Passive Imaging Metric Sensor
PNT	Positioning, Navigation and Timing
ROI	Return On Investment
SDA	Space Domain Awareness
SLR	Satellite Laser Ranging
SSA	Space Situational Awareness
SST	Space Surveillance and Tracking
STEM	Science, Technology, Engineering and Mathematics
STFC	Science and Technology Facilities Council
STM	Space Traffic Management
UHF	Ultra High Frequency
UKRI	UK Research and Innovation
US SSN	US Space Surveillance Network

1 Executive Summary

The UK Space Agency commissioned CGI to facilitate a study into the requirements and opportunities for space domain awareness in the UK. This study was conducted with the endorsement of UKspace and GNOSIS and has been compiled from the contributions of over 40 academic and commercial entities within the UK space sector.

DEFINITION OF SDA

This study defines SDA as the identification, characterisation and understanding of any factor in the space domain that may affect space operations or impact the safety of space-based or space-enabled assets.

INTERNATIONAL CONTEXT

The UK ranks in the bottom half of G20 nations in terms of general space sector spending and the majority of UK space funding is applied to the military, in contrast to many other nations. It has a relatively small number of sensor capabilities and is largely reliant on other nations for SDA data and services.

BENEFITS OF SDA

Financial

The **estimated cumulative ROI based on an investment of £568m up to 2030 is £2.1bn**, based on the mitigated cost of a loss of space services or assets and the potential revenue of other space activities enabled by SDA.

Strategic

The national and defence space strategies have both identified and prioritised the need for an SDA capability to support the UK's ambitions in space. In addition to delivering on these priorities, development of SDA capability also demonstrates clear progress against all four pillars of the National Space Strategy and all three strategic goals of the Defence Space Strategy.

Sustainability

The sustainability of the space domain, the assets within it, and the services they provide is of such paramount importance to the UK economy that it should not be considered as a potential expense but as fundamental necessity that cannot be done without. SDA is vital to ensuring the sustainable and ongoing use of space through the continual ability to monitor, manoeuvre, and protect space assets.

SDA has a substantial impact on the sustainability of individual missions with high levels of SDA reducing the need to manoeuvre helping to conserve fuel use and increase mission duration whilst also minimising service disruption. It also enables additional sustainability technologies such as in-orbit servicing to extend mission duration and management and removal of space debris to reduce conjunction risks.

UK SDA LANDSCAPE

The UK boasts a world-renowned academic sector which is heavily engaged in research and development of capability across all areas of the SDA spectrum. Equally, the UK commercial space sector contains significant expertise and proven experience in delivering capability into a variety of national and international missions. This experience could be leveraged to help close a number of capability gaps that have been identified, largely around sensing capabilities. The identified gaps are as follows:

1. Inability to track objects down to 1cm
2. Insufficient cataloguing to deal with increasing number of entries
3. Lack of southern hemisphere tracking
4. Insufficient accuracy to support conjunction warning
5. Inability to track certain objects during daytime
6. Sparse measurement of space weather effects
7. Limited ability to monitor satellite transmissions

OPPORTUNITIES

To help close these gaps and deliver a UK SDA capability, a number of opportunities have been identified and grouped into three thematic areas:

1. **Sovereign sensor development –** The provision of new sensing capabilities to take advantage of UK and overseas territories, improve existing sensors or fill capability gaps.
2. **Non-sovereign sensor capability –** Enhance or expand data sets through agreements and relationships.
3. **Analytics –** The production of reliable, assured, and potentially bespoke products to enable decision making.

CONCLUSIONS

The protection of space assets and the services they provide is of paramount importance to the UK economy that it should not be considered as a potential expense but as fundamental necessity that cannot be done without. Development of an SDA capability will leverage the strengths in the UK space sector to provide this. This capability must be dual use to ensure civil and military collaboration and maximise the national return on investment and the National Space Operations Centre concept, endorsed in both the national and defence space strategies, can be used to develop this. The national and defence space strategies have also identified SDA as a priority area and an SDA-specific strategy is now needed to build on them and unlock the potential of SDA, the technologies it enables, and the UK organisations to deliver it.

RECOMMENDATIONS

Recommendation 1 - SDA Strategy: A cross-Government SDA strategy and vision is required to cohere academia, industry, civil and military entities and provide clarity on intended aims for the UK in SDA.

Recommendation 2 - SDA Advisory Group: Establish an advisory group for SDA to advise and guide on developing UK SDA capability. The group should include members from across academia, industry as well as civil and military space.

Recommendation 3 - Maintaining International Collaboration: The UK should attempt to maintain the strongest possible international ties including with ESA, Five Eyes and CSpO partners, and other nations.

Recommendation 4 - R&D for Sensor Improvements: The UK should invest in the procurement of more sovereign sensors to improve its sensing capability and international credibility as well as contribute to closing gaps in global capability

Recommendation 5 - National Space Sustainability Research Institute: A National Space Sustainability Research Institute should be considered to simplify and coordinate funding for research and innovation activities.

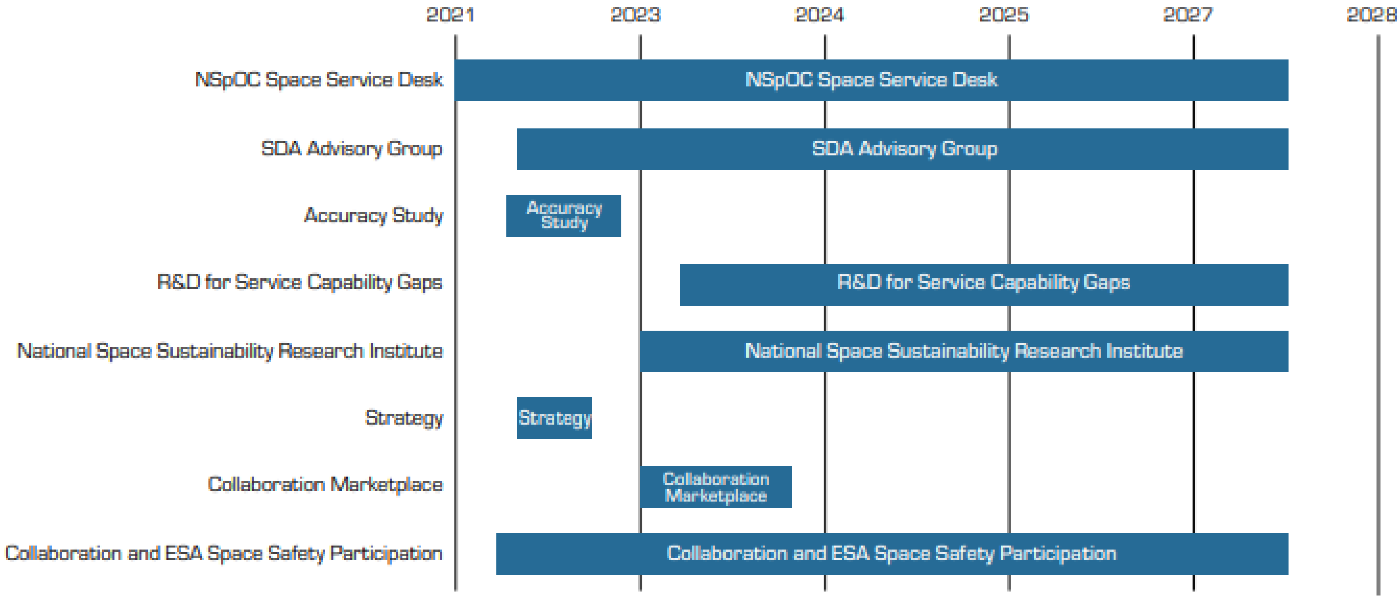
Recommendation 6 - Data Accuracy Study: A study should be commissioned to assess the cost/benefit of increasing data accuracy to identify the point of diminishing returns. This study should conclude with a set of target figures for accuracy improvement over time to 2030 that can inform a plan for sensor enhancement.

Recommendation 7 - Collaboration Marketplace: A collaboration marketplace should be established to facilitate the matching of academic research with industrial demand, increasing visibility of activities and paving the way for more efficient sponsoring of research.

Recommendation 8 - Space Service Desk: A national space operations centre, bringing together the civil, military, and commercial sectors would allow for the collection, consolidation, and exploitation of SST data to produce high quality analytical products for a range of users.

ROADMAP

A candidate roadmap has been developed to help inform a SDA-specific strategy and complete the study.



2 Introduction

The UK Space Agency is aware of the growing risk to orbital assets and is working with the MOD to develop UK national Space Domain Awareness (SDA) capabilities to detect, warn, manage, and mitigate orbital events. The UK's National Space Strategy (NSS) [1] highlights SDA as one of our four high growth areas, as well as specifying space sustainability and a National Space Operations Centre (NSpOC) as deliverables in a 10-point plan. The recently published Defence Space Strategy (DSS) [2] identifies SDA and Space Command and Control as priorities.

2.1 Aims

- To strengthen the UK Space Agency's understanding of the commercial and industrial opportunities in the SDA market segment
- To update the UK Space Agency's knowledge of the breadth and depth of UK industry and academic actors who could participate in the SDA market segment
- To provide robust data (for example economic, regulatory, social, or financial) on how a UK SDA capability could benefit the UK
- To elicit industry and academic views on how a UK SDA capability could be delivered and maintained

2.2 Approach

This study has been produced under the direction of a steering group comprising representation from UKspace (SDA Working Group, Regulatory Advisory Group, Security and Defence Committee), GNOSIS and the Satellite Finance Network.

UKspace and GNOSIS communications channels have been used to engage the UK SDA community across industry, government, academia, and research communities.

Using these channels, a questionnaire has been sent to the UK SDA community and responses followed up with a series of more focussed meetings. The outputs of these engagements have been consolidated with a review of existing literature to produce this report – a perspective from across industry, academia, and government in the UK with the endorsement of UKspace and GNOSIS.

2.3 Caveats and Limitations

- The study focuses only on the civil and commercial demand for and opportunities within SDA.
- It is recognised that military operators will participate heavily in the generation and utilisation of SDA however military viewpoints have not been considered extensively in this study
- All figures presented in the study are based on publicly available information. Due to the nature of SDA and the space domain in general, it has not been possible to obtain full or detailed information about the spending and capabilities of some nations

3 SDA in context

“Every business will be a space business” [3]

Space permeates our way of life in all other sectors, across all other domains and is critical to our prosperity, the functioning and security of our society, and our relationships with other nations. Whilst the UK space sector in its own right is worth £16.4 billion, employs over 45,000 people, and directly contributes £6.6 billion to UK GDP [4], the use of space technologies across all sectors underpins the generation of over £360 billion per year to the UK economy. [1]. The UK space sector is also growing at a faster rate than that of the general economy ensuring that its value and the impact it has on the wider national and global economies will only continue to increase.

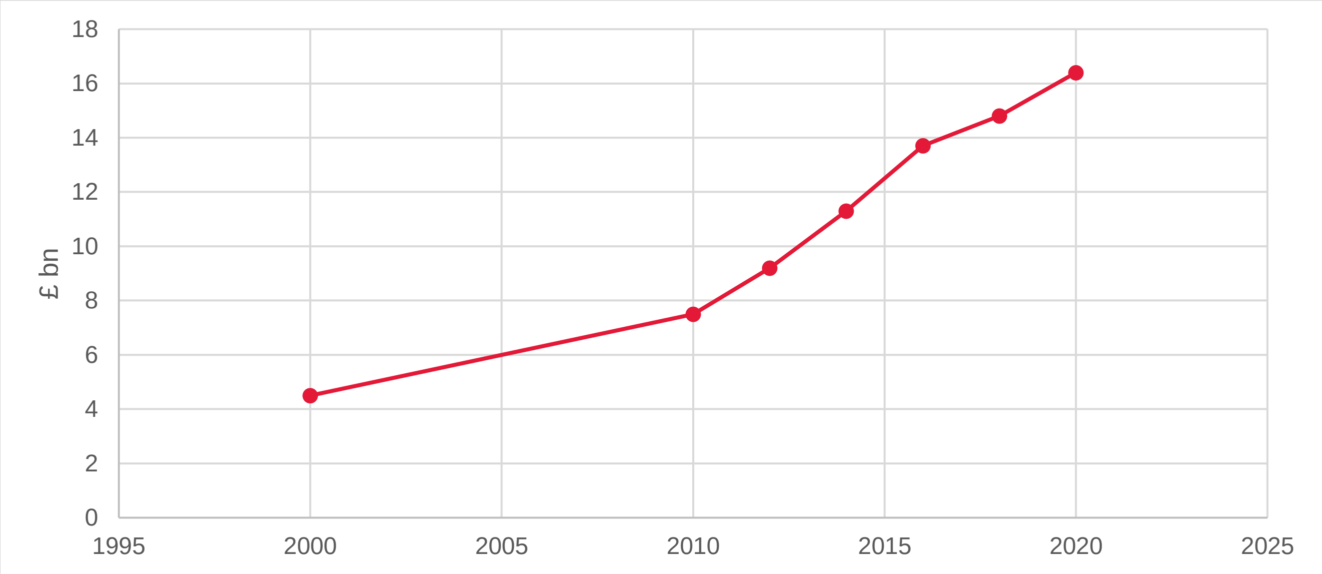


Figure 1: UK space industry turnover from 2000-2020

This increasing dependency and reliance on Space was recognised by way of it being designated part of UK Critical National Infrastructure in 2015, the elevation of the National Space Council to a Cabinet committee in 2020 and through the reorganisation of the military side of UK space and the establishment of Space Command in 2021.

It is therefore critical to ensure that space-based assets and ground segment capabilities are protected against the numerous threats and hazards, environmental or man-made, accidental, or intentional, which accompany operations in this domain. It has been estimated that a temporary disruption to satellite services in the UK would result in a loss of around £1bn in economic activity per day of disruption [5].

Space is a global market. Space-enabled technologies in the UK may use data generated from non-UK-owned assets, therefore any events in space that affect non-UK owned assets may still have a significant impact on the daily lives of all in the UK. The number of launches into the Low Earth orbit (LEO) region is rising, with 2021 being the most active year to date increasing the chance of satellite failure and the risk of collisions. The total value at risk in LEO is estimated at $4.6bn [6]. In the Geostationary Orbit (GEO) region, where most communications and broadcast satellites reside, the risk of collision threatens at least $35bn worth of assets, of which only 8% is insured [7].

With the risk of such substantial losses, it is imperative that we gain a better understanding of the space domain, the risks in, through and from it, and the actors operating in it. Enhancing space surveillance and tracking (SST) capabilities will inform satellite owners and operators, with a greater degree of accuracy, of the potential risks to their assets. Forecasting space weather with a greater degree of certainty and understanding of the potential impacts to on-orbit and ground segment capabilities will inform planning to ensure more continuity or faster recovery of service. Using intelligence inputs to help characterise and attribute threats and hazards will ensure faster and more appropriate responses and help to ensure the continued peaceful and prosperous use of space in what is now considered to be one of the five warfighting domains.

This understanding of the space domain is Space Domain Awareness, and it is a fundamental enabler to all current and future space capabilities and activities and therefore to the way of life in the UK as we know it.

3.1 SDA Scope

“The effective identification, characterization, and understanding of any factor, passive or active, associated with the space domain that could affect space operations and thereby impact the security, safety, economy, or environment of our nation.” – *US Space Command* [8]

Space Domain Awareness is a term used infrequently, inconsistently and in some cases interchangeably with Space Situational Awareness. The study has followed a definition in-line with those provided by US Space Command and the UK Defence Space Strategy.

The factor that most distinguishes SDA from SSA is the inclusion of characterisation; understanding not only what is happening but why and in the case of a man-made threat, who is responsible. Space domain awareness provides causality and attribution through space surveillance, tracking and situational awareness, thereby enabling appropriate, risk-balanced decisions and courses of action. The term is equally applicable to civilian, commercial, academic, and military entities.

The study considers the following as key inputs to space domain awareness:

- Detection, tracking, identification and cataloguing of man-made and natural orbital objects and launches
- Characteristics and operating parameters of satellites
- Space weather
- Conjunction and re-entry assessment screening
- Intelligence
- Monitoring of electromagnetic spectrum activity

The following are not considered to form part of SDA but are supported by it:

- Launch operations
- Satellite operations (space, link, and ground sectors)
- Offensive and defensive space control

- Space traffic management
- Space-based capabilities/services (e.g., communications, PNT, ISR, environmental monitoring, missile warning, IoSM, debris removal)
- Licencing, regulation, treaty adherence

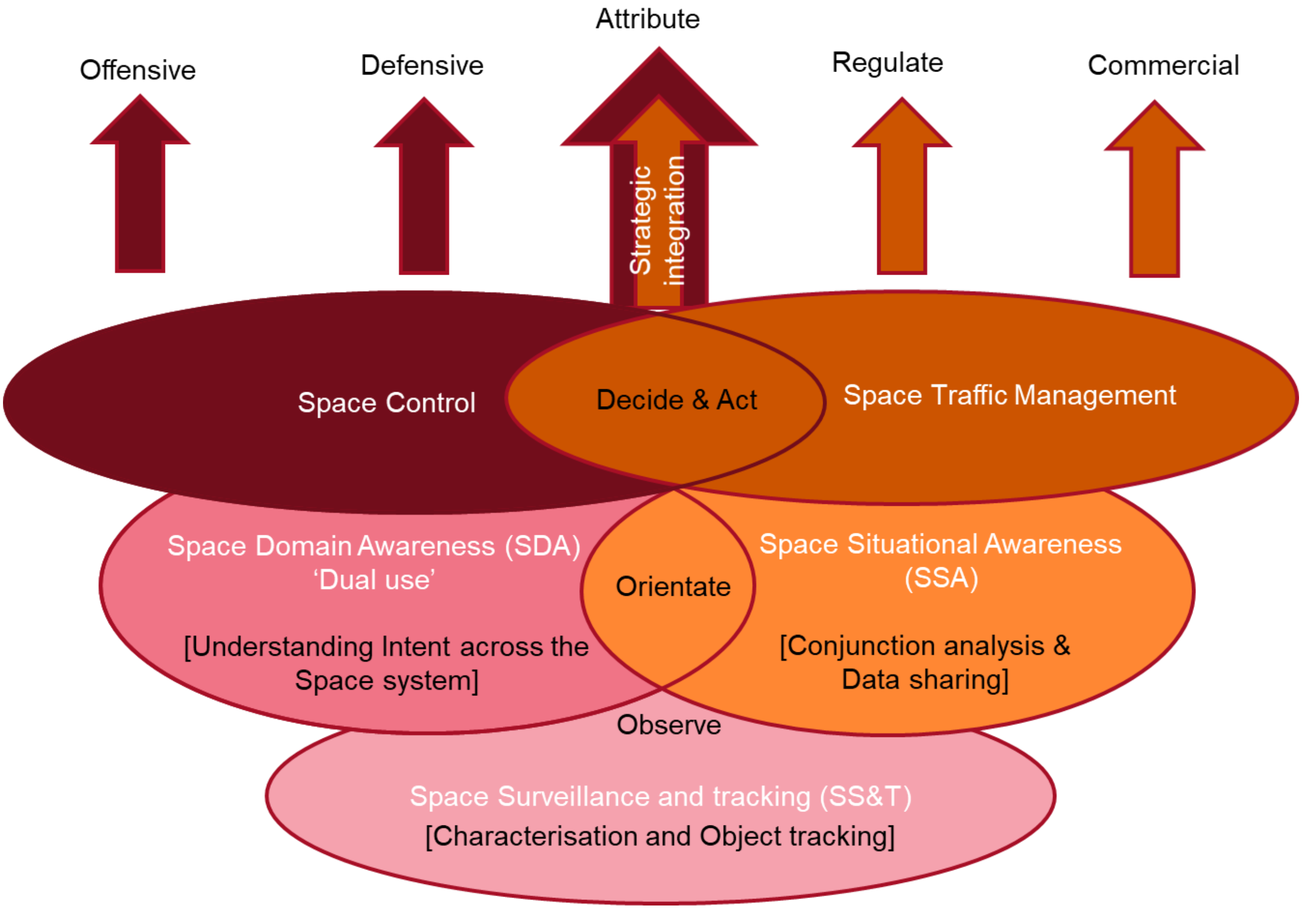


Figure 2: Scope and boundaries of SDA

3.2 Role in UK

"A fundamental enabler of all other space capabilities" – *Defence Space Strategy*

The DSS recognised the fundamental role of SDA in enabling other space capability and listed it as second of seven prioritised themes. It also noted an additional £85m in funding allocated to SDA over the next ten years.

