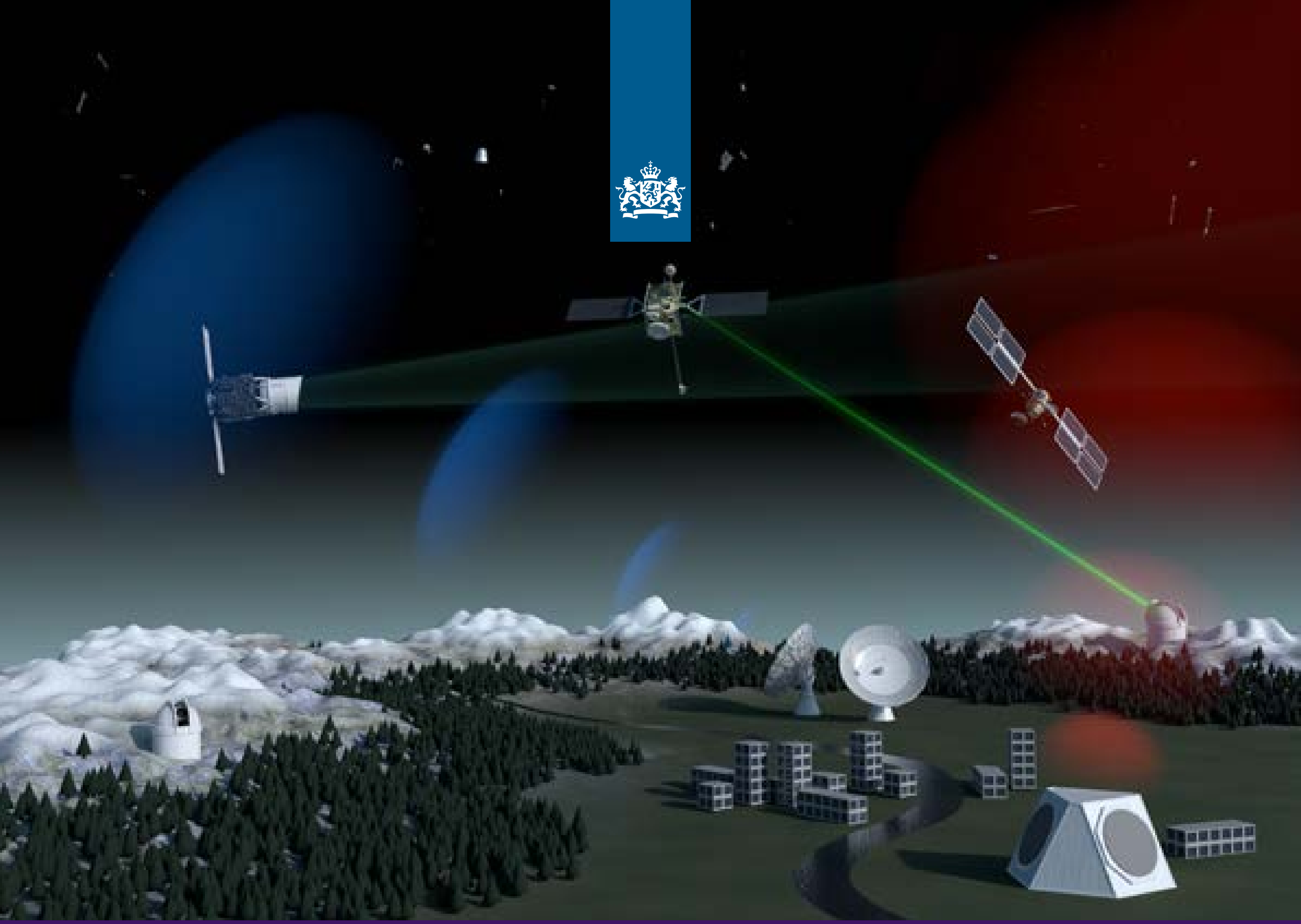

SSA for Verification

"Feasibility study on the use of space surveillance and tracking (SST) for the verification of responsible behaviour in outer space"

Netherlands Space Office (NSO)

This study was commissioned by the Ministry of Foreign Affairs of the Kingdom of The Netherlands

Foreword

The expansion of space activities and participants has increased the exposure of vital space assets to potential vulnerabilities. As a country committed to the international rule of law and multilateral cooperation, the Netherlands recognizes the urgent need for clear rules and effective verification mechanism for activities in outer space.

Against this background, the Security Policy Department (DVB) of the Ministry of Foreign Affairs asked the Netherlands Space Office (NSO) to examine whether and how Space Situational Awareness (SSA) – and more specifically Space Surveillance and Tracking (SST) – could be used to verify responsible behaviour in space. This study assesses both the technical possibilities and the multilateral feasibility of such an approach.

The findings show that SSA can play a meaningful role in a verification efforts. By enabling the objective observation of activities in orbit – such as close-proximity operations, debris creation, or irregular manoeuvres – SSA provides a basis for assessing compliance with agreed norms. In doing so, it opens the door to accountability and diplomatic engagement. SSA is therefore more than a technical capability: it is a practical tool for strengthening international stability.

This work aligns with the Dutch space security policy outlined in the 2021 letter to Parliament. In that letter, the government highlighted the value of SSA in monitoring adherence to behavioural norms in space and preventing misperceptions or escalation. The report also contributes directly to Mission 6 of the Dutch Long-Term Space Agenda: strengthening the international legal framework governing space activities. By combining technical expertise with diplomatic ambition, the Netherlands seeks to help build a space environment rooted in security, sustainability, and international cooperation.

I thank the NSO team and all contributing experts for their work. This feasibility study provides strategic insight and a solid foundation for advancing SSA technology and data sharing, with the aim of enhancing space security and promoting responsible conduct in orbit. In addition, it can serve as a valuable contribution to international discussions on verification mechanisms.

NSO welcomes the task of studying space related issues and to provide insights from our perspective. We extend our appreciation to the Ministry of Foreign Affairs for this opportunity and for the confidence placed in our expertise.

Harm van de Wetering
Director, Netherlands Space Office

◄ *Artist's impression of space debris.*

Abbreviations

Abbreviation	Definition
CA	Collision Avoidance
CAM	Collision Avoidance Manoeuvre
CDM	Conjunction Data Message
EUSST	European Union Space Surveillance and Tracking
GEO	Geostationary Earth Orbit
GBSS	Ground Based Space Surveillance
HIE	High Interest Event
IR	Infrared
JCO	Joint Commercial Operations
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
OEWG	Open Ended Working Group
PAROS	Prevention of an Arms Race in Outer Space
Pc	Probability of collision
RF	Radio Frequency
RSO	Resident Space Object
SLR	Satellite Laser Ranging
SBSS	Space Based Space Surveillance
SSA	Space Situational Awareness
SST	Space Surveillance and Tracking
TCA	Time of Closest Approach
TraCSS	Traffic Coordination System for Space
TLE	Two Line Element
UNODA	United Nations Office for Disarmament Affairs

Table of Contents

1 Introduction

1. Introduction

Countries are increasingly recognizing the critical role that space systems play for humanity and have introduced numerous initiatives aimed at maintaining outer space as a peaceful and secure domain. As space becomes a strategically more and more important domain for countries, more congested and contested, the risk of incidents is expected to rise substantially. Space security has thus become a significant concern for the international community.[1]

Multilateral space security discussions are not new. The idea of the 'prevention of an arms race in outer space' (PAROS) emerged for the first time in 1978 and not long thereafter PAROS was added as an item to the agenda of the Conference on Disarmament. Space security matters are also discussed by the Disarmament Commission and the First Committee of the General Assembly, which adopts multiple space-security related resolutions every year.

