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Command and Control of a Multinational Space Surveillance and Tracking Network

Joint Air Power
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Author
Lt Col Andrea Console (ITA AF)

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The Joint Air Power Competence Centre
von-Seydlitz-Kaserne
Römerstraße 140
47546 Kalkar
Germany

Telephone: +49 (0) 2824 90 2201
Facsimile: +49 (0) 2824 90 2208
E-Mail: contact@japcc.org
Website: www.japcc.org

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The Executive Director of the Joint Air Power Competence Centre (JAPCC)

SUBJECT:

Command and Control of a Multinational Space Surveillance and Tracking Network

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All NATO Commands, Nations, Ministries of Defence and Relevant Organizations

Space Surveillance and Tracking (SST) is the ability to detect and predict the position of space objects in orbit around the Earth, and is generally recognized as a fundamental component of Space Situational Awareness (SSA). In particular, it serves a number of different purposes, both civil and military. For instance, it is an enabler for the safety of operations in Space, because it provides satellite owners/operators with vital information to avoid in-space collisions with space debris or other satellites. The current plans for the launch of mega-constellations (constellations of hundreds to thousands of satellites) and the exponential growth of space debris make this capability essential for any space activity. SST can also significantly contribute to military operations, as it provides information to produce the Recognized Space Picture (RSP); such as the opponent's ISR satellites overflight forecasts and updated insight about opponent's space capabilities. Last but not least, SST is an enabler for most counter-space capabilities as it provides the position of the target satellites with the accuracy required for such applications.

A serviceable SST capability relies on timely and accurate data as well as fast and effective processing and dissemination capabilities. In particular, a network of SST sensors with location and technological diversity is essential to provide uninterrupted surveillance and tracking around the globe and increased accuracy because it allows exploiting the strengths and compensating for the limits of the different techniques employed. For instance, passive optical SST sensors (telescopes) provide precise angular information, but they need clear nights to operate. On the other hand, radars are barely affected by local weather conditions and provide excellent information about ranges, but they usually can only detect objects in lower orbits (LEO). Additionally, satellite owners and operators provide another important contribution to an effective SST capability because they usually have the most accurate positional data for their satellites and know any planned satellite manoeuvre.

In such a complex environment it is self-evident that collaborative and multinational SST is not only the least expensive, but probably the only way to achieve an effective SST. The recent establishment of several multinational agreements for cooperative SST, such as the USSTRATCOM's SSA Sharing Programme and the EU SST framework, seems to confirm this assessment.

This white paper aims at providing a reasoned compendium about SST and multinational SST networks. In particular, it addresses the analysis of several architectural solutions for SST networks to identify and evaluate applicable C2 models. The document starts with a knowledge base about SST and its contribution to SSA. It defines the relevant terms of reference and

JOINT AIR POWER COMPETENCE CENTRE
Joint Air Power Competence Centre | **centre de compétence de la puissance aérienne interarmées**
von-Seydlitz-Kaserne | Römerstraße 140 | 47546 Kalkar | Germany/Allemagne | Tel +49 (0) 2824 90 2201 | Fax +49 (0) 2824 90 2208 | www.japcc.org
NCN: +234 or 239 2201 | **E-Mail:** contact@japcc.org

describes its applications, both for civil and military purposes. It also illustrates the architecture of a generic SST system and provides several examples of existing national and multinational SST endeavours, with particular reference to the European Union (EU) SST framework. Finally, it provides a NATO perspective on emerging multinational SST endeavours, providing advice on why and how NATO should try to promote such agreements.

I hope that you will find this document informative as well as useful. As usual, thoughtful insights from our readers are welcome. In this regard, please feel free to contact the JAPCC's C4ISR and Space Branch via e-mail at C4ISRS@japcc.org.

Klaus Habersetzer
Lieutenant General, DEU AF
Executive Director, JAPCC

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An Air Force Wideband Enterprise Terminal (AFWET) stands poised under a protective covering on Offutt Air Force Base, Neb. AFWET terminals communicate with a variety of satellites and keep military branches and other government agencies connected worldwide.

CHAPTER 1

Introduction

A significant number of devices we currently use in everyday living rely on space, to some extent. In fact, satellites provide us with many space-based products and services that are fundamental for both civil and military purposes, such as communications, navigation, precise timing, or space-based earth imagery. As a matter of fact, our demand for space-based products and services is rapidly rising, as the revenue trend of the global satellite industry in the last decade shows (chart 1). For this reason, the satellite population is continuously growing, as well as the related amount of space debris, which includes inactive satellites and other defunct human-made objects in earth's orbit.

This implies that satellites fly under an increasing threat of collision; thus, satellite operators should constantly monitor the trajectories of space objects to reduce such risk. Space Surveillance and Tracking (SST) is the detection of space objects to determine and predict their orbits. Ground and space-based SST sensors and the related processing facilities form the basis of the capability, which can work in a standalone mode or a network. In particular, pooling SST sensors and facilities to build an SST network, as well as sharing SST data and information, are effective ways to better exploit the available assets to deliver improved products. At best, an SST network can even assume a multinational scope, thus including assets and data that multiple nations provide.

1.1 Aim and Scope

The creation of a multinational network of SST sensors is a clever solution to enable the capabilities of the participants to be leveraged. However, to achieve its best performance, an SST multinational network needs unrestricted data sharing and proper management to optimize survey and tracking campaigns. In particular, to efficiently task such a network, nations require a well-structured and unambiguous Command and Control (C2) chain. The aim of this study is to identify the way ahead for the development of an efficient C2 model for a multinational SST network, based on an analysis of the possible architectural solutions. The study will also advise on the approach that NATO should consider with regards to any raising multinational SST initiative that involves NATO countries.

1.2 Assumptions

This study assumes that national budget constraints provide an incentive for nations to find collaborative solutions to achieve a more effective SST capability. It also assumes the willingness of the nations to collaborate to provide improved SST products. Furthermore, this implies a generally positive attitude of nations towards pooling SST assets and sharing SST data.

1.3 Methodology

To set the scene, this study initially introduces the importance of space for civil and military activities by presenting some relevant examples of space-based services. Next, the focus shifts to the threats that


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RF transmissions technicians set up antenna and signals for SATCOM.

menace satellites and space-based systems in general. The study then presents Space Situational Awareness (SSA) as a way to mitigate the risk to space assets and activities. Specifically, the study introduces the three components of SSA (according to the definition adopted in the EU, which this study also embraces), with a particularly detailed reference to SST. Moreover, the study describes sensors categories and the whole SST processing chain for a better understanding of a complete SST system.

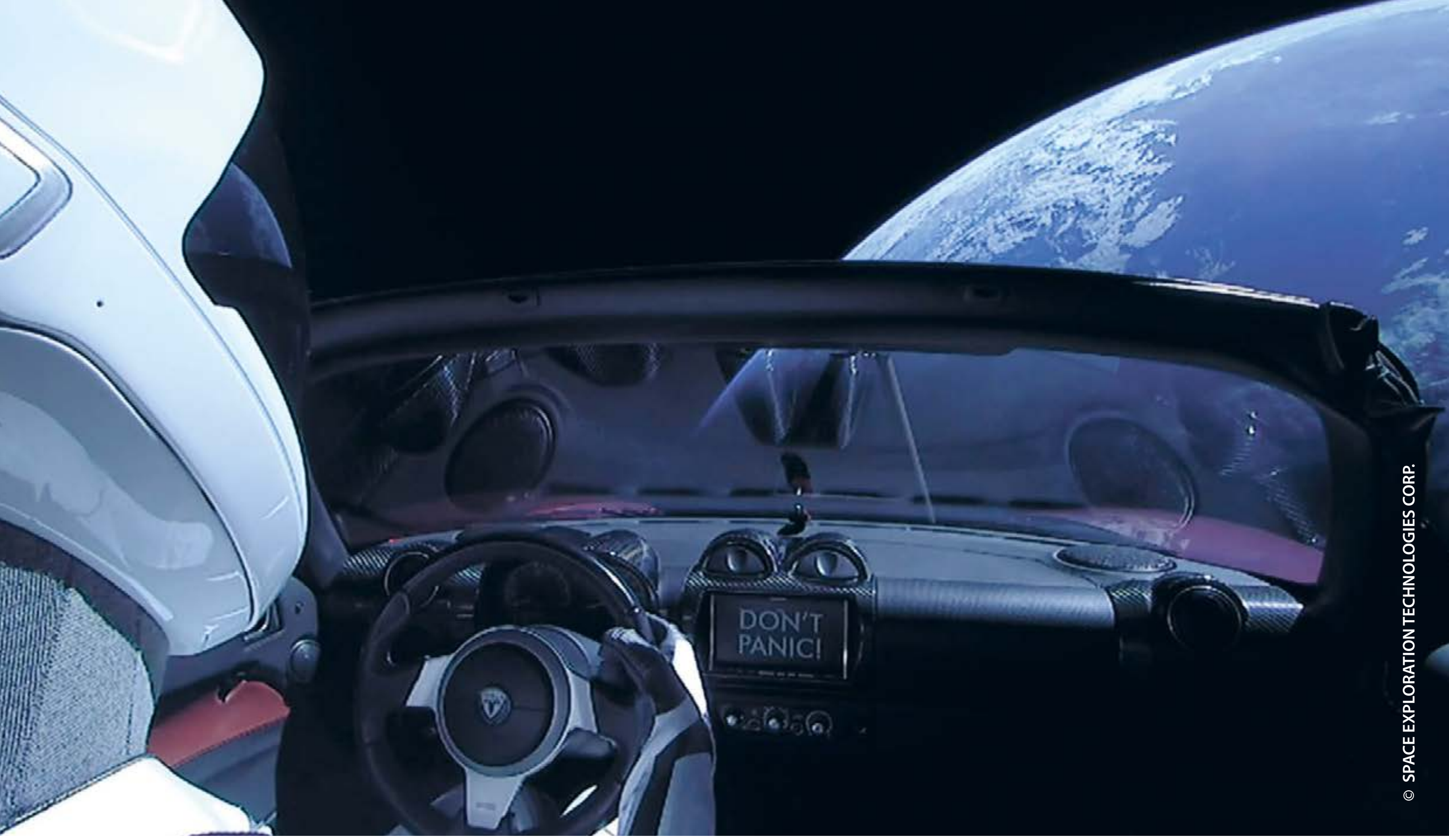
Next, this white paper presents some examples of national SST systems. For the purposes of this study, only the US and some European space-faring nations were considered. The paper also describes some examples of bilateral and multilateral agreements and collaborations, as well as the European Space Agency (ESA) SSA program.

The list of relevant examples of multinational SST cooperation continues with a detailed description of the European SST project, including its military implications and possible connections with NATO needs.

Finally, after discussing motivations and obstacles relevant to the creation of a multinational SST network, the study conducts a systematic analysis of the possible architectures for an SST network, taking into account benefits and limitation of each proposed design. Again, the study accounts for possible interactions between NATO and a multinational SST network, including NATO Allies, and proposes advisable ways ahead.

1.4 Limitations

Research and analysis associated with this study included both open and classified sources. Nevertheless, to permit the widest dissemination, the resulting white paper has been kept at the unclassified level. In particular, only publicly available information about national SST assets has been considered. In fact, considering that the information provided only serves the study's purpose of showing the complexity of a complete SST system, one does not require a deeper knowledge of the technical details of the listed assets.



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In 2018, SpaceX successfully launched its Falcon Heavy rocket carrying Elon Musk's Tesla Roadster, complete with a dummy driver named 'Starman', into space. The on-screen display message 'Don't Panic!' pays homage to the sci-fi comic novel Hitchhiker's Guide to the Galaxy.

CHAPTER 2

Terms and Definitions

This chapter aims to introduce the terminology adopted in this study and to provide a common base for all readers regardless of their background. For the same reason, greater detail is offered on complex concepts that need some context.

Some of the terms used in this study do not have a worldwide-approved international definition, yet. For this reason, one can consider the following proposed definitions valid only for the purposes of this study, and thus devoid of any legal or political implications.

2.1 Outer Space, or Simply Space

Outer space is the physical universe beyond the earth's atmosphere.

2.2 Orbit

An orbit is a curved path in space that is more or less indefinitely extended (parabolic or hyperbolic orbits) or of a repetitive character (elliptical or circular orbits), like the orbit of the Moon around the earth. There are six commonly considered geocentric (around the earth) orbits:

- The Low Earth Orbit (LEO), which includes all the possible orbits below 2,000 km of altitude above Mean Sea Level (MSL);

- The Geosynchronous Orbit (GSO), which has an altitude of roughly 35,786 km MSL and takes one sidereal day (roughly 23 hours, 56 minutes, and 4 seconds) for a satellite to complete the orbit;

- The Geostationary Orbit (GEO), which is a particular circular GSO inclined 0° to earth's equatorial plane (i.e. directly above the equator);

- The Medium Earth Orbit (MEO), located between LEO and GEO;

- The Highly Elliptical Orbit (HEO), which is an elliptical orbit with high eccentricity. Specific examples of HEO orbits include the Molniya orbits, named after the Molniya Soviet communication satellites that used them, and the Tundra orbits;

- The High Earth Orbit, less common, which includes any geocentric orbit above the GSO.

2.3 Space Object

Space objects include any man-made object in outer space.

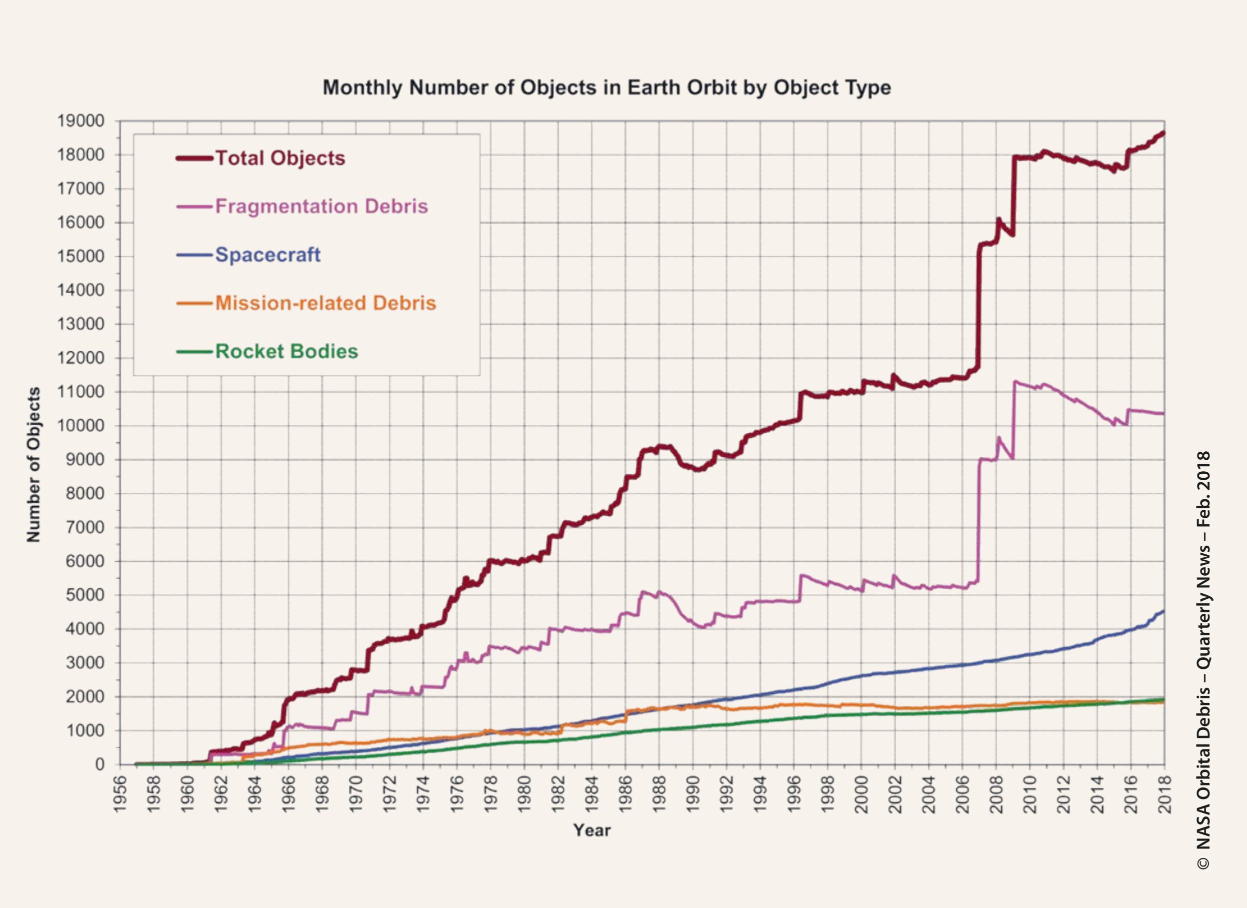
2.4 Spacecraft

A spacecraft is any space object designed for travel or operation in outer space.

2.5 Space Debris

Space debris includes any man-made space object, including fragments and elements thereof, in earth's orbit or re-entering earth's atmosphere, which is non-functional or no longer serves any specific purpose.

Space junk is one of the principal threats to satellites. The US Space Surveillance Network (SSN) has more than 15,000 objects in its catalogue, but it is estimated



© NASA Orbital Debris – Quarterly News – Feb. 2018

Figure 1: Monthly Number of Catalogued Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in earth orbit officially catalogued by the US Space Surveillance Network. 'Fragmentation debris' includes satellite breakup debris and anomalous event debris, while 'mission-related debris' includes all objects dispensed, separated, or released as part of the planned mission.

Chelyabinsk Event: a huge meteor flew over the Urals in the early morning of 15 February 2013. The fireball exploded over the city of Chelyabinsk and caused damage to buildings and hundreds of injured. This photo was taken about 200 km away, one minute after the explosion.

that more than 500,000 pieces of debris bigger than 1 cm are currently in earth's orbit,[1] mainly in LEO. Additionally, there are many millions of smaller pieces of debris that are not tracked because they are too minute to be detected by current technology. While the proper shielding of space can mitigate the threat from the smallest particles, collisions with larger objects can damage or even destroy a satellite due to the high kinetic energy involved at relative propagation velocities – above 8 km/s. To avoid such collisions, spacecraft controllers must manoeuvre them, but these avoidance manoeuvres come at the cost of the limited onboard propellant.

2.6 Space Situational Awareness

While there is no universally accepted definition for SSA, it can be generally understood as the ability to accurately characterize the space environment and activities in space. Civil SSA, with reference to the EU definition of SSA, combines positional information on the trajectory of objects in space (mainly using optical telescopes and radars) – including natural bodies like asteroids – with information on space weather. Military and national security SSA applications also include intelligence activities, such as the characterization of the objects in space, their capabilities and limitations, and whether they pose potential threats. On the other hand, Near Earth Object (NEO – see paragraph 2.8) events are less significant from a military perspective. To avoid misunderstanding, publications sometimes refer to military SSA as Space Domain Awareness.

2.7 Space Weather

Space weather is the collection of physical processes beginning at the Sun or outside the solar system, and

NEO diameter	Impact energy (Megatons)	Typical interval (years)	Effect
2 mm		1 per hour for each location on the earth	Nice meteor
3 m	0.002	0.5	Fireball, meteorites reach ground
10 m	0.08	5	Big fireball, fear, shock wave, 5-fold energy of Hiroshima bomb
40 m	5	300	Tunguska-like explosion or crater
140 m	220	10,000	Regional destruction, Tsunami
500 m	10,000	200,000	Continent-wide destruction
1 km	80,000	700,000	Million deaths, global effects
10 km	80,000,000	100,000,000	End of human civilization

Table 1: Expected effects for an impacting NEO with respect to its size – Data source: Gerhard Drolshagen, Detlef Koschny, Reference impact scenarios – an example, Presented in ESOC, Darmstadt, 6 Feb 2014.

ultimately affecting human activities on earth and in space. It comprises particles and radiation coming from outer space.

Space weather can potentially affect numerous sectors: broadcasting, weather services, space-based telecommunications, navigation, power distribution, and terrestrial communications, especially at northern latitudes. For instance, solar activities can influence earth's ionosphere, affecting some specific types of electromagnetic (EM) communications that propagate through the ionosphere or by ionospheric reflexion. For example, solar activities can degrade, disrupt, or deny High Frequency (HF) communications, Satellite Communications (SATCOM), or space-based Positioning, Navigation, and Timing (PNT) services. More generally speaking, severe space weather conditions can inhibit satellite operations and even permanently damage the space assets. The aim of space weather prediction, which is a component of SSA, is to provide timely regional forecasts for these effects to minimize their impact through the development of contingency plans and to enable satellite operators to activate protection measures.

2.8 Near Earth Objects

NEOs are natural objects that can potentially collide with earth and cause lethal effects on a global scale. As a part of SSA, NEO-related capability refers to the ability to assess the relevant impact risk and propose potential mitigation measures. NEOs are described as any asteroid or incoming object closer than 0.3 AU (1 AU = 1 Astronomical Unit = distance Sun–Earth = 149.6 million km). There are more than 600,000 known asteroids in our solar system and almost 10,000 of them are NEOs. NASA provides a free list of past and predicted NEOs through the website of the 'Center for Near Earth Object Studies' (CNEOS). A remarkable example of the possible effects of a significant meteoroid burst is the 'Tunguska event'. On 30 June 1908, something suddenly knocked down nearly 80 million trees over an area of 2,150 km^2 in Siberia. The most plausible hypothesis for this event is the explosion in the atmosphere of a small comet or an asteroid-like meteorite with a diameter of 30–60 m.

2.9 Space Surveillance and Tracking

SST is the ability to detect and predict the movement of space objects in orbit around the earth. Thus, the purpose of this capability is to contribute to the overall SSA, whatever definition of SSA one may consider. The data an SST system generates can contribute to the active protection of space-based infrastructure from in-space collisions. Additionally, intelligence operators can use SST to gather information on the nature of a space object, such as discovering unknown satellites or assess their activity and efficiency status (Space Object Identification (SOI)). Clearly, the purpose of this activity is usually military-oriented; however, in some cases, it can also be useful for planning effective satellite manoeuvres.

A complete SST system includes not only the SST sensors and the relevant management structures but also all the facilities one needs to establish a full SST processing chain, from the data collection and fusion to the information analysis.

SST systems provide 'surveillance' and 'tracking' of space objects. In particular, the 'surveillance' aims to detect new objects and determine their initial orbit. Afterwards, it allows the revisit of existing catalogue objects and the delivery of new measurements. On the other hand, the purpose of 'tracking' is to sharpen up the orbits of the space objects, whether they are initial orbit determinations that need refinement to create new catalogue entries or scheduled measurements for the day-to-day catalogue maintenance.