Likewise, the NSS identified SDA as one of the eight key civil and defence capability priorities for the UK and whilst not acknowledged explicitly in the strategy, SDA plays a fundamental underpinning role in enabling each of the remaining seven priorities: **Satellite Communications, Earth Observation and Intelligence, Surveillance and Reconnaissance, Command and Control and Space Capability Management, Space Control, PNT, Orbital Launch Capability,** and **In Orbit Servicing and Manufacturing.** The NSS also states that the UK has the potential to take a leading role in some of the space sector's largest and fastest-growing markets over the next 5-10 years. This would leverage UK expertise in analytics, AI, and app development to develop products and services for a number of applications including SDA.

Currently, the UK Space Operations Centre (UKSpOC) based at RAF High Wycombe serves as the focal point for data gathered from a network of sovereign and foreign sensors including most prominently the radar array at RAF Fylingdales. The UKSA leads the civil side of UK SDA capability via its Space Surveillance and Tracking (SST) programme.

The Met Office Space Weather Operations Centre (MOSWOC) provides space weather 24/7 forecasting and warning services to Government, emergency service providers, CNI operators and the public. It is the only centre of its kind in Europe [9] and contributes data and expertise to international initiatives such as the PECASUS concept which provides space weather advisories to aircraft according to ICAO regulations [10], as well as precise atmospheric density predictions to ESA.

3.3 UK SDA Capabilities and Landscape

3.3.1 Sensor capabilities

The UK currently possesses a small number of sovereign sensing capabilities. This section will give a brief overview of some of the main facilities.

3.3.1.1 Radar

The UK's radar assets include the Solid-State Phased Array Radar (SSPAR) at RAF Fylingdales and the Chilbolton Advanced Satellite Tracking Radar (CASTR).

RAF Fylingdales

The SSPAR at RAF Fylingdales in North Yorkshire is a 3-faced radar providing 360° of coverage on the UHF band. Part of the US Space Surveillance Network (US SSN), and the only sensor within the US SSN to provide 360° of coverage [11], it provides detection and tracking of space objects as through a joint agreement between the UK and US. Though tasked with SST as an auxiliary function, its primary purpose is to provide missile early warning to the US and UK as part of the US Ballistic Missile Early Warning System.

Chilbolton

The CASTR at the Chilbolton Observatory in Hampshire forms part of the Space Monitoring Facility generating SST data on objects in Low Earth Orbit. Operated by the Science and Technology Facilities Council (STFC), it is undergoing upgrades improve its sensitivity and detect smaller objects such as space debris [12].

3.3.1.2 Optical

The UK's optical sensing capabilities include the Chilbolton Optical Advanced Tracking System (COATS), and the Starbrook telescope at Troodos in Cyprus.

COATS

The Chilbolton Optical Advanced Tracking Sensor is a transportable automatic optical sensor, able to track space objects in the LEO, MEO and GEO regimes with an accuracy of 50m at a 1000km range [13].

Starbrook

The Starbrook telescope is operated by Space Insight and located in the Troodos mountain range in Cyprus. A wide field 10cm aperture telescope, it provides surveillance of space objects in the GEO region.

3.3.1.3 Laser

The UK's satellite laser ranging (SLR) capabilities include the Space Geodesy Facility at Herstmonceux. A facility of the National Environment Research Council, the Space Geodesy Facility forms part of the International Laser Ranging Service and the International GNSS Service networks providing high-precision tracking of retroreflector-fitted satellites at altitudes of between 300km – 42000km to an accuracy of 1cm [14].

Figure 3: UK owned/operated sensor capabilities

3.3.2 UK SDA Landscape

Previous analysis in 2020 by MAPAnalytica, SJE Space and InverseQuanta [15] assessed known commercial and academic entities in the UK SST market. This analysis has been used as a baseline to map the UK SDA landscape as the study considers interest in SDA to be implicit for organisations involved in SST.

3.3.2.1 Academia

The UK has long been renowned for the strength and contributions of its academic and scientific communities with UK institutions consistently occupying places in the top 10 of global university rankings. The space sector holds a similar level of renown with the UK being the fourth largest contributor to scientific papers in this sector after the US, China and Germany [16] and second behind only the US when it comes to the top 10% most cited space publications [17].

Institution overview

UK-based institutions are engaged in research activities across the SDA spectrum. This section gives a high-level summary of the activities of each institution although it should be noted than many institutions are active in multiple areas. A map of UK institutions active in areas related to SDA is provided at Figure 5 and further information on the activities of each institution is available in Appendix A.

SENSOR OPERATION

A number of institutions have access to or operate sensing facilities including the **University of Warwick** which operates the SuperWASP facility based in the Canary Islands and South Africa and primarily tasked with the search for exoplanets. The **University of Manchester's** Jodrell Bank Centre for Astrophysics contains the Jodrell Bank Observatory. Formerly tasked with tracking space probes, it now primarily focuses on radio astronomy. The Liverpool Telescope, based in the Canary Islands and operated by **Liverpool John Moore's University** is a fully robotic facility that in 2021 made observations of an in-orbit maintenance procedure in GEO [18]. **Queens University Belfast** leads a consortium of research institutions which has supplied sensing equipment to the world's largest telescope, the Daniel J. Inouye Solar Telescope in Hawaii.

SPACE WEATHER

Imperial College London is active in space weather simulation, developing amongst other things, magnetospheric models to simulate solar wind and better predict space weather. The **University of Lancaster** is also active in modelling space plasma to better understand the risks and effects of space weather on ground-based and in-orbit assets. The **University of Reading** tracks the propagations of coronal mass ejections (CME) to improve predictions of effects of CME on Earth as well as also forecasting solar wind. The **University of Surrey's** Surrey Space Centre is a world-leading facility involved in the design and development of space vehicles. It has considerable expertise on the effects of space weather on space systems and contributes to research as part of the EU's SPACESTORM project.

SPACE DEBRIS

The **University of Southampton** has developed the DAMAGE space debris model which has been used to provide analysis for the UKSA since 2004. It is also a member of the Inter-Agency Space Debris Coordination Committee (IADC) which aims to coordinate efforts to deal with space debris. The **University of Strathclyde** is currently engaged in research looking at the use of hyperspectral imaging to detect and characterise space debris as well as partnerships with **Imperial College London** to use AI and improved modelling to provide better collision avoidance.

SENSING TECHNIQUES

Heriot-Watt University is engaged in research into multi-sensor multi-target tracking techniques for improved SSA and is the UK headquarters of Celestia, a company specialising in satellite tracking systems. The **University of Cambridge's** Cavendish Astrophysics Group conducts a wide range of research programmes into sensing techniques for a number of sensors such as the Atacama Large Millimetre Array, James Clerk Maxwell Telescope and Magdalena Ridge Observatory although these are primarily tasked with study into the formations of stars and planets. The **University of Edinburgh** collaborates with researchers at Lockheed Martin's Advanced Technology Centre on the application of survey astronomy techniques to space situational awareness and is developing its Space Innovation Hub in partnership with the Satellite Applications Catapult. The **University of Leicester's** Space Research Centre is focused on developing novel sensors and optics. It has previously been involved in missions such as the James Webb Space Telescope and is currently engaged in the development of the International Cherenkov Telescope Array, a ground-based high energy gamma-ray telescope. The **University of Bath** has designed a constellation of in-orbit radar sensors to detect space debris below 10cm [19]. It has also produced research on the risks of space weather to GNSS capabilities. **Durham University** hosts the Centre for Advanced Instrumentation which undertakes research into optical tracking techniques including Adaptive Optics for Satellite Laser Ranging and novel passive optical sensing capabilities for LEO and GEO.

SPACE LAW AND GOVERNANCE

Northumbria Law School at **Northumbria University** teaches and researches Space Law and has published extensively on the legal and ethical underpinnings of space governance.

DATA ANALYTICS

The **University of Oxford** is involved in the development of advanced data analysis methods to model planetary signals alongside complex noise sources, whether stellar or instrumental. Oxford is also using AI in a study for the UKSA regarding SSA and STM of satellite constellations in partnership with Cranfield University.

CASE STUDY: UNIVERSITY OF WARWICK

WARWICK
THE UNIVERSITY OF WARWICK

SDA activities	**Established Centre for Space Domain Awareness (CSDA) in 2021**
Facilities	**SuperWASP** in the Canary Islands and South Africa primarily tasked with the **search for exoplanets**.
Collaboration	Working with **Dstl on LEO/GEO surveys, sensor architecture and object characterisation** amongst others

Other initiatives

A number of academia-led initiatives to contribute to UK SDA have been established including GNOSIS, SWIMMR and the Centre for Space Domain Awareness.

GNOSIS

The Global Network on Sustainability in Space (GNOSIS) is an STFC-funded network launched at the end of 2019 to forge broader collaboration between scientists and industry to understand and solve the increasing challenges relating to space weather and debris. GNOSIS activities aim to inform technological and commercial roadmaps, as well as space policy and investment decisions - to ensure the continued viability of the space operating environment. GNOSIS organises thematic meetings and “jargon busting” workshops to facilitate discussions aimed at bringing scientists and industry together. It also provides seed funding for joint projects and part-funding for graduate students. As of February 2022, there were 300+ members representing: industry; public organisations; and more than 50 universities and research institutions (36 from across the UK, the rest in other geographies) [20].

SWIMMR

The Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR) programme is a four-year programme started in 2019 to improve the UK’s space weather monitoring and forecasting capabilities. Led by STFC in collaboration with the Natural Environment Research Council (NERC) and with an investment of **£20m**, SWIMMR consists of a mixture of open research calls and commissioned works to develop and deploy new instruments, models, and services to support the MOSWOC and the UK space weather community [21].

CENTRE FOR SPACE DOMAIN AWARENESS

Established by the University of Warwick in 2021, the Centre for Space Domain Awareness (CSDA) brings together a number of researchers from across the university to address a number of SDA-related issues including modelling and prediction of space weather, improved object tracking through human-machine teaming and object characterisation [22].

STEM shortage

Naturally, academia is reliant on the continued flow of STEM (Science, Technology, Engineering and Mathematics) students through the education system and into research roles. The much-reported global shortage of STEM graduates threatens the progress of science in tackling some of the most pressing issues of our time; climate change, future pandemics, and the ever-increasing risks in space amongst them. However, there are a few promising signs that the UK is beginning to tackle this challenge. Amongst Five-Eyes partners the UK ranks first for the share of STEM students in tertiary education and second behind Germany in the larger Combined Space Operations (CSpO) initiative [16]. More positively still, analysis from 2018 indicated an increase in the number of A-level students choosing STEM degrees. All STEM subjects except ICT showed an increase in share of students from 2008-2018 [23]. With the 2018 cohort having either recently graduated or graduating soon, this should demonstrate some progress toward closing the STEM gap.

Rank	Nation	Share of STEM students in tertiary education	Five-Eyes	CSpO
1	Germany	30%	No	Yes
2	United Kingdom	26%	Yes	Yes
3	France	25%	No	Yes
4	Canada	22%	Yes	Yes
5	New Zealand	21%	Yes	Yes
=6	Australia	18%	Yes	Yes
=6	United States	18%	Yes	Yes

Figure 4: Share of STEM students in tertiary education amongst CSpO nations

Figure 5: UK academic landscape

3.3.2.2 Industry

The UK commercial space sector is, in many areas, flourishing and is home to a wide range of entities with an interest and expertise in SDA and its constituent technologies. This study has engaged with organisations from areas including sensor development, sensor operation, data analysis, spacecraft operation, and insurance. This section gives a high-level summary of the activities of some commercial organisations although it should be noted than many organisations are active in multiple areas. A map of UK commercial organisations active in areas related to SDA is provided at Figure 6 and a brief overview of each organisation's SDA-related activities is at Appendix B.

SENSORS

BAE Systems develop high-reliability, space-resilient mission payloads and ground solutions including radio frequency (RF) and infrared (IR) sensors. **Lockheed Martin** are one of the world's largest aerospace companies. In the SDA domain, their prime contribution is the development of the Space Fence radar system capable of detecting objects in orbit down to 1cm. **Lumi Space** is aiming to build the world's first global, commercial satellite laser ranging (SLR) service. This will be used to detect objects in all orbital regimes and with a greater level of accuracy than currently possible. It will also allow for the validation of optical observations and may pave the way for using laser technology to move space debris into a safer orbit. **Goonhilly** are leaders in commercial satellite communications and from their Earth Station in Cornwall, are able to communicate with and track satellites in the LEO regime. **Space Insight** operate the Starbrook array in Cyprus, providing observational data to the UKSA and previously to the EUSST programme.

CASE STUDY: LUMI

Lumi

Context	Lumi is aiming to build a **global network of Satellite Laser Ranging stations** able to detect space objects and debris in every orbital regime from LEO to GEO and to a finer level of granularity with increased accuracy.
Benefits	The data provided by Lumi will allow **the validation of radar and optical observations** whilst **fusing data with optical observations** enables the validation of models of size, shape, and albedo.
Future Research	Determination of the **material composition** of debris objects and an **active retroreflector** to enable **remote and unambiguous identification** of a satellite and status.

SPACECRAFT MANUFACTURE

Airbus is the largest commercial aerospace company in the UK and manufactures satellites for telecommunications, EO, and PNT programmes. It also manufactures the Astrobus series of LEO platforms which could potentially be used for SST. **SSTL** is one of the most prominent satellites manufacturers in the UK and manufactured the Canadian Sapphire mission alongside COMDEV which contributes to the US SSN. **Boeing** design and build advanced space and communications systems for military, commercial and scientific uses including satellites for the planned US Space Force Space Based Surveillance System (SBSS). **Astroscale** is developing missions to aid space sustainability such as Active Debris Removal (ADR) and End of Life (EoL) services as well as offering in-orbit platforms for sensors to aid data collection for SDA. **Spire Global** specialises in the rapid development of satellite capability and its Lemur-2 platform could host SST payloads in altitudes of up to 600km.

DATA AND ANALYTICS

Deimos has extensive experience in SDA activities across Europe including in space weather, SST and Near-Earth Objects. In addition to developing operational systems for ESA, Deimos offers commercial services based on data collected by their Sky Survey system. **LeoLabs** operates a worldwide network of ground-based, phased-array radars to generate high resolution data on objects in LEO**.** It also offers commercial SDA products based on its data such as SST, collision avoidance and Launch and Early Orbit (LEOP) services. **NORSS** offers satellite tracking and space situational awareness, consultancy to plan and deliver effective operational use of space and a range of training for satellite operators and controllers. It also offers mission support in a range of areas including conjunction analysis, space weather impacts, and regulatory compliance. **Clutch Space Systems** offer a range of products and services to increase the utility and capacity of ground stations using high-performance software to reduce the need for costly and bespoke hardware. **MAP Analytica** has considerable experience in space surveillance operations and horizon scanning and has worked closely with the UKSA and STFC. **Seradata** produces SpaceTrak, the leading launch and satellite database, providing significant contributions to SST and analysis of all launched satellites. **ThinkTank Maths** is part of the SaxaVord SDA Consortium looking to provide assured space traffic management services. Their novel mathematical methods will reduce space object position and orbital uncertainty, providing more accurate SDA and potentially reducing manoeuvring requirements.

CASE STUDY: NORSS

Context	NORSS provides **end-to-end space situational awareness** using its LEO Optical Camera Installation (LOCI) at Kielder Observatory.
Benefits	The system has the ability to characterise the photometric data extracted from satellite streak images. **Light curve characterisation can be used to exploit key LEO characteristics** of satellites.
Future Research	To build a **global network of LOCI tracking sensors** to provide high quality tracking data

CONSULTANCY

CGI delivers complex, mission-critical space systems and software which has supported the missions of over two hundred satellites. CGI have also developed and delivered the AURORA system into the UKSpOC to form part of the national SST capability. **Inverse Quanta** offers consultancy to SST and space systems as well as into defence and security**. Roke** offer R&D consultancy services and have capabilities in RF sensor design that could be exploited to access the signatures that active satellites generate. This information could help verify the EoL status of satellites and ensure compliance with international law and regulation. **Alden** provide commercial, legal, and regulatory advice and have been involved in a number of SSA articles and studies as well as on practical and licensing aspects and ADR and IOSM matters. They are currently leading on work to establish a space sustainability kitemark and are involved in the establishment of a Space Sustainability Institute at Space Park Leicester.

INSURANCE

Marsh are insurance brokers specialising in covering complex risks. This includes the risk of space debris and other hazards in the space environment.

Figure 6: UK SDA industrial landscape

3.4 International Comparisons

This section sets UK general space spending and SDA capability in the context of other nations, focusing heavily on G20 nations, ESA and CSpO allies.

3.4.1 General space spending

The overall picture for the UK in space in an international context is not a particularly strong one. The nation lags a number of other nations both in terms of its sovereign space capability and its spending in the sector. Amongst G20 nations the UK ranks in the bottom half of combined civil and defence government space spending as a percentage of its GDP.

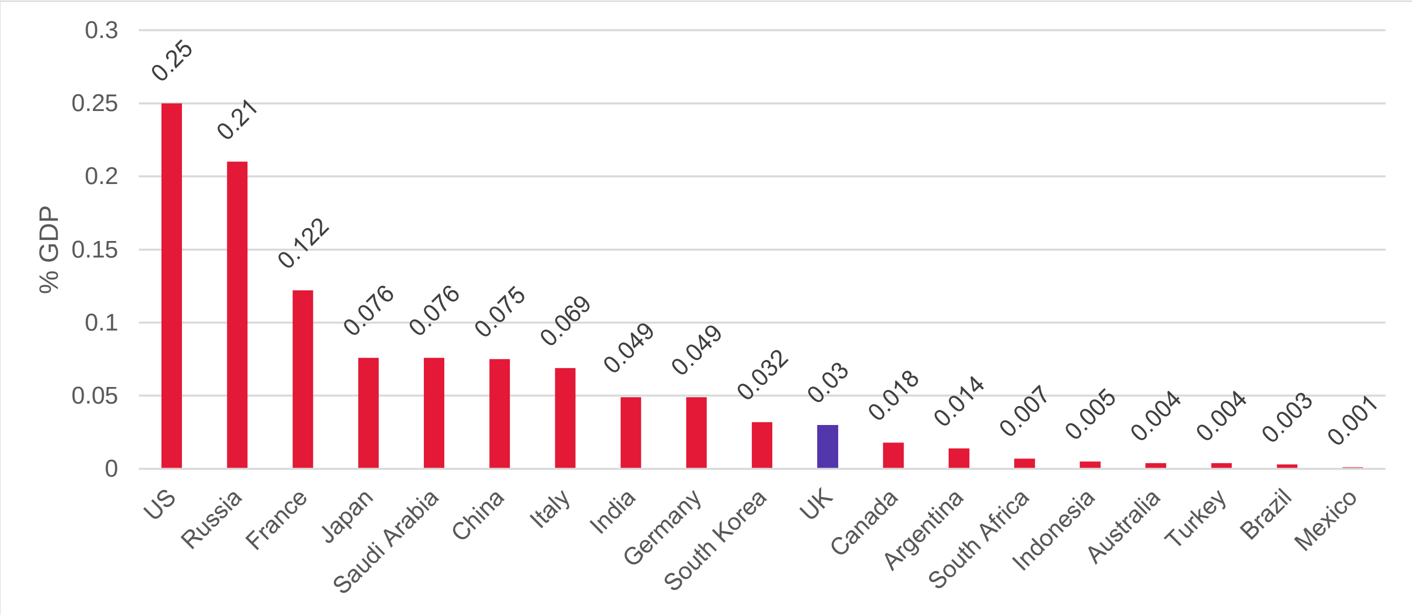


Figure 7: Government space budgets (Civil & Defence) of G20 nations as a % of GDP (2020) [17]

In contrast to many other nations, the UK diverts the majority of its government space spending to Defence meaning that amongst its Combined Space Operations Initiative allies, UK Civil spending is comparatively low [24].

