# Presentation of the European Union Space Surveillance and Tracking (EU-SST) R&D Plan

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**ABSTRACT**

The EU SST programme evolved into a fully-fledged component of the European Union Space Programme adopted on April 28, 2021, after it has been set up in 2016 on the basis of the "Decision of the European Parliament and the Council Establishing a Space Surveillance and Tracking Support Framework" adopted on April 16, 2014. The EU SST contributes to the global burden sharing of ensuring the safe, sustainable, and guaranteed access to, and use of, space for all. Its primary objective is the provision of space-safety services, namely, to protect spacecraft from the risk of collision, to monitor uncontrolled re-entries, and to surveillance the in-orbit fragmentation of space objects, on the basis of proprietary and third-party measurements and orbit data. For that purpose, the design and the performance analysis of a global EU SST system architecture providing best value for money, on a medium- and long-term basis, has been established as one of the main activities of the EU SST.

To facilitate a sustained long-term evolution and enhancement of the EU SST, the EU SST Partnership put in place a Research and Development (R&D) plan consisting of of hardware and software activities. For the implementation of the EU SST R&D plan, the members of the Partnership not only coordinate research efforts within the EU SST programme and in coherence with national R&D programmes, but also actively involve industry, academia and start-ups in the development of these activities.

The EU SST R&D plan has the objective to increase the European strategic autonomy in the SSA domain, while fostering the competitiveness of the European commercial ecosystem. For this purpose, the EU SST has set up the European Union Industry and Start-ups Forum (EISF). This forum started on April 26, 2022. It provides a platform to foster the innovation and competitiveness of the SSA commercial sector, in order to achieve a higher level of strategic autonomy in Europe through a structured dialogue between the EU SST Partnership, the European Commission, industry, and start-ups.

The paper intends to provide an overview of the EU SST R&D plan. The first part of this plan will include improvements the cataloguing step of the EU SST system thanks to R&D activities on sensors, algorithms, and methods. For the next three years, the EU SST will contribute to and support innovations not only on sensors with well-established technologies (radars, lasers, on-ground optical sensors) but also space-based sensors.

Many elements of the Space Based Surveillance System (SBSS) technology are challenging such as the repartition between on-ground and on-board delegated computations, observation strategies, and compression algorithms. As this technology has the potential to improve detection capabilities considerably and, thus, the results of the cataloguing function, the EU SST addresses these questions on behalf of the European Union.

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In addition, further improvements on uncertainties considerations in analytical propagation, attitude and manoeuvres determination thanks to observed data or radio frequency emission characterization are planned in order to improve cataloguing and long-term predictions, which are key features needed for services provision.

As the space popultion is continuously evolving, the simulation system currently used to evaluate the long-term scalability of the EU SST regarding the space population by drawing a recommended network composition, will be improved thanks to digital twin concepts, details of which will be described in this paper.

Besides, as the EU SST intends to be a catalyser for the European commercial ecosystem, a platform hosting commercial services demanding a high security level for data protection and confidential use will be developed. Planned R&D activities on a secure network will be presented in this paper, such as assessing the benefits of Distributed Ledger Technologies in an operative context dealing with space operations.

Finally, this R&D, details of which will be described in the paper, aims to increase operational services such as Collision Avoidance (CA), Re-entry prediction (RE), and Fragmentation detection (FG) ensuring a high reactivity level of services and high-fidelity analysis provided by the EU SST.

# 1. INTRODUCTION

## 1.1 European Union Space Surveillance and Tracking (EU SST) framework

During the last decades, the number of objects in orbit has been steadily increasing, encouraging the provision of services related to achieve Space Surveillance and Tracking (SST) activities such as conjunction and re-entry analysis in one hand, but also fragmentation detections in the other hand. The decision [7] ("SST Decision" hereinafter) established the SST Support Framework 'to contribute to ensuring the long-term availability of the European and national space infrastructure, facilities and services which are essential for the safety and security of the economies, societies and citizens in Europe'.
The EU SST, created then, was using a sensor network (composed of on-ground optical sensors, tracking and surveillance radars and laser stations) to locate space objects (spacecraft or debris), in order to determine latest orbits first, predict future trajectories then, and finally, assess consequences and risks on the environment. In the end, EU SST was committed to provide to any European space operators three main services, namely, Collision Avoidance (CA), Re-entry prediction (RE), and Fragmentation detection (FG).