The United Nations Office for Disarmament Affairs (UNODA) and the Secure World Foundation have organised expert sessions that have highlighted the importance of Space Situational Awareness (SSA) in the context of monitoring and enforcing responsible behaviour in outer space. Enhancing SSA capabilities can enable attribution and verification, both under the current outer space legal framework and in the context of any future legally binding instruments addressing the prevention of an arms race in outer space (PAROS).

Space Situational Awareness (SSA) in general, and space surveillance and tracking (SST) in particular have been identified as a possibility to help verification of responsible behaviour in outer space.[2] Improved SSA capabilities would offer a more comprehensive understanding of orbital activity and enhance the safety of space operations, while also supporting security objectives. This includes detecting unusual or hostile behaviour, identifying compromised satellites, issuing alerts regarding vulnerabilities, and mitigating threats to essential services.3

SSA is a broader strategic concept that includes SST but also encompasses understanding the behaviour and threats in the space environment. SST is the technical process of detecting, tracking, cataloguing, and predicting the trajectories of objects in Earth orbit (satellites, debris, etc.).

In the field of Space Situational Awareness (SSA), the terms surveillance and tracking are often used together, yet they refer to two distinct but complementary activities for monitoring objects in Earth's orbit.

Surveillance refers to the broad, systematic observation of space with the aim of detecting, identifying, and cataloguing objects. This process focuses on scanning wide areas of space, often without targeting specific objects, in order to identify new satellites, space debris, or unexpected events such as satellite break-ups or unannounced launches. Surveillance is essential for maintaining an up-to-date picture of the space environment, ensuring that newly appearing objects are detected and characterized as early as possible. It plays a critical role in space security, collision prevention, and debris management by identifying potential risks before they become immediate threats.

In addition, **tracking** is the precise, continuous monitoring of known objects whose presence and general orbits are already established. Once an object has been detected and catalogued, tracking provides detailed information on its position and trajectory over time. This allows for accurate predictions of where the object will be in the future, which is vital for tasks such as collision avoidance, conjunction analysis, and the detection of orbital manoeuvres. Unlike surveillance, which casts a wide net, tracking focuses on specific targets to refine their orbital data and ensure their movements are well understood.

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1 Azcárate Ortega, A., & Erickson, S. (2024). OEWG on reducing space threats: Recap report. UNIDIR. https://doi.org/10.37559/WMD/24/Space/01

2 Christensen, I., & Samson, V. (Eds.). (2024). Space situational awareness fact sheet. Secure World Foundation. https://www.swfound.org/publications-and-reports/space-situational-awareness-fact-sheet

3 Vieux, J. I. (2025). The importance of space security for the Global South. UNIDIR. https://unidir.org/the-importance-of-space-security-for-the-global-south/

◄ *Satellite tracks on the night sky.*

In essence, surveillance is about discovery, keeping watch over space to find and classify objects, while tracking is about precision, following known objects to maintain accurate knowledge of their behaviour and future positions. Together, these activities form the backbone of SSA to ensure safe and sustainable operations in increasingly congested orbital regions.

SSA data also plays a key role in the tracking and verification of space security activities. SSA in general can help both in identifying patterns of normal space activities and when space objects diverge from those normal patterns. SSA can also help verify that behaviour follows international agreements, whether these are non-legally binding norms, rules and principles of responsible behaviour, or as part of legally binding instruments. Broadly speaking, SSA is good for verifying whether something has or has not happened in space; determining why that did or did not happen is not part of SSA, but rather for analyses that pull in a wider set of data from different sources.[4]

Having a robust and independent SSA capability also brings benefits from a more diplomatic perspective. It supports monitoring and verifying adherence to current and future international agreements on responsible space conduct, and enables follow-up action when violations occur through mechanisms like verification and attribution.

A verification process typically consists of three key stages: (i) monitoring and gathering data on the activities of States; (ii) performing a technical evaluation of that data; and (iii) making an informed assessment of whether a State is meeting its obligations. Verification is both a technical and political endeavour. While no system can guarantee perfect results, an effective verification regime should enable prompt identification of (potential) violations and serve as a deterrent to non-compliance. Certain provisions of international space law—such as Articles VIII, and IX to XII of the Outer Space Treaty—can support verification efforts.[5] Additionally, various data collection tools and methodologies, including those aimed at improving SSA, contribute to the process. Nonetheless, the effectiveness of these efforts may be limited by technical constraints and political challenges that restrict data sharing and international cooperation.[6]

Exactly what constitutes responsible behaviour in space is subject of the same multilateral debates. Initial views of UN member states have been compiled in the report of the Secretary-General on reducing space threats through norms, rules and principles of responsible behaviours (2021)[7], though geopolitical and technical developments have evolved in an ever increasing pace since then. The characterization of actions and activities that could be considered responsible, irresponsible or threatening and their potential impact on international security is therefore beyond the scope of this report.

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4 Christensen, I., & Samson, V. (Eds.). (2024). Space situational awareness fact sheet. Secure World Foundation. https://www.swfound.org/publications-and-reports/space-situational-awareness-fact-sheet