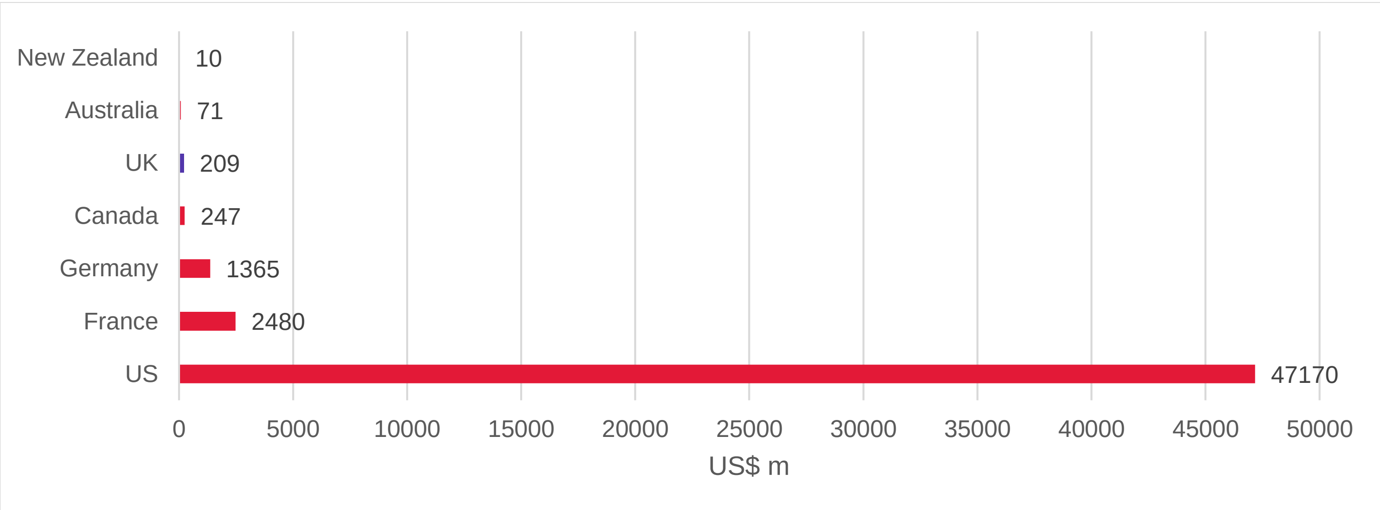


Figure 8: Government space spending (Civil only) of Combined Space Operations Initiative (CSpO) members (2019)

Despite its relative under-funding on a national level, on an international level, the UK continues to play a leading role in the European Space Agency, being the fourth largest individual contributor to the ESA 2022 budget, despite withdrawal from the European Union resulting in the UK's exclusion from participating in a number of European programmes such as Galileo and EGNOS.

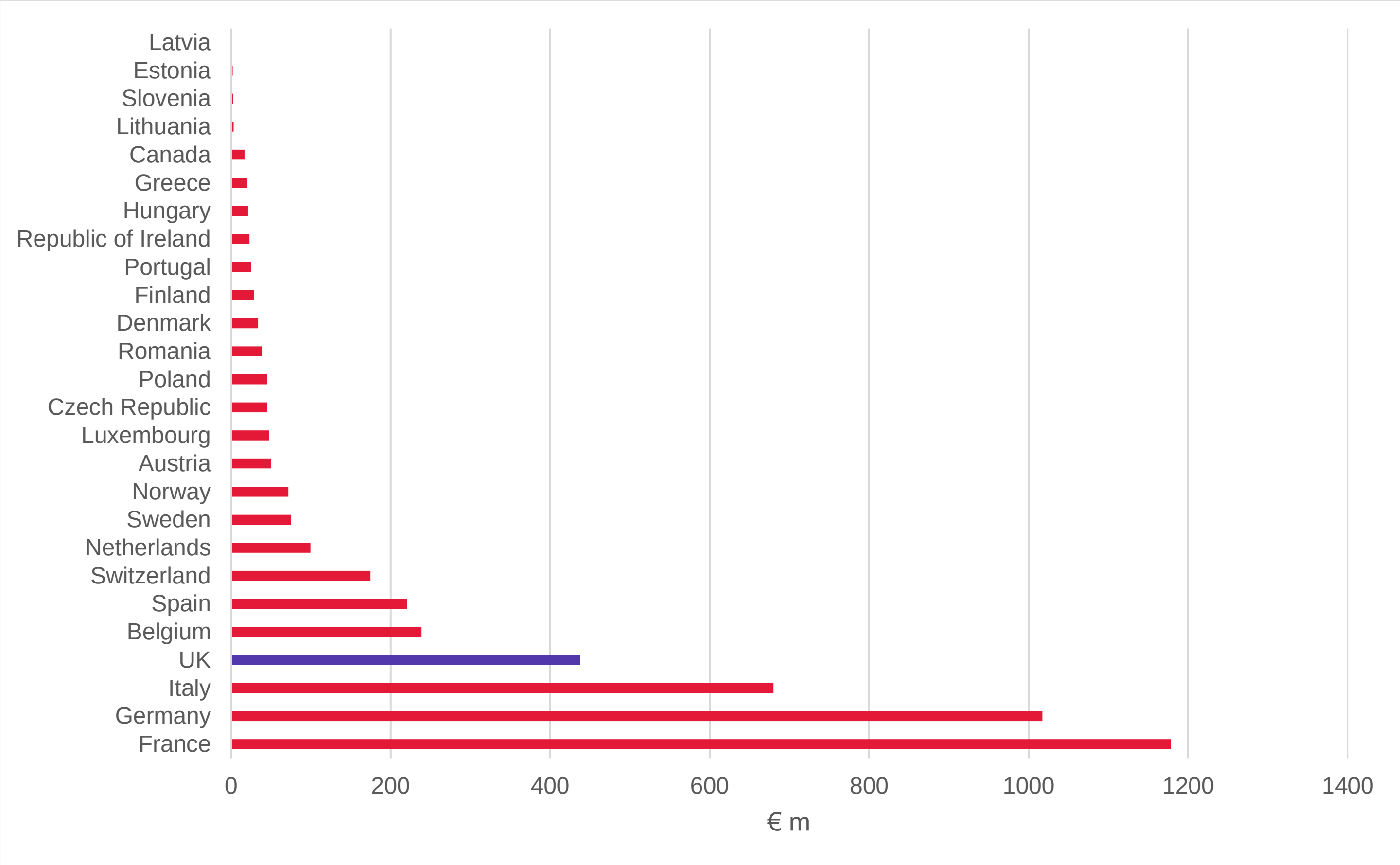


Figure 9: ESA contributions by member states (2022) [25]

Data for domestic and international spending on SDA or SSA activities specifically is harder to find as much of this information is classified. With respect to the UK, the DSS announced £1.4bn of additional funding to be spent over the next ten years to 2032. Of that, £85m was earmarked for Defence SDA, £970m for ISR which feeds into SDA and £145m for Space Control which is supported by it. Whilst the DSS lists SDA as the second of seven prioritised capability themes, ahead of both Space Control and ISR, the level of funding attributed to it does not fully reflect this.

The increasing prioritisation of SDA is a global trend. Japan, in its 2021 space budget acknowledged the need to build on SDA/SSA capability with a stated intention to invest $185m in the year 2022/23 on space surveillance and tracking. This is in support of its ambition to launch full-scale SSA operations in 2023 in partnership with the US [26].

3.4.2 International SDA programmes

3.4.2.1 ESA Space Safety Programme

ESA's Space Safety programme originally started life in 2009 as the Space Situational Awareness programme. Encompassing space weather monitoring, Near-Earth Object detection and space surveillance and tracking, the programme sought to expand and coordinate the ESA sensor network, integrate existing space weather capabilities, and develop new and novel technologies such as satellite laser ranging and optical surveillance techniques. In 2019 the SSA programme was succeeded by the Space Safety programme which built on the progress made by its predecessor and began to incorporate space mission planning for activities such as In-Orbit Servicing and debris removal. In its final year of operation, the SSA programme commanded 0.46% of the ESA budget, totalling €27.22m of which the largest contribution came from the UK [24]. The 2022 budget for the Space Safety Programme was €110.9m, representing 1.6% of ESA's total budget [27].

The Space Safety programme encompasses five main activity areas [28]:

1. Core (fundamental activities around space weather, planetary defence, and space debris)
2. Lagrange (Vigil) Mission (Space weather mission outside the Earth-Sun line)
3. Hera (Asteroid inspection and interception)
4. In-Orbit Servicing/Removal
5. CREAM (Collision Risk Estimation and Automated Migration)

The UK has been the largest contributor to the Vigil Mission, making it one of the most important Member States for this ESA programme. However, UK participation in other SDA-related aspects of the programme has been somewhat limited.

Space Weather

The space weather component of the Space Safety programme comprises the ESA Space Weather Service Network providing space weather observations, results, and models as well as a number of analytical products. The network can be accessed via an online portal [29] and a space weather helpdesk provides first and second line support to registered users. The helpdesk is based at the SSA Space Weather Coordination Centre in Belgium. The UK contributes significantly to the Space Weather Service Network via the MOSWOC as well as coordinating the Expert Service Centre (ESC) for Heliospheric Weather via STFC RAL Space in Harwell, one of five ESCs within the network.

3.4.2.2 EUSST

The European Union Space Surveillance and Tracking programme (EUSST) provides a number of free-of-charge services to registered users. Collision avoidance, re-entry analysis and fragmentation analysis are offered to any civil or commercial owner, operator or authority based in any EU member state. These services are currently provided to over 135 organisations affecting more than 240 European satellites and data is obtained from a network of 38 sensors located within the member states of the SST Consortium. The performance and level of service of EUSST appears to be highly rated by its consumers, scoring 8.5/10 for overall satisfaction in its most recent User Feedback Campaign in December 2020 [30]. The UK no longer participates in or provides any data or services to the EUSST programme following its withdrawal from the European Union although EUSST services are still available to UK-based users.

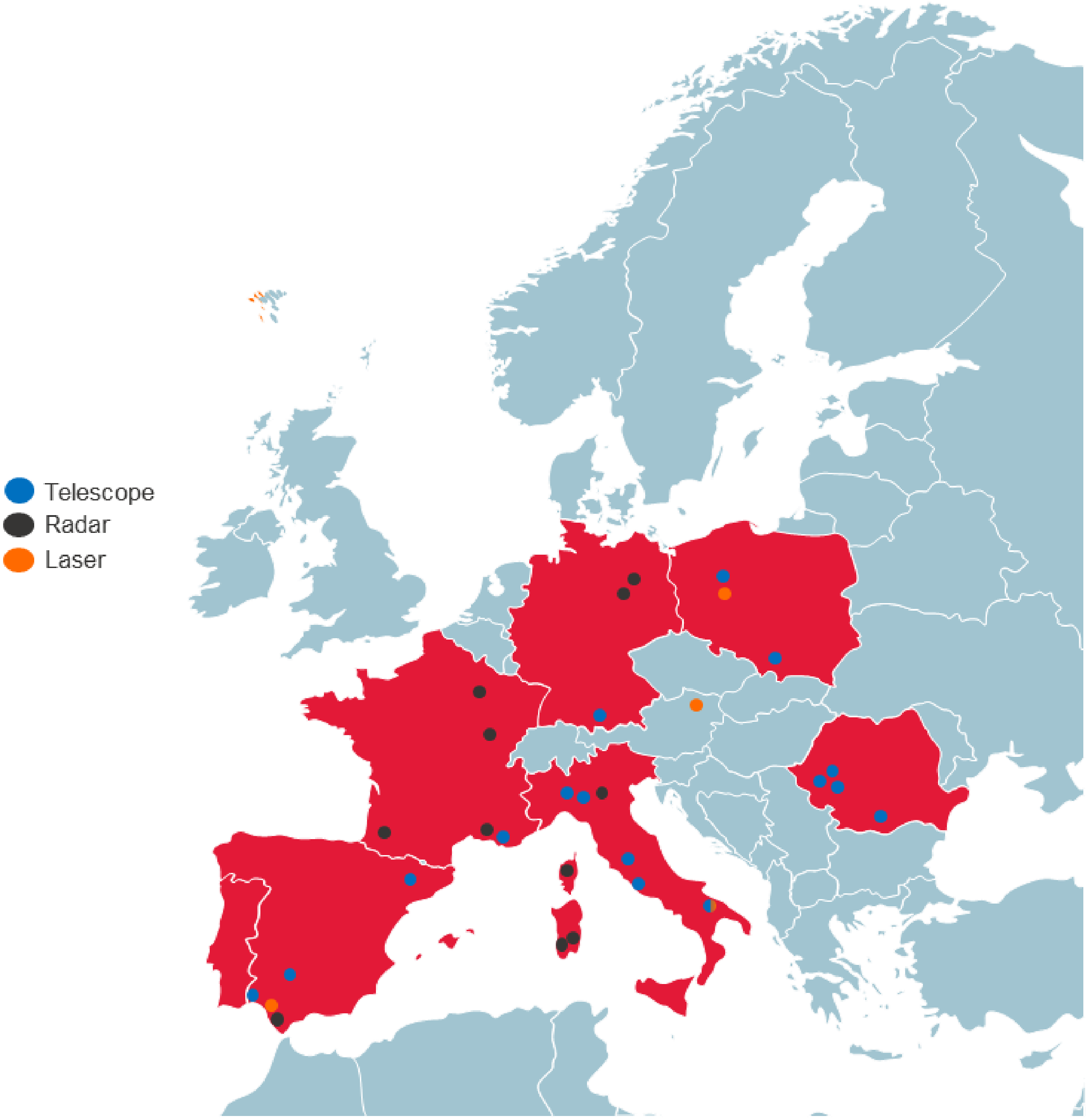


Figure 10: Distribution of EUSST sensors within SST Consortium member states [31]

3.4.2.3 US Space Surveillance Network

The US Space Surveillance Network (US SSN) is operated by US Space Force under the command of US Space Command and is dedicated to the detection, tracking, identification, and cataloguing of objects in Earth orbit. The US SSN is the largest SST network in the world, operating over 30 ground-based and 6 in-orbit sensors. It provides three levels of space situational awareness products; basic SSA services to registered users of its SpaceTrack public website, emergency services direct from 18 Space Control Squadron, and advanced services such as COLA and additional collision avoidance and conjunction analysis services that require the signing of a SSA sharing agreement with US Space Command. The UK contributes to the US SSN via the radar array at RAF Fylingdales.

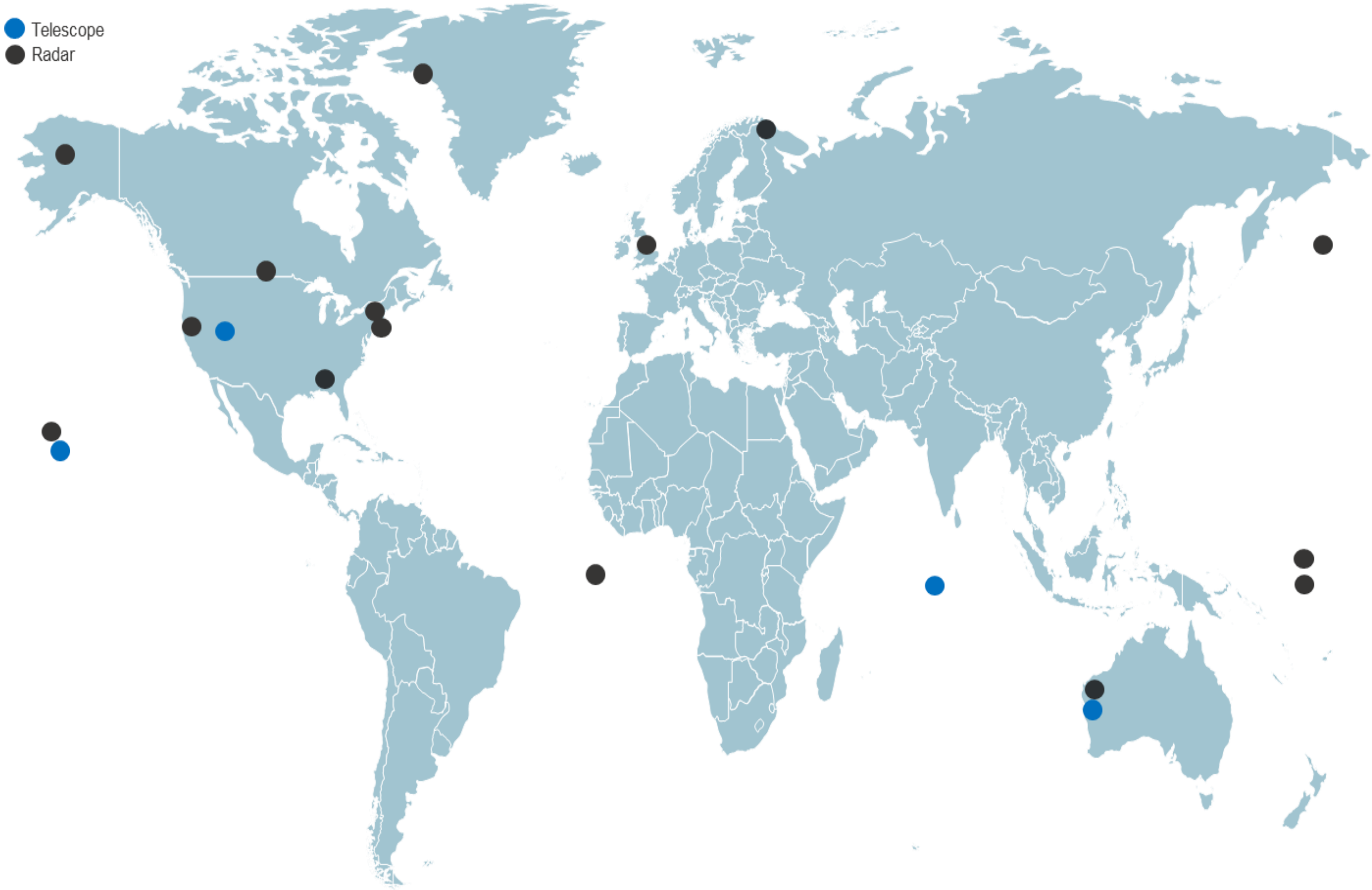


Figure 11: Distribution of sensors within US Space Surveillance Network [32]

3.4.2.4 Sensing capabilities of select NATO nations

A list of sensor capabilities of a select group of NATO nations has been compiled from publicly available information and is at Appendix D. This details the radar, optical and laser assets of the US, France, Germany, Italy, and Spain. At the NATO 2021 Summit, NATO members agreed to strengthen space domain awareness. Supported by €6.7m funding from Luxembourg, NATO plans to develop a Strategic Space Situational Awareness System to enhance capabilities. [33]

4 Opportunities and Benefits

4.1 Key requirements for SDA delivery

The study sought the views of UK industry and academic on the key requirements to delivering SDA. A number have been identified and can be broadly grouped into two categories: technological and organisational. The map in Figure 12 illustrates the relative frequency with which various requirements were highlighted.