2.10 Space Object Identification

SOI is the analysis of SST data to determine satellite characteristics such as size, shape, ephemeris, motion, and orientation. SOI information can serve several purposes. For example, it can help determine the operational status of various payloads, or it may support the prediction of upcoming manoeuvres for third-party satellites (e.g. deorbiting). The process of using SOI data, in conjunction with other intelligence resources, to determine the nature of unidentified payloads is called 'mission payload assessment'. The *US Department of Defense* introduced the acronym SOI in the 1997 *Glossary for Ballistic Missile Defence*.

2.11 SST Sensor

An SST sensor is a device or a combination of devices, either ground-based or space-based, one uses to measure physical parameters related to space objects, such as, but not limited to, size, location and speed.

2.12 SST Data

SST data is the raw output of any SST sensor.

2.13 SST Information

SST information is the result of processing SST data, from one or multiple sources, to obtain content that is readily meaningful to the recipient.

2.14 SST Products and Services

An SST product is the tangible result of an SST processing activity, while an SST service is the structured delivery of SST data, information, or products by an SST service provider.

2.15 Conjunction Assessment

The Conjunction Assessment (CA) is the process of identifying close approaches between two orbiting objects.

2.16 Conjunction Summary Message

The Conjunction Summary Message (CSM) is a fixed-format ASCII message that contains information about conjunction between two space objects. A CSM includes time of closest approach, miss distance/relative speed, closest approach relative position/velocity, object identifiers, observation statistics, orbit parameters, co-variance, modelling flags, and notes.[2]

2.17 Conjunction Data Message

The Conjunction Data Message (CDM) Recommended Standard specifies a standard message format for use in exchanging spacecraft conjunction information between originators of CAs and satellite owner/operators and other authorized parties. These messages provide satellite owner/operators with the relevant information about conjunctions between objects in space to enable consistent warnings by different organizations employing diverse CA techniques.[3] The CDM is the format agreed upon by the leading space agencies of the world. It replaces the CSM in most recent SSA-related applications.

2.18 Recognized Space Picture

The Recognized Space Picture (RSP) is a military-specific SSA product. It provides a consistent and coherent scenario representing the real-time picture of space in terms of satellite-related information, offering specialized features and analytic capabilities for measurements, reports, and graphs. Essentially, it provides a current, comprehensive representation of the possible threats to the operational functionality of military satellites. The RSP is the result of the validated fusion of aggregated data from various sources, including intelligence sources. Its purpose is to show the military and political authorities the situation in space and its consequence on planned, current military operations on the ground and/or in space, mainly by the:

- Identification and characterization of all space assets of interest (own and opponent's);
- Prediction of the position of all space assets of interests (own and opponent's);
- Identification and characterization of future/present threats to own space assets;
- Identification and characterization of future/current space threats to own or friendly ground operations, population, property, etc.;
- Alert information in case of a confirmed threat.

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1. Garcia, Mark, 'Space Debris and Human Spacecraft', NASA webpage – https://www.nasa.gov/mission_pages/station/news/orbital_debris.html, accessed on 23 Feb. 2018.
2. 'Conjunction Summary Message Guide', space-track.org website – https://www.space-track.org/documents/CSM_Guide.pdf, accessed on 23 Feb. 2018.
3. 'Conjunction Data message recommended standard', The Consultative Committee for Space Data Systems, Jun. 2013.


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A SpaceX Falcon 9 rocket lifts off from Cape Canaveral Air Force station Friday, 3 March 2016, carrying the SES-9 communications satellite.

CHAPTER 3

The Importance of Space Services and SSA as a Means to Ensure Their Continuity

Today, the availability of space-based products and services has become crucial for an incredible number of civil and military applications. The reliance on space is quickly growing to the point that many people do not even realize how deeply a sudden interruption of such services would impact the world. Moreover, only a few have some understanding of all the risks that threaten space systems – particularly the 'space segment' – including collisions with debris, anti-satellite (ASAT) weapons, adverse space weather, and cyberattacks. As every risk management course teaches, the risk level for a possible negative event is calculated as the product of likelihood and consequences. In the case of the potential loss of any critical space-based service, the consequences would be dramatic, and the likelihood is rapidly increasing due to the exacerbation of the aforementioned threats, which this paper will later describe in more detail. In a nutshell, a lot of everyday technologies that people usually take for granted are at risk, and it is consequently necessary to raise the awareness of these conditions to urge investments on possible countermeasures.

3.1 Space for Civil and Military Purposes

Space is involved in a long list of commercial and civil activities, but it is also fundamental for military purposes. For instance, broadcast and point-to-point, high-speed, beyond-line-of-sight communications – like the data links Unmanned Aircraft Systems (UASs) require – heavily rely on GEO satellites. The geostationary orbit, also called the GEO belt, is one of the geosynchronous orbits. Geosynchronous orbits have an orbital period equal to the earth's rotational period (sidereal day), meaning that after

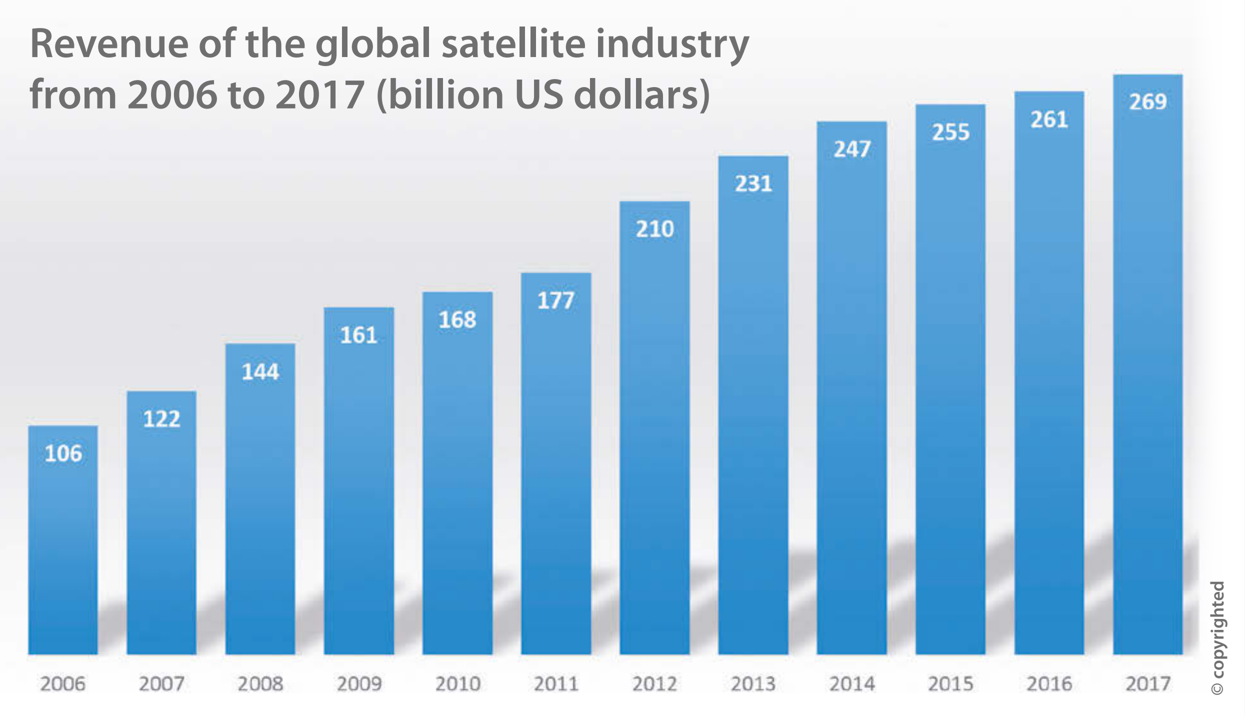


Figure 1: Data source: Satellite Industry Association.

a sidereal day, an object in a GSO returns to the same position in the sky for an observer on earth. In this case, an object in GEO appears motionless at a fixed position in the sky to ground observers. For this reason, and due to their long distance from the earth's surface, GEO satellites are ideal to ensure constant coverage over a huge area, such as TV and radio broadcasting services or broadband long-range data links. In particular, a single GEO satellite can cover more than one-third of the globe constantly, meaning that three GEO satellites are enough to ensure global coverage, apart from higher latitudes, which are preferably reached by HEO like the Molniya orbit. As a result, GEO satellites are also ideal to ensure a continuous global observation of the earth using the smallest possible number of satellites. Some examples of missions for earth observation GEO satellites include weather and climate monitoring and detecting infrared emissions from missile or spacecraft launches (Overhead Persistent Infrared (OPIR)) to provide space-based early warning of a missile attack. However, since GEO satellites are considerably farther from the earth's surface than LEO satellites, they are not the best choice when a particularly high optical is required.

Clearly, nations and commercial firms that operate satellites highly covet an orbit with such a precious peculiarity, and the GEO can, thus, easily become overcrowded. However, according to current space law, it is not possible to buy or rent an orbit. For this reason, every nation tries to reserve a slot of the GEO belt for itself by positioning its GEO satellites first and maintaining the position, which is the only way to 'secure a seat'. This is only a rough simplification of the process because the real procedure is far more complex. For instance, the positioning of a new satellite requires the approval of the International Telecommunication Union (ITU) – an agency of the United Nations – who is responsible for ensuring that it does not cause EM interference with the existing GEO satellites.

Below the geosynchronous region, there is the MEO. Navigation satellites, like those of the Global Positioning System (GPS), GLObal NAvigation Satellite

System (GLONASS), and the European Global Satellite Navigation System (GALILEO) constellations, predominantly occupy this region. In particular, navigation satellites are usually deployed in high MEO for several reasons, such as an adequately broad coverage for each satellite, reasonable revisit time over their ground control centre(s), reduced influence of the Van Allen radiation belts, and the substantial absence of atmospheric drag.

Currently, global space-based navigation systems deliver position information and navigation assistance for commercial land, air, and sea travels, including tracking of goods. However, since these systems also offer precise time information, they are commonly referred to as PNT service providers. Time information is essential for a broad set of time-dependent needs, from data networks synchronization to accurate timestamp recording for monetary transactions. A precise time reference is also important for military applications, such as synchronization in some secure communication devices that rely on frequency hopping. In short, PNT services encompass much more than simple navigational functions; rather, they provide essential contributions to more everyday activities than most people imagine.

The LEO region is the portion of outer space relatively close to earth, roughly between 160 and 2,000 km. The excessive atmospheric drag from gases in the exosphere, which make orbital flight unsustainable, determine its inner boundary, while the inner Van Allen belt, whose radiations are deadly to electronic circuits, limit its outer boundary. Due to the LEO region's particular features, satellite designers usually choose it for communication, earth observation, and intelligence satellites. In fact, due to the low altitude, it is the simplest and cheapest space region to reach. It provides the lowest latency and the minimum link budget requirements for SATCOM (i.e. less power). Therefore, LEO constellations are ideal for providing a reliable global-coverage solution for point-to-point communications, such as the Iridium constellation, which provides an effective way to reach remote areas with no infrastructures. The low altitude also guarantees the best resolution for earth observation satellites for a given sensor, as well as the strongest signal for Signals Intelligence (SIGINT) satellites. For all these reasons, nations and commercial space companies have placed the majority of satellites, as well as all crewed space stations to date, into the LEO region.

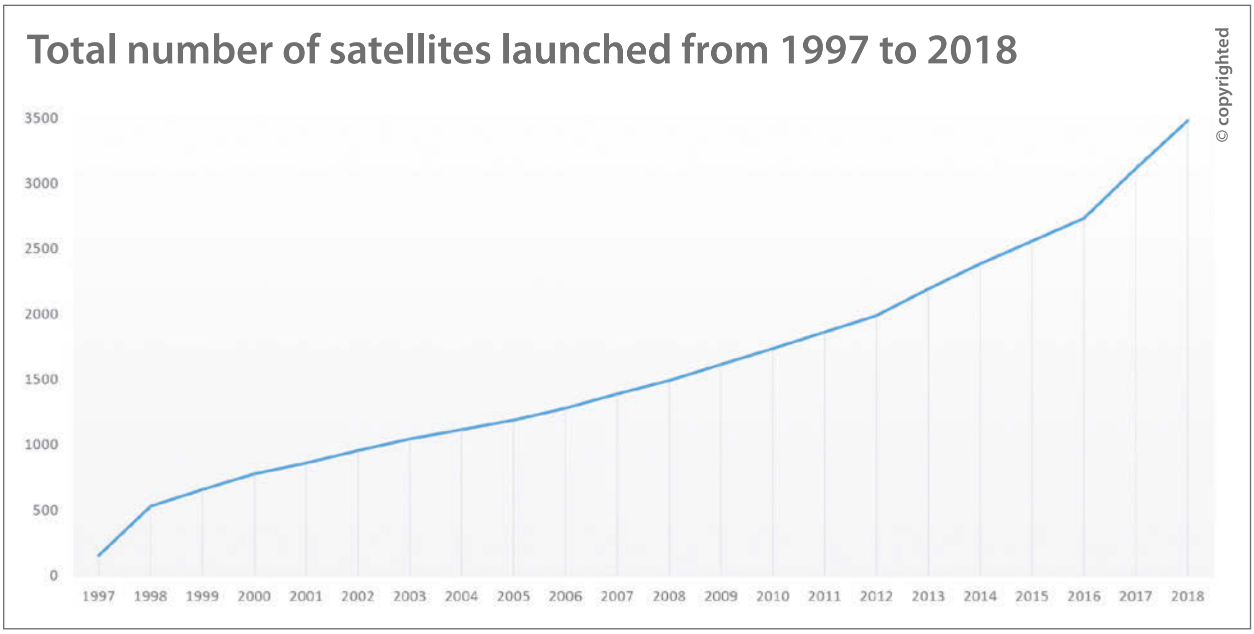


Figure 2: Data source: www.space-track.org.

The 3.67-metre, 75-ton Advanced Electro-Optical System telescope is the largest telescope in the US Department of Defense used for satellite tracking. The telescope moves fast enough to track low-earth objects such as satellites and missiles, while also tracking man-made objects in deep space and performing space object identification data collection.

Despite the numerous advantages of placing a satellite in the LEO regime, low earth orbits also yield some relevant disadvantages or limitations. For instance, a LEO satellite is visible only for a few minutes per transit and, due to the low altitude, it is an easy target for kinetic ASAT weapons. Some amount of atmospheric drag also still affects LEO satellites, so they need to intensively use their autonomous propulsion systems to keep their orbital level over time. Moreover, the risk of collision between satellites, or between satellites and debris, is higher because LEO is the most congested orbital region.

3.2 Space for NATO

The previous section depicted some examples of specific military applications of satellites. In today's technology-driven warfare environment, military operations generally rely on some sort of space support. NATO, in particular, depends heavily on space as a force multiplier, as the Allied Joint Publication (AJP) 3.3 (B) clearly states.[1] Space support to NATO operations today includes contributions to positioning, navigation, communications, weather forecasts, intelligence, missile warning, and personnel recovery. Satellite imagery is also useful for Intelligence Preparation of the Battlespace (IPB), for Battle Damage Assessment (BDA), or for improving the maritime situational awareness, useful in counterpiracy operations, for instance. Essentially, nearly every NATO operation today has some dependency on space because NATO assets and NATO capabilities require space-sourced data, information, or services in one way or another.

In a nutshell, satellites enable a wide range of civil and military applications in today's environment, including critical communications and emergency services. Thus, any shutdown or loss of space-based services could affect everyday life seriously, or undermine the success of a military operation. Realising the pervasiveness and high relevance of space-based data, products, and services in everyday life and in national security is the first step in understanding the importance of protecting space resources.

3.3 Risk to Space Assets: the Growing Menace

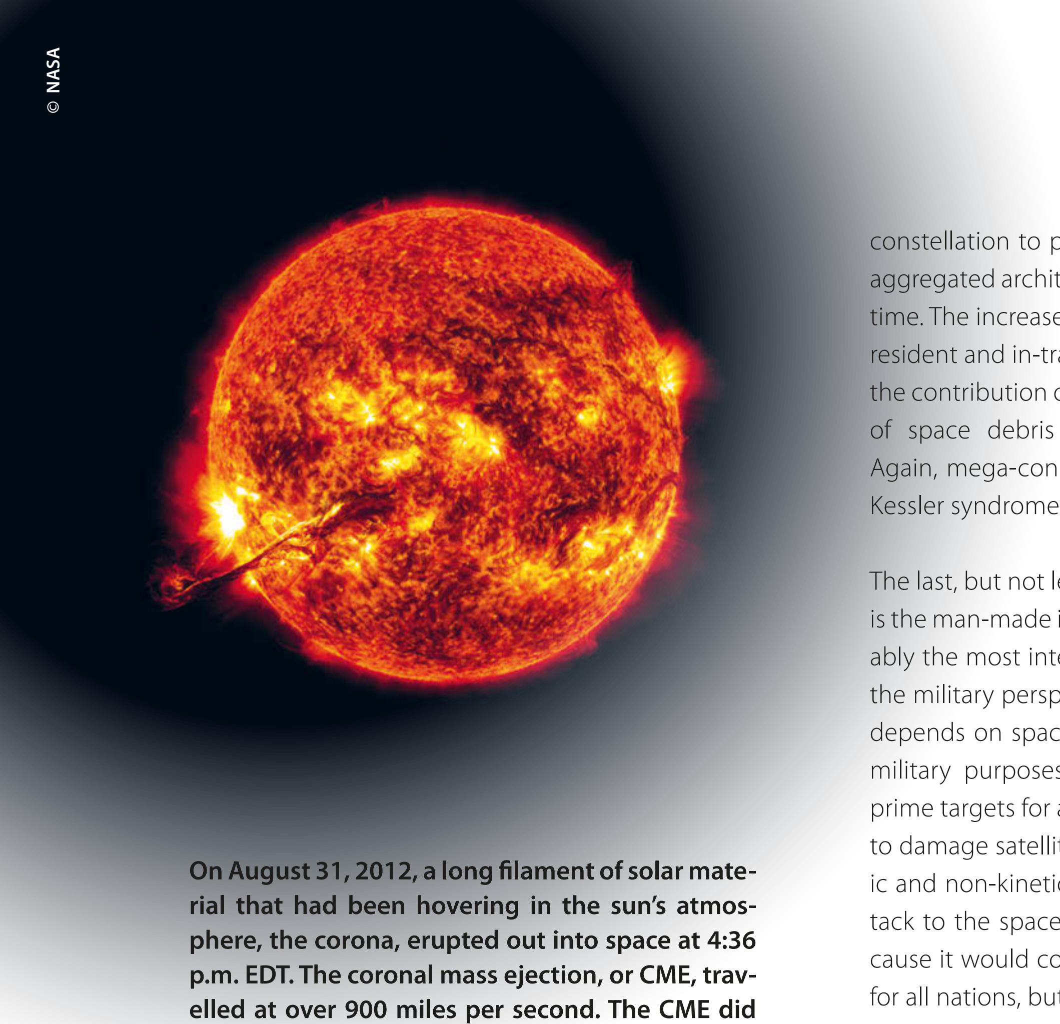
Once it is clear that space is a fundamental asset for a variety of civil and military purposes, it becomes evident that preservation of space capabilities, freedom of action, and access to space is paramount. In fact, a number of hazards, both natural and man-made, threaten satellites, and constantly endanger the availability of the space-based capabilities people take for granted.

On the 'natural' side, space weather is the primary concern. Space weather refers to the dynamic conditions in earth's outer space environment. It is the effect of the interactions between the energy the Sun produces in terms of EM radiation and electrically charged particles and the earth's geomagnetic field. Van Allen radiation belts, geomagnetic storms, geomagnetically induced currents, and ionospheric disturbances, are only a few examples of space weather-related phenomena. For instance, ionospheric disturbances can reduce GPS accuracy. Worse, high-energy events, like geomagnetic storms can produce failures and even permanently damage satellites through direct radiation or electrostatic charging. Unfortunately, scientists still do not have a complete understanding of solar dynamics; thus the space weather forecast horizon is limited. Currently, the available solutions to the space weather risk include hardening satellites to make their electronics less vulnerable, ensuring the redundancy of vital satellite components, and increasing the number of available satellites for a given service (proliferation). However, one should also bear in mind that in the case of a major adverse space weather event, no protection would be sufficient, even for any electrical devices on earth, let alone the devices in space.

Additionally, satellites must cope with the harsh environmental conditions of outer space: vacuum, extreme thermal cycles, and intense vibration during the launch phase, all without the possibility to physically repair the hardware (apart from some exceptional cases, as happened for the Hubble Space Telescope).

Natural hazards for satellites, however, represent only a small part of the list of existing threats. Indeed, man-made menaces – both unintentional and intentional – pose an increasing risk. Accidental man-made threats mainly involve space debris. Space debris is essentially composed of the man-made objects that remain in orbit as a result of space activities. It includes non-operational satellites, used rocket stages, and fragments that disintegration, erosion, and collisions in space cause. Due to the increasing number of satellites nations and companies are deploying every year, and due to some specific catastrophic events of the past that dramatically increased the amount of debris in space, like the Chinese ASAT testing in 2007,[2] or the unfortunate collision between an Iridium satellite and the Kosmos 2251 satellite in 2009,[3] the probability of a collision in space between an active satellite and a piece of debris (or another active satellite), is rapidly growing. According to the latest edition of 'Orbital Debris' (May 2018), a quarterly publication of the NASA Orbital Debris Program Office,[4] the list of man-made officially catalogued space objects currently amounts to 18,922 units the size of a baseball/orange or larger, including active and defunct satellites. However, there are at least 500,000 pieces of debris the size of a marble or larger, and many millions of pieces of debris that are so small, that current SST systems cannot track them.[5] The biggest concern related to the increase of space debris is the greater risk to trigger the dreadful Kessler syndrome: debris which collides with other debris producing new debris in a vicious circle, which fatally contaminates the orbital environment and denies access and any operations in space for centuries.

Since the debris problem afflicts all space-faring nations, they have established common practices for mitigating the creation of new debris, like the customary employment of collision avoidance manoeuvres and the passivation (depletion of all energy reservoirs) of satellites at the end of their operational life. End-of-life disposal procedures also include deorbiting to earth – for LEO spacecraft – or re-orbiting to a 'graveyard orbit' for GEO satellites. All these guidelines are included in several international



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On August 31, 2012, a long filament of solar material that had been hovering in the sun's atmosphere, the corona, erupted out into space at 4:36 p.m. EDT. The coronal mass ejection, or CME, travelled at over 900 miles per second. The CME did not travel directly toward earth but did connect with earth's magnetic environment, or magnetosphere, with a glancing blow causing aurora to appear on the night of Monday, September 3.

standards, like the 2011 International Standards Organization (ISO) Standard 24113 on debris mitigation requirements, which nations are gradually transferring into actual regulations.[6] Unfortunately, their worldwide implementation is still pending.