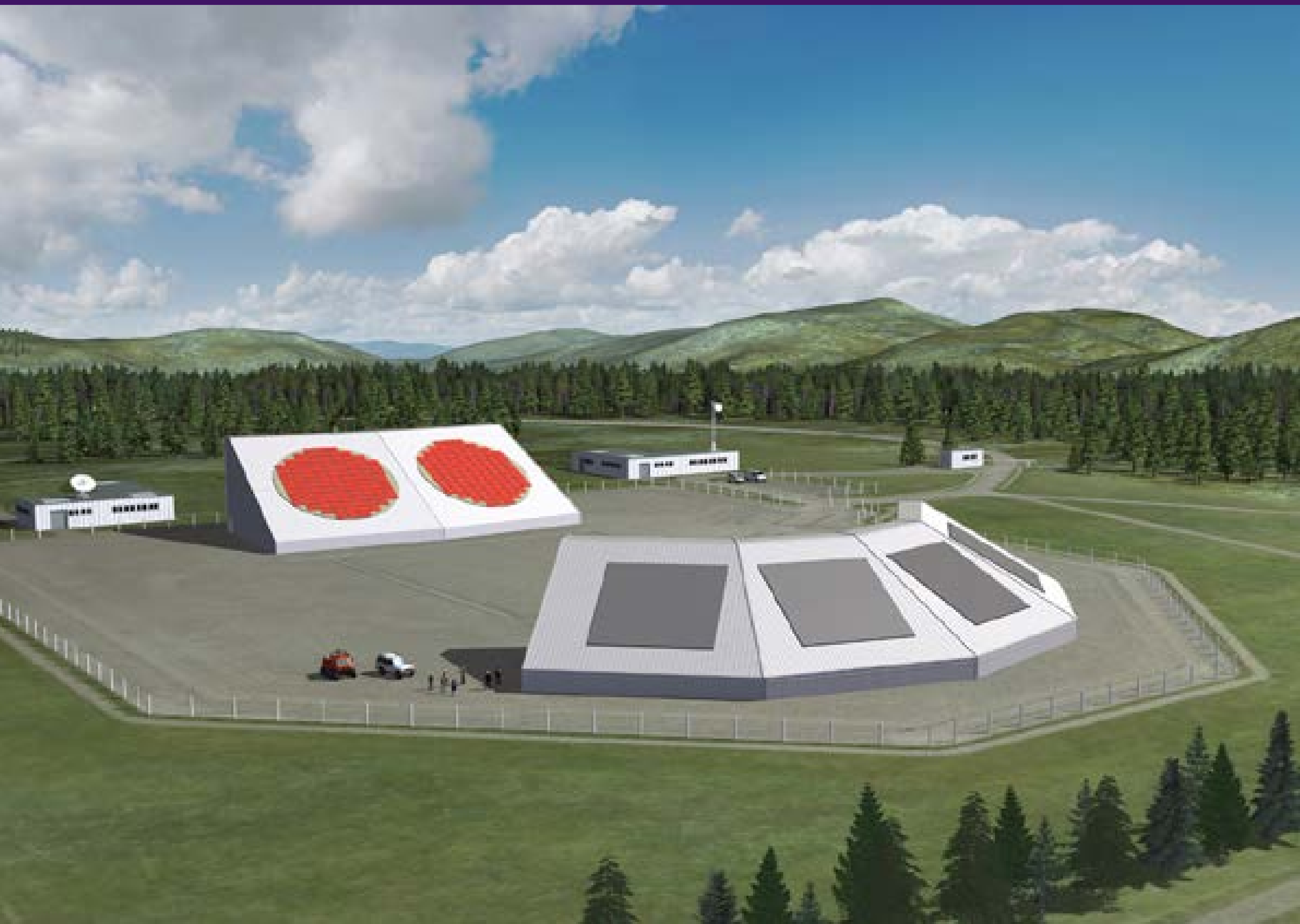
5 For instance, Article VIII can be interpreted as a form of verification, since the state of registry holds jurisdiction and control over a space object, effectively overseeing its activities. In the registration process, a state must provide specific information, such as the object's orbital parameters and its intended purpose. While this information is far less detailed than SSA data, it still helps identify the responsible state and offers some indication of the object's potential capabilities.

6 Lohani, R., & Delaflora Cassol, L. (2025). 2024 Outer Space Security Conference report. UNIDIR. https://doi.org/10.37559/WMD/25/Space/01

7 United Nations. (2021). Report of the Secretary-General on reducing space threats through norms, rules and principles of responsible behaviours (A/76/77). https://documents.un.org/

Space is becoming increasingly more congested. ▶

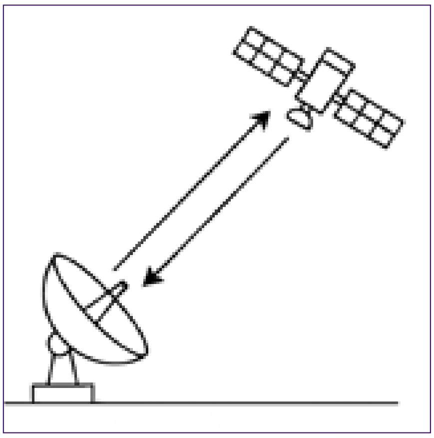
2 Technichal feasibility



2. Technichal feasibility

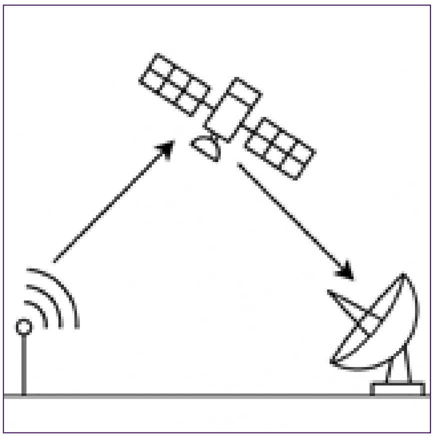
SSA systems encompass several components that are necessary if used for verification purposes. Understanding the building blocks and their respective limitations will shed light on potentially necessary steps required in order to move forward. Because of coverage limitations a network of globally distributed **sensors** is required as well as data sharing between satellite owner-operators and sensor networks. There are different types of sensors, namely radar, optical, or laser. This section will give an overview of the different sensor types and their use cases.

Types of sensors



Radar Systems

Radar systems are particularly useful for space surveillance and tracking objects in Low Earth Orbit (LEO), having the capability to operate regardless of weather conditions and time of day. One such example is the US Air Force Space Fence, declared operational in March 2020 and able to track objects below sizes of 10cm through an S-band radar system. While radars could in theory be used beyond LEO to cover Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO), this technology becomes expensive to operate for higher altitudes as the power required to track an object is proportional to the fourth power of the distance to the target. Different types of radar systems have been employed for space surveillance, with tracking and immobile antennae working in bistatic mode (where one antenna emits a pulse and another receives the return), as well as phased-array antennae tracking multiple satellites simultaneously with no moving mechanical parts. These are composed of thousands of small phased elements used to electronically steer the system.

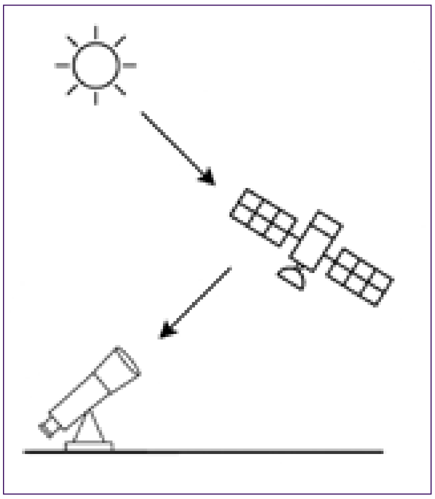


Bistatic and Multistatic Radar Systems

Bistatic radar systems, which utilise separate transmitter and receiver locations, offer several advantages over traditional monostatic radar systems where the transmitter and receiver are co-located. This configuration allows for greater flexibility in tracking objects across different regions of space and improves coverage of objects in various orbital regions. Bistatic radar systems are increasingly being employed in SSA to provide more comprehensive tracking and to fill gaps left by traditional radar systems.