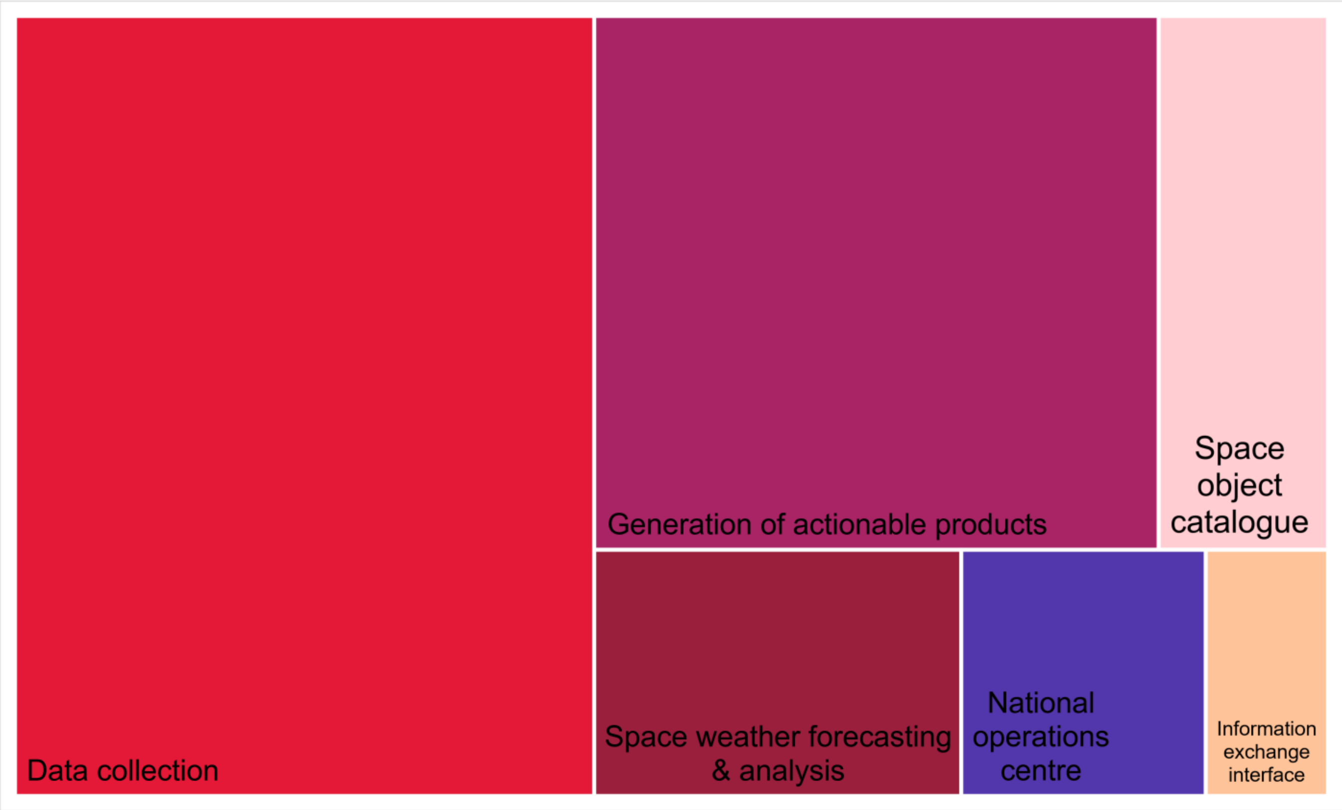


Figure 12: Aggregation of key SDA requirements as mentioned by study respondents

4.1.1 Technological requirements

4.1.1.1 Data collection

The collection of SST data is fundamental to the generation of SDA and was the most consistently highlighted requirement communicated to the study. Data collected from a network of on-ground an in-orbit sensors, encompassing radar, optical and laser sensing capabilities both UK-owned and foreign provides the structure upon which all SDA is built. The UK has a limited network of sovereign sensors and is therefore heavily reliant on data obtained from other nations and via commercial providers.

4.1.1.2 Analysis and processing

The aggregation, analysis, and processing of sensor inputs from raw data into actionable information is a key requirement for conducting SDA. To distinguish it from SSA, SDA requires not only orbit data analysis but characterisation of the object. Additionally, given the recent proliferation of constellation satellites and the enhanced sensing capabilities of the US Space Fence, there is a requirement for new identification and catalogue formats to support the increased numbers.

4.1.1.3 Product generation

The purpose of SDA is to ensure the safety of operations in space. This requires the generation of actionable information and high-quality products and services to spacecraft owners and operators. Examples include collision warning, re-entry prediction and fragmentation analysis which form the core of the free services provided by EUSST as well as space weather forecasts and impact assessments.

4.1.2 Organisational requirements

4.1.2.1 Strategy

The National Space Strategy and the Defence Space Strategy have been published, with both documents highlighting SDA as a priority area for the UK. However, these high-level strategies do not provide insight or direction into the UK's ambitions in SDA and therefore generate uncertainty between government and industry. A coherent SDA strategy and vision is a key requirement to effectively cohere academic, civil, industrial, and military entities. A candidate roadmap to SDA delivery is presented at Figure 17 to help inform the strategy.

RECOMMENDATION 1 – SDA STRATEGY

To effectively bring together academia, industry, civil and military entities, the UK requires a coherent, cross-Government SDA strategy and vision. This will provide clarity on the intended aims for the UK in SDA and enable industry and academia to deliver against them and provide assurance that the UK is committed to the long-term development of SDA.

4.1.2.2 Coherence and dual use

Following on from a strategy, enabling effective coherence between academic, civil, industrial, and military entities is another key requirement for SDA. Securing the continued safety of space operations is a paramount importance to all operations in or reliant on space, therefore space domain awareness must be dual use. Effective data sharing is required to ensure the production of timely, actionable information and governance is required to facilitate interoperability between the various entities. Characterisation, which is the key distinguisher of SDA from SSA, requires the effective blending of civil and military data. Without this, characterisation and therefore SDA cannot be achieved.

RECOMMENDATION 2 – SDA ADVISORY GROUP

An advisory group for SDA should be established and membership extended to industry leaders and academics as well as civil and military representatives to advise and guide on developing UK SDA capability. The group should make recommendations on capability and data procurement and the UK's contribution to global SDA as well as support policy and decision making

4.1.2.3 International collaboration

Whilst some limited space domain awareness can be achieved alone, resilient and reliable SDA requires international collaboration acting in the interests of a shared public good. A number of international partnerships exist to provide elements of SDA, including the US SSN and EUSST. It is vital that the UK play an active part in bilateral or multilateral collaborations in space, as it is already doing with contributions to the US SSN, the UK-Australia Space Bridge (see 4.3.2.2) and the ESA Space Weather Service Network.

RECOMMENDATION 3 – MAINTAINING INTERNATIONAL COLLABORATION

The UK should attempt to maintain the strongest possible ties with ESA and attempt to participate and collaborate in joint programmes to strengthen global SDA for the common good. Outside of ESA, the UK should look to establish, where not already extant, bilateral data sharing agreements with Five Eyes partners and other nations to continually ensure access to a wide variety of high-quality data.

4.2 Capability Gaps

Technical input by SJE Space identified a number of capability gaps to be addressed for SDA [34]. A subset of these were presented to study participants for validation and to determine any existing research into them. The study confirmed the validity of all identified gaps.

8. Inability to track objects down to 1cm
9. Insufficient cataloguing to deal with increasing number of entries
10. Lack of southern hemisphere tracking
11. Insufficient accuracy to support conjunction warning
12. Inability to track certain objects during daytime
13. Sparse measurement of space weather effects
14. Limited ability to monitor satellite transmissions

4.3 Opportunities for SDA development

4.3.1 Sovereign sensor development

Expanding the UK's network of sovereign sensor capabilities is a key area of opportunity in SDA. Accuracy of observations is fundamental to our understanding of the space environment and is necessary in providing assured, high-quality information for the generation of SDA. Increasing the number of sensors available for observations ensures greater validation of results whilst establishing sensing capability in other parts of the world broadens the range of observations available and takes advantage of different geographic or meteorological conditions. Additionally, whilst the UK possesses the radar array at Fylingdales, the data obtained from it is unavailable to commercial operators. Enhancing the UK's sensor capabilities should also aim to provide more sovereign data to commercial and non-military users.

There are a number of trade-offs to determine the most appropriate and applicable sensor for a given task or location, but the most effective outcome is derived from the fusion of inputs from across all sensor types including those located in orbit. Positioning sensors in orbit would overcome some of the terrestrial issues with optical sensors such as poor weather and day/night cycles. In-orbit sensors would also offer greater ability to detect smaller objects as a result of reduced range to the target. There is potential to utilise platforms available from the likes of Airbus and Astroscale (see Section 1.1.1.1) to launch and position these sensors.

Whilst a degree of replication is necessary to provide validation of observations, it is paramount that new sensor developments do not simply duplicate what is currently available. SDA, and the generation of SST data to support it, are global exploits and cannot be achieved by any one nation alone. Therefore, it is crucial that UK contributions to global tracking capability focus on providing unique, supplementary, or higher quality data than currently available making use of UK geography or technological developments.

Additionally, a demand signal generated from SDA-related sensor provision would stimulate and strengthen UK sensor manufacturing, providing a secondary benefit to national enterprise in the sector.

RECOMMENDATION 4 – CLOSING CAPABILITY GAPS

The UK's relative trailing position in global space and SDA gives it the opportunity to craft a strategy aimed at filling the gaps in global capability. Investment in sovereign sensors can help to close these, either through offering novel sensing methods or installing sensors into regions of low coverage, improving the UK's sovereign sensing capability, and adding to the UK's credibility in international governance and participation in the space sector. This would represent a small but noticeable step in catching up to its allies as well as enhancing global SDA for the benefit of all.

4.3.2 Non-sovereign sensor capability

Almost all national SDA capabilities will rely on non-sovereign sensor data. The UK could look to use the following sources:

4.3.2.1 EUSST

Following the withdrawal from the European Union, the UK is no longer part of EUSST although UK users are still able to access its services. The EU is currently defining rules around approving users from non-EU countries [35] and there was clear consensus from study respondents that should this opportunity arise, the UK should seek immediate re-entry into the EUSST programme to facilitate better data sharing and collaboration with European partners.

4.3.2.2 Space Bridge

The 'Space Bridge' partnership signed in 2021 between the UK and Australia can be leveraged to develop mutually beneficial SDA capabilities such as observational data sharing, developing sensor networks which may provide greater coverage of the southern hemisphere, and collaborating on the creation and delivery of analytical products.

4.3.2.3 G7 and other nations

In 2021 the G7 nations issued a joint statement to commit to the safe and sustainable use of space [36]. This focused largely on the growing issue of space debris and other in-orbit hazards making collaboration and cooperation in SDA essential to meeting these commitments. The 2021 Memorandum of Cooperation between the UKSA and the Japanese Aerospace Exploration Agency JAXA and Memorandum of Understanding with the Canadian Space Agency on joint activities and information sharing in space present additional avenues for exploration of collaborative SDA development. The UKSA also holds memoranda of understanding with twenty other nations for the use of space for peaceful purposes [37].

4.3.2.4 Commercial sources

A small number of commercial organisations such as LeoLabs provide SST and SDA data and services which could be used to augment national sensor data and service delivery.

4.3.3 Analytics

4.3.3.1 Space service desk

The UK can create high quality bespoke products for other entities, leveraging its considerable academic and commercial expertise and becoming a service desk for global SDA. Data is the single most important aspect of SDA and if UK is dependent on external sources, then consideration needs to be given to provenance, trust, accuracy, including the calibration data for the sensors, and reliability of the supply of the data.

4.3.3.2 SDA integrators

Currently there are no UK organisations that integrate the whole SDA process and provide SDA products. There may be an opportunity for the UK to provide not only raw sensor data but aggregation of data, expert interpretation of it and actionable information to other nations and owner/operators. To achieve this would require further study on the requirements of various services but could leverage both UK generated & obtained data as well as the MOSWOC's space weather expertise.

4.4 Benefits of SDA

4.4.1 Overall financial benefits

The financial benefits of SDA were difficult to establish given its primary role as a fundamental enabler to space operations and activities rather than a revenue-generating activity. Instead, the financial benefits were assessed against two broader themes; the mitigated cost of a loss of space services or assets as a result of enhanced SDA, and the potential revenue of other space activities that are directly enabled by enhanced SDA. The **estimated return on investment for UK SDA development may reach £2.1bn by 2031** based on risk reduction and opportunity enablement and a **total investment of £568m** (see Section 7.3).

4.4.1.1 Mitigation against loss of GNSS service

Global Navigation Satellite systems (GNSS) provide position, navigation and timing services that underpin much of the world's economy and society. Many countries, including the UK, are reliant on applications leveraging GNSS and as such a denial of or disruption to service would have wide-ranging and costly effects. A number of threats to GNSS exist, both to the on-orbit assets and the ground segment facilities, including space weather events, collision of GNSS satellites with space debris, and deliberate denials of service via jamming or anti-satellite weaponry. Space domain awareness helps to mitigate these risks by providing, amongst other things, accurate space weather forecasts and impact assessments, enhanced tracking, and conjunction analysis of space debris in regions occupied by GNSS satellites, and characterisation services to identify potential threats to assets in the orbit, link, or ground segments. A 2017 study by London Economics [38] estimated that GNSS provides a Gross Value-Added benefit of **£1.2bn per year** to the UK economy and an additional **£5.5bn per year** in utility benefits. Likewise, it estimated that the economic impact of a loss of GNSS services would total **£5.2bn over five days**. GNSS-enabled location-based services, such as Uber, Ocado and a myriad of other examples, have grown at pace since 2017. Multiple market forecasts project continued compound annual growth rates for location-based services of 20% or more. It would be reasonable to assume that £5.2bn figure would be more than double today.

4.4.1.2 Enabling In-Orbit Servicing and Manufacturing

In-Orbit Servicing and Manufacturing is an emergent market identified by the Space Growth Partnership in 2018 as being one of the key growth areas of the UK space industry. A 2021 report into the opportunities for the UK in IOSM estimated that the global market may be worth more than $4.4bn by 2030 and suggested the **UK should target capturing $1bn of this market** by the end of the decade [39]. Enhancing the UK's space domain awareness capabilities will help to unlock this value by enabling activities such as active debris removal with greater debris tracking capabilities and close proximity operations with increased observation accuracy.

4.4.1.3 Enabling Space-Based Solar Power

Space-based solar power is a concept of collecting solar power with satellites and distributing it back to Earth. The UK commissioned a study in 2020, conducted by Frazer Nash Consultancy, to determine the feasibility and benefits of developing a space-based solar power capability. It found space-based solar power to be both technically and economically feasible and capable of generating an additional **£1.30 of GDP for every £1 spent** over the life of the programme [40]. This initiative would also contribute to Net Zero goals as well as demonstrate the scientific and engineering power of the UK. As with all other space-based activity, space domain awareness would play a crucial role in ensuring the continued operation and success of the space-based solar power programme, primarily by ensuring the safety and security of the solar collection satellites through enhanced collision warning and avoidance services and more accurate tracking and monitoring.

4.4.1.4 Launch and COLA

The UK can establish itself as a launching nation by providing services such as Collision on Launch Assessment (COLA) as part of an overall launch package. COLA relies on effective SDA to determine positions of objects in orbit and their collision risk. Whilst some nations such as Australia charge an additional fee for COLA and other such as the US will provide COLA for free if the launch contains a US payload, offering these services as complimentary to launch may set the UK apart and attract prospective launch customers to UK spaceports. Current and planned UK launch facilities are primarily located in regions away from the most valuable areas such as London and the South East. As a result, the additional revenue brought to spaceports through a more attractive launch package will help to increase the value of the sector in these areas.

4.4.2 Regional financial benefits

The 2020 Size & Health of the UK space industry report noted that whilst all UK regions are home to headquarters of space organisations, the majority are concentrated in the London and South East regions. Accordingly, these value of the space sector in these areas is considerably higher than in most other UK regions. The academic landscape as shown in Figure 5 shows more geographic spread with leading institutions involved in space and space domain awareness located in the North East, North West, and Midlands regions. Ensuring that academia is able to remain a key contributor to SDA, through increased collaboration and clear funding (see Section 5.1.2), should result in these institutions continuing to prosper whilst proximity to leading institutions involved in space and SDA may influence commercial organisations into establishing facilities nearby and increasing the space sector value in these regions.

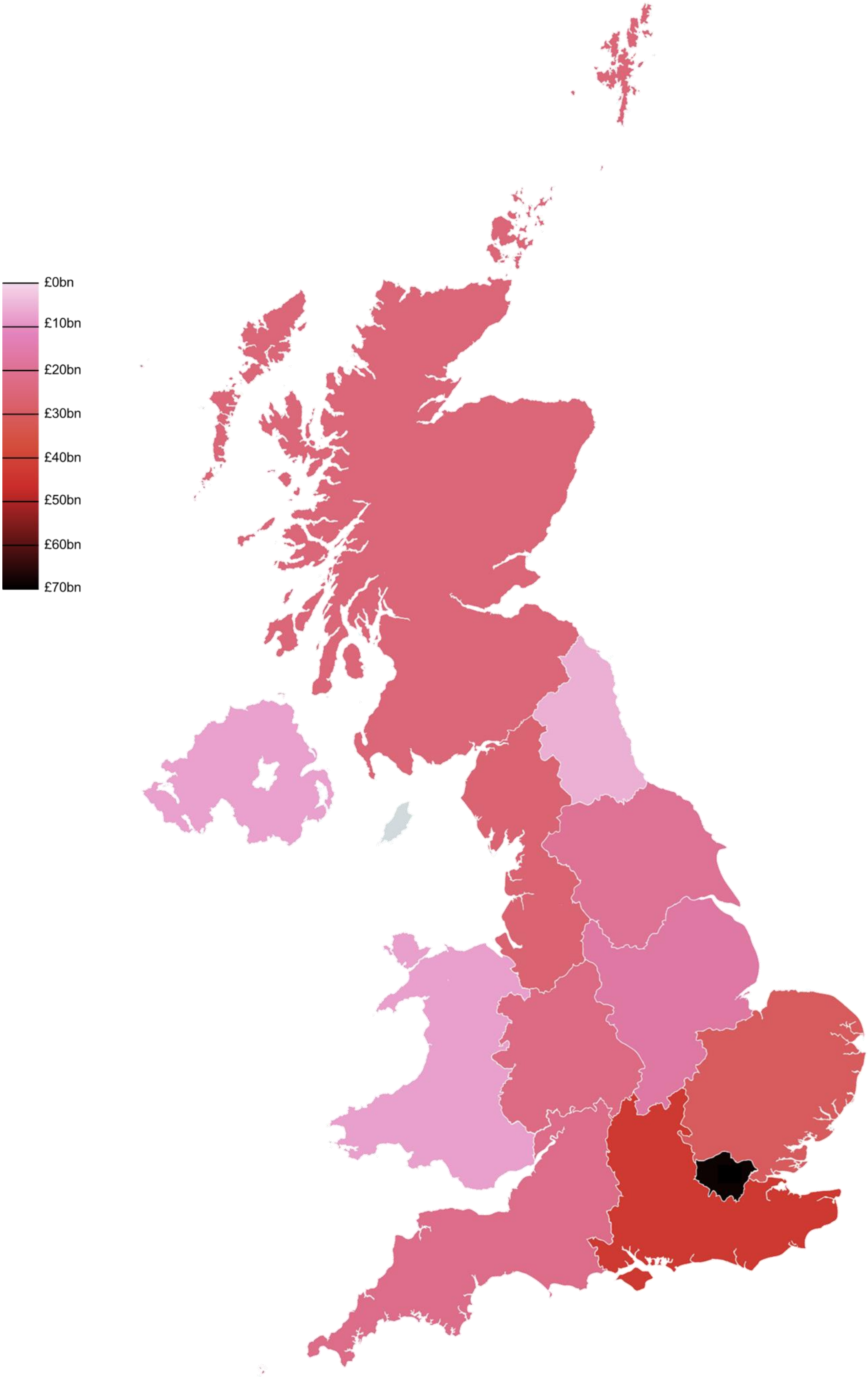


Figure 13: Space sector value by UK region (2020) [4]

4.4.3 Strategic benefits

4.4.3.1 Credible space nation

The UK is reliant on space sensor data provided by other nations and organisations. To move the UK to a better position to deliver on the current Government emphasis of a 'Science Superpower' and an 'Innovation Nation,' this reliance must be reduced. Investing in additional sensor capacity or analytical capabilities to provide high-quality products to aid global space domain awareness will not only help to lessen the reliance on other nations but also help to re-establish the UK as a key, credible, and reliable partner in the field by providing valuable contributions back into the global space community.