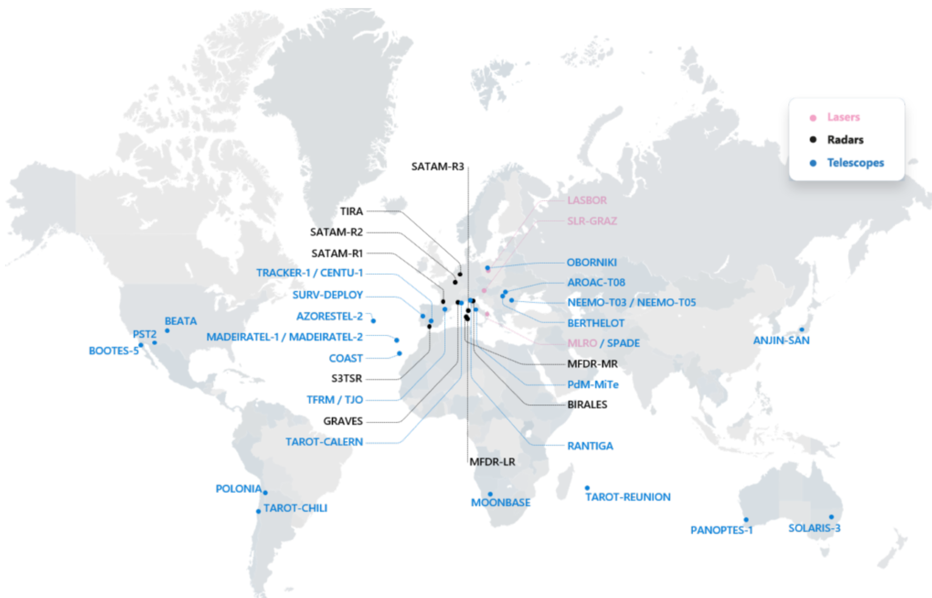


Fig. 1: EU SST operational network (July 2022)

On the November, 2022, EU SST turned to a partnership of 15 delegations[1] working together to improve process around SST thanks to an operative side on one hand, and a Research and Development (R&D) side on the other hand.

[1]Austria, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Latvia, the Netherlands, Poland, Portugal, Romania, Spain, and Sweden

## 1.2 Future needs for Space Surveillance

Since the beginning of the space conquest, which started officially in 1957 when Spoutnik-1 was the first human made object put in near Earth orbit, the space population has been growing until reaching more than 27000 currently referenced objects. Despite some of them come back continuously to Earth because of physics, there are more launches than decays, as described in figure 2 ([24]).

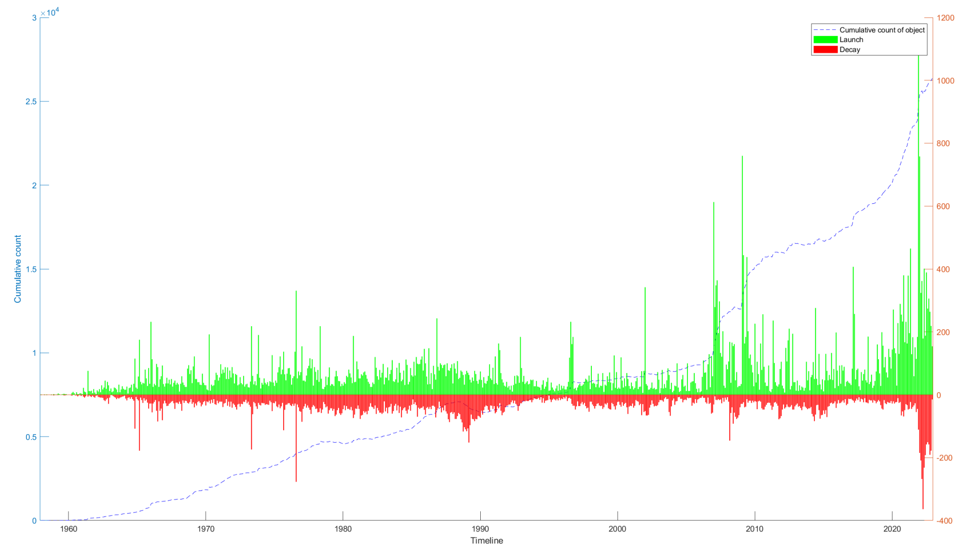


Fig. 2: Number of Launch and Decay per month and the cumulative count of object remained in orbit as function of time. In order to handle fragmentations, launch is more considered here as the first detection epoch than the rocket launch epoch.