These radar systems can track objects in all orbital regimes, including LEO, MEO, and GEO, by leveraging multiple sensor locations. The use of multiple radar stations enables improved resolution and more precise measurements of an object's position and velocity. Bistatic radar systems are particularly effective in monitoring space debris, providing coverage across a wider area and enhancing the accuracy of orbital predictions. By using separate transmitters and receivers, bistatic radars can also mitigate some of the limitations associated with traditional radar systems, such as shadowing effects or line-of-sight obstructions. As such, bistatic radar systems contribute to a more robust and comprehensive SSA infrastructure for monitoring space objects across all altitudes.

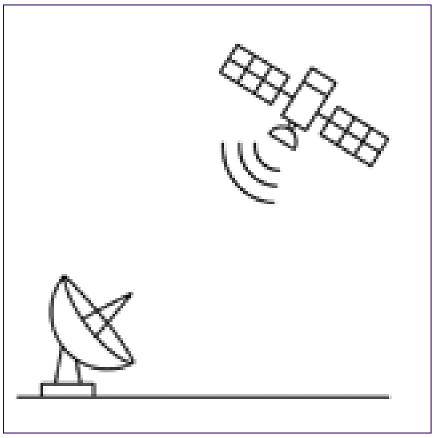
◄ *Artist's impression of SSA radar system.*



Optical Sensors (Telescopes)

Optical telescopes can be used to supplement radar systems in order to more efficiently track spacecraft in and GEO. Optical systems offer a cost-effective and lower-power alternative to radar for satellite and debris tracking in these higher orbits. However, the short observability of objects in LEO makes optical telescopes less suitable for LEO tracking. These systems rely on visible light and can only operate during nighttime, with cloud cover posing an additional limitation.

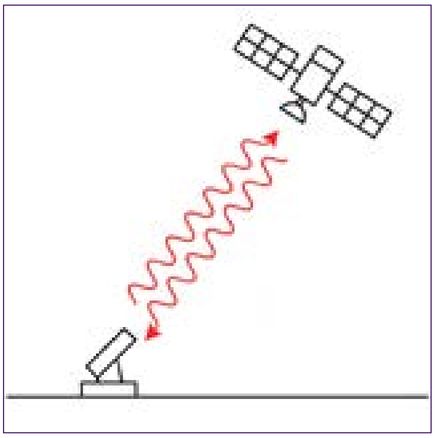
Despite these constraints, optical telescopes remain essential for cataloguing defunct spacecraft and smaller space objects. Both survey telescopes, which feature a wide field of view for broad area scanning, and tracking systems, offering a narrower field of view with higher accuracy, contribute to the detection and tracking of space debris. Their ability to provide high-resolution imagery aids in identifying object characteristics and enhancing overall SSA.



Passive RF Sensors

Passive radio frequency (RF) sensors play an essential role in SSA by detecting signals emitted or reflected by space objects. These sensors do not actively send out signals but instead "listen" to the RF emissions from satellites and other space objects. These signals include communication signals, telemetry, and navigation emissions, which are inherently present in the electromagnetic spectrum. Passive RF sensors are crucial for tracking satellites in MEO and GEO because these orbits often host operational satellites that actively communicate with ground stations or other satellites.

In LEO, passive RF sensors are less effective due to the dense and fast-moving nature of the objects, which makes it difficult to detect signals continuously. However, for MEO and GEO, passive RF sensors are highly beneficial as they can detect satellite emissions over extended periods, providing continuous tracking data without the need for active engagement. These sensors also enable the monitoring of potential unauthorized or malicious RF activity in space, such as jamming or spoofing attempts. Since RF emissions can be traced to specific satellites, passive RF sensors contribute to ensuring compliance with international space traffic regulations and identifying potential violations of international agreements.



Satellite Laser Ranging (SLR)

Laser equipment is frequently used to track space debris in orbit. While past iterations of this technology required retroreflectors to be fitted on-board a satellite in order for it to be tracked, thus significantly limiting its range of use, recent developments have allowed laser tracking to be reliably used on “non-cooperative” objects. This category necessarily includes space debris, whose position can be tracked by illuminating the object with a laser beam and using receivers on the ground to track it. Measurement campaigns have been carried out to evaluate the reliability of this system[8]: using receivers at three different sites enabled a success rate of 60% in tracking the object’s orbit, pinpointing non-cooperative debris or spacecraft to one order of magnitude more precisely compared to radar. In addition, while many of the limitations of optical

8 Wang, P., Steindorfer, M. A., Koidl, F., Kirchner, G., & Leitgeb, E. (2021). Megahertz repetition rate satellite laser ranging demonstration at Graz observatory. Optics Letters, 46(9), 2200–2203. https://doi.org/10.1364/OL.418135

▲ *Satellite Laser Ranging station.*

systems apply to laser tracking, powerful lasers can be used for day-time operations, although further research and development activities are required to increase the system's reliability.

However, the use of SLR could also be interpreted as blinding efforts. The 2021 Secure World Foundation Global Counterspace Capability Report[9] points out that lasers can be used for dazzling or damaging satellites' imaging sensors, the satellite bus, or its subsystems. Low-power lasers ranging from as little as 10 W are capable of dazzling and temporarily blinding satellite imaging sensors, while even a 40 W laser star guide system can easily permanently damage silicon photosensor arrays or silicon diodes. Notably, this latter power level is appropriate for laser ranging of space debris. Therefore, SLR for non-cooperative targets requires higher power lasers, which come with the risk of dazzling, temporarily blinding, or permanently damaging sensors, potentially causing events that escalate tensions.

9 Samson, V., & Weeden, B. (2021). The Secure World Foundation's 2021 global counterspace capabilities report. Secure World Foundation. https://www.swfound.org/publications-and-reports/2021-global-counterspace-capabilities-report

Future prospects in SSA: Space Based Space Surveillance (SBSS) and advanced cameras

Despite advancements in ground-based networks, technical constraints such as weather interference and geographic coverage gaps persist, driving the development of space-based solutions to enhance SSA's role in verification.

Ground Based Space Surveillance (GBSS) will remain the foundation of SSA efforts for the foreseeable future. However, Space Based Space Surveillance (SBSS) efforts are expected to increase and contribute significantly to SSA. SBSS offers distinct advantages over ground-based systems, as operating outside of the Earth's atmosphere eliminates some of the limitations of ground based telescopes, such as atmospheric turbulence and weather constraints. From space, sensors have a clear, stable view of the orbital environment, leading to more accurate and continuous observations.

These advantages, however, come with higher costs. Deploying and operating satellites in orbit requires significant investment, both for the development of sensor systems and for launch services. While CubeSats often provide a lower-cost alternative in many space applications, recent studies have shown that they do not offer significant improvements for space-based surveillance systems, as their limited aperture size and challenging optical design for ultra-wide fields of view result in poorer optical performance compared to existing ground-based sensor systems. Furthermore, unlike GBSS, where sensors are fixed to specific locations on Earth, SBSS assets orbit the planet, requiring careful consideration of orbital design and system architecture. Operators must determine optimal orbits for SBSS satellites to ensure effective coverage, persistent monitoring, and efficient use of resources, especially in the case of constellations.