4.4.3.2 Delivering against the space strategies

The NSS identified four pillars to achieving its goals in space:

1. Unlocking growth in the space sector
2. Collaborating internationally
3. Growing the UK as science and technology superpower
4. Developing resilient space capabilities and services

Developing a space domain awareness capability will demonstrate progress against all four pillars, either directly or through the additional space technologies that it enables.

Pillar 1 – Unlocking growth in the space sector	**Pillar 2 – Collaborating internationally**
Space domain awareness is fundamental in ensuring the safe and sustainable operation of all space assets. It is therefore key to enabling growth in the space sector through other technologies such as space-based solar energy, in-orbit servicing and manufacturing and collision on launch assessments as previously highlighted.	Space domain awareness is not a sovereign endeavour. Whilst UK owned and operated sensors and analytical facilities will provide vital contributions, SDA requires effective international collaboration to share data, task foreign sensors and maintain custody of space objects. Space domain awareness is an excellent example of effective international collaboration and an enhanced UK SDA capability will further demonstrate the UK's commitment to its international partners.
Pillar 3 – Growing the UK as a science and technology superpower	**Pillar 4 – Developing resilient space capabilities and services**
To grow the UK as a science and technology superpower it must reduce its reliance on other nations for space data and services and endeavour to provide more back to the international community. The UK is home to a wide range of world-leading companies and academic institutions who have contributed to a number of domestic and international space accomplishments. With clear direction and funding, space domain awareness can provide the ideal opportunity to leverage this expertise.	SDA is at the heart of increasing the resilience and sustainability of space capabilities and services. As an essential component to the continued operation of space services, space domain awareness reduces the risk to on-orbit assets through enhanced conjunction analysis, collision avoidance and space weather forecasting. With the support of increased space domain awareness, the UK can develop and operate space capabilities and services with increased resilience and lower maintenance costs.

Equally, SDA capability development will present tangible progress towards the three strategic themes set out in the DSS:

1. Protect and Defend
2. Enhance Military Operations
3. Upskill and Cohere

Strategic Theme 1 – Protect and Defend	Strategic Theme 2 – Enhance Military Operations
Space domain awareness is the key to identifying and attributing threats to space systems thereby protecting UK space-based and space-enabled assets. Accurate characterisation and attribution of threats will also inform a proportionate response and enable effective offensive and defensive space control to ensure the safety and security of the UK, its allies, and partner nations.	The dual use nature of SDA means that in addition to enabling civil and commercial space operations, it is also fundamental to the delivery of military operations using space capabilities. Space is key to the Integrated Operating Concept 2025 (IOpC25) aim of Multi-Domain Integration which is reliant on the protection of PNT and communication services from space. SDA is vital in ensuring the continued operation of these services amid threats from space debris, space weather and hostile acts.

Strategic Theme 3 – Upskill and Cohere
Developing an enhanced SDA capability in the UK will require the close cooperation of UK military, civil, commercial and academic entities. This will generate a strong demand signal for qualified and educated individuals from all sectors in order to design, manufacture, operate and improve SDA systems to grow and maintain the UK's presence in this area.

4.4.4 Sustainability

The UK can become a global leader in space sustainability, setting the standard for other countries to follow. It has already committed to implementing the voluntary long-term sustainability guidelines of outer space activities [41] and is in the process of establishing an industry-led sustainability kitemark linked to licensing and environmental, social, and governance (ESG) standards to assist in raising finance and a Space Sustainability Institute. SDA will also contribute to the sustainability of space through a reduction in the manoeuvring requirements of objects in orbit, extending the lifespan of assets and reducing fuel consumption.

SPACE SUSTAINABILITY KITEMARK

A space sustainability kitemark is being developed to cover the design, manufacture, launch, operation, and demise of satellites. This industry-led standard, devised by industry and academia in collaboration with the CAA, will provide evidence of compliance with international sustainability best practice and will form part of the CAA satellite licensing process with final discretion left to the CAA.

It is envisioned that the expertise generated by the UK in this area as a result of the kitemark will contribute towards attractive trading and partnership propositions with other nations and demonstrate the UK's commitment to maintaining a safe and sustainable operating environment in space.

SPACE SUSTAINABILITY INSTITUTE

There is a proposal to establish a Space Sustainability Institute at Space Park Leicester led by the University of Leicester and in partnership with Alden Legal, several universities, and industry bodies. The Institute will lead global R&D on sustainability initiatives and contribute to the design and implementation of the sustainability kitemark. Related proposals being developed in other parts of the UK demonstrate the growing appetite amongst the academic community to make space sustainability a research priority.

REDUCED MANOUVREING

Enhancing SDA capability to provide accurate predictions of collisions will reduce the number of unnecessary manoeuvres performed by a satellite to avoid potential conjunctions. This could result in better service coverage as manoeuvres can cause satellites to temporarily lose their scheduled position and additionally should result in a cost saving due to the time and resources saved in planning and executing a potential manoeuvre. Furthermore, a reduction in fuel usage through fewer manoeuvres could considerably extend the lifespan of assets and reduce the number of additional launches required.

4.5 Barriers to SDA development

A number of barriers to achieving an effective and coherent SDA capability have been identified:

4.5.1.1 Lack of detailed SDA strategy

The fundamental, underpinning issue that has been identified during this study is a lack of clarity and agreement on what the UK's ambitions for SDA are and who the emphasis is on to deliver them. Government are not subject matter experts and rely on industry to articulate the art of the possible. However, whilst there is a great deal of expertise, experience, and enthusiasm in industry to develop SDA capabilities, without direction from the government there is a lack of coherence blocking potential progress.

Whilst SDA is prioritised in both the National and Defence space strategies, there is little detail as to what the UK's aims in this area are or what the £85m earmarked in the DSS for it over the next 10 years is to be spent on. It is unclear what the Civil funds available for SDA are.

4.5.1.2 Lack of sovereign sensors

The UK is heavily reliant on obtaining sensor data from other nations leaving it heavily exposed to risks to international relationships and bilateral or multilateral agreements. The UK's withdrawal from the European Union and subsequent departure from the EUSST programme means that reliance on data provided by the US Space Surveillance Network is near total. Whilst the risk of loss of access to this data is low, should this occur the UK has insufficient sovereign sensing assets to provide a suitable level of coverage to protect its sizable investments in space such as the Skynet and OneWeb systems. Without investment in sovereign sensing capability, there will continue to be safeguarding risk for these taxpayer-funded assets.

4.5.1.3 Funding

Significant barriers around SDA and more general space funding were identified. On an international level, the funding directed for space domain awareness in the DSS falls far short of what other nations have pledged for the area. As an example, Japan's intended SDA budget for the year 2022/23 is more than double the UK's budget for the next 10 years.

On a national scale, the study has identified a number of barriers regarding the access to funding for research in the SDA/SSA/SST areas. There is a perception that the level of funding for research activities is too low, too short-term focused and released in instalments that do not allow for continuous and coherent research. The application processes for research funding can also be arduous and require significant resource allowance which can preclude some smaller-scale researchers. Similarly, the approvals process within larger companies can prove prohibitive for sponsoring research.

4.5.1.4 Collaboration

Collaboration between industry and academia is vital to provide a viable dual use SDA capability but is inhibited by lack of significant and long-term sustainable funding for academia and fundamental differences in the way the two sectors operate. Study participants responded that there is insufficient awareness of each other's activities. Industry are not aware of what research is ongoing that may help them, academia is unaware of the needs of industry and opportunities to collaborate and commercialise their research.

5 Operating Models

5.1 Funding

5.1.1 Funding sources

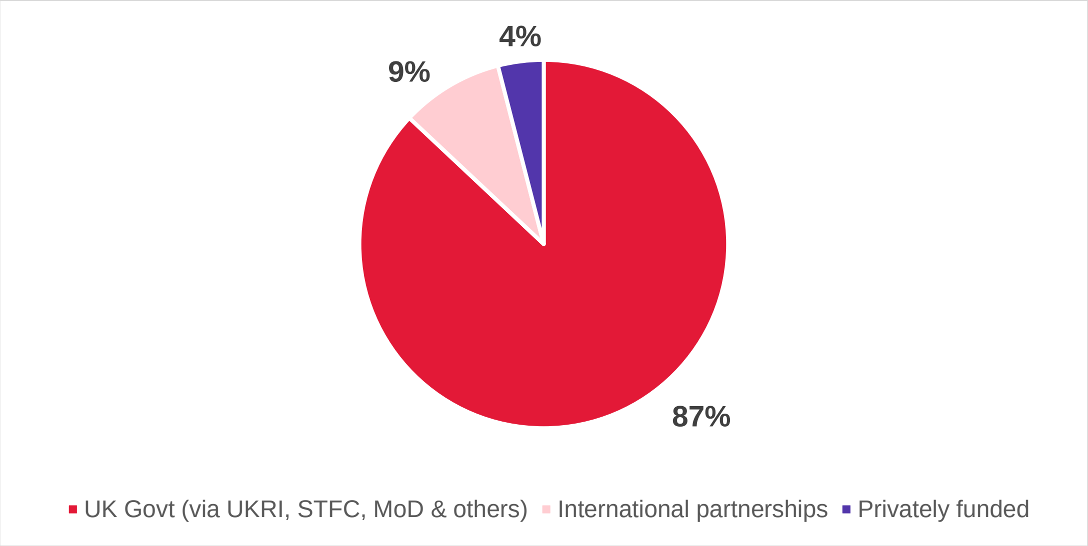


Figure 14: Primary SDA R&D funding sources as suggested by study contributors

The study addressed the question of how and by whom UK SDA R&D activities should be funded. Study participants responded near unanimously that primary funding should come from a national, government-funded programme aligned with a clear roadmap aimed at progressing R&D to a state of sufficiently clear return on investment to attract additional industrial funding. It was also noted that the UK's relationship with and commitment to ESA is essential to ensure that work continues to contribute to international efforts and fill gaps rather than risk duplication of funding.

5.1.1.1 UK national funding

The study returned broad agreement that SDA is a public good and should be funded by the UK Government as a centralised national programme including academia, industry, and UK civil entities. Positioning the Government as the initial customer for SDA will ensure the provision and maintenance of a safe and sustainable space environment and create a platform for commercial space opportunities such as those identified in 4.4.1. Once this is in place, commercial funding for the continued development of SDA can be considered. The increase in commercial activity as a result of SDA should also result in some indirect cost recovery through additional corporation and income tax revenues.

5.1.1.2 International funding

There is a possibility of additional funding for SDA capability from international collaborations and partnerships although the study respondents agreed that the area of opportunity has diminished following the withdrawal from the European Union and the EUSST programme. Despite this, the UK may be able to utilise its space relationships with other nations and supranational groups as identified in 4.3.2 to secure funding agreements and other collaborative endeavours for mutual benefit. It is imperative that UK SDA R&D remain closely aligned with international activities to avoid double-funding and duplication of existing capability.

5.1.2 Duration and scope

The study received strong input that quantity, delivery, and timescales of research funding is insufficient to ensure the progression of research into deliverable capability. Respondents felt that in general research funding suffered from short-termism with small sets of funding provided at intervals which do not fit with research timescales. Within academia, generally there is not capacity to support short-term programmes as there is in the commercial sector and instead a greater focus on long-term development without short-term return.

The process of applying for funding was also highlighted as potential prohibitive factor for some smaller-scale researchers. SDA benefits the UK across many different sectors and as such research scope can transcend the boundaries of individual research councils. Simplifying the process would reduce the resource burden of applying for funding and make it a more attractive proposition for to small-scale applicants.

RECOMMENDATION 5 – NATIONAL SPACE SUSTAINABILITY RESEARCH INSTITUTE

The funding mechanism for academic research should be revised to remove some of the main barriers to new and novel research. Primarily this should seek to simplify the application procedure, making funding available across various research councils - as recognition that the space sector underpins our way of life in all other sectors. The funding available also needs to be significant and long-term to ensure research can be taken through to deliverable capability. Government should consider establishing a National Space Sustainability Research Institute as a mechanism for simplifying and coordinating research and innovation funding.

5.2 Monetising

A key area of interest for the study was to identify which aspects of SDA, if any, could be monetised to provide a return on investment to the UK. **No clear route to monetisation has been identified** with the consensus of study respondents being that SDA is a public good that provides safety for the utilisation of space and that it should not be charged for. Capabilities that underpin SDA, such as SST, SSA as well as operations that are reliant on SDA such as STM have clearer and higher potential monetisation routes that are not explored in this study. A small set of potential monetisation routes for components of SDA have been highlighted, the clearest opportunities focusing around providing better, faster, and more accurate services than those currently available free-of-charge.

5.2.1 Raw data

Data acquired from additional sovereign sensors, ground-based or in-orbit, can be sold to other nations to supplement their own data or to commercial organisations.

5.2.2 Bespoke products

The UK could look to provide bespoke products and services using a combination of sovereign data and data acquired from other sources. This would emulate to a degree the model followed by commercial SDA providers such as LeoLabs and could cover specific applications such as damage assessments, insurance, and maintenance estimates as well as determining more detailed information about targets such as its spin and tumble rate. This could be provided as part of the space service desk opportunity identified in Section 4.3.3.1 and could look to close a number of the capability gaps stated in Section 4.2.

5.2.3 Increased accuracy

US SSN and EUSST already provide free basic SDA services as well as 24/7 support to operators/owners. For the US SSN this includes satellite catalogue data, re-entry predictions and position data in the form of Two-Line Element (TLE) sets and for EUSST comprises collision avoidance, re-entry analysis and fragmentation analysis services. Whilst there is limited scope to monetise this basic level of data, the UK could look to provide high-precision data for operations requiring a higher level of accuracy than is already freely available. A higher level of accuracy could generate significant operational cost savings through a reduction in the number of manoeuvres required and the subsequent fuel savings and mission life extension. As an example, the high level of accuracy with which Arianespace achieved the orbital insertion of the James Webb Telescope resulted in a significant saving on expected propellent requirements, as a result potentially doubling its mission lifetime [42].

RECOMMENDATION 6 – DATA ACCURACY STUDY

A study should be commissioned to assess the cost/benefit of increasing data accuracy to identify the point of diminishing returns. This study should conclude with a set of target figures for accuracy improvement over time to 2030 that can inform a plan for sensor enhancement.

5.2.4 Licencing fees

SDA is an enabler for safe and sustainable launching facilities, therefore there may be an opportunity to part-fund SDA capability development and improvement through a proportion of revenue generated from launch licensing fees. However, caution will be required to ensure that fees do not drive spacecraft operators elsewhere.

5.3 Collaboration

Effective domestic and international collaboration is one of the key requirements to successfully conducting SDA. As an international endeavour and shared interest, SDA relies on the sharing of sensor data, access to sensor networks and fast and reliable production of assured analysis products.

5.3.1 Domestic collaboration

The view from the UK industrial and academic sectors is that UK SDA programmes should be cross-sector, ensuring that defence, civil, commercial, and academic entities can all benefit from data sharing and collaborate. It is the opinion of industry that the programme should be civil-led as a defence-led programme may preclude effective collaboration with civil, commercial and academia due to data sensitivity and classification.

MILITARY - CIVIL

An excellent example of effective Military-Civilian collaboration and cooperation exists at the Swanwick air traffic control centre where military and civil air traffic control staff work together to ensure the safe passage of civilian and military aircraft over mainland UK and its coastal waters [43]. As a joint and integrated centre, military and civil operators are able to work side-by-side to effectively communicate and share data.

Physical colocation may not be required for a joint SDA capability and a number of geographically separate sites will add resilience and mitigate against a loss of service. However centralised data is required to ensure that military, civil and commercial operators are able to operate effectively together but deliver against their differing requirements separately and ensure no complete dependency on one another.

INDUSTRY - ACADEMIA

Effective collaboration between the academic and industrial sectors is crucial to leverage the considerable expertise and experience in both. Whilst there are examples of successful collaboration in this area, study participants highlighted that collaboration is hampered by fundamental differences of approach, research timescales and available funding. There is a need to better cohere the activities of academia with the demands of industry to provide good levels of awareness of the requirements and capabilities on both sides.

RECOMMENDATION 7 – COLLABORATION MARKETPLACE

To further encourage and nurture innovation, a collaboration marketplace should be established to bring academia and industry into alignment - building on the foundations established by the GNOSIS network. This would help to facilitate the matching of academic research with industrial demand, paving the way for faster and more efficient sponsoring of research. A similar recommendation was made to the European Council in 2019.

5.3.2 International collaboration

International collaboration for the generation of SDA is fundamental for all nations but particularly the UK due to its reliance on other nations for sensor data. Data obtained from international collaboration can augment data generated from sovereign sources. A number of international partnerships exist as detailed in Section 3.4, the most relevant to the UK being the US Space Surveillance Network of which it is a member, and EUSST of which it was a member prior to the UK's withdrawal from the European Union. Loss of access to EUSST was clearly identified as a significant disadvantage and it is recommended that the UK explore potential routes to re-entry as the EU is currently defining the rules regarding approval of users from non-EU countries [35].

5.3.3 The case for NSpOC

The NSS committed to the development of a joint civil/defence National Space Operations Centre as part of its prioritisation of a space command and control capability. This was endorsed by the DSS and will play a key role in ensuring the dual use of UK space capabilities. The concept of the NSpOC was put to study respondents and met with largely heavily positive feedback. The need for coherence of UK military, civil and commercial entities has been clearly articulated and such a capability would also provide the platform to explore the space service desk opportunity.