Besides space debris, other active satellites represent a threat, too, due to the risk of collision in space. The current number of resident satellites already poses some concern, but the problem will become even more evident after the planned launch of the first mega-constellations. Some companies, such as OneWeb, Boeing, SpaceX, and Samsung have projects to develop huge constellations of thousands of satellites in LEO to deliver broadband communications across the entire globe. At the same time, the *US Defense Advanced Research Projects Agency* (DARPA), with the Blackjack program, is developing a meshed constellation of nanosatellite-class military satellites that will integrate with the OneWeb constellation to provide a low-cost, wide-scale, disaggregated architecture with an enhanced response time. The increased risk of collision in space for both resident and in-transit satellites is obvious, as well as the contribution of this kind of project to the growth of space debris due to out-of-service satellites. Again, mega-constellations raise the spectre of the Kessler syndrome.

The last, but not least, kind of threat on this short list is the man-made intentional threats, which are probably the most interesting and critical menaces from the military perspective. A country whose economy depends on space systems or that needs space for military purposes should consider its satellites as prime targets for an opponent. There are many ways to damage satellite capabilities, through both kinetic and non-kinetic means. A high-energy kinetic attack to the space segment is probably unlikely because it would compromise the space environment for all nations, but the ground segment is still a possible target. Additionally, a space-capable opponent still has the alternative to employ a spacecraft to approach a target satellite in space and make it inoperative by using electronic or kinetic means. Non-kinetic attacks include jamming, dazzling, and spoofing. Jamming is the use of EM power to disrupt a data link. Depending on the type of attack, it can impact the user segment locally or even the satellite itself. For example, low power jammers for GPS receivers are quite cheap and easy to find. Dazzling is the use of a laser to blind – temporarily or permanently – the electro-optical (EO) sensor of an imagery satellite. Finally, spoofing is the use of EM power to interfere with a data link to provide false information. For instance, GPS data can be spoofed to provide false positioning information. However, spoofing also can represent an actual threat to satellites: an adversary can manipulate the telemetry from the satellite to the ground segment to provide erroneous positional data, forcing the satellite operator to plan a wrong and possibly dangerous manoeuvre. Aggressions like the ones described above can be considered as a form of cyberattack, even if, more properly, a cyberattack would imply an offender who directly tries to send telecommands to the satellite. Generally, cyberattacks involve 'activities undertaken via digital means to infiltrate, reconnoitre, exploit, disrupt, deny access to and/or destroy systems and/or data',[7] including the possibility that an opponent takes control of a satellite system or a communications network. Cyberattacks are a growing menace also for satellites because they do not require expensive technologies for a nation or even non-state actors to implement them, so nearly any potential adversary could fairly easily develop a dreadful cyber capability. For this reason, cyber-defence is essential. Unfortunately, an effective cyber-defence is harder to implement and far more expensive than offensive cyber operations, because all the hardware and software must be secured and continuously monitored. Developers of military systems naturally tend to protect their systems against cyberattacks, while commercial systems are likely to be less resilient due to the associated costs. However, commercial satellites are increasingly dual-use, meaning that organizations use them for both military purposes and critical civilian activities, including air traffic control, train control, and electricity grid monitoring. This situation clearly exacerbates the concern for the cyber threat.[8] [9]

3.4 Civil SSA to Ensure Safe Operations in Space

One can take steps to reduce the vulnerability of space systems: hardening or installing redundant satellite components; employing anti-jamming techniques; duplicating ground stations; developing the capability to replace satellites quickly; and distributing the task of a single satellite among clusters of smaller satellites. These are all typical mitigation techniques designers routinely employ in both military and commercial satellite systems. Additionally, nations or commercial firms can place spare satellites in orbit to rapidly substitute for inefficient homologous satellites, as happens with the GPS and GALILEO constellations. In extreme cases, and particularly for military missions, ground- and air-based components also can provide regional backup rather than global backup.

Nevertheless, for any mitigation measure to be effective, awareness of the situation in space remains a key prerequisite since it permits the proper and timely response to most menaces, like collisions in space, theoretically ensuring the long-term sustainability of space activities. This kind of awareness of 'what is about to happen to artificial satellites in outer space' is known as SSA.

As already stated in Chapter 2, there is no one commonly agreed definition of SSA. According to the EU definition, SSA includes three main areas: knowledge of space weather; analysis of NEOs; and SST.

The objective of a Space Weather Centre is to study the effects of these events to provide timely forecasts and accurate information (space weather products) to mitigate the adverse impacts from them. For space weather products, timing is essential because only short-term forecasts are available based on scientific observations of the Sun. However, even if space weather events cannot be avoided, some mitigation procedures are available, such as shielding or shutting down sensitive devices.

The term NEO also refers to a kind of event that humans cannot control. Scientists are investigating NEO deflection methods, but at the moment there are no established procedures in case of harmful NEO approaches. However, a timely response, especially in terms of the evacuation of the estimated impact areas, can help save lives, at least in the case of minor events.

With respect to the previously listed components of SSA, SST is different. It actually provides satellite operators and owners with an effective tool to protect their assets by performing collision avoidance. The main purpose of an effective SST capability, at least from a civil perspective, is to detect, monitor, and react in a timely fashion to any hazardous approach of an extraneous satellite or piece of debris to the space assets under one's control. Many nations are increasing their investments to develop their SST capabilities rapidly. This is a clear sign that the perceived importance of SST is rising.

The main focus of this study will be on the SST component of SSA. Specifically, in the next chapter, the paper provides a comprehensive description of the components and functions of an SST capability.

3.5 SSA for Military and NATO Needs

From a military perspective, SSA is mainly achieved by exploiting SST capabilities and space weather information to provide an effective military advantage. In particular, NATO defines SSA as 'the requisite current and predictive knowledge of the space environment and the operational environment upon which space operations depend.'[10] This definition includes knowledge about one's own and an opponent's space systems capabilities, operational readiness, and limitations, as well as environmental conditions, events, threats, and activities (both current and planned) in, from, toward, or through space. Furthermore, AJP 3.3 version B states, 'SSA also incorporates the use of intelligence sources to provide insight into adversary use of space capabilities and their threats to own space capabilities while in turn contributing to the commander's ability to understand adversary intent.'[11] For this reason, even if NATO no longer owns any space assets since 2010, and relies on space-based services that the Coalition nations provide voluntarily, SST still can provide crucial information for a NATO commander during operations.

Specifically, SST services that contributor nations offer to NATO can provide the following functions:

- Offer operational and tactical information about the situation in space to the benefit of own/friendly forces (protection against opponent Imagery Intelligence (IMINT) and SIGINT);

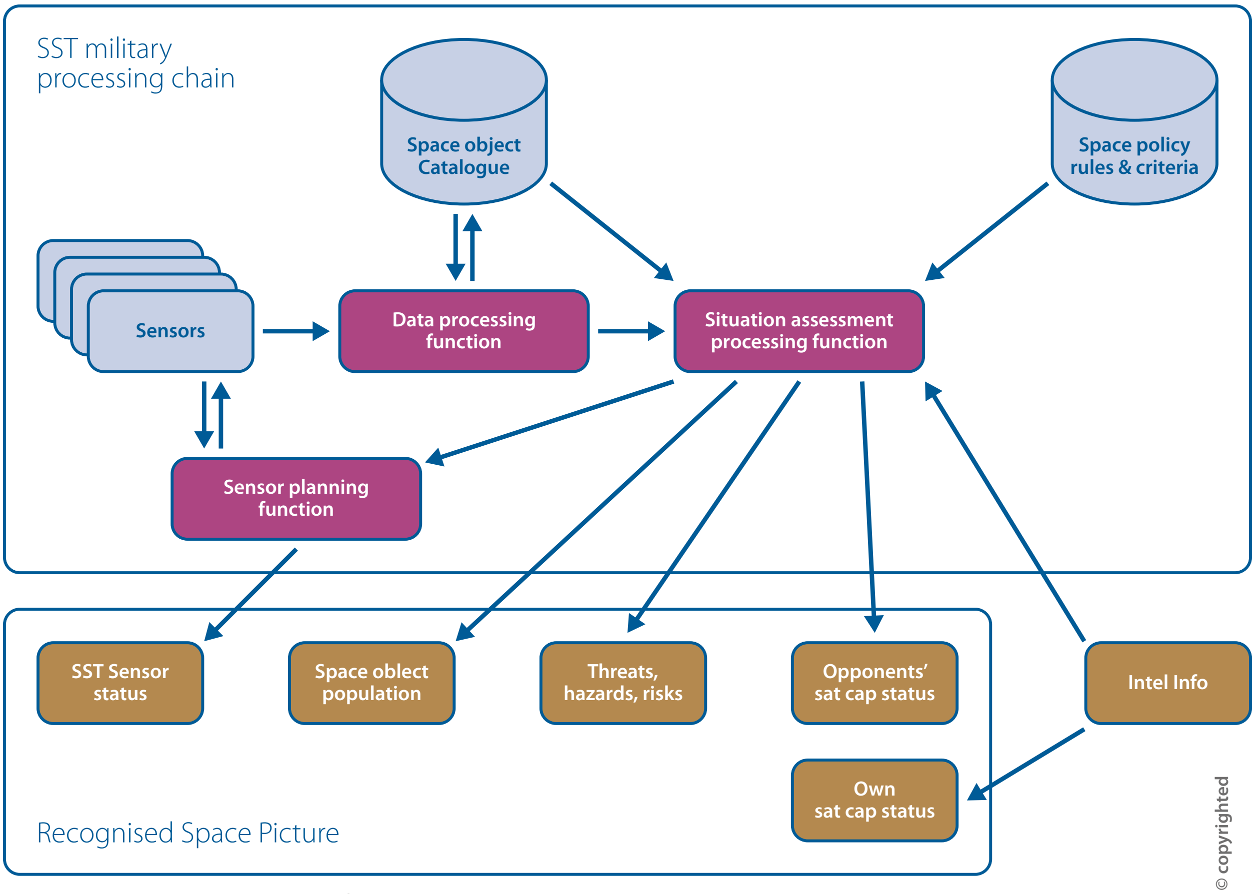

Figure 3: A possible scheme of an RSP production chain.

- Contribute to the evaluation of the space capabilities of other nations;

- Evaluate the space capabilities used by other nations for military purposes;

- Identify intentional threats and hostile acts towards military and other critical space systems;

- Identify any use of weapons in space.

Space professionals can aggregate SST, space weather, and intelligence information to generate the RSP. The RSP may include information about the population of space objects – including details about opponents' space capabilities, the efficiency state of friendly and opponents' satellites, the evaluation of threats, hazards, and risks, and any space-related alert. As with any operational picture, its purpose is to provide a comprehensive and integrated picture of the 'battlespace' – in this case, outer space – to support accurate assessment and situation-aware decision-making. For this reason, a common understanding exists that SST services have an intrinsic sensitive nature and remarkable military applications.[12]

3.6 Summary

This chapter provided an overview of the importance of space-based products in everyday life with some simple examples, but also highlighted the increasing importance of space for military purposes. However, it also showed how all these benefits people commonly take for granted are under a continuous and growing threat. This is a big issue for modern-day civilian life, but it is even a bigger concern from a military perspective because the sudden and unexpected unavailability of any space-based capability can severely impact military operations. For this reason, for both civilian and military purposes, SSA is a relevant part of the answer. Moreover, SSA has an added value for a commander in operations because it is the main source of valuable operational and tactical information relevant to one's own and an opponent's space capabilities.

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The Sodium Guidestar at the Air Force Research Laboratory Directed Energy Directorate's Starfire Optical Range. Researchers with AFRL use the Guidestar laser for real-time, high-fidelity tracking and imaging of satellites too faint for conventional adaptive optical imaging systems. The SOR's world-class adaptive optics telescope is the second largest telescope in the Department of Defense.

CHAPTER 4

The Architecture of a Complete SST Solution

An SST capability is the complex result of systems and processes that work together to provide SST products and services. Sensors, such as telescopes or radars, are the primary source of SST data, in terms of position, characteristics, and trajectory of earth-orbiting space objects. These data need to be processed, analysed, and correlated with the entries in an up-to-date space objects catalogue, and with information provided by owners/operators of active satellites. The resulting information forms the basis for subsequent sensor tasking and for improving and maintaining the catalogue itself, which defines the core of an SST capability. In fact, the information contained in the catalogue is the primary source for SST products and services, which are the final output of the process.

In short, an SST capability is a production line from observations to SST products and services.

4.1 Space Situational Awareness – SST Products and Services

For this study, an SST product is a tangible result of an SST analysis, while an SST service is the structured delivery of SST products from an SST service provider. Some services are dedicated to satellite owners, and others to civil protection, while still others mainly have a military purpose. This section of the study will describe six typical examples of SST services: the satellite conjunction alert service, the re-entry prediction service, the in-orbit fragmentation detection and characterization service, the satellite positioning service, the satellite overflight service, and the satellite operative status assessment service.

4.1.1 Satellite Conjunction Alert

The Satellite Conjunction Alert Service is usually the first SST-related service that comes to mind. For a satellite operator, commercial or governmental, receiving a warning every time that another space object endangers his satellite is paramount to have the opportunity to reduce the probability of collision with an avoidance manoeuvre, when necessary. As explained in the previous chapter, collision prediction and avoidance continues to grow in importance due to the increasing amount of both operational space assets and debris and the risk that they pose to the sustainability of space activities itself. The Satellite Conjunction Alert Service delivers collision alerts in the form of a probability estimation of a collision. According to the precision of the available trajectory data, the service calculates an 'ellipsoid of uncertainty' representing the error covariance around each space object. If the analysis of the orbit predictions foresees an intersection between two ellipsoids with a resulting collision probability above a predefined threshold, the service will alert the impacted satellite operators to perform an avoidance manoeuvre. It is worth noting that because a satellite's lifespan depends on its propellant availability, which is clearly limited, satellite operators should avoid unnecessary or non-optimized manoeuvres.

Since 2010, the United States Strategic Command (USSTRATCOM) provides a conjunction analysis service, which is free for registered satellite owner/operators. Note that this service provides conjunction alerts, but the evaluation of the level of risk, the decision to perform an avoidance manoeuvre or not, and the study for the best possible action and its consequences is still up to the owner/operator.[1]

An interesting approach which helps the satellite owner/operator deal with space conjunctions involves the use of a 'Man in the Middle' (MIM) service, like the NASA Robotic 'Conjunction Assessment Risk Analysis' (CARA) or the French 'Conjunction Analysis and Evaluation Service: Alert and Recommendations' (CAESAR). These types of services take care of the conjunction analyses that involve satellites or orbits under their responsibility, exchanging precise ephemeris between the satellite owners/operators and the conjunction messages provider (18th Space Control Squadron (18 SPCS), in the case of USSTRATCOM). By doing so, the satellite owner/provider can rely on an effective collision forecast service and a skilled and centralized support service with a broader view on the current situation for collision avoidance manoeuvres.[2]

4.1.2 Re-entry Prediction

Another useful SST-related service is re-entry prediction. Debris in lower orbits progressively loses its kinetic energy due to atmospheric drag, finally re-entering the atmosphere. Larger and stronger pieces of debris can survive the re-entry and hit the earth's surface, posing a risk to people and infrastructures. Re-entry prediction services can exploit this SST data to forecast these kinds of events and to calculate the probable area of impact to warn the national government to take appropriate actions.

4.1.3 Fragmentation Alert

In the case of a collision between space objects, or when explosions of defunct satellites or rocket bodies happen in orbit, a new cloud of debris is usually created. In the simplest cases, a space object splits into few parts. In these cases, it is important to survey the area and characterize the newly created objects as soon as possible to enable rapid evaluation of the new situation and to help satellite owners/operators take contingency measures.

4.1.4 Satellite Positioning

SST data can also improve, or in some cases substitute for, a satellite's own telemetry function. For example, organizations can employ specific SST facilities, like laser ranging stations, when they require a particularly high-precision position. Additionally, smaller and cheaper satellites can avoid bringing on-board dedicated positioning hardware, and instead rely only on SST data to fix their positions.[3]

4.1.5 Overflight Calculation

Satellites travel in predictable orbits that can be accurately determined. According to Kepler's laws, satellites in lower orbits are the fastest, while geostationary satellites appear in a fixed position for an observer on the earth's surface. Knowing the list of visible satellites and their positions in the sky at any time has interesting applications. For example, a commander's staff can plan military operations considering the over-

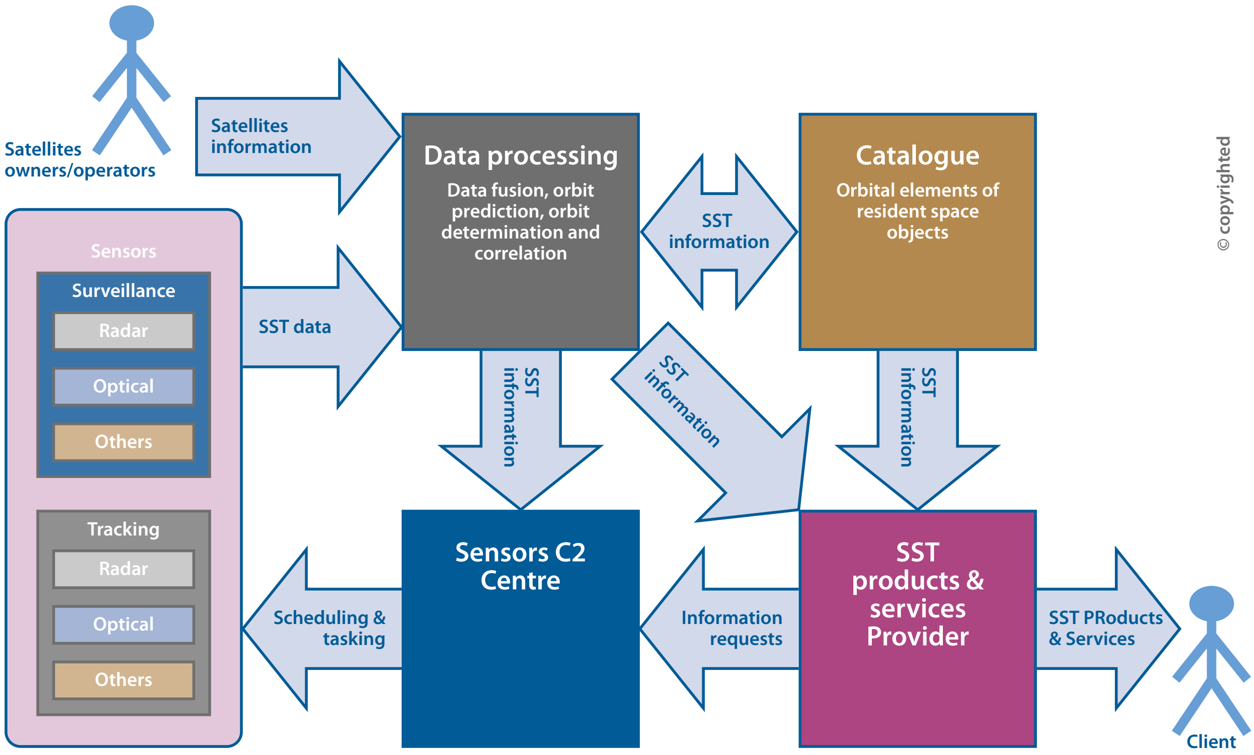


Figure 1: Possible scheme of a complete SST functional architecture including data flow.

flight of friendly ISR satellites for IPB or BDA, or exploit the known overflights of an adversary's ISR satellites to ensure the protection of covert operations or counterintelligence activities. However, the knowledge of satellite overflights is useful for more than just military intelligence purposes. GLONASS constellations such as GPS and GALILEO, depending on the current satellite configuration from the user point of view, can exhibit different levels of performance. This effect is known as Geometric Dilution of Precision (GDOP), and its awareness can be crucial for civil and military applications that rely on high positional precision.

4.1.6 Satellite Operative Status Assessment

SST also can provide information on a satellite operative status. For example, by analysing the so-called 'light curve' (i.e. a graph showing the light intensity with respect to time) that a tracking telescope can provide, an expert can easily recognize a tumbling satellite. In this case, it is highly probable that the satellite owner has lost all control of it. Similarly, high-resolution observations in the infrared EM band can detect the temperature rise of a specific subsystem of a satellite (e.g. the payload) as proof of its activity. This kind of service clearly has an intelligence purpose and is thereby mainly of military interest.

4.2 SST Sensors: Types and Specialization

The first element of the SST chain is the sensors. They provide the data for the other components of an SST system. There are several types of SST sensors, each one with a specific scope. For this reason, one usually classifies SST sensors by technology (optical, radar, laser, etc.), by orbit (LEO, MEO, GEO), or by purpose (surveillance or tracking).

4.2.1 SST Sensors by Technology

Historically, the backbone of an SST capability is composed of ground-based radars and telescopes. In particular, a radar calculates the position of targets with respect to its position by emitting radio waves at a specific frequency and with a specific waveform and analysing the signal reflected by the target. There are monostatic, bistatic or multistatic radars, according to the position of the transmitters and receivers. In a monostatic radar, the transmitter and receiver are co-located, while in a bistatic radar a distance comparable to the target distance separates them. Finally, in the case of multiple transmitters and/or multiple receivers, the radar is called multistatic. Since it provides some parallax, a bistatic system can achieve greater accuracy in the positioning of the target, but it usually has a higher cost. For the same reasons, a multistatic system can provide even more precise data, but at even greater expense.

SST radar systems usually operate in 'staring mode' for surveillance purposes, meaning that they point to a fixed direction and register all the objects passing within the radar beam. Nevertheless, if they have adequate steering capability, radars can also track objects. Some bigger radars, such as the mechanically steered German Tracking and Imaging Radar (TIRA), even can calculate the shape of a crossing space object through the use of an imaging technique named Inverse Synthetic Aperture Radar (ISAR). To improve their steering capability, modern radars also employ phased array antennas, which are steered electronically. They are much faster and can even track many objects at once, or perform quasi-simultaneous surveillance and tracking.

To sum up, SST radar sensors have several strengths: they are only slightly affected by the local weather; they can offer a 24-hour service, and they can easily survey large sectors, but also track one or more objects at the same time and measure distances (known as 'range') with great precision. On the other hand, this technology has some intrinsic limitations, too. For example, since the particular space object needs to be 'illuminated' by the transmitter, the maximum detection distance depends on the transmitter's EM power and the receiver's sensitivity. For this reason, radars are mainly used for LEO satellites surveillance and tracking. Moreover, since the Radar Cross Section (RCS) of a target decreases rapidly when its size is less than the radar wavelength, smaller objects are invisible to the radar.