Within SBSS, optical systems are considered the most promising candidate. Optical SBSS sensors operate similarly to ground based telescopes by detecting sunlight reflected from satellites. These systems are relatively straightforward to produce and operate, making them a cost effective option. However, optical SBSS also faces limitations. For example, when satellites pass through the Earth's shadow, they cannot be observed as no sunlight is available for reflection, creating observation gaps.

Infrared (IR) SBSS represents a specialized capability with distinct advantages. Besides observing reflected IR radiation from the sun, IR sensors can detect the intrinsic heat radiated by satellites, making them effective for observations even when sunlight is unavailable. Moreover, IR systems can detect events such as thrusting manoeuvres, as propulsion generates heat signatures visible in the infrared spectrum. On the other hand, IR systems are significantly more expensive, as they must be actively cooled in space to reduce thermal noise. Without sufficient cooling, the sensors would primarily detect their own heat emissions, reducing their effectiveness.

Star trackers can also be used for SBSS. These relatively simple, low resolution optical instruments are mounted on many satellites to determine their orientation by comparing observed star fields with known celestial maps. When an unidentified object, such as another satellite, passes through the field of view, it appears as an unexpected light source. By filtering out the known stars, these intrusions can be isolated, providing incidental but valuable SSA data. Although not designed primarily for surveillance, star trackers could contribute to SBSS efforts.

The developments in SSA are not solely space based. Ground based networks still leave room for improvement. An opportunity could be provided particularly by the use of advanced optical cameras. These systems offer a cost-efficient alternative to large telescopes, with units priced in the order of 70,000 euros compared to 200,000 to 300,000 euros for professional telescopes. The lower price enables wider deployment, enhancing geographical coverage and redundancy. While individual cameras may not match the performance of high end telescopes, their distributed network architecture provides more coverage, making them a potential complement to existing GBSS infrastructure.

Satellite Laser Ranging station. ▶

▲ *Artist's impression of two satellites colliding.*

Conclusions on sensors' capabilities

Combining data from many different types of sensors, both ground- and space-based, that are also distributed around the globe provides a much more complete picture of the space environment and of activities in space. Any effective SSA system will consist of a well geographically distributed network and a variety of different sensors.

The technical requirements for effective monitoring and verification of satellites depend heavily on the specific orbital regime, as different altitudes and orbital dynamics impose distinct challenges.

For LEO, where satellites move rapidly relative to the Earth's surface, radar systems are the primary sensor type. High sensitivity tracking radars with fast repositioning capabilities provide the continuous, all-weather coverage and precise tracking needed for reliable monitoring and collision avoidance. Optical telescopes are generally unsuitable for LEO, as they cannot track fast-moving objects effectively and are affected by atmospheric conditions.
For MEO and GEO, the situation is different. Satellites in these regimes appear to move much more slowly, especially in GEO where they remain stationary relative to the Earth's surface. Optical telescopes, both ground-based and space-based, are therefore the preferred tool. They offer high angular resolution and precise positional data critical for catalogue maintenance and long-term orbit verification. Radar systems are generally less effective in these higher orbits due to range limitations.

Accuracy requirements also vary for the different orbital regimes. In LEO, a higher observation frequency or a lower revisit time is required due to the high density of satellites and short warning times. In MEO and GEO, a lower observational frequency or longer revisit time is acceptable. However, in those orbital regimes accurate astrometric[10] position measurements are required.

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10 *Astrometric* refers to the precise measurement of the positions and movements of celestial objects.

From Sensor Data to SSA Information Products

The sensors described above generate raw or minimally processed measurements, such as azimuth, elevation, range, range rate (Doppler), apparent magnitude, or RF signal characteristics, collected by ground-based and/or in-orbit assets. Fusing observations from multiple, geographically dispersed sensors is the most effective way to improve orbital accuracy and reduce uncertainties, directly benefiting spaceflight safety. Studies have shown measurable accuracy gains from such multi-sensor fusion.

However, much of this data originates from sensors owned by defence organisations or other dual-use systems, and security considerations often prevent its release outside the owning network. Increasingly, commercial SSA sensors contribute valuable data, but here too, proprietary and contractual constraints typically limit wider sharing. As a result, neither the European Union nor the United States routinely share raw sensor data beyond their own SSA systems.

From these raw measurements, orbit determination processes compute tracks and ephemerides[11]—state vectors with associated covariance matrices that quantify positional uncertainty—using either general perturbation models, which produce broadly disseminated Two-Line Elements (TLEs), or more precise special perturbation models for operational use; these orbital solutions form the basis for key information products such as Conjunction Data Messages (CDMs), which are generated by screening ephemerides for close approaches and include predicted time of closest approach (TCA), miss distances, and probability of collision (Pc).

SSA data products support several operational services, including the Collision Avoidance (CA) service, which provides Conjunction Data Messages (CDMs) and Candidate Collision Avoidance Manoeuvre (CAM) screenings to evaluate whether planned manoeuvres might create new conjunction risks; the re-entry service, which issues predictions for uncontrolled atmospheric returns to support risk assessment and mitigation; and the fragmentation service, which delivers notifications and analyses when new debris is detected following break-ups or collisions. Together, these services enable effective collision avoidance, high-interest event alerts, and long-term orbit verification, and they also allow inferences about space activities such as proximity operations or unannounced manoeuvres, while recognising that intent and non-kinetic effects remain beyond the direct detection capability of SSA.

In addition to sensor data, SSA networks receive owner/operator-provided ephemerides, which are often more accurate than sensor-derived solutions but rely on the operator's timely and accurate delivery. The European Union, through the upcoming EU Space Act, plans to require operators to provide further operational details, including hard-body radius and manoeuvre information, to enhance the precision, reliability, and verification value of SSA products and services.[12]

11 An *ephemeris* (plural: ephemerides) refers to a set of data that provides the precise location and velocity of a satellite at a specific time. It's essentially a predicted orbital path. The accuracy of the ephemeris data directly impacts the accuracy of the receiver's position calculation. Any errors in the ephemeris can lead to errors in the estimated location.

12 European Commission. (2025, June 25). Proposal for a regulation on the safety, resilience and sustainability of space activities in the Union (EU Space Act). https://defence-industry-space.ec.europa.eu/document/download/0adeee10-af7a-4ac1-aa47-6a5e90cbe288_en?filename=Proposal-for-a-Regulation.pdf

3 Multilateral feasibility

3. Multilateral feasibility

Regional SST networks: EUSST, JCO, and TraCCS

There are existing SST sensor networks that are either patrimonial (government owned), private (commercial), or amateur networks. The most common ones are public networks with the United States government operating the largest network of sensors. Thus, the US maintains the most complete catalogue of space objects. The number of commercial SSA providers has been growing and are offering SSA data services based on their own radars or telescopes. More companies are being established that are currently deploying their sensor networks.

Patrimonial versus commercial sensors

When using SSA for the verification of responsible behaviour in space, it is important to consider the differences between patrimonial and commercial sensors within the SSA network.