RECOMMENDATION 8 – SPACE SERVICE DESK

A national space operations centre, bringing together the civil, military, and commercial sectors would allow for the collection, consolidation, and exploitation of SST data to produce high quality analytical products would allow for the exploration of the space service desk opportunity. Developing a capability that is cross-sector will simplify the process of sharing data, ensuring it is not locked behind military over-classification and fully leverage the expertise in the commercial and academic space that has been identified in this study.

5.4 International Comparisons

This section provides a brief overview of the SDA coordination centres of a select group of other nations. Many of these coordination centres have recently been established, reflecting the relatively recent focus on SDA and as such unclassified information on these centres is somewhat scarce. The civil/military finding splits have also been identified, giving an idea of the relative responsibility that nations place on each sector to conduct SDA.

SDA COORDINATION CENTRES

UK		
Departments responsible for SDA	Military	Civil
	Royal Air Force – UK Space Command	UK Space Agency (UKSA)
Operating Centre	UK Space Operations Centre (UKSpOC)	

US		
Departments responsible for SDA	Military	Civil
	US Space Command	Department of Commerce
Operating Centre	18SPCS, Vandenberg Space Force Base	

Germany		
Departments responsible for SDA	Military	Civil
	German Air Force – Centre for Air Operations	German Aerospace Administration (DLR) – DLR Space Administration
Operating Centre	German Space Situational Awareness Centre (GSSAC)	

France		
Departments responsible for SDA	Military	Civil
	French Air and Space Force - French Space Command (CdE)	National Centre for Space Studies (CNES)
Operating Centre	None known	

Spain		
Departments responsible for SDA	Military	Civil
	Spanish Air Force	None known
Operating Centre	Spanish Space Surveillance and Tracking Operating Centre (S3TOC)	

Japan		
Departments responsible for SDA	Military	Civil
	Japan Air Self Defense Force (JASDF) – Space Operations Squadron *(from 2023)*	Japan Aerospace Exploration Agency (JAXA)
Operating Centre	None known	

MILITARY/NON-MILITARY FUNDING

Where possible, the military/non-military funding split for general space activities has been assessed. The UK space sector is military-dominant and, compared to all other nations considered in this analysis, is an outlier in that it diverts the majority of its government space spending to the military rather than the civil and commercial space sectors [24].

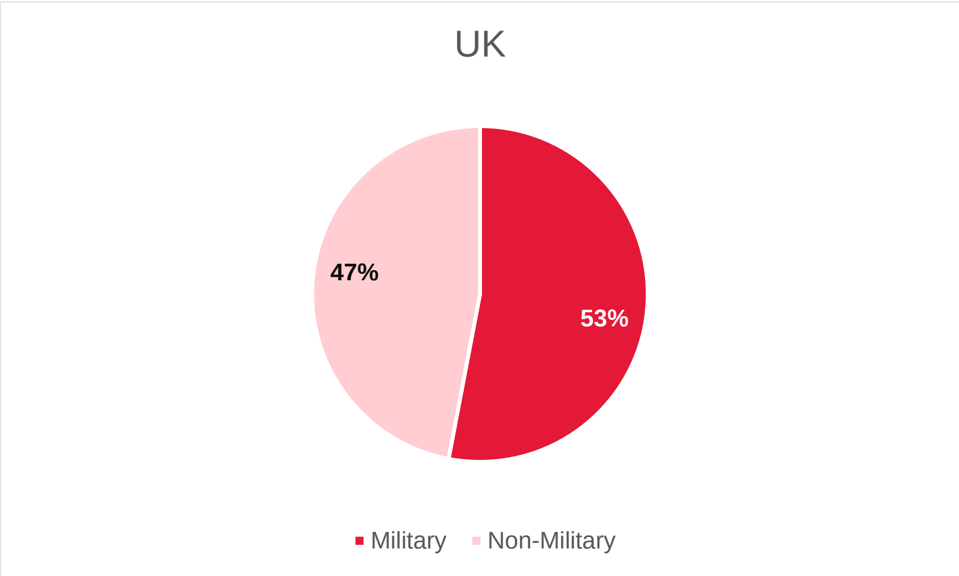


Figure 15: Proportion of UK space spending attributed to Military and Non-Military sectors

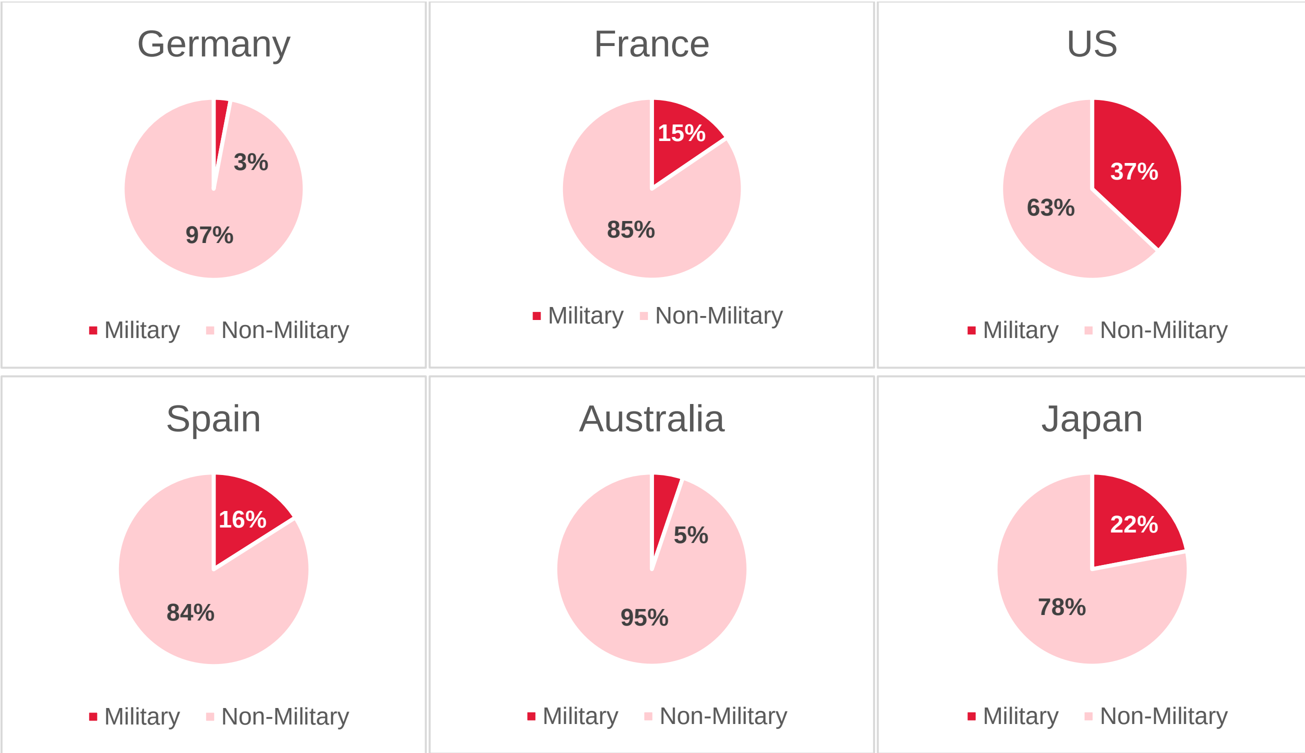


Figure 16: Proportion of space spending attributed to Military and Non-Military sectors for selected nations

6 Conclusions

THE NEED FOR SDA

Global economies and ways of life have reached a stage of critical dependency on space-based and space-enabled services. As the demand for space increases and the congestion in the LEO and GEO regimes with it, enhanced awareness, and management of the risks in, through, and from space are crucial for the continued functioning of our society The need for assured and actionable products to support decision making will continue to grow as the levels of space debris continue to increase. Robust and effective space traffic management will depend on rapid and efficient decision making supported by the fusion of sensor data from multiple sources around the globe into products and effective communication and collaboration channels to distribute them. Assured and validated data will inform everything from risk management decisions for insurers to mission-critical decisions for the military. All of which is made possible with space domain awareness.

SDA is crucial to the safe and sustainable operation of space-based assets and will underpin all future activities in the sector. It is a public good that must be provisioned to enable the continued use of space.

Investment in SDA is an investment in all space capabilities. It will secure the present and future of the existing capabilities the world is so reliant upon such as satellite communication, PNT and Earth Observation as well as unlock the potential of new and novel space technologies such as In-Orbit Servicing and Manufacturing, Active Debris Removal, and space-based solar power.

UK STRENGTHS

These new and novel technologies are being spearheaded by UK academic and commercial organisations and through continued investment will deliver enhanced SDA capability. The UK's academic sector is globally renowned and respected with many UK institutions consistently ranking amongst the best in the world. This is a strength that is being tapped into through research sponsored by UKRI and commercial organisations although more can and must be done to fully engage academia and facilitate effective collaboration with industry.

The UK commercial space industry is also thriving and in addition to the SDA-enabled technologies listed above, has a vital role to play in developing and delivering the capabilities required for generating SDA itself from industrialising new technology to delivering end-to-end SST services. There is a wealth of space expertise, experience, and enthusiasm within the UK ready to be deployed and awaiting clear direction to begin to move towards the shared interest of securing the UK's future in space.

THE NEED FOR STRATEGY

The national and defence space strategies have recognised the importance of SDA and prioritised it accordingly. They must now be used as a basis to define an SDA-specific strategy, articulating the UK aims and ambitions in SDA, and setting out the available funding and timescales with expected deliverables and measurements of progress. The Defence Space Strategy has also indicated the level of additional funding attributed to developments in SDA which, whilst a good start, will need to be increased to make a serious contribution to global space domain awareness, particularly given the level of funding announced by international partners, allies, and potential adversaries. Funding for R&D must be set out the strategy but must also be increased, made more sustainable and easier to access, and focused on activities that provide tangible and considerable progress towards goals defined in the SDA-specific strategy.

DUAL USE

The UK space sector is, in contrast to many other nations, military dominant. However, with over 1200 UK commercial and academic organisations involved in space-related activities, effective collaboration between military and civil space is essential. The obvious synergies between military and civil requirements for SDA means that a dual use approach to capability development (as is already underway through the enhancement of the UKSpOC) will serve to optimise the use of available funding and maximise the national return on investment. The National Space Operations Centre concept, endorsed in both the national and defence space strategies was also explored through the study and garnered support from civil respondents for its proposed aim and operating model.

OPPORTUNITIES

There are opportunities for the UK to exploit in three primary areas: enhancing its sovereign sensing capabilities, acquiring additional data from external sources, and offering analytical products. To achieve the former, the UK can look to use its unique geography to provide novel observations in addition to its current capabilities such as those located in Cyprus. The UK can also explore the usage of its territories in the south Atlantic and collaboration with allies and partner nations, such as through its recent Space Bridge partnership with Australia, to acquire or provide additional high-quality data. With regards to providing analytical products, the UK could use its NSpOC concept to synergise the best in military, civil and commercial capability to deliver high-quality or bespoke products to other nations or commercial operators.

BENEFITS

Much of the financial benefit and return on investment from SDA comes from the mitigation of risk to and enablement of all current and future space services and technologies. The monetary value of protecting GNSS services alone stands at over £1bn per day and the potential damage to the societal and political fabric of the UK is enormous. The protection of space assets and the services they provide is of such paramount importance to the entirety of the UK economy that it should not be considered as a potential expense but as fundamental necessity that cannot be done without. SDA is not a service that is extensively monetised by other nations but is instead largely provided, at least on a basic level, for free as a public good and for the benefit of safe and sustainable space operations.

That is not to say there is no financial incentive for the procurement and development of SDA capability. In addition to the monetary risk mitigated, SDA unlocks the value of the new and novel technologies identified earlier with the targeted UK share of the IOSM market valued at $1bn by 2030 and the potential benefits of space-based solar power estimated in the tens of billions. Whilst not the primary driver for SDA, the estimated cumulative return on investment for SDA, based on an investment of £568m up to 2031 is £2.1bn based on risk reduction and opportunity enablement.

As a national capability developed for the benefit of the UK population and economy, Government should become the initial customer for SDA. By doing so, and in turn establishing the direction and funding to engage the UK’s considerable commercial and industrial expertise, Government will ensure a safe and sustainable space environment and unleash the potential of all commercial space opportunities. This will also realise the strategic benefit of SDA which is to provide capability that demonstrates delivery of all four pillars of the National Space Strategy and against all three strategic goals of the Defence Space Strategy.

7 Recommendations and Roadmap

7.1 Recommendations

Recommendations below are numbered based on their order of appearance in the document. For clarity, these recommendations have been grouped into four separate themes.

7.1.1 NSpOC Recommendations

RECOMMENDATION 8 – SPACE SERVICE DESK

A national space operations centre, bringing together the civil, military, and commercial sectors would allow for the collection, consolidation, and exploitation of SST data to produce high quality analytical products would allow for the exploration of the space service desk opportunity. Developing a capability that is cross-sector will simplify the process of sharing data, ensuring it is not locked behind military over-classification and fully leverage the expertise in the commercial and academic space that has been identified in this study.

RECOMMENDATION 2 – SDA ADVISORY GROUP

An advisory group for SDA should be established and membership extended to industry leaders and academics as well as civil and military representatives to advise and guide on developing UK SDA capability. The group should make recommendations on capability and data procurement and the UK's contribution to global SDA as well as influence policy and decision making

RECOMMENDATION 7 – COLLABORATION MARKETPLACE

To further encourage and nurture innovation, a collaboration marketplace should be established to bring academia and industry into alignment. This would help to facilitate the matching of academic research with industrial demand, paving the way for faster and more efficient sponsoring of research. A similar recommendation was made to the European Council in 2019.

7.1.2 Sensor Recommendations

RECOMMENDATION 6 – DATA ACCURACY STUDY

A study should be commissioned to assess the cost/benefit of increasing data accuracy to identify the point of diminishing returns. This study should conclude with a set of target figures for accuracy improvement over time to 2030 that can inform a plan for sensor enhancement.

RECOMMENDATION 4 – R&D FOR SENSOR IMPROVEMENTS

The UK's relative trailing position in global space and SDA gives it the opportunity to craft a strategy aimed at filling the gaps in global capability. Investment in sovereign sensors can help to close these, either through offering novel sensing methods or installing sensors into regions of low coverage, improving the UK's sovereign sensing capability, and adding to the UK's credibility in international governance and participation in the space sector. This would represent a small but noticeable step in catching up to its allies as well as enhancing global SDA for the benefit of all.

7.1.3 R&D Recommendations

RECOMMENDATION 1 – SDA STRATEGY

To effectively bring together academia, industry, civil and military entities, the UK requires a coherent, cross-Government SDA strategy and vision. This will provide clarity on the intended aims for the UK in SDA and enable industry and academia to deliver against them and provide assurance that the UK is committed to the long-term development of SDA.

RECOMMENDATION 5 – NATIONAL SPACE SUSTAINABILITY RESEARCH INSTITUTE

The funding mechanism for academic research should be revised to remove some of the main barriers to new and novel research. Primarily this should seek to simplify the application procedure, making funding available across various research councils - as recognition that the space sector underpins our way of life in all other sectors. The funding available also needs to be significant and long-term to ensure research can be taken through to deliverable capability. Government should consider establishing a National Space Sustainability Research Institute as a mechanism for simplifying and coordinating research and innovation funding

7.1.4 Collaboration Recommendations

RECOMMENDATION 3 - MAINTAINING INTERNATIONAL COLLABORATION

The UK should attempt to maintain the strongest possible ties with ESA and attempt to participate and collaborate in joint programmes to strengthen global SDA for the common good. Outside of ESA, the UK should look to establish, where not already extant, bilateral data sharing agreements with Five Eyes partners and other nations to continually ensure access to a wide variety of high-quality data.

7.2 SDA Roadmap

The following example roadmap is based on the recommendations given in Section 7.1

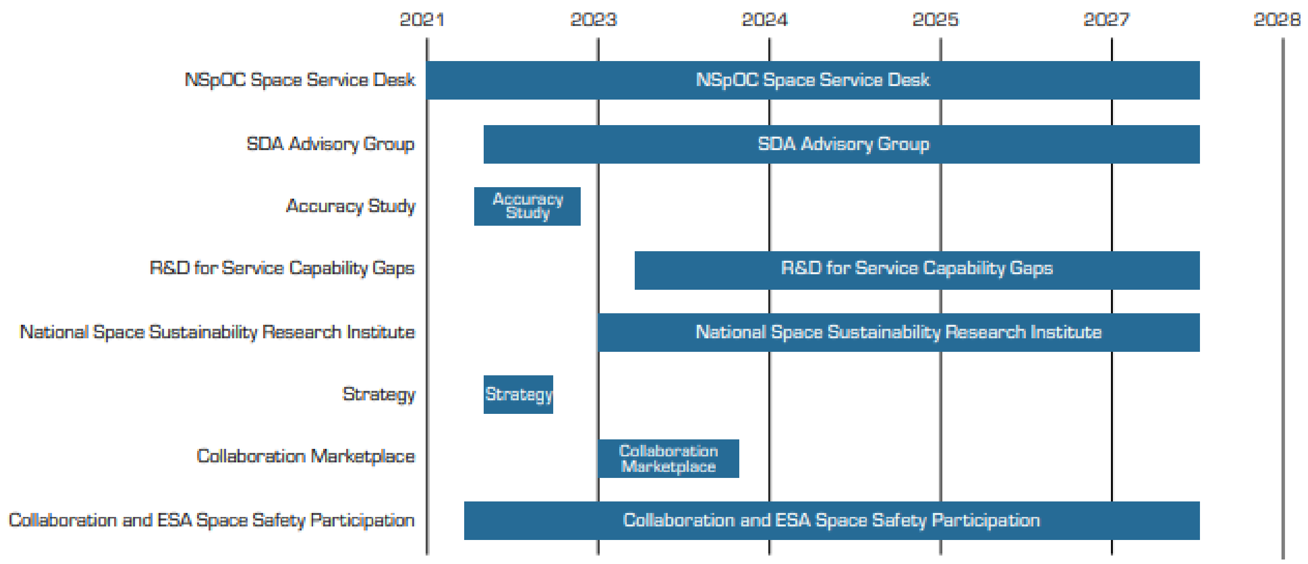


Figure 17: Candidate roadmap for SDA delivery

7.3 Investment and Expected Returns on Investment

The following high level investment estimates are provided for information only. They are based on the roadmap given above, figures supplied during the study and the current ESA Space Safety budget proposals. It is assumed that some of the sensor development, such as Space Based SSA sensors and Laser Ranging may be funded via the current ESA programs.

The investment figures are as follows:

- NSpOC investments are based on figures supplied by industry and current values ESA budget requests to provide similar facilities under the ESA Space Safety program. This does not include funding existing UKSA or Space Command facilities or personnel.
- New sensor investments are based on figures supplied by industry and current values ESA budget requests for Space Weather, VISDOMS and similar projects. This does not include the budget for Lagrange (Vigil). This does not include funding existing UKSA or Space Command facilities or personnel.
- New SDA R&D investments are based on figures supplied by industry and current values ESA budget requests for COSMIC, Competitiveness Element and similar projects.

The Return-on-Investment estimates are high-level lower estimates based on:

- The value of the UK investments, given in the investment columns, on the assumption that the majority of the work will be done in the UK.
- The export values of the skills and data developed on the basis that the skills will enable UK companies to access non-UK opportunities (such as USA and Australia) and that the SDA data generated can either be sold or exchanged with UK allies.
- Value of space-based services relying on more precise SSA, including space based solar power and In-orbit servicing and manufacturing. The values taken only represent a small percentage of the values of these services to UK, see Section 4.4.1.2, to provide a lower estimate.