© MDA/NASA

Sapphire is a Canadian LEO small satellite for space surveillance designed to monitor space debris and satellites within an orbit from 6,000 to 40,000 kilometres above Earth. It is operative since 2013.

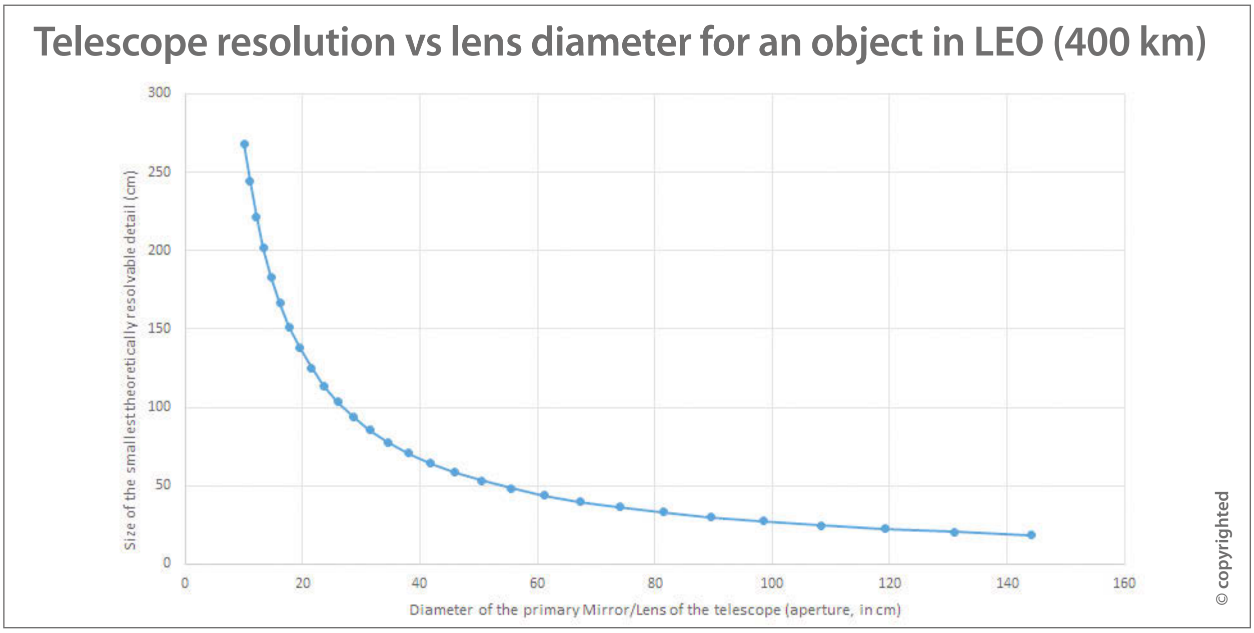


Figure 2: Theoretical resolution of a telescope according to the Rayleigh criterion.

Telescopes are also widely used for SST. Using lenses, mirrors, or a combination of the two, they collect EM radiation that an object emits or reflects across the visible spectrum (and slightly above/below, according to their specific purpose) to form an image of the object on the imaging sensor (Charge-Coupled Device (CCD) or Complementary Metal-Oxide Semiconductor (CMOS)). Depending on a telescope's specific requirements, the designer can optimize it to cover large areas of the sky or to deliver high-resolution images of space objects. In general, larger telescopes spot fainter and faster objects because they benefit from a greater photon collection rate, and provide higher resolution. However, optical systems are still usually smaller than radar systems of similar capability. This means that national or commercial agency to which the equipment is registered can easily install or relocate them according to specific requirements.

Unlike radars, EO SST sensors do not need to illuminate the object, so they do not have limitations in distance and do not require as much power as radars do. On the other hand, since the light reflected or produced by a space object is usually very dim, telescopes for SST can be used only in the dark of night, which is a major limitation. Moreover, space objects need to be in a favourable lighting condition for the EO SST sensor to efficiently spot or image them. In fact, an EO SST sensor may not detect space objects characterized by a low surface reflectance or shadowed from sunlight. High-resolution imagery of LEO objects is also possible, and it is particularly useful to characterize not only shape and size of space objects but also to reveal the operational status of a satellite, which is more of an intelligence-oriented task. However, since the resolving power of a telescope is proportional to its diameter, it requires at least mid-sized telescopes (main mirror diameter of 50 cm and above) to achieve the desired resolution level. Additionally, to achieve the highest resolution, satellite owners/operators usually employ complex Adaptive Optics (AO) systems to reduce the effects of the atmospheric turbulence – the so-called 'seeing'. Conversely, the optical imagery of GEO and MEO objects is much more difficult to accomplish because it would – in theory – require mirrors with a diameter of 50 metres and above. In any case, even relatively small telescopes are capable of obtaining the so-called 'curve of light' of a space object. The curve of light is a graph that represents the intensity of reflected light versus time across the orbit. An expert can correlate this information with the operational status of a satellite (e.g., a tumbling satellite, which is unlikely to be operational, will show a rapidly swinging curve of light), or can use the information to distinguish a satellite from a piece of debris.

In general, local environmental conditions primarily influence the performance of ground-based optical systems. The main drawback of EO sensors is that they require good weather conditions and clear skies to operate. Additionally, the location for the installation of an SST telescope must be chosen wisely, because the presence of light pollution, which is a direct consequence of human presence close to the area where the telescope is installed, severely affects its performance. For these reasons, besides ground-based telescopes, space-based EO sensors are particularly effective. They provide a complementary and valuable approach to EO surveillance and imaging because they are neither affected by weather conditions in earth's atmosphere (space weather could still affect them), nor atmospheric turbulence and light pollution. On the other hand, their reduced manoeuvrability can be an issue, in particular for SST satellites in lower orbits. There are dedicated SST optical satellites – particularly suitable for the surveillance of the relatively slow GEO objects – and contributing imaging satellites, which are primarily dedicated to earth observation, but which can also be pointed towards space objects. Additionally, there are LEO, HEO and GEO multi-spectral satellites, pointed towards the earth, which are effectively employed to provide an early warning service for launches of rockets and missiles, such as the US Space-Based Infrared System (SBIRS). Clearly, they do not provide SST data in the strict sense, but they can help to identify an un-notified satellite launch. For this reason, they also can contribute to the overall SSA.

Spectroscopy is another possible use of telescopes for SST purposes. Spectroscopic imaging allows experts to identify the material contained in a space object. This is done by analysing the spectrum of the received light, thus providing additional data to help characterize it. Once again, particularly with fast objects that fly in lower orbits, this technique requires quite large telescopes to achieve an adequate spectral resolution. A proof of concept for this type of application is the experimental French OSCEGEANE *(Observation Spectraleet Carat Erisation des satellites GEostAtioNnairE)* project.[4]

Laser ranging is another technique that can be effectively used for SST purposes. It is particularly interesting because it provides very precise ranging and position measures. Currently, lasers are effectively used to measure the distance to cooperative targets – which are satellites equipped with retro-reflectors – with an accuracy of a few centimetres and below.[5] The Natural Environment Research Council (NERC) Satellite Laser Ranging (SLR) station at Herstmonceaux, England,[6] is a clear example of a laser ranging observatory for accurate orbit measurement on cooperative spacecraft. In the future, according to some promising experiments on laser illumination of bigger pieces of debris, such as old rocket bodies, [7] [8] one also could apply the laser ranging technology effectively to non-cooperative targets in LEOs and lower MEOs. For example, the SLR station in Graz, Austria, successfully tracked non-cooperative objects of different sizes, at distances between 500 km and up to 3,000 km. Furthermore, the station operators also experimented with 'multi-static' laser ranging to generate a significantly more precise orbit prediction.[9]

In any case, like any optical solution, laser ranging is not sufficient to establish and maintain a complete space debris catalogue, primarily due to environmental limitations. However, it could be well-suited for precise orbit determination of any object with a predicted collision course within a few days. Accurate laser-determined orbits might help avoid unnecessary anti-collision manoeuvres, thus saving fuel and extending the lifespan of active satellites.

Finally, operators can also track active satellites using ground-based radiogoniometers. In particular, Electronic Intelligence (ELINT) and Communications Intelligence (COMINT) techniques can be used to locate a satellite and identify its mission. These sensors are more useful for intelligence purposes than for satellite safety. Nevertheless, they can provide valuable information for civilian satellite operators, too, since the presence of EM emissions usually constitutes a 'proof of life' for a satellite. In fact, in the case of an imminent foreseen collision, trying to contact the owner of a non-operative satellite to plan a collision avoidance manoeuver would be pointless and a waste of precious time.

4.2.2 SST Sensors by Purpose

Considering their purpose, SST sensors can be divided into two main families: surveillance and tracking sensors. The objective of a surveillance sensor is to observe the highest possible percentage of space objects that pass above the horizon. This implies that a surveillance sensor needs a very high sensitivity to spot smaller objects. Surveillance sensors are essential for an SST capability because they provide new entries for the catalogue. They are perfect tools for building up the catalogue of objects and for day-to-day catalogue maintenance. Usually, surveillance sensors do not actively look for space objects, but instead, wait passively for them to enter their field of view. This is why they constitute a sort of 'fence' with respect to overpassing objects. The Italian BIRALES (BIstatic RAdar for LEO Survey) or the upcoming US 'Space Fence'[10] are clear examples of this approach. However, the fence can also be generated by scanning the sky so fast that the sensor detects most passing objects. This is a common practice for radar systems, which can improve their range and accuracy by reducing the field of view, but it is often a requirement for optical SST systems for LEO surveillance, which usually have a much smaller field of view by design. Based on their characteristics, radar sensors are perfect for LEO surveillance because they can survey large portions of the sky easily and still provide precise range measurements. EO sensors are suitable, too, but they need fast mounts, fast telescopes (low ratio between the focal length and diameter), and wide and fast CCDs. On the other hand, telescopes are more commonly employed in GEO surveillance and tracking because the GEO belt is relatively narrow and, so, easier to explore. Moreover, it is far above a radar's maximum range. For similar reasons, telescopes are also efficiently used for surveillance and tracking of MEO and HEO objects.

As stated, in addition to space surveillance, SST sensors are used for tracking space objects. Tracking sensors typically have better resolution and a smaller field of view in comparison to surveillance sensors, and they are thus unsuitable for detecting new space objects. For this reason, SST tracking sensors are usually employed to follow already known space objects to

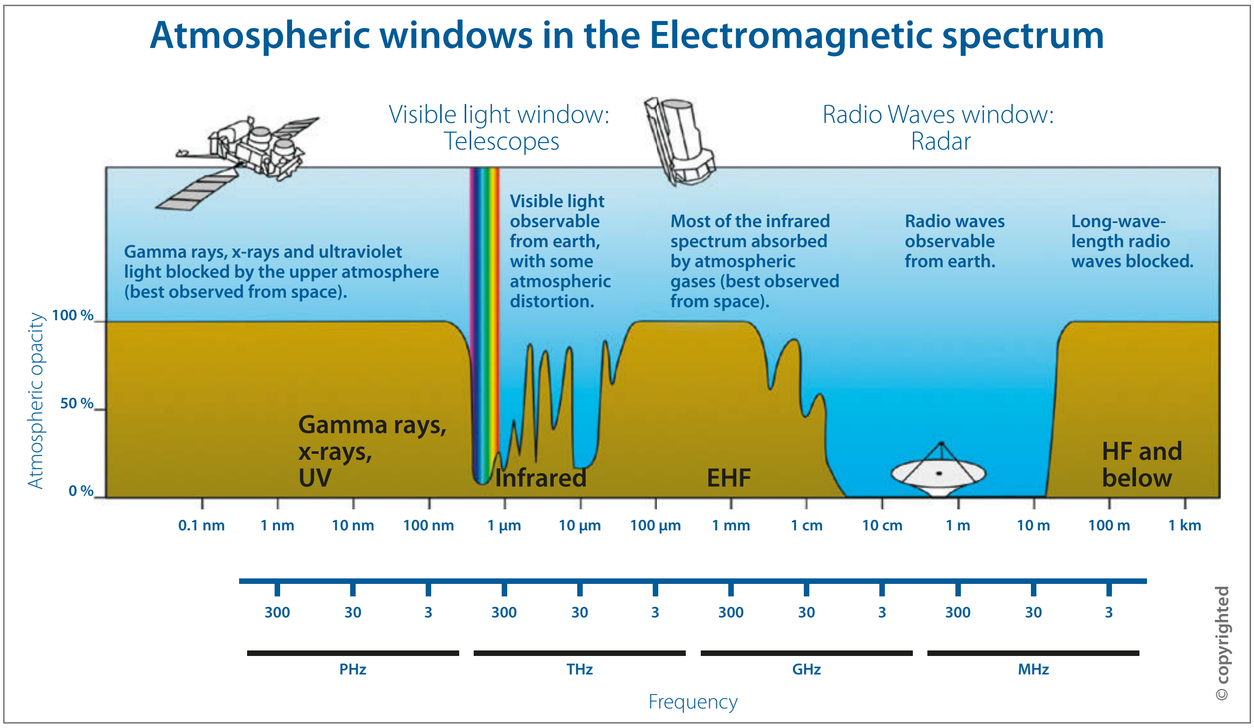


Figure 3: Electromagnetic transmittance or opacity, of the Earth's atmosphere. Derivative work from a NASA product (source: The Multiwavelength Universe poster, https://spaceplace.nasa.gov/posters/en/).

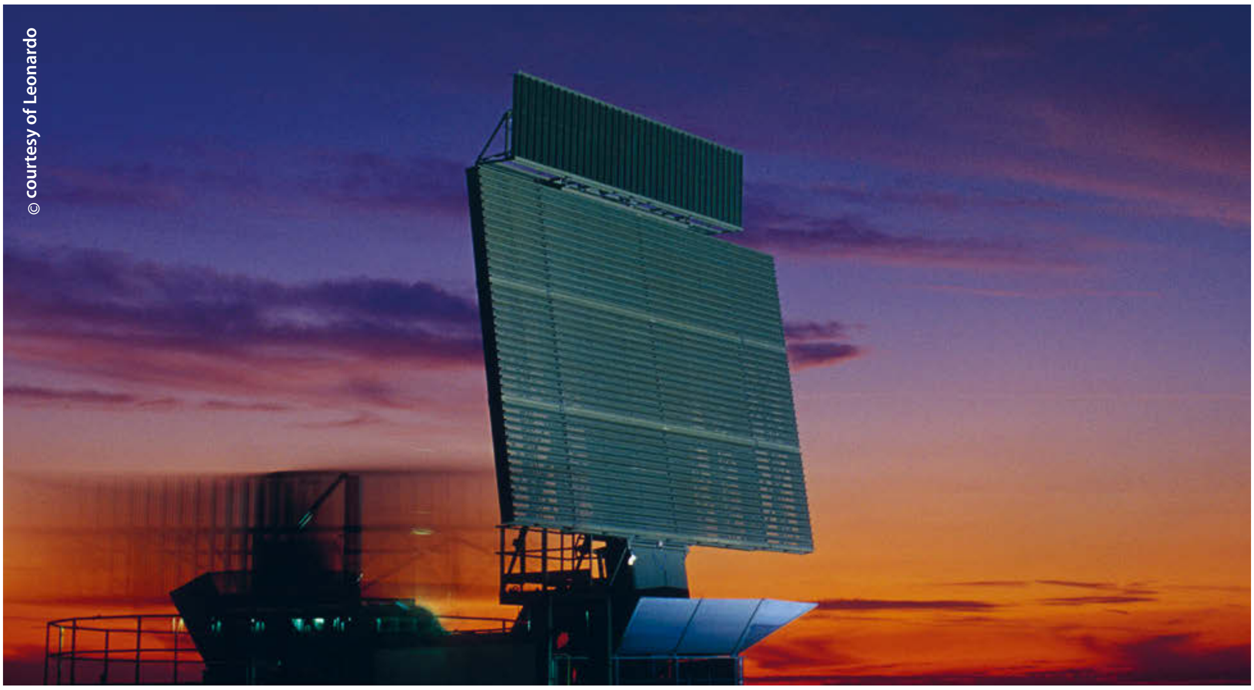
collect relevant detailed data. For example, they can provide a more precise orbit fix to better estimate if a piece of debris may potentially collide with an operational spacecraft. They can also provide imagery or spectroscopic analysis of the space object to understand the purpose of a satellite or the composition of a piece of debris. In short, their main purpose is the maintenance and improvement of the catalogue information.

Surveillance and tracking sensors can be optimized for LEOs, MEOs, or GEOs. In general, tracking objects in lower orbits requires either fast mounts or sensors with a wider field of view, while objects located in orbits farther away are easier to track.

4.2.3 Sensor Blending

As explained in the previous paragraph, there are several types of SST sensors, employing different technologies and dedicated to specific purposes. Unsurprisingly, none of those alone is sufficient to achieve an effective SST capability. On the one hand, surveillance sensors are fundamental for creating and maintaining an SST catalogue. On the other hand, to improve the quality of the information stored in the catalogue and consequently its profitability, nations and commercial firms need sensors that can track space objects in all earth orbits with the desired level of precision. Consequently, an effective SST capability needs to exploit the advantages of different sensor types.[11]

For example, phased array radars and wide-field telescopes are perfect for searching predefined and tasked volumes of space for object detection, or the initial tracking and characterization of LEO and high LEO objects. In particular, wide-field optical sensors can provide a low-cost capability augmentation to a radar facility. Higher frequency (S-Band or X-Band) radars can deliver highly accurate information about tracking, range, shape, and structure (polarimetric and imaging radars) of the observed objects, while telescopes with imaging and spectroscopic capabilities can be useful to integrate the data. Laser tracking of proper targets ensures the highest orbital accuracy for lower orbits, while space-based high-resolution EO platforms can provide imaging capability for GEO objects.


© courtesy of Leonardo

Leonardo's RAT31 DL radar is an advanced, L-band, solid state solution for 3D surveillance that has also been successfully employed for SST purposes by the Italian Air Force.

Spectral and position diversity among the sensors can bring extra information to the system. For example, with respect to spectral diversity, co-located radars and optical sensors can improve range and angular precision compared to a single sensor. Regarding position, observing the same target from different geographical locations enhances the accuracy of the measurement.

A very interesting example of sensor blending comes from the DARPA, with the 'OrbitOutlook' programme.[12] One can summarize its approach as 'leverage any sensor but never trust any'. The objective of this program is to demonstrate a cost-effective, autonomous, modular, and scalable system to more effectively monitor the growing space population by collecting SSA data from any source, assessing the sources' biases and uncertainties, and exploiting the data to deduct SSA information. However, one must validate incoming data from lower-tier sources through comparison with high-confidence assets. Corroborated support from top-tier assets and historical information are vital to ensure the reliability of the data. Nevertheless, this is a notable experience that demonstrates how it is possible to obtain better SSA information even from lower-confidence data sources.

4.2.4 Sensors Tasking

A network of SST sensors, but even a single SST sensor, needs to be properly managed to maximize its effectiveness. As previously defined, tracking sensors follow known space objects to collect relevant detailed data. In principle, a tracking sensor should track all catalogued items, as soon as are they are visible, for all the necessary time to gather all possible data. In reality, there are technical limitations, and tracking, therefore, requires prioritization. Furthermore, operators must coordinate multiple, heterogeneous, and/or geographically distributed sensors to achieve better effectiveness with respect to a defined objective. For this reason, a network of SST tracking sensors requires a C2 centre for tasking. On the other hand, steerable surveillance sensors may need C2 as well. Depending on the specific service required, some areas could be more interesting than others, so they could require a shorter revisit time. Again, accurate tasking is essential to coordinate multiple surveillance sensors for the best collective results.

4.3 Data Processing

Raw data that SST sensors produce are meaningless without proper data processing. Data processing is the procedure that extracts structured information from raw and unorganized data. For example, data from different sources, including both SST sensors and catalogues, need to be correlated to identify new objects or update existing ones. Usually, data come from sensors of the same type but from different locations – to take advantage of different visibility over the orbit or of the different perspective (parallax) – or from co-located sensors using different technology (e.g. radar and optical). Data fusion is the process to merge these data into the detection of specific objects. This is a fundamental step to validate a new object discovery or to enhance the quality of the resulting information, both in terms of accuracy and precision. The ultimate goal of this process is to improve and update the catalogue with orbital data to predict the behaviour of a space object (tracking) by propagating its orbit.

However, these activities do not complete the processing chain. Even the most detailed catalogue is useless without the capability of analysing the data and understanding their implications. For this reason, a data exploitation system is an essential element of any SST architecture to deliver effective SST products, such as conjunction warning and re-entry warning messages.

4.4 Catalogues

The catalogue is the core of an SST architecture and the main source for providing SST-related services. It allows SST operators to reconstruct object orbits (orbit determination), distinguish new space objects from already known ones (correlation), and task the sensors to update the information as required. The information contained in the catalogue is the result of a production chain involving observation and data processing. To ensure effective SST products, each of the several thousand objects listed in the catalogue needs to be accurately reviewed on a regular basis through new observations. This means that once a catalogue has been created, it must be maintained to stay relevant.

Another interesting aspect of SST catalogues is that nations, and particularly defence organizations, usually classify the detailed information on satellites that have mainly, or exclusively, military purposes. Therefore, an SST catalogue typically includes 'sensitive' information. Moreover, nations usually consider the precise ephemeris of civilian space assets as vital information – and thus sensitive – because those assets represent an essential component of the national information infrastructure. The owner of the catalogue defines the list of the classified space objects and may decide to hide or disguise sensitive information from a third party. For this reason, nations usually only share SST information under specific security agreements. Undoubtedly, this a major showstopper for a globally shared SST catalogue, and it is still a very delicate situation to deal with even for the 29 countries comprising the Alliance. Security aspects of SST data sharing will be better elaborated in Chapter VII.

4.5 Reasons for a Collaborative SST

SST is an inherently international and cooperative venture. Data sharing among multiple, heterogeneous, globally distributed sensors, as well as specific information that only satellite owners/operators can provide, are essential to delivering effective SST services. In particular, sensors based on different technologies provide different capabilities that complement each other to achieve a clearer picture. Moreover, one must consider the geographical location of sensors. For example, a space object in GEO can only be seen within a specific range of latitudes and longitudes, and low inclination LEO orbits are physically unreachable from higher latitudes, regardless the sensor technology, due to the curvature of the earth. Even space-based SST assets are usually designed for the observation of specific orbits.