Space safety and security can be seen as two sides of the same coin[13] when it comes to the practical implementation for verification purposes. Although space security and safety are distinct from one another, the two are also interrelated, and can intersect and overlap. SST does not make a distinction between a risk or threat, therefore all SSA capabilities can be used for verification purposes irrespective of the fact if they are a civilian or military system.

Patrimonial ground based sensors offer significant advantages for SSA by ensuring that nations have full ownership and control over the sensor's operations. This means that observations can be scheduled based on national priorities, and data can be collected whenever needed without reliance on external parties. However, this control comes with limitations in terms of data sharing. Countries are often reluctant to share all observations from patrimonial sensors within multinational networks, especially when these involve their own military satellites or sensitive space activities. Additionally, measurements taken at the technical limits of the sensor's capability are frequently withheld, as sharing them could reveal performance characteristics and technological advantages that military entities prefer to keep classified. Hence one will always end up with an incomplete database and catalogue.

On the other hand, commercial sensors present a practical way to significantly expand sensor coverage and improve data availability within SSA networks. Instead of investing in building, owning, and maintaining an extensive sensor infrastructure, the network can purchase observation data from commercial providers, increasing global coverage. This approach allows for flexibility and rapid scaling of surveillance capacity. However, it also reduces operational control. The tasking, quality, and availability of data depend entirely on the commercial agreements in place. Moreover, access to the data is temporary and conditional on the continuation of the contract. Once the contract ends, the observational capability is no longer guaranteed, making the reliance on commercial sensors a trade-off between flexibility and long term strategic independence.

SSA Networks

Key networks in SSA and STM are EUSST, JCO, and TraCSS. Each offers a distinct approach to tracking objects in orbit and ensuring the safety of space traffic. While all three operate with a common goal, they differ in structure, scope, and geographical focus.

The European Union Space Surveillance and Tracking (EUSST) program represents Europe's coordinated effort to build an independent SSA capability. Managed by a consortium of EU Member States, EUSST relies on a network of ground-based sensors primarily located across European territory. Its services are designed to support European governments, satellite operators, and critical infrastructure by providing services for collision avoidance, fragmentation analysis,

13 Erickson, S., & Azcárate Ortega, A. (2023). To space security and beyond: Exploring space security, safety, and sustainability governance and implementation efforts. UNIDIR. https://doi.org/10.37559/WMD/23/Space/06

◄ *Optical Ground station keeps watch on the skies.*

and re-entry predictions. Although the patrimonial sensor infrastructure is predominantly located in Europe, EUSST's tracking operations extend globally, covering objects in LEO, MEO and GEO. The program reflects Europe's strategic ambition to reduce dependence on non-European data sources and enhance its space autonomy. Due to the limited geographical coverage of radar systems, the network is not yet independent in monitoring the LEO regime.

Established in 2020 by U.S. Space Command, the Joint Commercial Operations (JCO) initiative reflects a growing international and military-commercial partnership to enhance space domain awareness (SDA) and operational collaboration. JCO leverages commercial sensor networks to deliver unclassified SDA and alerting services. The JCO is now organised under the US Space Forces for Space (S4S) Component[14], supporting U.S. military forces as well as allied and partner nations. A defining feature of the JCO is its virtual, globally distributed operations center, known as JCO Global. This structure allows for 24/7 global coverage using a "follow-the-sun" model, with crews operating during local daylight hours across three regional cells: JCO-Americas, JCO-Meridian, and JCO-Pacific. The commercial network comprises 150 surveillance sites with a variety of sensory types worldwide. Participating nations include Australia, New Zealand, France, the United Kingdom, Colombia, Brazil, Canada, Japan, NATO, and others. Through this cooperation, member nations have access to an unclassified, virtual Space Operations Center (SpOC).

In addition, the Traffic Coordination System for Space (TraCSS) is the U.S. government's latest initiative to enhance civil space traffic management. Developed by the Department of Commerce, TraCSS is designed to provide free services to operators worldwide. Although it is still in development, TraCSS aims to gradually transition space traffic management responsibilities away from the U.S. military to a civilian authority, as outlined in U.S. Space Policy Directive-3. The system builds on data from existing military tracking infrastructure (such as USSPACECOM's Space-Track.org) but is intended to evolve into an independent, civilian-led STM platform. Like EUSST and JCO, TraCSS offers global coverage, but its services currently prioritise U.S. operators as part of a phased rollout.

Comparison between the different systems and data availability

EUSST and TraCCS both provide free services aimed at enhancing spaceflight safety and sustainability. However, the data sharing policy they adhere to differs significantly.

EUSST primarily shares operational safety information with registered users. This includes Conjunction Data Messages (CDMs) containing probability of collision (Pc) estimates, risk assessments for High Interest Events (HIEs), additional tracking results when relevant, collision avoidance manoeuvre (CAM) trade-space plots, fragmentation notifications, and detailed reports for re-entry events. These services are focused on ensuring timely and accurate risk mitigation for spacecraft operators within the EUSST network.

However, EUSST does not currently share bulk data sets more broadly. Notably, owner/operator contact information, spacecraft attributes, and ephemerides with planned manoeuvres are collected but not redistributed. Currently, EUSST does not provide open access to its full object catalogue. However, a subset of the EU catalogue may be released in the future, which would align EUSST more closely with data-sharing practices observed in other SSA programs. Additionally, EUSST does not offer routine candidate manoeuvre screening for non-collision avoidance manoeuvres, nor does it provide a system for anomaly reporting. While EUSST maintains a platform for coordination among spacecraft operators, access is restricted to EUSST registered users only.

TraCSS takes a more open approach to data sharing, aiming to increase transparency and support independent analysis by operators and the wider space community. TraCSS provides registered users with a database containing satellite attributes, owner/operator contact information, and submitted ephemerides, including planned manoeuvres. Portions of this information, such as Two-Line Element (TLE) data and elements of the space object catalogue, will also be made publicly available.

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14 U.S. Space Forces – Space. (2025, June 10). S4S fact sheet. https://www.spaceforces-space.mil/Portals/64/S4S%20Fact%20Sheet%20-%2010%20JUNE%202025.pdf

TraCSS offers comprehensive collision avoidance services similar to those provided by EUSST, including CDMs, risk assessments, emergency event notifications, CAM options, and additional tracking data. Moreover, TraCSS uniquely provides candidate manoeuvre screenings for routine spacecraft manoeuvres and facilitates anomaly reporting, encouraging operators to report non-nominal spacecraft conditions that could affect safety.

Despite this broader data-sharing approach, TraCSS does not yet provide certain services. Re-entry monitoring is planned for the future, and launch collision avoidance services are still under development. While TraCSS envisions facilitating greater coordination among spacecraft operators, a dedicated space traffic coordination platform is not yet in place.

Joint Commercial Operations (JCO) is a collaborative framework developed by the U.S. Department of Defense (DoD) in partnership with commercial space companies to advance space domain awareness (SDA) and space safety. Originally launched in 2021 under the U.S. Space Force, JCO enables real-time coordination and testing between the U.S. military and commercial SSA providers.