Two scenarios are presented. The ambitious scenario in Section 7.3.1 assumes that the UK has achieved its ambitions in developing space-based services and has generated the required level of SDA to enable them. The conservative scenario in Section 7.3.2 is calculated on an assumption that the UK still has a substantial space-based economy but has not achieved its ambitions in developing the space-based services as listed above and that other nations have stepped in to develop this capability instead.

7.3.1 Ambitious scenario

This scenario is based on stated UK ambitions in IOSM and space-based solar power.

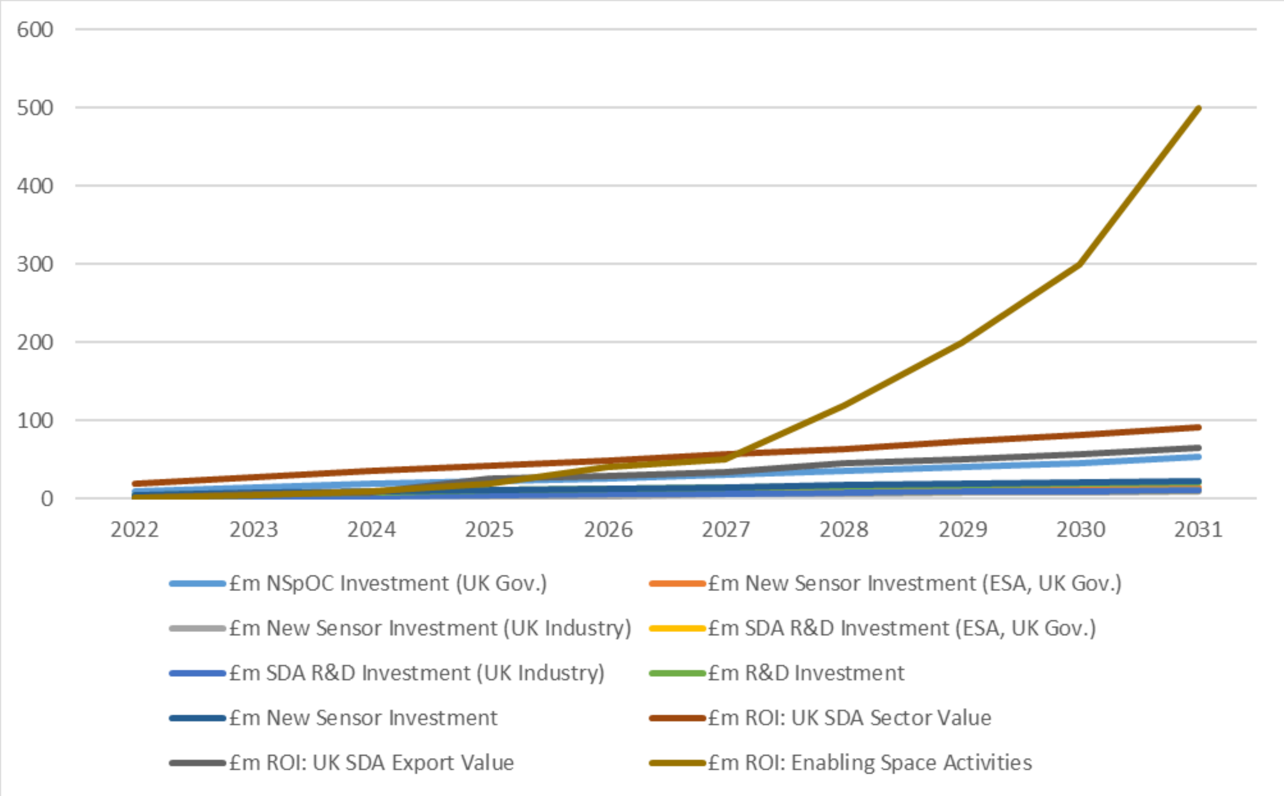


Figure 18: Estimated ROI to 2031

Year	£m							
	NSpOC Investment (UK Gov.)	New Sensor Investment (ESA, UK Gov.)	New Sensor Investment (UK Industry)	SDA R&D Investment (ESA, UK Gov.)	SDA R&D Investment (UK Industry)	ROI: UK SDA Sector Value	ROI: UK SDA Export Value	ROI: Enabling Space Activities
2022	10	3	3	3	2	19	2	2
2023	15	4	4	4	3	27	5	5
2024	20	5	5	5	3	36	7	10
2025	23	9	2	6	4	42	25	20
2026	26	10	3	7	5	49	29	40
2027	30	9	6	8	6	56	34	50
2028	35	10	7	9	7	64	45	120
2029	40	11	8	9	9	73	51	200
2030	46	13	8	10	10	82	57	300
2031	53	14	9	10	10	92	64	500

Figure 19: Breakdown of estimated ROI to 2031

7.3.2 Conservative scenario

This scenario is based on the UK not achieving its stated ambitions in developing space-based services but still having a substantial space-based economy.

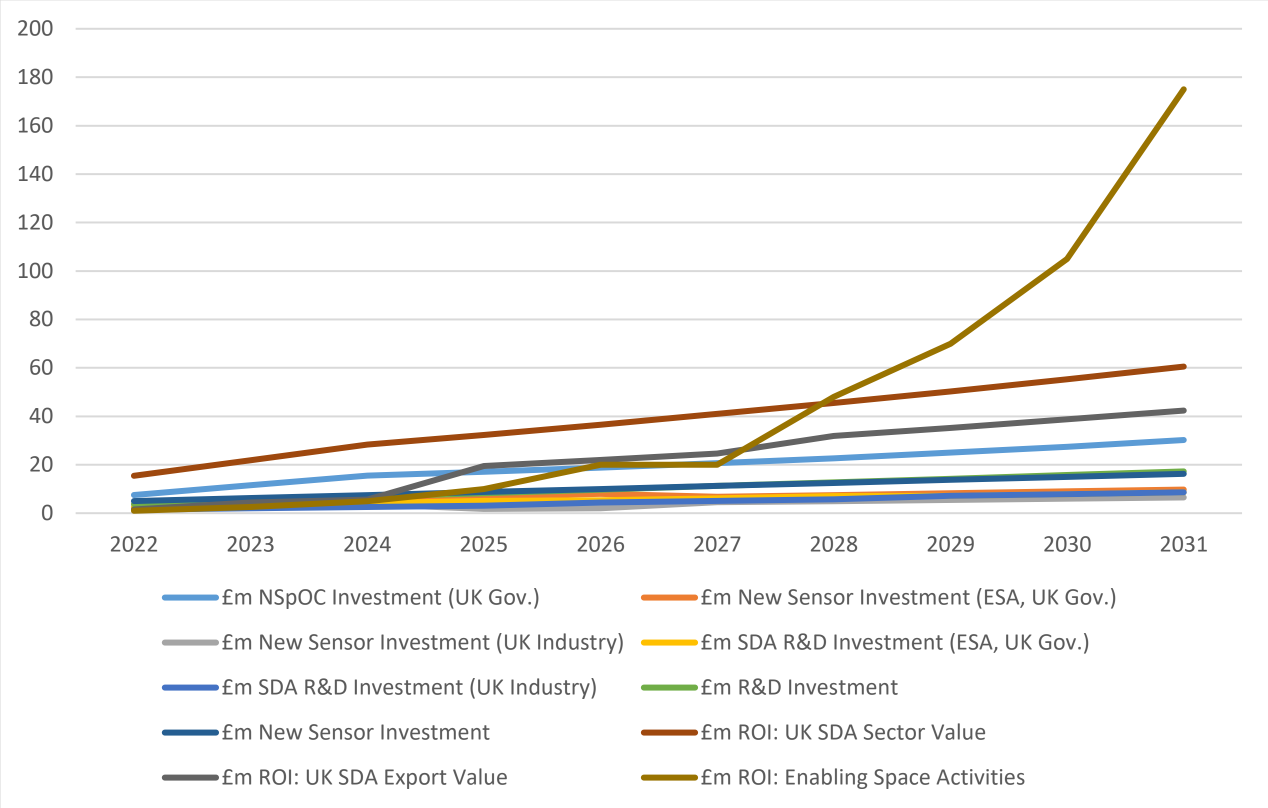


Figure 20: Conservative estimated ROI to 2031

Year	£m							
	NSpOC Investment (UK Gov.)	New Sensor Investment (ESA, UK Gov.)	New Sensor Investment (UK Industry)	SDA R&D Investment (ESA, UK Gov.)	SDA R&D Investment (UK Industry)	ROI: UK SDA Sector Value	ROI: UK SDA Export Value	ROI: Enabling Space Activities
2022	8	3	3	2	1	15	2	1
2023	12	3	3	3	2	22	4	3
2024	16	4	4	4	3	28	6	5
2025	17	7	2	5	3	32	19	10
2026	19	8	2	5	4	37	22	20
2027	21	7	5	6	5	41	25	20
2028	23	8	5	7	6	46	32	48
2029	25	8	6	7	7	50	35	70
2030	27	9	6	8	8	55	39	105
2031	30	10	7	9	9	61	42	175

Figure 21: Breakdown of conservative estimated ROI to 2031

8 References

[1] HM Government, “National Space Strategy,” HM Government, 2021.

[2] Ministry of Defence, “Defence Space Strategy,” Ministry of Defence, 2022.

[3] KPMG, “30 Voices on 2030 - The future of space,” KPMG, 2020.

[4] know.space, “Size & Health of the UK Space Industry 2020,” UKSA, 2021.

[5] WPI Strategy, “Securing our future in space,” UKspace, 2020.

[6] London Economics, “Commercial Space Surveillance and Tracking Market Study,” UKSA, 2020.

[7] AXA, “Space Risk Update,” 2022.

[8] “New SMC Focus: Space Control, 'Domain Awareness',” 21 Oct 2019. [Online]. Available: https://breakingdefense.com/2019/10/new-smc-focus-space-control-domain-awareness/. [Accessed 3 March 2022].

[9] Department for Business, Energy & Industrial Strategy, “UK Severe Space Weather Preparedness Strategy,” BEIS, 2021.

[10] PECASUS, “About Us,” [Online]. Available: https://pecasus.eu/?page_id=265. [Accessed 13 March 2022].

[11] Royal Air Force, “Commander of UK Space Command visits RAF Fylingdales,” 3 June 2021. [Online]. Available: https://www.raf.mod.uk/news/articles/commander-of-uk-space-command-visits-raf-fylingdales/#:~:text=The%20Solid%2DState%20Phased%20Array,can%203000%20miles%20into%20space.. [Accessed 13 March 2022].

[12] Science and Technology Facilities Council, “Chilbolton Observatory,” [Online]. Available: https://www.chilbolton.stfc.ac.uk/Pages/Space-Monitoring-Facility.aspx. [Accessed 13 March 202].

[13] D. Ladd, “Technical Description of a Novel Sensor Network Architecture and Results of Radar and Optical Sensors contributing to a UK Cueing Experiment,” Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference, 2017.

[14] Space Geodesy Facility, “Satellite Laser Ranging,” [Online]. Available: http://sgf.rgo.ac.uk/work/slr.html. [Accessed 13 March 2022].

[15] MapAnalytica, SJE Space, Inverse Quanta, “UKSA Future SST Markets Research,” UKSA, 2020.

[16] OECD, “The Space Economy in Figures: How Space Contributes to the Global Economy,” OECD Publishing, Paris, 2019.

[17] OECD, “Space Economy for People, Planet and Prosperity,” OECD, 2021.

[18] The Liverpool Telescope, “Monitoring Maintenance in Geostationary Orbit,” [Online]. Available: https://telescope.livjm.ac.uk/News/#MEV2. [Accessed 7 April 2022].

[19] University of Bath, “Space Debris Imaging,” [Online]. Available: https://www.bath.ac.uk/publications/technologies-available-for-licensing/attachments/space-debris-imaging.pdf. [Accessed 7 April 2022].

[20] GNOSIS, [Online]. Available: https://gnosisnetwork.org. [Accessed 13 April 2022].

[21] UKRI, “SWIMMR (Space Weather, Instrumentation, Measurement, Modelling and Risk),” [Online]. Available: https://www.ralspace.stfc.ac.uk/Pages/SWIMMR.aspx. [Accessed 5 April 2022].

[22] University of Warwick, “Centre for Space Domain Awareness,” [Online]. Available: https://warwick.ac.uk/fac/sci/physics/research/astro/csda/. [Accessed 6 April 2022].

[23] “Rise in STEM popularity amongst A-level students,” 16 August 2018. [Online]. Available: https://www.sciencecampaign.org.uk/news-media/case-comment/rise-in-stem-popularity-amongst-a-level-students.html. [Accessed 4 March 2022].

[24] Space Foundation, “The Space Report Q2 2020,” Space Foundation, 2020.

[25] ESA, “Funding,” 2022. [Online]. Available: https://www.esa.int/About_Us/Corporate_news/Funding. [Accessed 7 March 2022].

[26] Space News, “Japan budgets a record $4.14 billion for space activities,” 9 March 2021. [Online]. Available: https://spacenews.com/japan-budgets-a-record-4-14-billion-for-space-activities/. [Accessed 4 March 2022].

[27] ESA, “Funding,” [Online]. Available: https://www.esa.int/About_Us/Corporate_news/Funding. [Accessed 5 April 2022].

[28] ESA, “ESA's new Space Safety Programme,” 6 February 2020. [Online]. Available: https://www.cosmos.esa.int/documents/336356/336472/ESAs_Space_Safety_programme_-_Koschny_2020-02-06+%283%29.pdf/89f2535e-a3fd-bc07-ce42-b51036b099f5?t=1581357083505. [Accessed 7 April 2022].

[29] ESA, “ESA Space Weather Service Network,” [Online]. Available: https://swe.ssa.esa.int/web/guest/. [Accessed 7 March 2022].

[30] EUSST, “Services,” [Online]. Available: https://www.eusst.eu/services/. [Accessed 8 March 2022].

[31] EUSST, “3rd EU SST Webinar: Building the future of SST,” 2021.

[32] Secure World Foundation, “US Policy and Capabilities on SSA,” 24 January 2019. [Online]. Available: https://swfound.org/media/206348/weeden-us-policy-and-capabilities-for-ssa.pdf. [Accessed 8 March 2022].

[33] [Online]. Available: https://www.nato.int/cps/en/natohq/news_185365.htm.

[34] S. Eves, *Space Domain Awareness Research Institute (SDARI) Technical Input,* SJE Space Ltd.

[35] EUSST, “FAQ,” [Online]. Available: https://www.eusst.eu/about-us/faq/. [Accessed 8 March 2022].

[36] UK Government, “G7 nations commit to the safe and sustainable use of space,” [Online]. Available: https://www.gov.uk/government/news/g7-nations-commit-to-the-safe-and-sustainable-use-of-space. [Accessed 6 April 2022].

[37] UK Government, “Memoranda of understanding (MOU): international,” 1 April 2022. [Online]. Available: https://www.gov.uk/government/publications/memoranda-of-understanding-international. [Accessed 6 April 2022].

[38] London Economics, “The economic impact on the UK of a disruption to GNSS,” UKSA, 2017.

[39] Astroscale, Fair-Space, Catapult, “UK In-Orbit Servicing Capability,” UKSA, 2021.

[40] Frazer-Nash Consultancy, “Space Based Solar Power,” Department of Business, Energy, and Industrial Strategy, 2021.

[41] “Committee on the Peaceful Uses of Outer Space - Scientific and Technical Subcommittee,” in *United Kingdom Update on its Reporting Approach for the Voluntary Implementation of the Guidelines for the Long-Term Sustainability of Outer Space Activities*, Vienna, 2022.

[42] ESA, “Precise Ariane 5 launch likely to extend Webb's expected lifetime,” [Online]. Available: https://www.esa.int/Science_Exploration/Space_Science/Webb/Precise_Ariane_5_launch_likely_to_extend_Webb_s_expected_lifetime. [Accessed 5 April 2022].

[43] Royal Air Force, “Swanwick (78 Squadron),” [Online]. Available: https://www.raf.mod.uk/our-organisation/stations/swanwick-78-squadron/. [Accessed 30 March 2022].

[44] Innovation Finance Advisory, “The future of the European space sector,” The European Commission, 2019.

[45] ESA, “New laser station lights the way to debris reduction,” 15 February 2022. [Online]. Available: https://www.esa.int/Safety_Security/Space_Debris/New_laser_station_lights_the_way_to_debris_reduction. [Accessed 7 March 2022].

Appendix A Academic organisations

Institution	SDA and related activities
Durham University	Hosts the Centre for Advanced Instrumentation, which includes a precision optics lab, a large Adaptive Optics research group and research into optical tracking techniques including Adaptive Optics for Satellite Laser Ranging and novel passive optical sensing capabilities for LEO and GEO. There is also a group researching responsible space exploitation and space ethics.
Heriot-Watt University	Research into multi-sensor multi-target tracking techniques for Space Situational Awareness; the theory and applications of multi-object estimation algorithms for sensor fusion problems; multiple object filtering that span the development of novel algorithms and methodology for multi-object tracking to the deployment and demonstration for commercial applications.
Imperial College London	Developing new innovative capabilities in space plasma and space weather simulations to better understand the interaction between the Earth and the Sun. Global simulations of the interaction between the magnetised solar wind plasma and the Earth's magnetosphere are crucial for placing satellite observations in the proper context and for providing a better understanding of magnetospheric structure and dynamics under all possible input conditions. Furthermore, magnetospheric simulations are a key component in efforts to predict space weather.
Liverpool John Moore's University	Operates the Liverpool Telescope, a major 2-metre primary diameter robotic telescope on La Palma. This telescope has the potential to monitor satellites in GEO orbit and scientific missions on more distant trajectories, such as Gaia. The system has been used to contribute to the Dstl project Phantom Echoes, which monitored the recent satellite servicing mission conducted by MEV-1.
Northumbria University	Teaching and research of space law and published extensively on the legal and ethical underpinnings of space governance
Queens University Belfast	Led the Inouye Solar Telescope project. This telescope allows the study of the physical processes at work in the Sun's atmosphere at unprecedented levels of detail. This telescope will improve our understanding of what drives space weather and help forecasters better predict solar storms.
University College London	Research into spacecraft orbit dynamics, working specifically on photon pressure effects (solar radiation pressure, thermal forces, earth radiation pressure).
University of Bath	Real-time autonomous systems for rapid discovery, identification, classification, and follow-up of astrophysical transients at optical and other wavelengths. Space technology applications in real-time data analytics and novel, patent-protected space-debris sensing technology
University of Bristol	Modern astronomy produces vast amounts of data, both direct images of the sky from telescopes operating at a range of frequencies and the results of processing these images in several ways. Sophisticated software is required to extract scientific results from these data. Work has focussed on processing catalogues of astronomical objects (galaxies and stars), particularly in the context of the emerging Virtual Observatory, the worldwide collection of interoperating astronomical data archives and tools.