Furthermore, SST is a very expensive venture for a single nation because a complete and autonomous SST capability requires multiple sensors, a complex processing chain, and at least one catalogue that needs continuous maintenance.

Collaboration and data sharing among nations are thus key concepts for effective SST, which is mandatory to ensure space sustainability and to enable safe and efficient space operations.

4.6 Summary

An SST capability can be considered as a production line from observations to SST services. SST services range over a wide spectrum, from satellite conjunction alerts to re-entry predictions and others, for both civilian and military purposes. Thus, an SST system is a complex network of several elements: SST sensors, which collect observations of space objects, and can have different specific purposes according to their technology and configuration; C2 centres, which optimize data gathering with respect to predefined SST requirements; catalogues containing the orbital data of detected space objects, which need constant maintenance and upgrading; and data processing centres, which transform data into meaningful information, such as orbital determination and prediction of each space object, in order to deliver effective SST products. Multiplicity, global distribution, and technological diversity of SST sensors are all added values that exponentially improve SST services quality. As a result, SST is an inherently international and cooperative venture. Additionally, establishing multinational cooperation on SST also is an effective solution for reducing costs for each nation.

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Air Force Research Laboratory's 3.6-metre, 75-ton Advanced Electro-Optical System (AEOS) telescope under laser illumination at its Directed Energy Directorate's Air Force Maui Optical and Surveillance Site, Maui, Hawaii. The illumination resulted from the multi-wave length laser propagation experiments that were completed at over 10,000 feet and over a 90-mile path between Mauna Loa on the island of Hawaii and the Air Force site atop the extinct volcano, Haleakala, on Maui, Hawaii.

CHAPTER 5

SST within NATO Nations

This chapter will focus on the national SST capabilities of the NATO countries. In particular, this chapter will provide a selection of the European allies with a larger space footprint, together with the main space actor in the Alliance, the US. For each nation, a list of government-owned facilities will be presented, both civil and military. This chapter also will introduce some examples of existing bilateral and multilateral SST agreements. To provide a broader overview, it will also disclose some details about the ESA SSA programme and present some examples of current commercial SST enterprises.

Since the importance of space-based capabilities is currently increasing, the protection of such capabilities is gathering importance as well. Thus, SST is currently a fast evolving business for all space-capable countries. For this reason, please bear in mind that the following reported information can become obsolete very quickly. Additionally, please further consider that to keep the study unclassified, this chapter only includes publicly available information.

In principle, a country can dedicate a national asset to SST purposes even if SST is not its primary objective. For example, most radars and telescopes can be used as SST sensors. Consequently, several nations currently exploit already existing assets for SST as a secondary objective. From this perspective, it is then possible to divide national SST assets into three categories:

- Dedicated SST assets, which are designed, built and employed exclusively for SST purposes;

- Collateral SST sensors, which have SST as a secondary objective;

- Auxiliary SST assets, which can collaterally be used for SST purposes if required, but which the national SSA authority usually does not control.

5.1 SST in the US

The US operates the largest fleet of satellites in the world, with around 600 currently operating satellites[1]. However, if we look at the total amount of space objects the US launched or created as a consequence of a US space activity, the list amounts to more than 6,000 objects[2]. So, it is clear that SST is a primary concern for the US to ensure the long-term, safe use of space. Therefore, it is no surprise that the US SSN is the largest in the world, and they maintain a comprehensive catalogue of space objects as well.[3]

The Joint Force Space Component Commander (JFSCC) – a functional component of USSTRATCOM – conducts the operational command and control of US space forces, and the Combined Space Operations Center (CSpOC) executes it. However, the mission to deliver primary SSA is assigned to the 18 SPCS, a tactical unit within the 21st Space Wing that also provides support to the US SSN. The 18 SPCS also maintains the catalogue of all artificial earth-orbiting objects, conducts conjunction analysis and provides warnings on possible collisions to all partners, and manages USSTRATCOM's SSA-sharing programme with foreign governments and commercial entities.[4]

The US SSN sensors include phased arrays radars – which the US uses primarily for missile warning – mechanical radars, and optical sensors. It also features space-based telescopes for tracking purposes, such as the first satellite of the future US Space-Based Space Surveillance (SBSS) constellation, SBSS-1, launched in 2004, and the Canadian Sapphire satellite, launched in 2013. The following list contains the publicly known US SST sensors.

5.1.1 Dedicated Sensors

- The **Ground-based Electro-Optical Deep Space Surveillance (GEODSS) System**, currently made up of three one-metre-aperture telescopes respectively installed in New Mexico and Hawaii;[5]

- The **Space Surveillance Telescope (SST)**, a 3.5-metre-aperture telescope that DARPA developed and recently moved to Australia to collect data from the southern hemisphere;

- The **GLOBUS II radar**, in Norway;

- The **AN/FPS-85 Space Track Radar**, an Ultra High Frequency (UHF) phased array radar the US has been using for space surveillance since 1988, located in Florida;

- The **AN/FPS-133 Air Force Space Surveillance System**, also known as the Space Fence, a network of Very High Frequency (VHF) radars that ceased operations in 2013. The upcoming new Space Fence, which the US expects to be operational in 2019 from the Marshall Islands (Kwajalein), and possibly from Australia in 2021,[6] will replace the old system.

5.1.2 Collateral Sensors

- The **Maui Space Surveillance System (MSSS)**, which includes the **Advanced Electro-Optical System (AEOS) telescope**, a 3.67-metre-aperture telescope, and several other telescopes for Long Wave Infrared and photometric data collection;

- The **Haystack Ultrawideband Satellite Imaging Radar (HUSIR), Haystack Auxiliary Radar (HAX), and Millstone Hill Radar**, a set of radars working on Ku, X, W bands with resolution up to 0.5 millidegrees,[7] located in Massachusetts;

The telemetry ship Monge in Brest harbour.

- **ALTAIR,**[8] a 45.7-metre VHF and UHF radar, and **ALCOR,**[9] a 12.2-metre C-band radar operating from the Marshall Islands since 1969;

- The **Ascension Range Radar**, a VHF radar for telemetry, tracking, and collateral support to space control operations;[10]

- The **Ground-Based Radar Prototype (GBR-P)**,[11] an X band, mechanically slewed, phased array radar located in the Marshall Islands.

5.1.2 Auxiliary Sensors

- The **Solid State Phased Array Radar System (SSPARS)**, based on the AN/FPS-132 Upgraded Early Warning Radar (UEWR), deployed at multiple sites;

- The **AN/FPQ-16 Perimeter Acquisition Radar Characterization System (PARCS)**, a UHF radar operating from northern North Dakota;[12]

Besides a vast network of SST sensors and an effective data processing chain for CA and warning dissemination, the US also has a number of bilateral data sharing agreements in place with commercial operators and governmental entities. Moreover, there is an active multilateral agreement with Australia, Canada, New Zealand and the United Kingdom not only to share data but also to share SST sites to leverage the geographical positions of the sensors.

5.2 SST in France

According to Space-track.org, the open website for SSA data that the Science Applications International Corporation (SAIC) developed under a JFCC Space/J3 contract, France is the European nation that owns the greatest number of earth-orbiting objects. To ensure an adequate SST capability to protect its active satellites and to support military purposes, France relies on radar and optical sensors. In particular, the list of French SST sensors includes:[13]

- The ***Grand Réseau Adapté à la Veille Spatiale* (GRAVES)**, a VHF bi-static surveillance radar located near Dijon (transmitter) and on the Plateau d'Albion (receiver), able to spot 1 m^2 RCS objects in the range 400–1,000 km coming from the south;

- Three **SATAM radars**, C-band tracking sensors operating from multiple locations (Suippes and Captieux, plus a mobile radar), not specifically dedicated to space surveillance. Their SST mission is to track debris for the management of collision risks and to predict atmospheric re-entry;

- The ***Bâtiment d'Essaiset de Mesures* (BEM) Monge tracking ship**, with three tracking radars belonging to the *Direction* Générale de *l'Armement* (General Directorate for Armaments – DGA)/Data Communications Equipment (DCE), dedicated to SST as its secondary mission.

- The **SPOC *(Systéme Probatoire d'Observation du Ciel)* telescope**, a wide-optical sensor for initial orbit determinations;

- The **TAROT System**, in partnership with the *Centre National d'Etudes Spatiales* (French Space Agency – CNES)/*Centre National de la Recherche Scientifique* (National Centre for Scientific Research, France – CNRS), comprised of two 25 cm Newtonian telescopes operating from the Calern Plateau in France and from the Silla Observatory in Chile. France primarily uses this system to detect gamma-ray bursts, but it also contributes to the detection and monitoring of space objects in the geostationary and GEOs, together with the 50 cm ROSACE telescope.

France also experiments with the spectral analysis of debris with the OSCEGEANE *(Observation Spectraleet Carat Erisation des satellites GEostAtioNnairE)* project[14].

All these sensors produce and deliver the data, together with additional information that intelligence, governmental partners, and open sources provide, to the Military Surveillance Operational Centre of Space Objects (COSMOS – Centre Opérationnel de Surveillance Militaire des Objets Spatiaux) for elaboration and analysis. This centre, which falls under the French Air Force, is responsible for dealing with SSA in France for civilian and military purposes.[15] It is located near Lyon and has been operational since 2014.

On the civilian side, the CNES *(Centre National d'Études Spatiales)* provides to registered satellite owner/operators a 'man-in-the-middle' SSA service named CAESAR (Conjunction Analysis and Evaluation Service: Alert and Recommendations).[16] CAESAR is a trial public service the CNES has delivered under subscription since 2012 – using the combined operational capacities of the French defence and the CNES – aimed at providing expertise for the analysis of the CDMs USSTRATCOM provides through the 18 SPCS. The objective of the service is to support registered satellite owner/operators by evaluating the collision risk level, and by triggering an alert whenever owners/operators need to consider avoidance actions. Also, it can provide support to plan the most appropriate avoidance manoeuvre.

5.3 SST in Germany

According to the latest space strategy of the German Federal Government, the orientation towards the principle of space sustainability is one of the guidelines for the German space policy, both in terms of avoiding the production of space debris and of protecting space assets from collisions.

The German Space Situational Awareness Centre (GSSAC) is the German national centre for SSA. The German government created it in 2009, and the German Air Force and the German Aerospace Administration (DLR) run it jointly. It receives SSA data from open sources, through international agreements, civil organizations, German sensors, and intelligence, to generate a RSP. It manages its database and delivers SST products, such as CAs, space weather forecasts and warnings, re-entry warnings and overflight warnings/information to its user network. This network includes multiple organizations, such as national satellite operators, and several Federal Ministries including Defence; Interior; Economic Affairs and Energy; Transport and Digital Infrastructure; and Environment, Nature Conservation, Building and Nuclear Safety. In 2016 the GSSAC went to 24/7 operations to meet the requirements for the European Union SST (EU SST) program. As of today, the GSSAC is still in a build-up phase, and it foresees fully operational capability in 2020.

The GSSAC has access to German SST assets, which includes the TIRA experimental system – a 34-metredisc, L and Ku band radar for tracking and imaging space objects – and in the near future, two SST telescopes and the GESTRA (German Experimental Surveillance and Tracking Radar) system, a quasi-monostatic, pulsed, phased array radar operating in L-band that the developer – the Fraunhofer Institute – plans to put into operations in mid-2019. The following bullets provide more details:

- The 34-m parabolic dish antenna **TIRA radar** uses L-band for tracking and Ku band for ISAR imaging. In tracking mode, the TIRA system can determine orbits from direction angles, range, and Doppler for single targets with a detection size threshold of about 2 cm at 1,000 km range. The antenna can be turned 360° in azimuth (horizontal) and 90° in elevation (vertical), with a full rotation taking 15 seconds. The GSSAC also can use the TIRA system as a bistatic radar in conjunction with the Effelsberg Radio Telescope, a 100-m radio telescope located near Bonn, to reduce the detection size to 1 cm.[17]
- The **GESTRA system** is expected to be operational in mid-2019. It is a (semi) mobile system with separate receiver and transmitter units housed in two 4 x 4 x 16 metre shelters. Both shelters feature a phased array antenna mounted on a three-axis positioner for an extended field of view. The system will be able to form a virtual fence with up to 90° coverage to spot any detectable passing object and to track it within the area of the antenna coverage with an electronically steered tracking beam.[18]

The two telescopes are commercial off-the-shelf (COTS) systems with a 400 mm aperture. Engineers will equip one of the telescopes with a CCD camera and the second one with a Full Motion Video (FMV) camera. Both are located in Uedem. Furthermore, the GSSAC can remotely control the telescopes.


© Wolkenkratzer

Radome of the TIRA, FHR Wachtberg, aerial view.

Sardinian Radio Telescope
on its inauguration day
(30 September 2013).

5.4 SST in Italy

Since 2011, the Italian Government has delegated the Italian Air Force (ITAF), in collaboration with the Italian Space Agency (ASI) and the National Institute for Astrophysics (INAF), to study the feasibility of a national SST network using existing sensors and processing capabilities. As a result of this activity, Italy now employs the following sensors for SST purposes:

- The **RAT-31 Fixed/Deployable Air Defence System Radars (FADR/DADR)**, an L-band, solid state, phased array radar primarily intended for air defence, which can operate in a monostatic configuration for space surveillance;
- **BIRALES (Bistatic Radar for LEO Survey)**, a bistatic UHF radar for surveillance located in Sardinia (transmitter) and near Bologna (receiver). It can detect sub-metric pieces of debris passing on the local celestial meridian of the receiver. The receiver, a radio telescope named Northern Cross, which operators can steer in declination, is an array of cylindrical-parabolic reflector antennas that can characterize the transit direction of the scattered objects in terms of right ascension and declination (or alternatively, in azimuth and elevation);

The Teide Observatory (el Observatorio del Teide), which hosts the IAC-80 telescope since 1991.

- **BIRALET (Bistatic Radar for LEO Tracking)**, a bistatic radar for tracking purposes, which employs the 64-metre Sardinia Radio Telescope (SRT) as the receiver. The receiver antenna can operate from 0.3 to 116 GHz. Its pointing accuracy is between 2 and 5 arc-seconds;

- The **PdM-MITE telescope**, a 350-mm fast telescope that uses separate CCDs for surveillance and tracking purposes. It can also collect some information about the spectral content of the light the target reflects for improved characterization of the piece of debris under investigation;

- The **VdV-CAS telescope**, a telescope similar to the PdM-MITE, which Italy employs for surveillance and tracking of the GEO belt;

- The **Matera Laser Ranging Observatory (MLRO)**, a laser station located in Matera, dedicated to the measurement of the exact orbital parameters of cooperative artificial satellites, i.e. those fitted with laser reflectors.

The sensors mentioned above gather and forward the data to the Italian SST Operations Center (ISOC). In this centre, the data that the national SST sensors provide are merged with those that the cooperation network provides, which includes US military sources, and in the future, the National Centre for Meteorology and Climatology (CNMCA, for space weather), and the SSA component of the ESA. The same facility is also responsible for processing the data to produce the RSP and deliver SST products and services to the final users, both military and civil. To ensure the protection of possibly sensitive SST information, all communications among the ISOC, the sensors, the cooperation network and the final users are encrypted and employ dedicated satellite links.

5.5 SST in Spain

The Spanish Space Surveillance and Tracking (S3T) system provides SST services spanning from collision risk assessment to the generation of the relevant CDMs, and from the detection and characterization of in-orbit fragmentations and collisions to the characterization and surveillance of uncontrolled re-entries of space objects into the earth's atmosphere. Spain bases S3T services on the S3T catalogue, which also uses external sources like the US 18 SPCS and the precise ephemerides provided by satellite operators to object data and orbital information. Spain bases the S3T system on a national SST Operation Centre (S3TOC) – for planning and tasking of sensors, data processing, and providing services – and on a set of ground-based SST sensors, the S3T Sensor Network (S3TSN), which includes radar, electro-optical and laser facilities. The S3OTC also offers support and recommendations to satellite operators in case they require risk mitigation actions.[19]

The list of Spanish SST sensors includes the following:

- The **Monostatic Space Surveillance Radar (MSSR)**, a close-monostatic, L-band radar located at the Santorcaz military base. It is owned by the ESA, but it contributes to the S3TSN since the end of 2016;

- The **S3T Surveillance Radar (S3TSR)**, a phased array, L-band radar that has successfully passed the final acceptance in December 2018 and is presently undergoing the operational calibration and validation campaign before its complete integration into the S3TSN;

Solid State Phased Array Radar (SSPAR) at RAF Fylingdales, North Yorkshire, UK.

- **Centu-1**, a wide-field telescope for searching debris on GEO and MEO regimes. It is owned by the Spanish company Deimos Electon, and it has contributed to the S3T since 2016;

- **Tracker-1** is a tracking telescope for refining the orbital data of debris on GEO and MEO regimes. It is owned by the Spanish company Deimos Electon and it has contributed to the S3T since 2016.

- The **Fabra-ROA telescope at Montsec (TFRM)** is an f/1 50 cm surveillance and tracking optical telescope located in the province of Lleida, Spain;

- The ***Telescopi Joan Oró* (TJO)**, a 1-m class tracking telescope owned by 'Institut d'Estudis Espacials de Catalunya'. It has contributed to the S3T system since 2016.

- **IAC-80**, an 80-cm telescope operated by the ***Instituto de Astrofísica de Canarias***. It is located on the Island of Tenerife in the Spanish ***Observatorio del Teide***. It has contributed to the S3T system since 2017.

- The **Burst Optical Observer and Transient Exploring System (BOOTES)** network, which contributes to the S3TSN since 2017 with a surveillance and tracking telescope (BOOTES-1) and three tracking telescopes (BOOTES 2, 3 and 5). The four telescopes are distributed around the globe – respectively in Mazagón (Spain), La Mayora (Spain), Blenheim (New Zealand), and Baja California (Mexico) – to ensure better coverage of the GEO belt.

- The **Laser Station of San Fernando (SFEL)**, owned by 'Real Observatorio de la Armada' (ROA) and managed by the 'Real Academia de Ciencias y Artes de Barcelona'. It is primarily dedicated to tracking cooperative space objects – i.e. those provided with laser retro-reflectors – orbiting in the LEO region.

5.6 SST in the United Kingdom

Like other space-faring nations, the United Kingdom (UK) also employs radar and electro-optical sensors for SST purposes. In particular, besides some SST dedicated sensors, they exploit a few collateral sensors as well. Here is a more detailed list for the UK:

- The **Fylingdales radar**, which is located in a Royal Air Force station in the North York Moors, England. The Royal Air Force operates and commands the station, but it is also one of three stations in the United States Ballistic Missile Early Warning System (BMEWS) network, with the other two stations in the network located at Thule Air Base, Greenland and Clear Air Force Station, Alaska. Three phased array, UHF radars, each with an effective aperture of 22 metres, make up the Fylingdales radar to achieve a near-hemispheric coverage. Its primary purpose is to provide missile early warning to the UK and US governments. The detection and tracking of orbiting objects is its secondary role, and operators share collected data between the UK and US. [20]

- **CASTR (Chilbolton Advanced Satellite Tracking Radar)**, which is located in Winchester, UK. It is a monopulse, S-band (3 GHz) radar with a 25-metre parabolic dish antenna. It is currently undergoing an upgrade to improve its SST capabilities.[21]

- The **PIMS (Passive Imaging Metric Sensor) telescopes**, which is operated by the United Kingdom Ministry of Defence. It is composed of three 40-cm Cassegrain telescopes, located respectively in Herstmonceux (UK), Gibraltar, and Cyprus, to cover about 165 degrees of the GEO belt.

- The **Starbrook telescope**, which is a wide-field, 10-cm refractor-type telescope located at Troodos, Cyprus. Its intended use is GEO belt surveillance. The British National Space Centre (BNSC) funded it in 2006 as an experimental surveillance system.

It is important to note that in addition to its SST capabilities, the UK also can count on the large amount of SST data and services that the US provides in the frame of the existing data sharing agreements between the two countries, such as the USUKA agreement. In other words, the UK can benefit from access to the largest available SST database, almost without restriction, even if disclosure of the contained information to third parties is limited.

5.7 Bilateral and Multilateral Agreements

Even if it is relatively easy to develop some SST capability, it is very difficult for a single nation to achieve a complete and effective SST without multinational cooperation. The reasons for the necessity of multinational cooperation in SST will be further addressed in chapter VII; however, the increasing number of international SST agreements in place is a clear hint that SST is not a business for a single nation.

USSTRATCOM's SSA Sharing Programme is one of the first examples of multinational SST data sharing. USSTRATCOM initiated the programme following the signing of the National Space Policy in 2010 and the National Space Security Strategy in 2011, to foster the responsible use of space and spaceflight safety under the leadership of the US.[22] At the end of 2016, the results of this programme included 11 agreements with governmental entities, 2 agreements with intergovernmental organizations, like the ESA, and 54 agreements with commercial partners.[23] According to these agreements, the partners usually share their SST information, and in exchange, they receive US SST information and a set of services such as pre-launch planning, launch collision avoidance, launch support, early and in-orbit collision avoidance, as well as end-of-life/disposal, deorbit, and re-entry support. The list of nations currently sharing data with the US includes the United Kingdom, the Republic of Korea, France, Canada, Italy, Japan, Israel, Spain, Germany, Australia, the United Arab Emirates, and Norway.

Moreover, the US also can boast another important agreement with Australia, Canada, New Zealand and the United Kingdom, also known as the 'Five Eyes' nations – the Combined Space Operations (CSpO) initiative.[24] These nations established this partnership in 2014, and it takes advantage of the already existing intelligence agreements among these nations for improved cooperation in SSA. In particular, sharing of

US Air Force Major General David D. Thompson, US Strategic Command director of plans and policy, left, and Jean-Jacques Dordain, European Space Agency director general, sign a new Space Situational Awareness data-sharing agreement at the ESA office in Washington D.C., 30 October 2014.

space-related information and resources to synchronize space operations allow the partners to increase reciprocal transparency, to improve the security and resilience of their space missions, and to optimize the use of the pooled assets for a more effective and efficient SSA.

Besides the agreements that involve the US and its wide SST network, there are also other significant bilateral SST initiatives, such as the partnership between France and Germany aimed at exchanging their respective surveillance (with the GRAVES radar) and tracking (with the TIRA system) capabilities for an improved collective SST in the LEO region. However, the biggest and most recent achievement in terms of multinational SST for the European countries is undoubtedly the EU framework for SST, signed by the EU Parliament in 2014. The next chapter will present this new partnership in detail.