JCO collaborates with several leading SSA companies, including LeoLabs, ExoAnalytic, Slingshot Aerospace, to name a few. Each company contributes different data types and tools under a shared operations model. This gives both good coverage and flexibility to the system, while of course also constraints if tasking of sensors cannot be prioritised,. JCO has started using SBSS in 2025 and is currently leading the efforts on a hybrid SSA network.

While the JCO format has some advantages in its global coverage and utilizing commercial SSA providers very effectively, its information is provided to military operators only and thus not publicly available.

Feature	EUSST	JCO	TRACCCS
Lead Entity	EU (government)	U.S. public-private operations initiative	U.S. DoD + commercial
Sensor Types	Radars, optical, laser. All sensor nationally owned	Radar, optical, RF, space based, data fusion, global coverage	US Military sensors (SSN) + commercial (radar, optical, RF)
Geographical Coverage	Primarily Europe	Global (U.S., NZ, Africa, etc.)	Global (U.S.-led, commercial inputs)
Data Sharing	Federated architecture: data is shared among members via a central SST Front Desk. Internal consortium + registered users	Selective: commercial-to-military, some public dashboards	Public safety data + restricted services
Catalogue Access	Internal, not (yet) public. Registered users can request object data for their satellites		Public catalogue (future replacement for space-track.org)
Primary Users	EU governments, satellite operators		Satellite operators, allied governments
Services	Collision Avoidance, Re-entry, Fragmentation	Orbital data and ephemerides Satellite manoeuvre detection Conjunction warnings (close approach predictions) Debris field tracking Proximity operations analysis Anomalous behaviour alerts Launch and breakup detection	

Global SSA data sharing for transparency

Limits of classification

The boundaries of classification mainly lie in the tension between transparency and security. For effective verification of responsible behaviour in space, one would ideally want to share as much observational data as possible within international partnerships. This includes detecting unusual manoeuvres, rendezvous and proximity operations, or other deviations in normal satellite behaviour. However, states (especially military organisations) are often reluctant to share raw observational data, particularly when it could reveal the performance limits of national, often military, sensors. Data that exposes the capabilities of sensors is usually classified and will not appear in publicly available databases. Similarly, observations involving state owned satellites, such as military satellites, are not shared. Hence, open catalogues of space objects will never be complete.

Moreover, essential information about the sensors within the network available within SSA networks is typically not made publicly available. While basic data about the objects such as ephemerides is often shared, more sensitive details are deliberately withheld. This includes the technical characteristics of sensors, such as their location, sensitivity, or coverage, as well as the uncertainties associated with inferred orbital parameters. Sharing these details could allow geopolitical competitors to reverse engineer the capabilities and limitations of the SSA network. For the same reasons, SSA networks hesitate to provide SSA services to nations considered unfriendly. As a result, while SSA cooperation and transparency are promoted publicly, in practice, the exchange of high-quality data and services remains constrained by strategic, political, and military considerations.

Data sharing within SSA networks is generally most common among nations with established partnerships and friendly relations. Within these trusted frameworks, countries are more willing to exchange information. However, as geopolitical relations are under increasing pressure, this willingness to share data declines. States become increasingly cautious about revealing information that could expose the capabilities or limitations of their space surveillance assets. Withholding knowledge of your capabilities prevents the opponent from gaining a strategic advantage.

Observing behaviour in space

For a reliable situational awareness picture in the context of SSA, the availability of reliable data is crucial. To ensure transparency and enable independent verification, it is essential to provide not only the derived ephemerides but also the associated uncertainties. Without the uncertainties associated with the orbital parameters, one cannot know how accurate the computed positions of objects are. In addition to that, the metadata about the sensor that performed the observation, must be preserved to ensure verifiability in case of an event of high interest. Without access to these elements, conclusions or claims about an object's position and behaviour remain unverifiable and therefore lack credibility in the international community.

In the context of verifying irresponsible behaviour in space, SSA primarily relies on tracking the positions and movements of objects in orbit. This provides information for detecting certain types of activities, but significant limitations remain. SSA can only provide a contribution to monitoring behaviour that requires close proximity. For example, SSA can be used to provide information on activities where a space object approaches or physically manipulates another satellite. SSA networks can determine with reasonable accuracy whether two objects were within a few hundred meters of each other, which is close in the context of satellites. With sufficiently frequent observations and good geographical coverage, it is feasible to detect close approaches or manoeuvres that force other satellites to adjust their trajectory.

Certain space based counter-space activities, such as damaging a satellite with high power electromagnetic radiation or chemical sprays, require the hostile satellite to be in close physical proximity to the target. In such cases, SSA can reveal that the two objects were near each other at the relevant time, providing circumstantial evidence that contributes to assessing the situation. However, SSA cannot confirm the actual use of an effector or the exact nature of the interaction — it can only show that proximity conditions existed in which such an event could have taken place, and some level of knowledge is necessary to determine if there has been a change of behaviour compared to the norm. Similarly, if a proximity operation results in observable orbital changes or the creation of debris, SSA can capture these consequences that can serve as supporting evidence.

Kinetic destruction using ground-based anti-satellite (ASAT) missiles is only partially observable with SSA. If such an attack produces debris, SSA networks can track the resulting fragments, making the attack indirectly visible. However, the launch of the ASAT missile itself or the initial strike is not detectable with SSA alone. Co-orbital ASATs could be detected using SSA.

Detection of permanently disruption of satellite operations through jamming, spoofing, or cyber operations is beyond SSA's scope. These activities affect the functionality of satellites but do not alter their position or trajectory, meaning SSA networks cannot detect them. Identifying the source of interference, distinguishing between hostile jamming and natural causes like space weather, requires other monitoring tools outside the SSA framework. Similarly, disabling ground stations or infrastructure used to control satellites is entirely outside SSA's reach.

Finally, intentionally creating long-lived space debris, such as seeding debris in specific orbits or failing to perform end-of-life manoeuvres, can be detected by SSA if the resulting debris is large enough and within the detection limits of available sensors. In LEO, SSA networks are capable of tracking objects down to several centimetres in size, allowing the identification of new debris clouds or fragmentation events. In higher orbits like GEO, only larger debris is reliably detectable with current sensor capabilities.