University of Cambridge	The astrophysics group conducts a wide range of research activities and projects, with particular emphasis on interferometry. Research includes imaging theory, phase retrieval, speckle imaging, atmospheric turbulence, seeing theory, wave-front analysis, and adaptive optics.
University of Edinburgh	Collaborating with researchers at Lockheed Martin's Advanced Technology Centre on the application of survey astronomy techniques to space situational awareness for several years, leading development of an archive for satellite data taken by Lockheed Martin at UKIRT and installing a prototype 'FireOPAL' detector at the Royal Observatory Edinburgh.
University of Lancaster	Research into space weather to investigate the mechanisms by which the Sun controls near-Earth space to better understand the risks posed to high-tech infrastructure both on and above the surface of our planet. The team also runs the AuroraWatch service which provides forecasts of displays of the northern lights over the UK.
University of Leicester	Home to wide-ranging engineering expertise of relevance to Space and other applications including mechanical, thermal, and optical engineering; space nuclear power systems; orbital and radiation analysis; digital and analogue electronics (including high speed electronics), and embedded (FPGA and processor) systems.
University of Manchester	Involved in Space Systems Engineering which has capabilities in spacecraft systems, payload development, spacecraft orbital aerodynamics and spacecraft propulsion, the group develops novel and innovative solutions through new systems approaches and technologies.
University of Oxford	Development of advanced data analysis methods for astronomical time-series data and uses Gaussian Process regression, a Bayesian probabilistic machine learning technique, to model planetary signals alongside complex noise sources, whether stellar or instrumental.
University of Reading	Research into space weather prediction using statistical techniques and the effect it has on humans and technology such as power grids, aircraft, and satellites
University of Southampton	Developed the DAMAGE space debris model, used to provide analyses for the UK Space Agency since 2004, as a member of the Inter-Agency Space Debris Coordination Committee (IADC). Developed IADC space debris mitigation guidelines for the disposal of Geostationary satellites and IADC recommendations for the operation of large constellations of satellites.
University of Strathclyde	Research into precise orbit determination and modelling of the dynamics of space debris. Developing high-fidelity numerical models of physical phenomena that affect the shape, attitude, and motion of resident space objects.
University of Surrey	Research into the effects of space weather on operational spacecraft, especially electrostatic phenomena, and single event effects.
University of Warwick	Established the Centre for Space Domain Awareness in 2021. Working with Dstl on LEO/GEO surveys, sensor architecture and object characterisation amongst others and also operates facilities such as the SuperWASP in the Canary Islands and South Africa which is primarily tasked with the search for exoplanets.

Appendix B Industrial organisations

Organisation	Description
AAC Clyde Space	AAC Clyde Space specialise in small-sat technologies to provide space data to organisations, governments, and educational institutions. Also conducts operations in Sweden, the Netherlands, USA, and South Africa.
Airbus Group Limited	Airbus is the largest commercial aerospace company in the UK. It designs and manufactures advanced satellites and systems for telecommunications, Earth observation, navigation, and science programmes. A significant percentage of TV programming for the county is broadcast by Airbus-built satellites in geostationary orbit. The UK's Skynet military communications network is managed by Airbus under a PPP contract. Airbus is also the manufacturer of the OneWeb satellites, a major UK-licensed mega-constellation which will be deployed in LEO. In the SSA domain, Airbus has led the construction of the Solar Orbiter probe, an ESA mission designed to gain an improved understanding of the Sun. It is anticipated that they will also be involved in future initiatives such as the proposed Lagrange (Vigil) mission. Airbus offers a range of capable satellite LEO platforms in the Astrobus series, all of which could potentially be used for SST – indeed, video imagery of Envisat collected by one of the Pleiades constellation of satellites has been seen in the public domain. Airbus has significant experience in developing remote sensing systems including the synthetic aperture radar technology behind the NovaSAR and Oberon satellite concepts. Synthetic Aperture Radar payloads designed for Earth observation suffer the limitation that signals above a frequency of 50 GHz do not propagate well through the Earth's atmosphere, and this limits the bandwidth that can be used, (and hence the resolution of the images that can be obtained). No such limitation applies to space-based systems, with the result that a satellite SAR designed for SST could deliver optical-quality data at extended ranges and in all target lighting conditions.
Alden	Alden are legal, regulatory, policy and consultancy experts with significant expertise in satellite, space and communications law, policy, and regulations. In the SSA/SDA area, they have been involved in a number of SSA articles and studies and are currently leading on work to establish a kitemark. Alden are also involved in the establishment of a Space Sustainability Institute at Space Park Leicester.
Astroscale	Astroscale's forthcoming mission, scheduled to launch in 2020, consists of two spacecraft; a Servicer (~184 kg) and a Client (~20 kg), will be launched stacked together. The mission is operated from the National In-orbit Servicing Control Centre Facility in Harwell, UK, which is being developed by Astroscale as a key part of the ground segment. In order to perform effective rendezvous and docking, the Astroscale Servicer will be equipped with sensors that allow it to perform proximity operations without endangering either the Servicer or its target. These sensors have significant potential for delivering new high-resolution "satellite inspection" products that could not be generated on the ground due to the range between the sensor and the target.
BAE Systems Plc	BAE Systems provide high-reliability, radiation-hardened space electronics, space-resilient mission payloads, and secure ground solutions for a variety of U.S. Department of Defense (DoD), national security, civil, and commercial/private space missions. Payloads of potential relevance to SST include radio frequency (RF) and infrared (IR) sensors, digital receivers, reconfigurable processing modules, and solid-state recorders. In particular, BAE Systems manufacture a satellite radar warning receiver which can identify when a satellite vehicle is being tracked.

Organisation	Description
Boeing Defence UK	Boeing design and build advanced space and communications systems for military, commercial and scientific uses, including advanced digital payload, all-electric propulsion and 3D manufacturing capabilities for spacecraft that can operate in the geosynchronous, medium-Earth-orbital, or low-Earth-orbital regimes. Boeing products include the Space based Surveillance System (SBSS) satellites
CGI	CGI delivers complex, mission-critical space systems and software which has supported the missions of over 200 satellites. CGI in partnership with the RAF and UKSA have designed, developed, and deployed the first element of AURORA software as part of work to enhance the current UK Space Operations Centre. AURORA forms part of the national Space Surveillance and Tracking capability and is used by analysts to monitor the increasing hazard of orbital debris. CGI has previously worked on European projects such as Galileo as well as domestic initiatives such as the transformation of the UKSpOC.
Clutch Space Systems	Clutch Space provide systems and services to increase the utility and capacity of ground stations through control, operation and communication with remote satellites and other platforms, including the telemetry, tracking & control, transmission, and reception of payload data for ground processing. The Clutch-AnyBAND range of products is a fully virtual ground station solution that offers operators a lower cost alternative for S- and S-/X- band transmissions. It is planned to be developed further to offer Ka, Ku and X-Band services.
Deimos Space UK	Deimos seeks to address the UK market for space systems, services and applications including Mission and Flight Engineering; Ground Segment Systems; Flight Software Systems; Global Navigation Satellite Systems; Remote Sensing Applications; Provision of Image Data from Deimos' satellites, and most relevantly here, Space Situational Awareness. Deimos has extensive experience in Space Situational Awareness (SSA) activities across Europe, covering the three main domains: Space Weather, Space Surveillance and Tracking, and Near-Earth Objects. The company has deep expertise in the analysis, design, development, and operation of SSA services. In addition to working on operational systems for ESA, they offer commercial services based on the data from their Sky Survey system.
GMV NSL	GMV NSL develop and deliver GNSS-based services, systems, solutions, and intellectual property. GMV NSL are Europe's leading GNSS company and one of the UK's leading space companies.
Goonhilly Earth Station	Goonhilly is able to conduct LEO/MEO constellation tracking, and has a secure, well-connected site to provide horizon-to-horizon views with almost no blocking. As a consequence, it has the capability to conduct bi-static radar tracking of objects in LEO (with a facility such as RAL's Chilbolton radar as the transmitter), and passive RF monitoring of satellites in all orbital regimes.
In-Space	Provides consultancy and experience in military, institutional and commercial space activities covering Earth Observation, Sat Comms, Navigation, Space Science and Space Exploration
Inverse Quanta Ltd	Consultant offering services covering SST, space systems, security and defence with significant business development and commercial experience. Exceptionally discerning numerical analyst
L3Harris	L3Harris designs and integrates agile and high-performance payloads and electronics for small and lightweight satellites. L3Harris is also helping make access to satellite intelligence more affordable for businesses, governments, and other organizations. Small

Organisation	Description
	satellites have the potential to increase the resiliency of government and commercial missions and enable affordable persistent coverage. The missions that L3Harris have developed could contribute significantly to monitoring the space environment in the RF domain. Another element of the L3Harris capability is the space situational awareness (SSA) capability that it acquired via the purchase of Applied Defence Solutions, who had previously developed a global network of optical sensors.
LeoLabs Ltd	LeoLabs is a US commercial company which aims to develop a global network of 6 radars, (including assets in both hemispheres), to generate a comprehensive catalogue of the objects in low Earth orbit down to 1 cm in size, and thereby secure commercial satellite operations. As the LEO ecosystem around our planet gets more congested, the risk of collisions rises, and the need to map the orbits of spacecraft, satellites and space debris grows with every launch. Meanwhile, new generations of commercial spacecraft, such as small and cube satellites, are causing a dramatic increase in imaging, communications, and human spaceflight prospects. LeoLabs' worldwide network of ground-based, phased-array radars enable high resolution data on objects in LEO, and LeoLabs is uniquely equipped to offer foundational mapping data and services to mitigate the risks of collisions. These services include rapid orbit determination, early operational support, and ongoing orbit awareness. LeoLabs provides its services to commercial satellite operators, government regulatory and space agencies, and satellite management services firms.
Leonardo	Leonardo manufactures high-tech equipment and sensors as well and manages satellite services and systems. Partnered with Thales and has a number of subsidiary companies such as Telespazio who provide mission control and analysis into ESA.
Lockheed Martin	Lockheed Martin are one of the world's largest aerospace companies. In the SST domain, one of their principal contributions is the development of the new Space Fence radar on the Pacific Island of Kwajalein. This S-band radar operates at a higher frequency than many of the existing space tracking radars, and hence will have the capability to track smaller objects in orbit. The US expect that the new fence will detect objects down to 1 cm in size, and NASA estimates that there are 500,000 objects of this size and larger in orbit around the planet, (mostly in LEO). It is currently unclear whether the data from this facility will be added to the publicly available catalogue, but it can be seen that it will almost certainly increase the size of the catalogue by an order of magnitude if this is the case.
Lumi Space	Lumi Space is aiming to build the world's first global, commercial satellite laser ranging (SLR) service. This will be used to detect objects in all orbital regimes and with a greater level of accuracy than currently possible. It will also allow for the validation of optical observations and may pave the way for using laser technology to move space debris into a safer orbit.
MAP Analytica	Extremely versatile analyst displaying novel expertise. Drawing on experience in space surveillance operations in the RAF, policy formulation in MoD and the Cabinet Office (including a PhD analysing US national space policy from 1960 to 2010) with horizon scanning (Global Strategic Trends out to 2040), MAP Analytica offer a wide range of conceptual and future focused analysis. Also mentors and tutors on a Senior Leaders MBA programme, bringing business experience to space issues.
Marsh	Marsh are insurance brokers specialising in covering complex risks. This includes the risk of space debris and other hazards in the space environment.
NORSS	NORSS offers satellite tracking and space situational awareness, consultancy to plan and deliver effective operational use of space and a range of training for satellite

Organisation	Description
	operators and controllers. NORSS supports space security, safety, and the development of industry standards, whilst campaigning for an effective regulatory framework. NORSS offers mission support in the following areas: - Tracking and control of satellite assets; Data interpretation; Conjunction analysis and collision avoidance; Security of space and applications of space technology; Dealing with space weather; Regulatory understanding / jurisdictions / compliance; Future proofing; Risk mitigation; De-orbiting; End-of-life solutions.
Qinetiq	QinetiQ design and deliver highly versatile small satellites and advanced subsystems for the commercial market. Their satellites combine the benefits of lower launch costs, with the capacity to carry sophisticated payloads, including high resolution cameras, remote sensing, tracking, radio, and data communications systems. Their highly manoeuvrable satellites are also capable of high precision pointing, a capability more typically associated with larger platforms. Such satellite capabilities could contribute to future on-orbit SSA missions.
Raytheon	Raytheon are a major US aerospace company with a wide portfolio of capabilities including optical IR and radar sensors. In the SST domain, Raytheon developed the optical and IR sensors for the is the Missile Defence Agency's Space Tracking and Surveillance System (STSS) that can detect and track ballistic missiles and other “cold” objects in space. IR tracking of objects in space using on-orbit sensors is a major potential contribution to the quality of the space catalogue in the future.
Roke Manor Research	Roke offers contract research and development and consultancy services in the field of nanosatellite technology. Roke have worked with Dstl as their principal supplier of nano-satellite research, assessing the potential use of small satellite technology in a range of military applications. This work included the production of flight-ready CubeSat hardware. In particular, Roke has capabilities in RF sensor design that could be exploited to access the signatures that active satellites generate. As an increasing focus is brought to bear on compliance with international standards and regulations, and as “space sustainability” ratings are developed, it will become ever-more to have independent verification of a satellite’s “end of life.” RF monitoring is perhaps the most reliable source of such information.
Seradata	Seradata produces SpaceTrak, the Space Industry’s leading launch and satellite database, which is a significant contribution to SST analysis and understanding. SpaceTrak provides comprehensive, consistent, independent, and authoritative information covering every launch and satellite since Sputnik. Note that the Seradata database does not currently cover debris objects.
Serco	Serco has expertise operating across all military domains, including space. In particular, in the UK Serco’s principal contribution to SST is to manage and support the operation of the BMEWS radar at RAF Fylingdales
Space Insight	Space Insight operates Starbrook, a ground-based optical sensor system for the surveillance of space, which is one of a new generation of wide field of view sensors that scan near-Earth space to discover and catalogue objects. The system was conceived by Space Insight as an innovative solution to the problem of monitoring the increasing population of man-made objects in the higher Earth orbits. Since 2016 the company has been providing the UK Space Agency with observations of space objects as part of the EU Space Surveillance and Tracking (SST) Programme.
Spire Global UK Ltd	Spire works with businesses & government to co-create and deploy customizable data collection satellites within just six months. This is secure, real-time data from custom payloads fitted to a customer's needs. Spire launches almost every month, and the

Organisation	Description
	satellites are built at a rate of up to two per week. The Spire Lemur-2 platform is designed for operation at altitudes of 600 km and below and could host SST payloads if required. A platform designed to be compatible with higher orbits, (i.e., including a propulsion system to ensure satellite deorbit within 25 years), would extend the range of applications that Spire's platforms and sensor technology can offer in order to address the problem of SST.
Surrey Satellites	A spin-off of the University of Surrey and now wholly owned by Airbus, Surrey Satellite Technology is the world's leading commercial small satellite company and has expertise in taking satellite missions from first concept through to on-orbit operations and data management, as well as delivering telecommunications, navigation, and remote sensing solutions to international customers.
Teledyne e2v	Teledyne e2v is a global manufacturer that designs, develops, and manufactures technology systems and components in healthcare, life sciences, space, transportation, defence and security and industrial markets.
Thales Alenia Space UK Ltd	A joint venture between Thales (67%) and Leonardo (33%), Thales Alenia Space also teams up with Telespazio to form the parent companies' "Space Alliance", which offers a wide range of space services and solutions. TAS has considerable experience in delivering satellites into the European market, (TAS was, for example, the prime contractor for Italy's Cosmo-Skymed satellites), and hence is one potential source of in-situ SST measurements via satellite telemetry measurements.
ThinkTank Maths	ThinkTank Maths is a mathematics research company active in many areas including space and with experience in sustainable space projects such as spacecraft thermal testing and re-entry survival. ThinkTank Maths is part of the SaxaVord SDA Consortium looking to provide assured space traffic management services to civil and commercial clients. Their novel mathematical methods will reduce space object position and orbital uncertainty, providing more accurate SDA and potentially reducing manoeuvring requirements

Appendix C Report Contributors

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ROYAL AIR FORCE

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Appendix D Sensing capabilities of select NATO nations

Nation	Capability	Type	Notes
US	Ground-based Electro-Optical Deep Space Surveillance (GEODSS) System	Optical	3x1m telescopes
	Space Surveillance Telescope (SST)	Optical	Situated in Australia to collect southern hemisphere observations, 3.5m telescope
	GLOBUS II	Radar	Located in Norway
	AN/FPS-85 Space Track Radar	Radar	UHF phased array radar
	Space Fence	Radar	S-band radar located in Marshall Islands and Western Australia. Can track 200,000 objects and make 1.5m observations per day
	Maui Space Surveillance System (MSSS)	Optical	Includes the Advanced Electro-Optical System (AEOS) 3.67m telescope for long wave infrared and photometric data
	Haystack Ultrawideband Satellite Imaging Radar (HUSIR), Haystack Auxiliary Radar (HAX), and Millstone Hill Radar	Radar	Set of radars working on Ku, X, W bands with resolution up to 0.5 millidegrees
	ALTAIR	Radar	45.7 UHF and VHF radar, Marshall Islands
	ALCOR	Radar	12.2m C-band radar, Marshall Islands
	Ascension Range Radar	Radar	VHF radar for telemetry, tracking and collateral support to space control operations
	Ground-Based Radar Prototype (GBR-P)	Radar	X band, mechanically slewed, phased array radar located in the Marshall Islands
	Solid State Phased Array Radar System (SSPARS)	Radar	Includes the SSPAR sensor at RAF Fylingdales
	AN/FPQ-16 Perimeter Acquisition Radar Characterization System (PARCS)	Radar	UHF radar
France	Grand Réseau Adapté à la Veille Spatiale (GRAVES)	Radar	VHF bi-static surveillance radar. 1m RCS objects from 400-1000km
	SATAM radars	Radar	C-band. Not dedicated to SST but tracks objects, conjunction analysis and re-entry
	Bâtiment d'Essaiset de Mesures (BEM) Monge tracking ship	Radar	

	SPOC (Systéme Probatoire d'Observation du Ciel) telescope	Optical	Wide angle for initial orbit determination
	TAROT system	Optical	2x25cm telescopes for detection and monitoring in the GEO region
Germany	TIRA	Radar	34m K (tracking) and Ku (ISAR imaging) band radar. 2cm at 1000km. Used in conjunction with Effelsberg radio telescope can reduce detection to 1cm
	GESTRA	Optical	
Italy	RAT-31 Fixed/Deployable Air Defence System Radars (FADR/DADR)	Radar	L-band solid state phased array radar. Intended for air defence, operates on monostatic configuration for space surveillance
	BIRALES (Bistatic Radar for LEO Survey)	Radar	Bistatic UHF radar <1m debris detection, LEO regime
	BIRALET (Bistatic Radar for LEO tracking)	Radar	Bistatic tracking radar
	PdM-MITE telescope	Optical	350mm fast telescope, can contribute to improved characterisation of debris
	VdV-CAS telescope	Optical	GEO regime tracking
	Matera Laser Ranging Observatory (MLRO)	Laser	
Spain	Monostatic Space Surveillance Radar	Radar	Close-monostatic L-band radar
	S3T Surveillance Radar	Radar	Phased-array L-band radar
	Centu-1	Optical	Wide-field telescope, GEO/MEO regimes
	Tracker-1	Optical	Tracking telescope, GEO/MEO regimes
	Fabra-ROA	Optical	f/1 50cm surveillance and tracking telescope
	Telescopi Joan-Oró	Optical	1m class tracking telescope
	IAC-80	Optical	80cm telescope
	Burst Optical Observer and Transient Exploring System (BOOTES)	Optical	1x surveillance and tracking telescope, 3x tracking telescope. GEO regime
	Laser Station of San Fernando (SFEL)	Laser	Tracking retroreflector-fitted objects in LEO region
	Izaña-1	Laser	First dual-purpose laser station, used for optical communications as well as tracking of cooperative objects

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