To conclude this examination of multinational SSA initiatives, the GLOBAL SENTINEL Exercise is another example of an SSA endeavour that is worth mentioning as an interesting booster for SSA cooperation among Ministries of Defence. This SSA forum has taken place since 2014 and allows the participating nations to develop and implement processes for combined SSA operations. Currently, it includes Australia, Canada, France, Germany, Italy, Japan, South Korea, Spain, the UK, and the US, and more nations are joining every year. The GLOBAL SENTINEL Exercise is a unique opportunity to contribute to the growth of multinational space culture, focusing on a federation of national capabilities. For example, during GLOBAL SENTINEL 2017, participating nations agreed to simulate a Federation Space Operation Centre (FedSpOC) to prove the value of a combined and integrated C2 capability, to ensure the sharing of respective best practices, and to develop common tools and procedures.

5.8 ESA SSA Project

> ***'The objective of the SSA programme is to support the European autonomous utilization of, and access to, space for research or services, through the provision of timely and quality data, information, services and knowledge regarding the space environment, the threats and the sustainable exploitation of the outer space surrounding our planet earth.'***
>
> *ESA Ministerial Council in November 2008*

In 2009, ESA started its SSA programme after recognizing the importance of protecting the critical infrastructure in space. Today, this optional programme involves 19 member states and comprises three main focus areas: space weather, NEOs and SST. To date, the contributing member states are Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, and the United Kingdom.[25]

From 2009 to 2017, the main focus of the programme was developing the technology and the system architecture in all the defined areas, especially integrating the existing European space weather infrastructure and developing new sensors for space weather and NEO. From 2017 to 2020, the programme, instead, will be aimed at developing space weather and NEO services and at continuing the research, development, and validation activities in the SST area. In particular, the core goals for the SST area for the next few years include the following: the development of a credible mission design and an engineering model of the sensor for a space-based SST component; the enhancement and maintenance of telescopes, laser ranging systems, and radar sensors – both nationally and ESA-owned; and the development of an SST core software for data processing and for planning and scheduling of sensors.

It is worth noticing that as a satellite operator, ESA itself needs SST information, too. For this reason, it has developed a Space Debris Office (SDO) to ensure operational support to ESA missions. The ESA SDO relies on SST data, information and services that both ESA SST facilities and external agencies, through SST data exchange agreements, provide the office. However, this activity is not currently part of the ESA SST programme.

5.9 Other SST Initiatives

In the broad spectrum of SST initiatives, it is also possible to find non-governmental SST partnerships. An example is the International Scientific Optical Network (ISON), which is a partnership of scientific and academic institutions organized by the Russian Academy of Sciences in Moscow. ISON currently consists of around 30 telescopes from 11 countries that the network members use for space surveillance. Thanks to the large number and heterogeneity of its sensors, ISON currently consists of more than 50 telescopes from 17 countries that the network members use for space surveillance.[26]

Understandably, satellite operators have a specific interest in having a solid SST capability available to ensure the safety of their space activities. For this reason, since 2009, some of the leading commercial satellite operators founded the Space Data Association (SDA). SDA is a not-for-profit entity based on the Isle of Man that currently includes Eutelsat, Inmarsat, Intelsat, and satellite operator SES as Executive Members, and Analytical Graphics, Inc. (AGI) as the Chief Technology Adviser. AGI designed and operates the Space Data Center (SDC), which is SDA's automated SSA system and uses operators and external SST data to provide CA, support against Radio Frequency Interference (RFI), and authoritative contact information for a given space object. Currently, SDA membership embraces about 30 satellite operators including governmental agencies and intergovernmental organizations. AGI, in particular, has recently announced the creation of a Commercial Space Operations Centre (ComSpOC) for an enhanced SDC that would no longer rely on third-party catalogue data.[27]

Finally, it is worth mentioning that, today, even amateur astronomers have easy access to a level of optoelectronic and mechanics technology sufficient for SST purposes. Objects in GEO are easy targets for an amateur astronomer, and modern, commercial, motorized telescope mounts can efficiently track small objects in the LEO region. The astonishing pictures of the ISS taken from the earth by some experienced amateur astronomers are a clear example of this capability. In particular, they have demonstrated the ability to routinely track classified national security payloads from several countries, even if it is just a sort of game for them. For this reason, it is not a surprise that the DARPA includes data from amateurs among the acceptable inputs for the collaborative SST 'OrbitOutlook' project.[28]

5.10 Summary

The objective of this chapter was to give an overview of the SST capabilities of some of the European spacefaring nations compared with the US, which owns the most extensive SST network in the world. It was also aimed at showing the notable number of bilateral and multilateral agreements already in place, and the clear tendency to turn SST into a global endeavour, notwithstanding all the related obstacles. The EU SST project, which was briefly introduced in this chapter, is another remarkable example of SST partnership, even if it is still in its early stages. The next chapter will better elaborate on the motivations, status, and future perspectives of this relatively new European venture.

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CHAPTER 6

The EU SST Project

On 16 April 2014, the European Union established – with the European Parliament Decision n. 541 – the so-called 'Framework for Space Surveillance and Tracking Support' in order to 'contribute to ensuring the long-term availability of European and national space infrastructure, facilities and services, which are essential for the safety and security of the economies, societies and citizens in Europe.' In particular, the objective of this 'support framework' is 'to establish an SST capability at European level and with an appropriate level of European autonomy' through:

- The creation of a network of European SST sensors owned by the Member States and ESA, ground- or space-based;
- The establishment and operation of processing functions to convert SST data into information;
- The conception of a function to provide SST services, such as collision risk assessment, fragmentation detection, and uncontrolled re-entry risk assessment

The framework is not meant to develop new sensors, but to integrate the existing ones, speeding up and reducing the costs for development of a European SST capability.

6.1 Why Does Europe Need an SST Capability?

Today, SST service providers include several governmental, international (e.g. ESA[1]), and commercial entities. However, the US is still the biggest contributor in terms of SST products and services for the


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Europe at night from space.

European countries. The CDMs produced by the 18 SPCS and the catalogue of earth-orbiting objects that the US maintains and shares, are remarkable sources of information for SSA purposes. Nevertheless, these services have some limitations. First of all, the public catalogue only includes unclassified data. This means that the US (and US partners) do not list their classified military satellites in the catalogue, nor do they provide their orbital elements. Moreover, the information is provided 'as is,' and any further analysis and assessment are the responsibility of the receiver. Thus, if the data provided is incomplete or inaccurate, the recipient must find additional data elsewhere. According to the 'Space and Security Panel of Experts' that the European Commission convened in 2004, US SST provided data are 'not exhaustive or not be made available at the needed time.'[2] Therefore, in order to protect its space-based infrastructure, Europe needs an autonomous capability to survey objects that pose hazards to its assets. Today, this exigency is becoming even more critical due to the increasing congestion of earth's most popular orbits.

Besides contributing to satellite safety, a European SST capability is also a fundamental enabler to achieving a re-entry prediction capability, which is essential to set up all the necessary actions in order to protect life and property from a re-entry event in a timely fashion. Moreover, minimizing or mitigating any harm that the re-entry of a European asset might cause is an important objective for European satellite owners and operators because they are legally accountable for any damage that their assets may cause. Clearly, the current involvement of the EU in space programmes like Galileo and Copernicus raises even more European concerns on this particular issue.

However, another, and perhaps more significant, reason for Europe to develop its own SST capability is to preserve and improve the space expertise of the European nations. In fact, knowledge is Europe's key resource in the twenty-first century for its economic and cultural wealth, and the stability of its social systems. Consequently, achieving European technological self-sufficiency in critical domains and maintaining independent access to space are essential objectives for the industrial and space policies of the EU.

The establishment of long-term SST space programmes is also fundamental for improving Europe's space technology and industrial base. In particular, as SST is a key capability for improving the understanding of environmental protection in near-earth space, Europe simply cannot continue to fully depend on third parties for SST services.

Last but not least, the sustainability of the two flagship European space programs, Galileo and Copernicus (the new name for GMES, the Global Monitoring for Environment and Security programme), critically depends on the availability of state-of-the-art SSA services, which need to be continuous and guaranteed for the long term.

6.2 Origins and Development of the EU SST Project

After the Treaty of Lisbon entered into force on 1 December 2009, the EU's competencies also include space. Specifically, according to Article 189 of the Treaty on the Functioning of the European Union, the EU is entitled to promote joint initiatives, support research and technological development, and coordinate the efforts needed for the exploration and exploitation of space in the context of the European Space Policy. In particular, in 2008, the Council affirmed the importance for the EU to play an active role in developing 'a European capability for the monitoring and surveillance of its space infrastructure and of space debris'.[3] In May 2011, the conclusions that the Council included in the Communication to the Commission entitled 'Towards a space strategy for the European Union that benefits its citizens,' and the Council Resolution of 6 December 2011 entitled 'Orientations concerning added value and benefits of space for the security of European citizens,' confirmed this need. Furthermore, it stated, 'the Union should make the widest possible use of assets, competencies and skills that are already existing or being developed by the Member States, at the European level and as appropriate internationally'.

As a result of these recommendations, the Commission proposed an SST support programme in February 2013.[4] The Decision of the European Parliament n. 541/2014 in April 2014, adopted the SST Support Framework programme, with the aim of networking national SST assets to monitor space debris, thus protecting European space infrastructures. In particular, the EU SST programme addresses only SST, which is one strand of SSA capability. The other two strands of SSA – monitoring of space weather and of near-earth objects – are part of the optional programme on SSA developed by ESA since 2009.[5]

Five nations volunteered to form the initial core of the 'EU SST Consortium': France, Germany, Italy, Spain, and the UK. These participating nations are represented in the Consortium through designated national entities – respectively CNES, DLR, ASI, the *Centro Para el Desarrollo Tecnológico Industrial* (CDTI), and the UK Space Agency (UKSA) – and contribute to the project by providing SST capabilities to the EU. The goal of the Consortium is to exploit existing national infrastructures and sensors to provide SST services. The European SST network offers services for monitoring and tracking space objects and debris, for assessing in-orbit fragmentations, break-ups, or collisions, and for monitoring uncontrolled re-entry of space objects into earth's atmosphere, providing an estimation of the timeframe and likely location of possible impact. Additionally, it supports space activities by generating collision avoidance alerts during all phases of spacecraft missions, from launch and early orbit, to in-orbit operation and disposal. The European Union Satellite Centre (SatCen), based in Torrejón de Ardoz, near Madrid, provides the portal for the distribution of SST products and services. As an interesting note, according to the

Decision of the European Parliament n. 541/2014, participating Member States, the Commission, and the SatCen are not liable for any damage resulting from the lack of, interruption, delay, or inaccuracy in the provision of SST services, nor for any action undertaken in response to the provision of SST services.

The EU SST Support Framework, which is funded through the European Union's Horizon 2020 research and innovation Programme, has the specific purpose to establish, operate, and evolve three functions:

- Sensor Function – Networking ground-based and/or space-based sensors of the Member States to collect SST data by surveying and tracking space objects;
- Processing Function – Processing and analysing SST data at the national level to produce SST information and products for SST services;
- Service Function – Providing SST services to the EU user community, such as spacecraft operators and civil protection authorities.

The Consortium Agreement, signed in June 2015, governs the activities of the EU SST Consortium through three decision-making bodies: the Steering Committee – for high-level decisions and liaising with the European Commission; the Technical Committee – for analyses and studies; and the Security Committee – for data policy issues.

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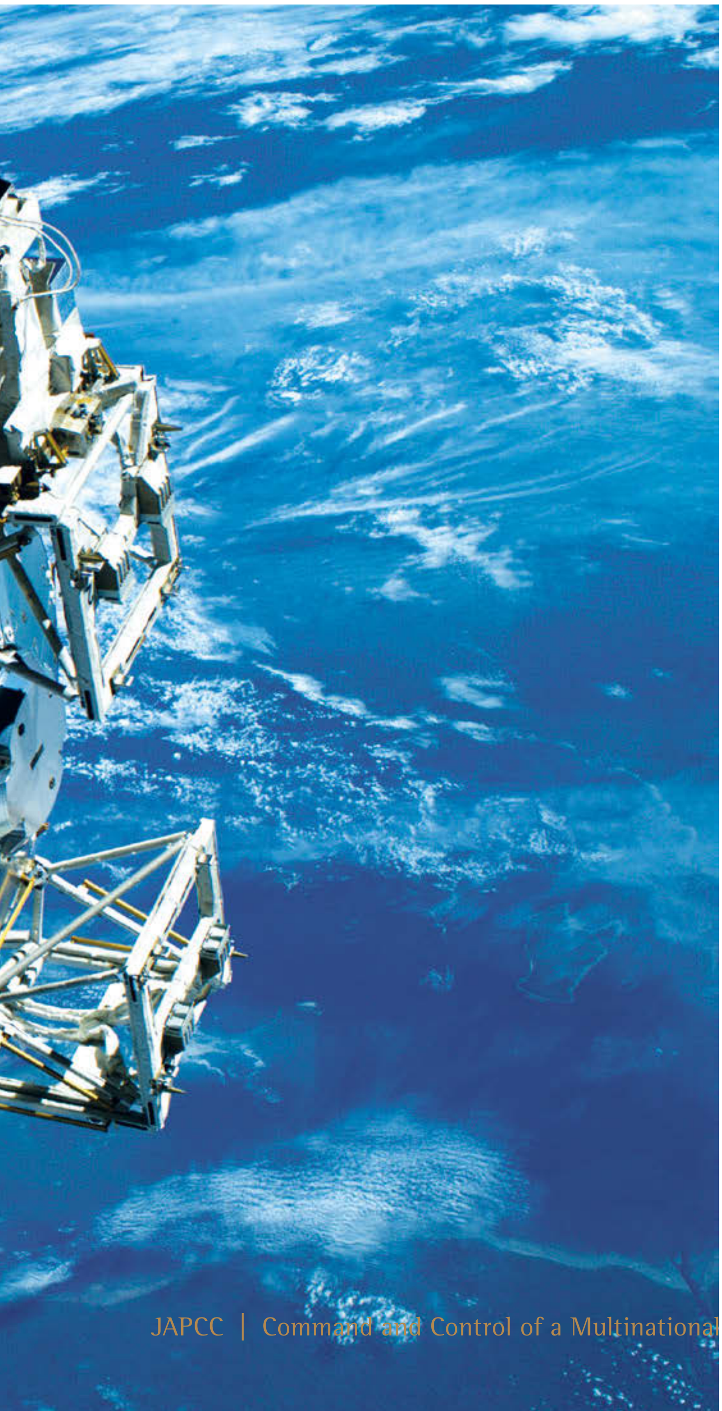
Originally, the EU SST Framework comprised three projects:

- **The Initial Service Delivery (1SST2015) project,** which started on 1 July 2016, aimed at delivering early SST services to Europe
- **The Service Provision (2SST2015) project,** aimed at consolidating SST Services and connecting national operations centres (OCs) and national sensors to an SST network
- **The Sensor Development (3SST2015) project,** currently ongoing, aimed at improving and upgrading the European SST network through Research & Development (R&D)



Currently, it comprises 1SST2016-17 and 2-3SST2016-17, which are the funding lines for the further development of the European SST Service provision function.

In short, the European Council uses resources from the 'ARTES Competitiveness & Growth' and the 'Horizon 2020 Research and Innovation' Programmes to improve SST national expertise, technology, and operations in order to provide effective services to Europe in a win-win scenario for all the involved stakeholders.

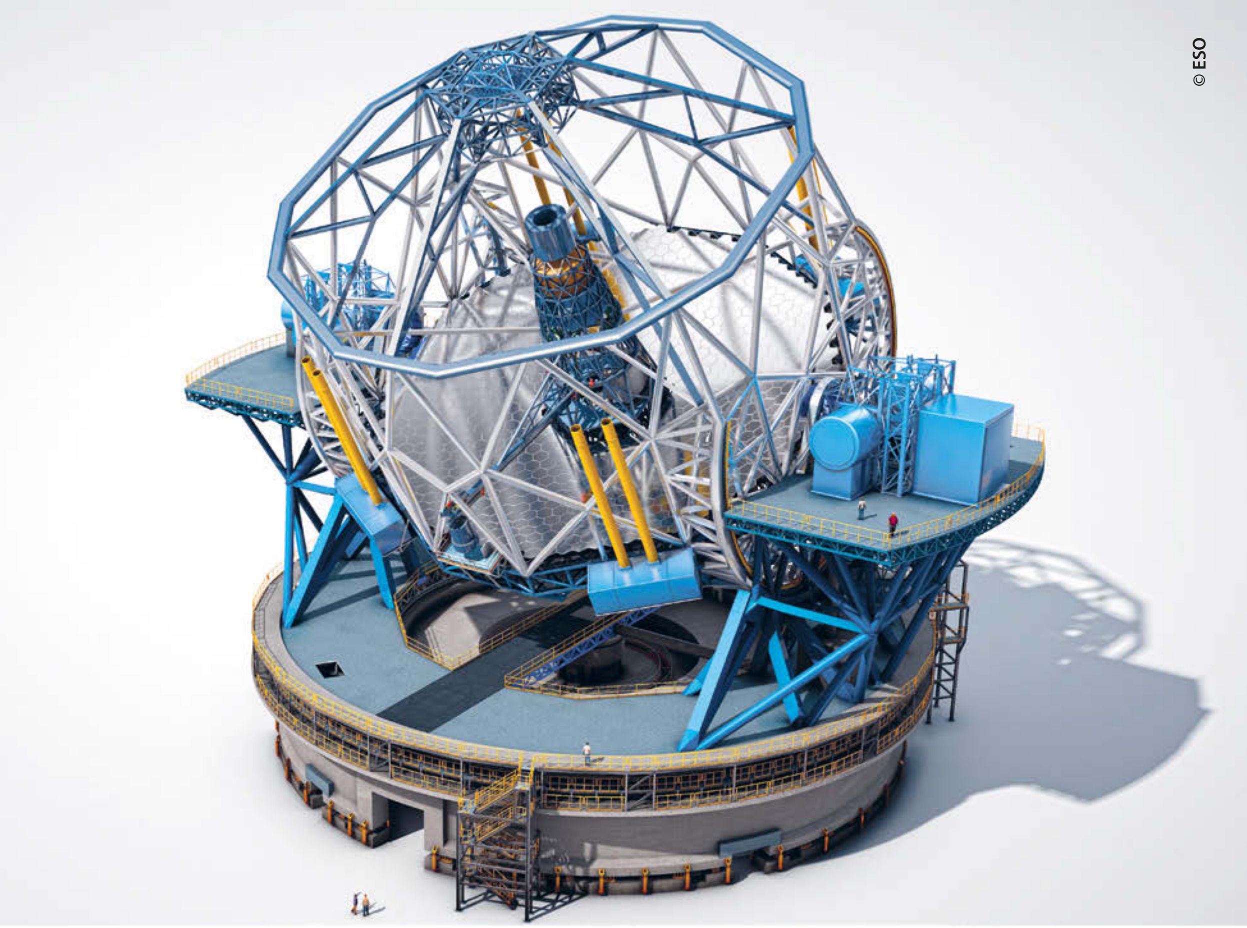
In June 2017, the EU already had 41 users of the early services provided through the SatCen. In particular, the SatCen provided the Collision Avoidance Service to 19 users for a total of 65 satellites, the In-Orbit Fragmentation Service to 26 users, and the Uncontrolled Re-entry of Space Objects Service to 29 users. After the first year of operations of the Initial Service Delivery, users generally have provided positive feedback on the quality of the services they received.[6]

One of the most recent challenges for the EU SST program is coping with the so-called 'Brexit'. Even if the vision of the UK government is to remain fully involved in programs such as Copernicus, Galileo and SST,[7] the fact that the EU mainly funds these programs clearly interferes with UK ambitions. Probably, Brexit will not impede UK participation in European space programs in terms of data access and usage, but taking part in large industrial contracts may pose a more difficult question.[8] It is probably too early to speculate on any future UK involvement in the EU's space programs but, in any case, Brexit does not change the substance of the EU SST program.

6.3 EU SST Project from a Military Perspective

A distinctive aspect of the EU SST project is its relationship with the national armed forces of the

Europe's Columbus space laboratory aboard the International Space Station.



The European Extremely Large Telescope, with a main mirror 39 metres in diameter, will be the world's biggest eye on the sky when it becomes operational early in the next decade.

member states. Since national SST resources often include a significant percentage of military assets, a serious multinational governmental SST endeavour cannot exclude the national Ministries of Defence. The French situation provides an extreme example of the inevitability of a close civil/military cooperation in SST. In fact, the French space agency – CNES – is dual in nature, since the French Ministry of Defence contributes to its annual budget.

For this reason, the Decision of the European Parliament n. 541/2014 explicitly includes both civil and military assets, and it clearly states that both civil and military user requirements drive the European SST network's provision of SST services. On the other hand, it also clarifies that 'purely military purposes should not be addressed by this Decision.' In other words, even if the SST services cannot deliver purely military products, like the Satellite Reconnaissance Advance Notice (SATRAN) or specific intelligence analysis, nations still can use them for military purposes or to provide some inputs for military products.

From a military perspective, this situation is a source of both concerns and opportunities. In one sense, it raises concerns about the opportunity of sharing classified data regarding military spacecraft (own or allied). Additionally, since SST is often a secondary task for most military sensors, nations should carefully consider their level of commitment to SST because it drains resources from their primary task, usually airspace control or missile warning.

On the contrary, a multinational cooperation in SST, which implies some degree of data sharing and capability integration, inevitably leads to better information, also for military purposes. It means improved SSA, which leads to an increased reliance on space-based capabilities.

6.4 EU SST Project from the NATO Perspective

Even if national leaders and representatives to the EU SST network somehow consider the military purposes of the network subordinate to the civil ones, NATO can find the existing linkage between the EU SST Framework and the military requirements of the participating nations undeniably useful. Although EU nations do not expect the EU SST network to provide products and services directly for NATO requirements, NATO member nations that are also EU member states can act as proxies to provide SST capabilities to the Alliance. However, this is not the main reason for NATO to be particularly happy about this European achievement. Improved security for the European space infrastructure also means improved reliability of the space capabilities that the European Allies provide to NATO and thus better support to NATO operations. Additionally, increased availability of the space-based military capabilities that the Allies provide substantially promotes NATO deterrence.

From a technical point of view, it is also worth mentioning that since the EU SST Framework aims to integrate the involved European SST assets, it also will inevitably lead to increased interoperability among them, at least at the European level. Interoperability is a fundamental NATO objective since the Alliance was funded in 1949, because it reduces duplication, enables pooling of resources and produces synergies. In particular, as will be explained in detail in Chapter VII, the ability to effectively pool and share SST assets and data is crucial to delivering high-quality SST products.