▼ *Malargüe tracking station.*

4 Conclusions and recommendations

4. Conclusions and recommendations

This report has outlined the range of sensors available for monitoring space activities, as well as the structure of sensor networks, in order to advance the conversation surrounding the use of SSA in verifying responsible behaviour in outer space. It finds that SSA can be used to verify actions in orbit. That is because, once in orbit, a space object generally follows a stable and predictable trajectory unless affected by natural forces, deliberate manoeuvres, or unexpected events like explosions or collisions. By maintaining updated orbital data, sudden deviations can be detected and analysed to determine whether they result from intentional actions or unforeseen incidents. SSA excels at identifying the results of visible, physical activities, such as debris-generating ASAT tests or proximity operations. It is less effective for activities like cyber-attacks or electronic warfare, which require complementary analysis.
Ground-Based Space Surveillance (GBSS) will continue to serve as the foundation of Space Situational Awareness (SSA) efforts for the foreseeable future. An effective GBSS requires a geographically distributed sensor network using a variety of sensor types (radar, optical, and laser) to fully monitor activities in different orbital regimes. There are different advantaged and disadvantages to the different types of ground based sensors: Radar systems are highly effective for tracking objects in LEO regardless of weather or time, though costs rise significantly for higher orbits; advanced bistatic and multistatic radars improve coverage and precision across LEO, MEO, and GEO. Optical telescopes complement radar, especially in GEO, offering cost-effective tracking and high-resolution imagery, though they are limited by daylight and weather. Passive RF sensors detect signals emitted by satellites, making them valuable for continuous monitoring in MEO and GEO, while also supporting detection of malicious activities like jamming. Satellite Laser Ranging (SLR) enables highly precise tracking of debris, even without onboard retroreflectors, but carries risks of dual-use, as powerful lasers can also dazzle or damage satellites.

Space-Based Space Surveillance (SBSS) is expected to play an increasingly important role in SSA, particularly in verification contexts. By operating above the Earth's atmosphere, SBSS avoids many of the challenges associated with ground-based systems, enabling more accurate and continuous observations. To improve space situational awareness and support verification, a hybrid approach combining GBSS and SBSS is needed. While space-based sensors enhance coverage and accuracy, especially in challenging orbital conditions, ground-based improvements using cost-effective technologies can complement the overall system.

There are several regional SSA networks (EUSST, TRaCCS, and JCO) with their own space object databases that can potentially contribute to a global SSA verification mechanism. Their combined sensors have a good geographical coverage and sensor type coverage. Their respective databases are not publicly available or in a limited form which limits the possibility to use them for verification. A possibility could be to work towards an independent organisation that has access to the databases for verification efforts. Commercial SSA data providers can contribute to a global effort and fill gaps in the public systems.

Finally, analytical capability is essential, as raw SSA data alone is insufficient. The information must be processed within reliable frameworks that can assess meaning. Effective verification should go beyond merely identifying violations—it should also foster trust, influence behaviour, and help create common norms and expectations for responsible conduct in space. Reliable SSA therefore requires verifiable data, including not just orbital positions (ephemerides) but also their uncertainties and sensor metadata. Without this information, assessments of object location and behaviour cannot be independently verified and lack credibility in the international context. Efforts should be made to work towards data sharing agreements beyond just ephemerides.

◄ *Artist's impression of in-orbit servicing ESA mission RISE.*

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◄ *One of countless satellites orbiting Earth.*

Annex I: SSA capabilities of the Netherlands

The Netherlands is developing national capabilities to contribute to SSA, in order to support its own space safety interests and the EUSST network. Several capabilities are being developed.

The Netherlands has six L-band radar systems, of which four are owned by the Royal Netherlands Navy and located on ships. Two are owned by the Royal Netherlands Air Force and located on land in the Netherlands. The radars are currently used for air defence and can be used for ballistic missile detection. The possibility to add SSA functionalities to these systems - specifically accurate all-weather/day & night Orbit Determination and Re-Entry tracking - is currently being explored.

The Netherlands is also working on FOTOS, an optical surveillance and tracking system designed for resident space object (RSO) detection and orbit determination, operating during twilight and nighttime hours. Each FOTOS station consists of two elements. One is a wide-angle surveillance sensor that scans the sky above 20 degrees to detect RSOs. The other is a tracking sensor that is automatically tasked to observe objects newly detected by the surveillance sensor, or systematically observes the GEO belt if no new detections occur. Two FOTOS stations will be developed of which one will be placed in the European territory of the Netherlands, and the other station will operate on one of the Dutch Caribbean islands. An API will be developed to ensure direct and efficient data sharing with EUSST, and operational readiness is expected in the first half of 2026. The system's limitation is that it is only operating during twilight and nighttime, and it needs cloud free conditions.

The Netherlands is also developing DistuRF, a passive RF interferometer system that operates between 30 MHz and 3 GHz, based on the concept of the LOFAR radio telescope. DistuRF is designed to be compatible with existing European SSA RADAR systems operating withing this frequency range. Hence, it is suitable for bistatic radar operations, receiving reflected signals from transmitters located elsewhere, enhancing detection and tracking capabilities. Additionally, DistuRF can contribute to space weather monitoring and is compatible with Belgian meteor detection capabilities. The system is still under development, and operations are expected in the second half of 2027.

In addition to these developments, the Netherlands explores the potential to adapt existing scientific infrastructure, such as the Dutch Open Telescope (located on the Spanish island La Palma) and the Westerbork Synthesis Radio Telescope, for SSA purposes, as well as expanding the FOTOS network of ground stations to other locations. Moreover, recently the Netherlands also started looking into a cooperation with France into developing an electro-optical SSA system with the possibility of accurate orbit determination and imaging.

The Netherlands is part of the EUSST partnership since 2022 and JCO since 2025. The first Dutch JCO operators will be trained in Q3 2025.

Annex II

ACTIONS IN SPACE	DETECTABLE BY SSA
Intentionally damaging/destroying objects in outer space	
disrupting the operation of sensors by means of laser dazzling; (A dazzler is a non-lethal weapon which uses intense directed radiation to temporarily disorient its target with flash blindness.)	No, this can happen from the ground.
damaging or disabling satellites using chemical sprays or high-power electromagnetic radiation;	SSA can provide circumstantial evidence by monitoring positions of hostile and target satellites.
kinetically damaging or disabling satellites by means of ground-based attacks; (ASAT?)	No, too short time window.
using a space object to physically manipulate other space objects, or intentionally causing a collision between two space objects.	Yes, positions and trajectories of satellites can be monitored.
Permanently disrupting satellite operations	
disrupting guidance commands by jamming radio signals or conducting cyber operations;	No, this falls outside the scope of SSA.
intentionally jamming and/or spoofing satellite signals;	No, this falls outside the scope of SSA.
disabling ground stations and other infrastructure used to control and operate satellites;	No, this falls outside the scope of SSA.
Intentionally creating long-lived space debris, including rendering satellite orbits unusable by intentionally dispersing ('seeding') space debris in those orbits.	Depends on the size of the dispersed debris.
Intentionally damaging and/or destroying objects on the ground, in the air or in outer space, using objects in orbit, as a result of which outer space and those objects in turn could be targeted by a counterattack.	No
Using satellites to approach or make physical contact with other operational satellites by means of rendezvous and proximity operations (RPOs) without the permission of the owner of the satellite that is the target of the operation can in certain cases be considered irresponsible behaviour. This includes intentionally hindering a space object in orbit and/or forcing it to perform an evasive manoeuvre.	Yes, SSA can measure the positions of the satellites.

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◀ *Artist's impression of rendezvous operation in active debris removal mission.*

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Cover: Variety of Space Situational Awareness sensors.