Therefore, NATO can leverage and extend this improved interoperability to achieve better integration among the Allies with respect to space capabilities. This implies that all NATO nations need to be involved in some manner. For this reason, it is more than opportune that NATO tries to get involved in the European SST project, through its leader national representatives, in order for the NATO Standardization Office to follow – and possibly cooperate in – the European SST project development process.

6.5 Summary

This chapter introduced the EU SST Framework, presenting its origins and development and analysing its possible military value. The EU SST Framework aims at creating a European SST capability for the security of its space infrastructure. Today, with the continuous growth of space debris and the increasing deployment rate of new satellites, the space environment is becoming more congested and dangerous. At the same time, the civil and military reliance on space-based capabilities is ever increasing. For this reason, the lack of SSA is not an option anymore. However, Europe does not consider the total reliance on a non-EU third-party provider of SST services as a valid alternative either, mainly because Europe needs to maintain and improve its expertise about space, which is a fundamental area for future technological development.

The EU SST Framework currently comprises three projects: the initial provision of SST services, the creation of an effective SST network, and improvement and development of the network. These three projects encompass the whole SST processing chain, from the sensors to the processing facilities to the service function.

The resulting EU SST network is not intended for military purposes – at least not exclusively. Nevertheless, since national SST data mostly derived from military assets, developers consider military requirements for the design of the provided services. This leads to a dichotomy: on one side, it raises concerns about the sharing of classified data and possibly about the diversion of military assets from their primary purpose, which is often airspace control or missile warning; but on the other side, it is an opportunity for the military users to receive better SST data, improve SSA, and obtain European funding to improve national military assets.

From a NATO perspective, the creation of a European SST network is highly profitable because it offers the European Allies a better SSA and increased reliability of their space-based capabilities. This translates into the possibility to provide improved space support in operations, which will increase NATO deterrence. Moreover, it is an opportunity to foster interoperability among SST assets, not only at the European level but also with the US and Canada. However, to exploit this opportunity, early involvement of NATO in the project – particularly the NATO Standardization Office through the national representatives – is absolutely necessary.

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Space Flight Operations Center at the Jet Propulsion Laboratory in La Canada, CA.

CHAPTER 7

Setting Up and Managing a Multinational SST Capability

In the previous chapters, it was explained that an SST capability is much more than just SST sensors. However, SST sensors are still the primary and essential source of SST data. A peculiar aspect of SST sensors is that they are never completely redundant. In fact, any additional SST data source with a sufficient precision can always be integrated (data fusion) to improve the final RSP. For example, sensors based on different technology can work together from the same location to complement respective capabilities, and analogous sensors operating from different positions can help improve the quality of the measures or overcome a misdetection by one element of the set. For this reason, an increased number of SST sensors usually leads to better SST products. The types, characteristics, and positions of SST sensors, as well as the coordination between the sensors, are all aspects that can be leveraged to optimize the effectiveness of the network.

7.1 SST is a Multinational Endeavour

As stated in Chapter IV, SST is inherently a multinational endeavour. The simple reason is that an effective SST network needs to include globally disseminated sensors due to the laws of orbital mechanics. For example, to monitor the whole GEO, nations must deploy at least three SST sensors uniformly distributed over the range of earth's longitudes. Space objects in LEO are visible from a specific SST sensor only when their ground tracks are nearby, and highest LEO satellites can be tracked for only roughly one-fifth of their orbit, at best. Additionally, the latitude where an SST sensor is placed sets the limits for its access to the LEO region. In fact, a sensor only can monitor orbits whose inclination is not smaller (in its absolute value) than the sensor latitude. However, SST sensors closer to the poles have the opportunity to see sun-synchronous satellites (the most common for LEO spacecraft) more times per day.[1] Additionally, due to particular lighting conditions or shadowing by celestial objects (eclipse), an optical sensor can miss the opportunity to detect a space object depending on its geographical location. For these reasons, there is an obvious need for multiple, diverse, globally distributed, and redundant SST sensors. This implies a considerable investment for a company or a single nation. Thus, the cost is an important driver that persuades nations to join in a collective effort for SST.

SST needs to be multinational for another fundamental reason: gathering data on active satellites directly from satellite owners/operators. Since satellite operators typically use on-board devices such as star trackers, positional gyroscopes, and PNT systems to keep their spacecraft on an assigned orbit (i.e. orbital station-keeping), they possess the most accurate positioning information. The resulting orbit determination is thus far more precise than what any SST capability can achieve.[2] Additionally, since satellite operators are in charge of any orbit manoeuvre for their spacecraft, they also have a better predictive awareness of the satellite position. On the contrary, an SST sensor can even fail to track a satellite that shifts too far from the expected position when it is out of the sensor's field of view. Therefore, collaboration from satellite operators undoubtedly adds significant value for an effective SST capability, even if they can only contribute with information about active satellites. The importance of this kind of SST data source becomes even clearer when one considers the upcoming mega-constellations, already mentioned in Chapter 3. In such a complex environment, it is crystal clear that multinational cooperation regarding SST is inevitable and essential.

7.2 Setting Up a Network of SST Sensors

Since there are no agreed-upon standards, designers continue to develop different SST systems based on varying technologies and architectures. This makes it very difficult for system integrators to create a federated SST network. However, the biggest challenge seems to lie at the political level.

From a merely technical perspective, we can consider three key roles for a federated network of SST capabilities: interoperability, synchronization, and prioritization. First, all nationally provided SST contributions – assets, data, information, or services – need to be **interoperable**. Even if one considers this role just a technical challenge, in reality, the adoption of a common sharing standard has political implications, as each nation will try to promote its own standard. Determining the level of interoperability is definitively a political issue as well, due to the security and sharing considerations with respect to national interests. Applicable levels of integration will be discussed later in this chapter.

Synchronization, the next step, is the capability of the nationally provided SST contributions to operate in unison, i.e. work in a timely manner for a common objective. For example, two SST sensors can track the same object at the same time, or in sequence across its orbit, for an improved orbit determination; or separate sensors can leverage their different points of view (position diversity) for a more precise positional fix. This role is not mandatory for a multinational network like the previous one is, but it definitely improves its effectiveness. Synchronization is an ambitious objective to accomplish because it requires complete interoperability and a common facility that at least can coordinate and control the SST sensors. The ownership of such a facility obviously would be another point of discussion among nations.

Prioritization closes this short list of roles that an effective multinational SST network should develop. Prioritization is the ability to operate the system to execute SST tasks according to their priorities. One can set the priorities in terms of imminence, criticality, or according to another agreed hierarchy. Once again, deciding the prioritization rules goes beyond a merely technical solution as it has profound political implications. For instance, the degree of priority of national tasks over multinational tasks for a national asset is one of the issues that SST partners would need to address. There are also other technical capabilities that could be considered desirable for a multinational SST network – such as harmonization, which is the ability to produce an optimized task plan for all the available SST assets considering priorities and capabilities – but going into such detail goes beyond the scope of this study.

The bottom line is that, besides technical challenges, there are a lot of aspects that nations need to be ready to consider and negotiate at a political level before considering a multinational approach to SST. What kind of data/information should be shared? How does a multinational SST network ensure that any resulting benefit is fairly shared among the contributing nations, both in terms of revenue – if any – and in terms of developing technical expertise for national industries? What kind of exchange mechanism should nations put in place to compensate for the capabilities provided by each contributor? The next section will elaborate on specific political issues that relate to the creation of an SST network and on possible associated solutions. Next, the technical aspect will be analysed, including possible network architectures and the associated implications.

7.3 Obstacles to a Multinational SST

As explained earlier, multinational cooperation seems the only viable solution to achieve an effective SST. However, it is a very challenging objective due to several concerns and obstacles that this approach raises. Besides the technical complexity of a global SST network, there are political and economic issues related to national interests that could potentially reduce enthusiasm for a multinational project.

7.3.1 National Authority

The first issue relates to the degree of national control on shared assets. The concerns are directly related to the requested degree of integration, i.e. the capability to act as a whole. In the case of complete integration, a multinational C2 centre would task all the assets, while multinational entities would conduct the entire data analysis process, from data fusion to product delivery. In practice, the national asset owner relinquishes the possibility to control its own SST resource, even when a specific national need is involved, because – in this extreme example – multinational tasks always have higher priority. This approach limits a contributing nation from achieving the best possible SST performance in the orbits where its active satellites fly because all the contributing nations need to discuss and agree among competing priorities. Understandably, larger contributors consider this situation a greater concern. A reduced degree of integration would be an easy fix, but it would come at the cost of a decreased effectiveness of the SST network and increased complexity of its management. In a possible scheme of operations, a multinational C2 centre could be in charge of preparing a task list to be negotiated with each nation. Additionally, the multinational SST network C2 system would require some specific mechanism to ensure fair negotiations, and the proper and timely management of urgent requests, both national and multinational.

7.3.2 Industrial Competition

Each space-faring nation tends to promote and to protect its national space industries. This means that they will likely push national technologies for the multinational group to consider for selection in common structures. On the other hand, top national technologies, especially if they have a military application, are sensitive. Hence, sharing complete SST data can be an issue because the data can reveal technical details about their source. Even reliability and limits of national SST assets can be an interesting source of information about national technological effectiveness, both for a military assessment and industrial competition. In particular, within a multinational environment, industrial competition is one of the main concerns. Thus, these are all problems that nations should consider when drafting rules of the cooperation.

7.3.3 Quantifying SST Contribution

An advantageous cost/benefit ratio is clearly a prerequisite for a nation to agree to contribute to any multinational initiative. Moreover, for a satisfactory level of cooperation, every contributor will desire the said ratio to be roughly the same for all participating members.

However, multinational cooperation based on sharing existing national assets, i.e. not developed for this purpose, implies some degree of disparity in the value of the offered capabilities that must be considered when it comes to quantifying each nation's contribution. Unfortunately, this is not an easy task to accomplish because it involves comparing different technologies, different parameters, and coping with the discrepancy between the advertised system performance and any possible technical limitation for a third party to fully exploit its capability. National interest in promoting own capabilities makes this task even harder. In fact, even if engineers and scientists can try to establish technical thresholds to provide an impartial scale for a rough evaluation, diplomatic interactions probably will still determine the final assessment.

7.3.4 SST Data Secrecy

Sharing SST data inherently involve some relevant security issues. First of all, the precise orbital parameters of some military satellites (orbital elements), can be classified. This means that the disclosure can constitute a security breach as it can reduce the effectiveness of the satellites in their military purpose (e.g. a military adversary can benefit from its knowledge about friendly ISR satellites overflights for conducting unobserved activities), or reveal potential satellite vulnerabilities. As a result, data exchange must obviously pass through secure channels and only among nations having specific security agreements in place. Another point of discussion is how to handle SST data and information relevant to an unknown object, especially if one cannot classify it conclusively as a piece of debris. On the one hand, since they could be related to a friendly classified spacecraft, data should be considered secret in the first place. Then, after the assessment, the appropriate authority could declassify the information if it relates to an unclassified object. On the other hand, one could say that since the object is visible to anyone who owns an adequate SST sensor, its positional data should be unclassified. The appropriate authority could then classify the derived information only if it relates to a classified object. It is worth noting that, with today's modern, easily available technology, even an amateur can easily buy an effective SST sensor (a telescope and a CCD camera) able to track any satellite.[3] Generally speaking, the above discussion relates to the well-known dispute between 'security through obscurity' versus 'security by design.' Is it better to rely on the secrecy of the design or of its implementation, or to rely on an inherently secure technology? While the armed forces historically prefer the first solution, contemporary software engineering believes in the second one. Nevertheless, a strong lock is probably safer than a weak lock, even if carefully hidden; and hiding an orbiting satellite is becoming increasingly harder.

As described earlier in this chapter, SST data deliver more content than just the orbital parameters of satellites and debris. They also convey precise details about the capabilities of the SST assets that produce those data. This fact can constitute an additional national concern about data sharing. Apart from the essential technical protections required, security issues are primarily political challenges. The solution lies in an adequate trade-off between the 'need to know' and the 'need to share' approaches, the so-called 'sweet spot'.[4] Once it is clear that a multinational SST is the only reasonable approach for an effective SSA, information sharing should become just a consequence.

7.4 Dealing with Security Issues

Security issues are a major concern facing a multinational SST endeavour. Even when all the agreements are in place, sharing sensitive information among all partners clearly increases the risk of insider threat. However, some solutions can decrease this risk without impairing the effectiveness of data sharing.

7.4.1 Trusted Third Party

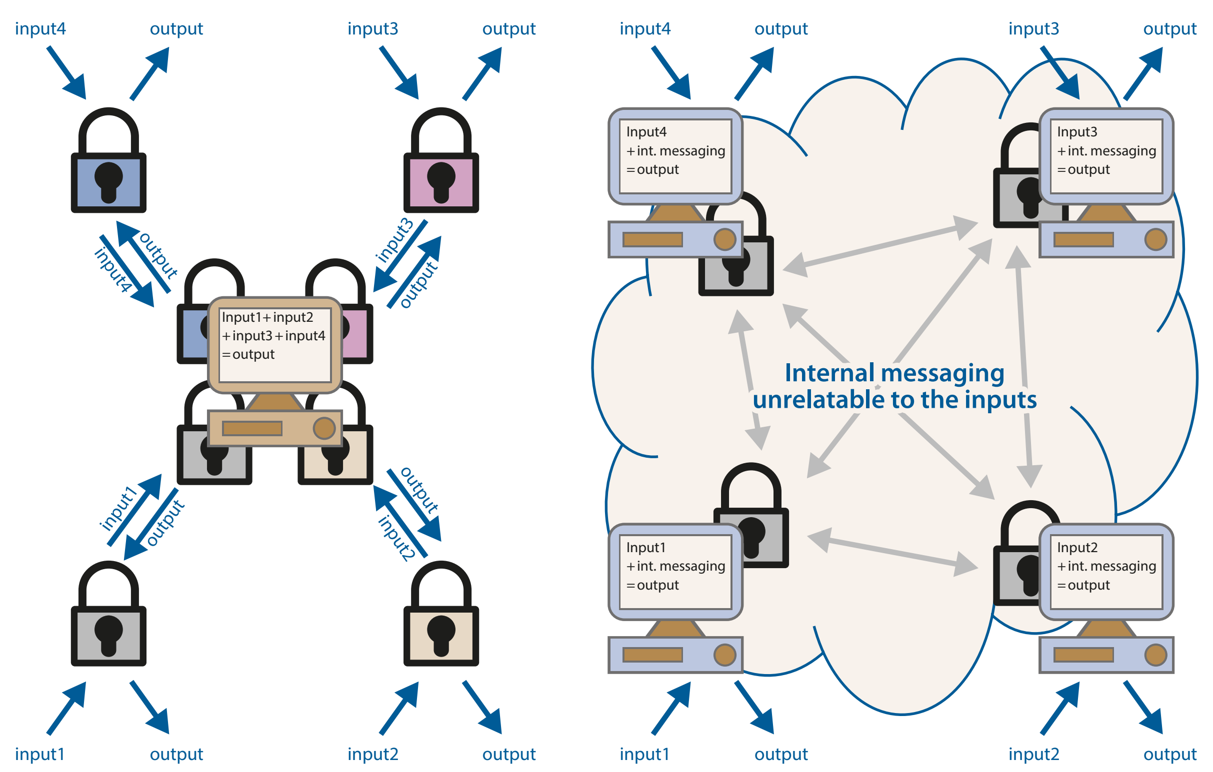
An efficient and commonly employed solution is that all participants share all data and information only with a trusted third party. Thus, minimizing the data spread also reduces the risk of a security breach. An example of this approach is the USSTRACOM SSA data-sharing program, which currently includes more than 60 commercial agreements, and several single-nation and intergovernmental agreements, with an increasing number of space-faring nations and intergovernmental organizations around the globe.[5] The European SST Support Framework adopts a similar approach by nominating the SatCen as the central hub for providing SST services based on information the contributing nations deliver.[6]

7.4.2 Secure Multi-Party Computation

Secure Multi-Party Computation (MPC) is a promising new approach to processing data coming from different sources, without requiring a trusted third party or actual data sharing.[7] In fact, MPC protocols consent to securely compute the output of a function while keeping the inputs private. The computation is distributed, meaning that every party introduces its data in a local trusted computer that runs a local portion of the protocol. The final output results from the interaction among all computers through specific messaging, which individuals cannot use to reconstruct the input data.

The application of this approach for all the common functions required for an SST network, from the tasking of surveillance and tracking assets to the conjunction analysis, would permit a multinational SST with reduced security-related issues. However, one drawback is that a multinational SST network would need more complex and expensive hardware to run the secure MPC protocols. Additionally, even if the sensitive information is substantially more protected, it is still technically possible to deduce some details on the input data by analysing the output (e.g. a collision

Trusted third party vs secure multiparty computation



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warning and the relevant suggested collision avoidance manoeuvre reveals the presence of something in a specific position).

7.5 Possible Architectural Solutions

SST products and services are the final results of a complex process, which starts from the preparation of a tasking plan for the SST sensors and proceeds through several steps to the desired output. For the design of a multinational SST system, the first and most important decision to make is how much of this processing chain shall remain at the national level, and how many steps nations will share at the multinational level. There is not an easy answer because any position of the boundary between national and multinational responsibility implies both pros and cons.

7.5.1 The Meaning of Command and Control for an SST Network

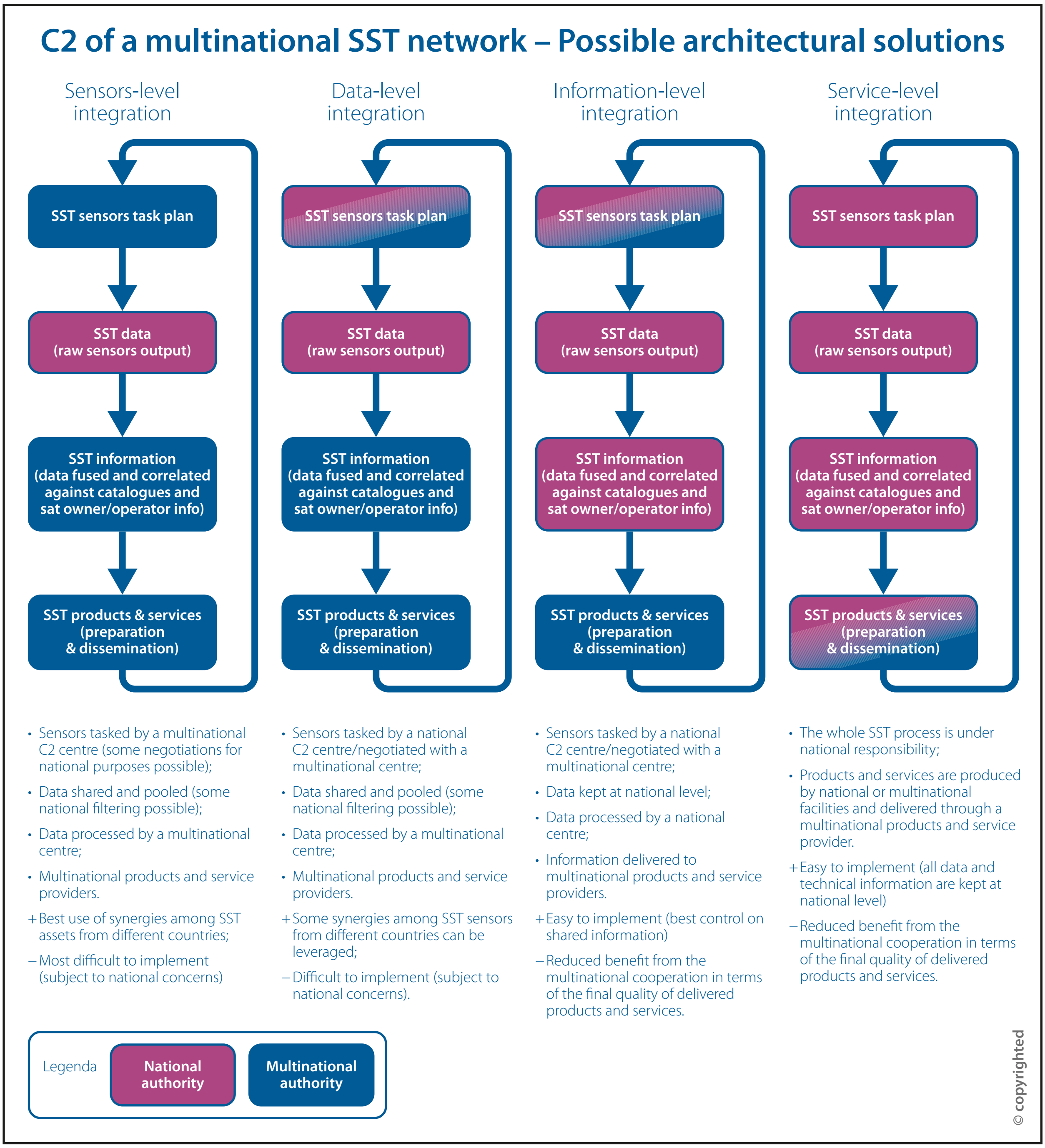
The expression C2 derives from military terminology and refers to the exercise of authority over the assigned forces. For example, according to the NATO definition, C2 encompasses the exercise of authority and direction by a commander over assigned and attached forces in the accomplishment of the mission.'[8] Translated to the SST scope, one can consider C2 as the authority to assign assets and decide objectives (command) and the function of actually operating the SST assets (control). In general, whatever the chosen architecture is, there are some key points to consider. First, a national asset will clearly maintain national ownership, even if part of a multinational network. As a result, maintenance will remain a national issue. Therefore, the owner nation, which is responsible for the availability of its pooled or shared SST assets, and which is ultimately liable for any problem caused by them, will also require maintaining control. Moreover, it is reasonable to assume that nations will conduct some national processing on all data their assets collect. The acquisition and transmission of data without monitoring the content are hardly conceivable for a governmental provider, especially in a multinational environment.

7.5.2 Sensors-level Integration

The first proposed architecture considers integration at the sensors level. A multinational C2 centre commands national SST sensors so that every sensor follows a multinational tasking order. In this scenario, a nation can check only the feasibility of the tasking plan and maintain the ability to task its assets in the case of urgent national activities. Some national data filtering is still possible because national SST sensors stay under partial national command and under complete national control. Data are shared and pooled for entirely multinational processing. This means that all data processing facilities, catalogues, products, and services providers also need to be multinational. This architecture easily allows the best optimization of the network by exploiting all the possible synergies among all nationally provided SST assets. For example, a tracking sensor can be repointed instantaneously according to the data provided from a survey sensor of another country, or a number of sensors of neighbouring states can be synchronized to follow the same object across a longer path. A problem with this approach is that, to build an effective network, nations must share all technical data about all the sensors involved. Moreover, the elements of the SST processing chain should be (or become) multinational because, if a single nation has the control of any step of the data processing, the accuracy of the final product cannot be validated.

7.5.3 Data-level Integration

The second proposed architecture on this list relates to integration at the data level. In this case, SST sensors are under national C2 but the resulting data are fused and correlated against the common catalogues in a multinational data fusion centre. To be effective, this multinational data fusion centre needs to receive detailed information from commercial and governmental satellites owners/operators, too. For an increased synergy among the SST sensors from different countries, a multinational C2 centre can be created to negotiate a prioritized tasking plan/order with the involved nations.



C2 of a multinational SST network – Possible architectural solutions

Sensors-level integration

- Sensors tasked by a multinational C2 centre (some negotiations for national purposes possible);
- Data shared and pooled (some national filtering possible);
- Data processed by a multinational centre;
- Multinational products and service providers.

+ Best use of synergies among SST assets from different countries;

– Most difficult to implement (subject to national concerns)

Data-level integration

- Sensors tasked by a national C2 centre/negotiated with a multinational centre;
- Data shared and pooled (some national filtering possible);
- Data processed by a multinational centre;
- Multinational products and service providers.

+ Some synergies among SST sensors from different countries can be leveraged;

– Difficult to implement (subject to national concerns).

Information-level integration

- Sensors tasked by a national C2 centre/negotiated with a multinational centre;
- Data kept at national level;
- Data processed by a national centre;
- Information delivered to multinational products and service providers.

+ Easy to implement (best control on shared information)

– Reduced benefit from the multinational cooperation in terms of the final quality of delivered products and services.

Service-level integration

- The whole SST process is under national responsibility;
- Products and services are produced by national or multinational facilities and delivered through a multinational products and service provider.

+ Easy to implement (all data and technical information are kept at national level)

– Reduced benefit from the multinational cooperation in terms of the final quality of delivered products and services.

Since national SST sensors stay under national control, some national data filtering is still possible. This approach still allows nations in the multinational network to leverage the synergies among the SST sensors, but less efficiently than with a sensor-level integration.

7.5.4 Information-level Integration

Proceeding through the steps of the typical SST processing chain, the next proposed architecture for a multinational network concerns the pooling of SST information (i.e. already processed SST data) from all contributing nations. In this case, every country retains the full C2 of its sensors, while a common facility provides SST products and services. This approach allows nations to filter the transferred content to control the details of the shared information. Again, a common C2 centre can be created to negotiate with national SST C2 centres regarding the priorities on information delivery and updates. However, the synergies among SST sensors from different countries are not leveraged in this architecture. In this case, compared to the previous solution, the contributing nations have the highest control on shared information, but this also results in a reduction in the quality of delivered products and services.

7.5.5 Service-level Integration

As the last proposed architecture for a multinational SST network, contributing nations would share only the output of their self-produced SST-related services. This approach implies the minimal possible level of integration among national SST capabilities because the multinational SST portal for products and services is the only common element. Catalogues can still be shared to improve the quality of the output, but the nations do not leverage any other kind of synergy among SST assets from different countries. This represents the easiest solution to implement from a political and technical point of view, but the SSA improvement that multinational cooperation would provide is less significant compared to the other proposed solutions.

7.6 An SST Architecture for the EU SST Project

As described in detail in Chapter 5, the EU SST framework aims to create an SST network that employs existing military and civil SST assets. European financing will thus contribute to the development of technology and expertise of the contributing nations while ensuring the availability of SST products and services for all EU nations in a win-win scenario. However, the actual effectiveness of the resulting SST network critically depends on the attitude of the contributing nations in terms of fairness in the governance of the multinational part of the processing chain and on their willingness to cooperate and share data and information. Indeed, colliding national interests can easily impair the entire project. For this reason, the best strategy is probably to foster an evolving architecture in a supervised environment. At the first stage, a service-level integration, which minimizes the risk of conflicting interests among the contributing nations, is simple and relatively effortless to implement. Then, after the establishment of solid relations and mutual trust, the architecture can evolve step by step towards the deeper levels of integration and better efficiency. To establish this virtuous circle, the European Commission needs to carefully supervise and guide the process, discouraging individualistic behaviours and biased decisions.

7.7 Possible NATO Integration with a Multinational SST Network

Today, NATO neither owns nor directly operates any spacecraft. Nevertheless, NATO operations heavily and increasingly depend on space-based capabilities that Alliance nations provide on a voluntary basis. SSA is thus a fundamental resource for NATO because it enables the efficient planning and use of such capabilities. Therefore, it is reasonable for NATO to take interest in an efficient SST network that would provide services and products. In particular, NATO could desire military-specific products, e.g. the monitoring of adversary satellites manoeuvres, for strategic assessment of possible hostile activities. Still, it is quite unrealistic for NATO to directly interact with a multinational SST network unless nations specifically create one for the Alliance. For example, NATO cannot expect the new EU SST network to directly contribute SST products and services for NATO operations because the EU also includes non-NATO nations and vice versa. Moreover, the EU SST network is officially mainly committed to civilian purposes.[9] Nevertheless, any nation that is both a NATO member and a contributor to a multinational

EU SST network can operate as a 'bridge' for NATO to deliver the needed products and services. Clearly, the multinational agreement should include rules and details about the possibility that any participating nation could share the output of the SST process with a third party. This is why it should be of particular interest for NATO to get involved in such programs through its member states from the very beginning to gain access to the indispensable multinational SST capabilities.

7.8 Conclusion

The multinational integration of national SST assets is a fundamental step for the sustainability of space activities. In an increasingly congested space environment, the optimal exploitation of the available SST resources is indispensable. Unfortunately, any attempt to design a multinational SST network reveals a clear trade-off between the effectiveness of a multinational SST system and the pursuit of national priorities, in terms of protection of sensitive information and national investments. Nevertheless, it should always be kept in mind that ensuring the long-term availability of space-based products and services is an absolute priority. In any case, achieving the best possible performance from a multinational SST network is not only a technical issue but also requires a relevant political involvement aimed at greater transparency and cooperation among nations. While technological integration of sensors and data processing is not easy, this latter part, the political involvement, is perhaps the more challenging commitment facing a multinational SST capability.

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1. For a better understanding, please refer to the Appendix 'A' – Basic Concepts of Orbital Mechanics.
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9. 'The provision of SST services should be driven by civilian user requirements. Purely military purposes should not be addressed by this Decision'–Decision n.541/2014/EU of the European Parliament and of the Council of the 16 April 2014 establishing a Framework for Space Surveillance and Tracking Support.

ANNEX A

Acronyms and Abbreviations

18 SPCS	18th Space Control Squadron
AJP	Allied Joint Publication
AO	Adaptive Optics
ASAT	Anti-Satellite
ASI	Italian Space Agency
AU	Astronomical Unit
BDA	Battle Damage Assessment
BNSC	British National Space Centre
C2	Command and Control
CA	Conjunction Assessment
CARA	Conjunction Assessment Risk Analysis
CCD	Charge-Coupled Device
CDM	Conjunction Data Message
CDTI	Centro Para el Desarrollo Tecnológico Industrial
CMOS	Complementary Metal-Oxide Semiconductor
CNEOS	Center for Near Earth Object Studies
COMINT	Communications Intelligence
COTS	Commercial off-the-shelf
CSM	Conjunction Summary Message
CSpOC	Combined Space Operations Center
DARPA	US Defense Advanced Research Projects Agency
DCE	Data Communications Equipment
DLR	German Aerospace Administration
ELINT	Electronic Intelligence
EM	Electromagnetic
EO	Electro-Optical
ESA	European Space Agency
FedSpOC	Federation Space Operation Centre
FMV	Full Motion Video
GDOP	Geometric Dilution of Precision
GEO	Geostationary Orbit
GLONASS	GLObal NAvigation Satellite System
GPS	Global Positioning System
GSO	Geosynchronous Orbit
GSSAC	German Space Situational Awareness Centre
HEO	Highly Elliptical Orbit
HF	High Frequency
IMINT	Imagery Intelligence
INAF	National Institute for Astrophysics
IPB	Intelligence Preparation of the Battlespace
ISAR	Inverse Synthetic Aperture Radar
ISO	International Standards Organization

ISOC	Italian SST Operations Center
ISON	International Scientific Optical Network
ITAF	Italian Air Force
ITU	International Telecommunication Union
JFSCC	Joint Force Space Component Commander
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MIM	Man in the Middle
MPC	Multi-Party Computation
MSL	Mean Sea Level
NEO	Near Earth Object
NERC	Natural Environment Research Council
OPIR	Overhead Persistent Infrared
PNT	Positioning, Navigation, and Timing
R&D	Research & Development
RCS	Radar Cross Section
RFI	Radio Frequency Interference
ROA	Real Observatorio de la Armada
RSP	Recognized Space Picture
S3T	Spanish Space Surveillance and Tracking
S3TOC	S3T system on a national SST Operation Centre
S3TSN	S3T Sensor Network
SAIC	Science Applications International Corporation
SatCen	European Union Satellite Centre
SATCOM	Satellite Communications
SATRAN	Satellite Reconnaissance Advance Notice
SBIRS	Space-Based Infrared System
SBSS	Space-Based Space Surveillance
SIGINT	Signals Intelligence
SDA	Space Data Association
SDC	Space Data Center
SDO	Space Debris Office
SLR	Satellite Laser Ranging
SOI	Space Object Identification
SSA	Space Situational Awareness
SSN	Space Surveillance Network
SST	Space Surveillance and Tracking
UAS	Unmanned Aircraft System
UHF	Ultra High Frequency
UK	United Kingdom
UKSA	UK Space Agency
USSTRATCOM	United States Strategic Command
VHF	Very High Frequency

APPENDIX A

Basic Concepts of Orbital Mechanics

This short annex intends to provide a very basic set of notes about satellites and their orbital mechanics to understand better the references provided in this study. It contains neither formulas nor theorems since it only gives some elementary hints on how satellite orbits work.

- Artificial satellites, in short *satellites*, are artificial objects that nations or companies have intentionally placed into orbit.

- A satellite's orbit always lies in a plane that passes through the centre of mass of the Earth. The angle between this plane and the equatorial plane is called the *orbit inclination*.

- The projection of the satellite's path over the surface of the Earth is called *ground track*. The ground track of a satellite with an orbit inclination equal to *i* is contained between the latitudes *i* and –*i*.

- The inclination and the height of a satellite's orbit define its field of regard, i.e. the total area on the ground that can be accessed from a satellite. It extends from the satellite ground track on both sides and increases with the satellite's height.

- Once in orbit, a satellite does not need constant powering to remain in flight, as aeroplanes do. However, satellites use small on-board propulsion systems to manoeuvre in space, when required

- The speed of an orbiting satellite is not arbitrary. Its orbit, and in particular its altitude at any given moment, determines its speed.

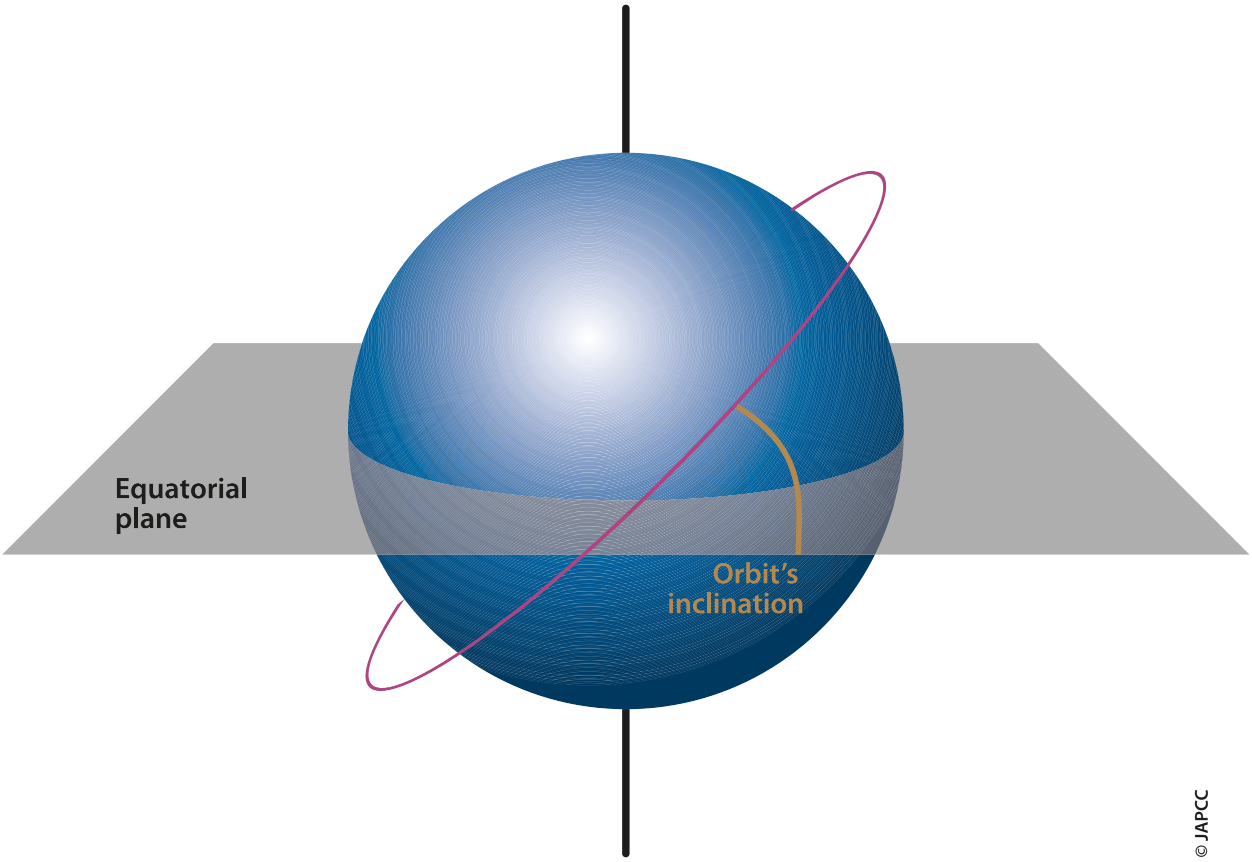

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Figure 1: Generic orbit around the Earth and its inclination.

- A satellite's orbit does not depend on its mass. All objects with the same velocity (speed and direction) at a given point in space follow the same orbit.

- Satellites closer to the Earth move faster than those at higher altitudes and, when one views them from the ground, they appear to cross the sky faster. Satellites in low earth orbits (LEO–hundreds of kilometres above the Earth) are the fastest with respect to the Earth, completing an orbit in 1.5 to 2 hours.

- Satellites in higher orbits move at slower speeds than those in lower orbits, and the distance that

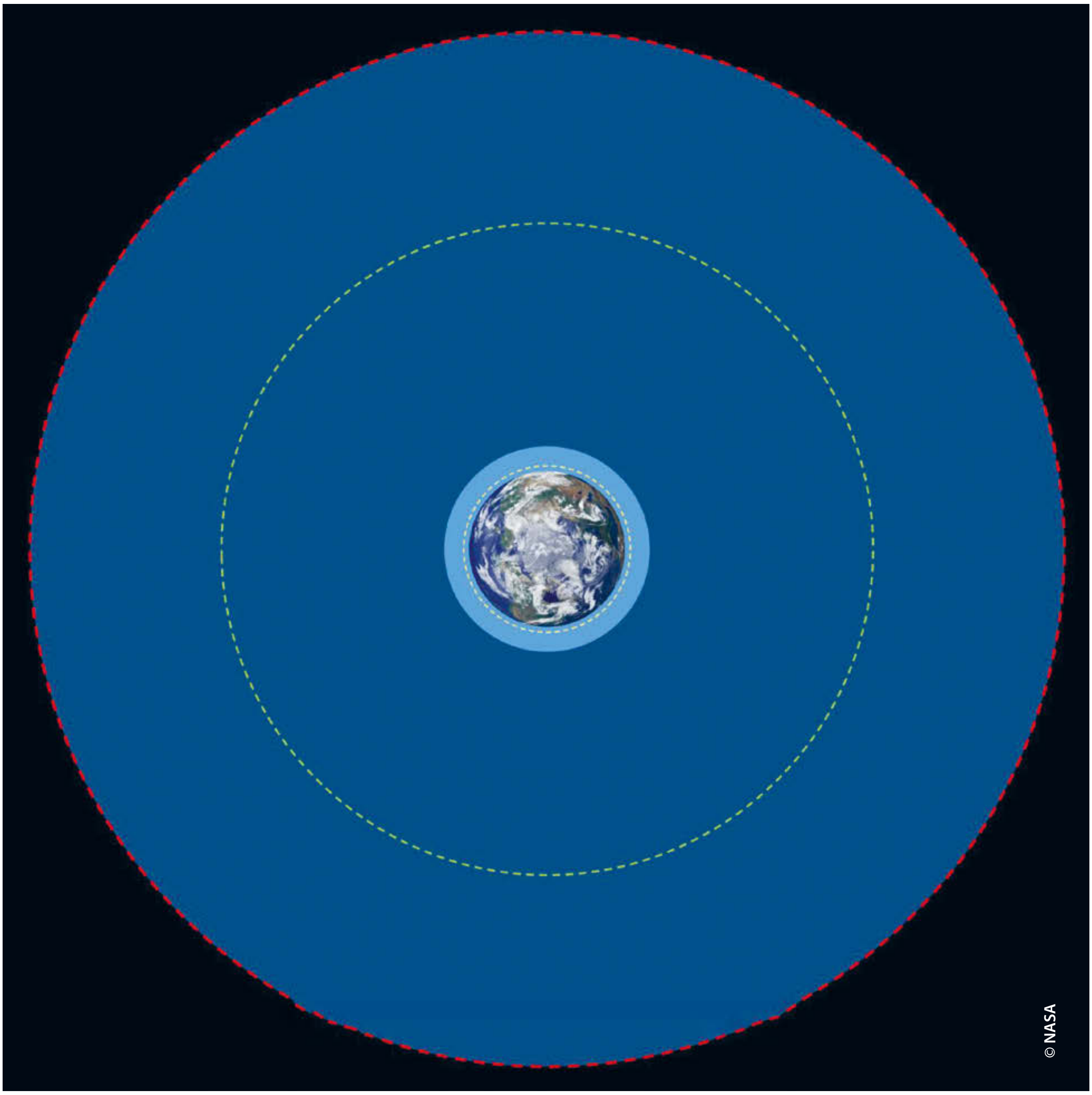

Figure 2: Main earth orbits to scale as seen from the north celestial pole. The area in light blue represents the low earth orbit region, the area in dark blue the medium earth orbit region, the red dashed line the geostationary orbit, the green dashed line the orbit of Global Positioning System (GPS) satellites, and the yellow dashed line the orbit of the International Space Station (ISS).

they travel in one orbit is longer. As a result, the time required for a satellite to complete an orbit (the orbital period) increases with altitude. In particular, there is a specific altitude (about 35,786 km from the surface of the Earth) that allows satellites to orbit at the same rate at which the Earth rotates; such satellites are called geosynchronous

- The geostationary orbit is a particular geosynchronous orbit with zero inclination. A geostationary satellite appears at a fixed point in the sky (on the celestial equator, i.e. the projection in the sky of the Equator) from the perspective of an observer on Earth

- The ground track of a satellite in equatorial orbits is on the Equator. In the case of GEO, it reduces to a single point on the Equator

- Satellites at higher altitudes can see more of the Earth's surface at one time than can satellites at lower altitudes. In particular, each geostationary satellite can roughly access one-third of the Earth. The Polar Regions are excluded from the coverage area of geostationary satellites due to their inclination from the perspective of the satellite.

- Due to their fixed position in the sky, geostationary satellites are conveniently used for communications and broadcasting. By contrast, they are less suitable to deliver high-resolution Earth imagery because of their higher distance from the Earth compared to LEO and MEO satellites.

- Since the Earth rotates underneath the satellite as it orbits, the ground track of a satellite in a polar orbit (an orbit that passes over both poles, thus having an inclination close to 90 degrees) can scan all the latitudes on Earth from a vantage position. For this reason, low altitude polar orbits are preferred for high-resolution Earth imagery. However, being closer to the Earth's surface makes these satellites more vulnerable to ground-based threats.

- A satellite constellation is a group of artificial satellites working in concert. Since satellites

© Map data: Google, NASA Earth Observatory.
Derivative work by Isana Kashiwai.

Ground track of the International Space Station (ISS) – example.

continuously move across the sky – except for geostationary satellites – the uninterrupted coverage of a particular location on Earth requires a satellite constellation.

- Manoeuvring a satellite, which means changing its attitude, speed or direction, can require a large expenditure of energy. The mass of propellant a satellite requires for manoeuvring increases exponentially with the amount of velocity change. The difficulty and cost of placing large amounts of propellant in space is thus a limit to satellite manoeuvring.

- Manoeuvres to change the satellite's orbital plane can require large changes in the satellite's velocity and can, therefore, require large amounts of propellant. By contrast, manoeuvres that alter the shape or altitude of the orbit but that do not change the orbital plane generally require much less propellant, especially if the satellite moves between low earth orbits.

- Electric propulsion systems (e.g. ion and hall thrusters) can generate substantially more velocity change per unit mass of fuel than conventional chemical propellants. However, they can currently provide only slow manoeuvring due to the low thrust they can deliver.

- Placing an object in orbit is much more demanding than simply lifting it to a high altitude. Although short- and medium-range ballistic missiles can reach the altitudes of satellites, they do not provide the needed speed for the satellite to remain in orbit. Even a long-range (10,000 km) intercontinental ballistic missiles (ICBM) cannot put its full payload into orbit without significant modifications.[1]

- The mass of the payload that a modern rocket can deliver into orbit is usually between 1 % and 5 % of its total mass at launch, depending on the orbit type. For instance, to place a satellite in GEO orbit, the farthest commonly used orbit, every ton of payload roughly requires 60 to 100 tons of propellant.[2]

- The location of the launch site and the intended orbit – both its height and inclination – impact the maximum mass a launch vehicle can place in orbit. In particular, since the rotational speed of the Earth's surface is maximum near the equator, launch sites close to the equator can benefit from that additional speed.

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1. There are several examples of 'converted' ICBMs used as space launch vehicles (SLV).
2. Estimation made on the basis of publicly available data for Ariane 5, Delta IV, Delta IV Heavy, Falcon 9, Falcon Heavy.

Notes

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Joint Air Power Competence Centre

von-Seydlitz-Kaserne
Römerstraße 140 | 47546 Kalkar (Germany) | www.japcc.org