Besides, each payload put in orbit, for many reasons, brings in the same time a few additional objects such as rocket body or little debris. Those extra bodies contribute to increase the number of objects orbiting the Earth. In addition, among the list of event leading to increase the space population, we can notice three main cases: collision, fragmentation and anti-satellite (ASAT) action. Among known collisions occurred in the past, we can notice Iridium-33 (LEO satellite) which collided Cosmos-2251 in 2009 and created more than 2000 catalogued debris [19]. Regarding ASATevents, the last referenced one targeted the Cosmos-1408 satellite on November 15, 2021, to create around 1500 debris larger than 10 cm [20]. While only debris larger than 10 cm are referenced, many more are typically created but remain undetected due to their smaller size. Then, all those events can be involved in sort of chain reaction leading to an uncontrolled situation.

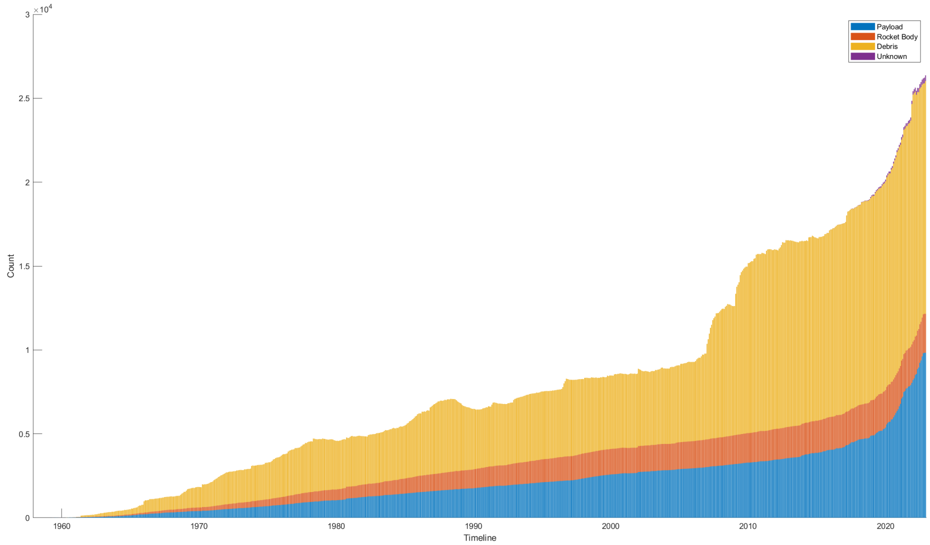


Fig. 3: Number of object orbiting around Earth per type: Payload, Rocket Body, Debris and unknown object.

As we can see on Fig. 3 ([24]), from decades, 35% of objects orbiting Earth are payloads, which means, the majority of them are unexpected or unwanted objects. That is why the space community needs means to detect all of those objects, and to analyse and prevent any conflictual situations as well.

Considering the LEO orbit for example, according to the IADC and reported in [18], we know the number of catastrophic collisions could highly increase (Fig. 4), thanks to long-term simulations. In additions to plenty of initiatives (such as Active Debris Removal (ADR) mission, space regulation, End of Life activities), providing an efficient collision avoidance service is crucial.

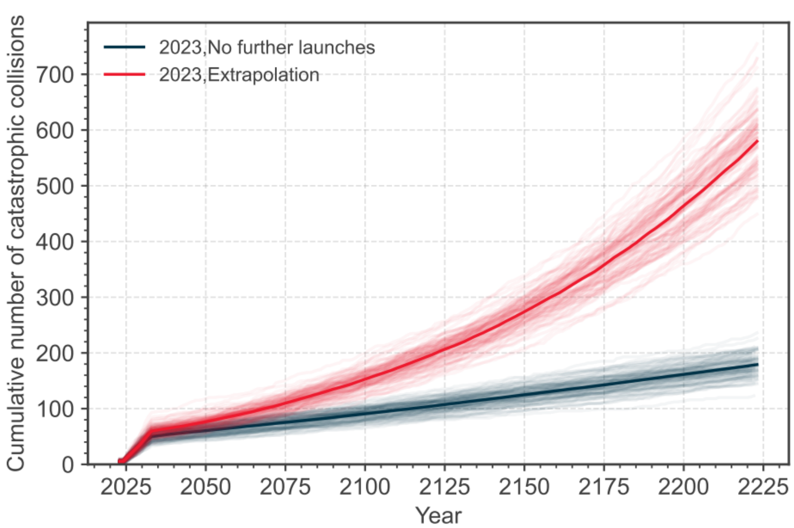


Fig. 4: Number of cumulative collisions in LEO in the simulated scenarios of long-term evolution of the environment [18].

## 2. PLANNED R&D ACTIVITIES

The overall R&D plan presented into this document is needs oriented, to provide services and, in the end, covering the needs related to the future space traffic management concept. This plan intends to improve overall part of EU SST to do so, by planning activities among the four main layers as described in the Fig. 5.

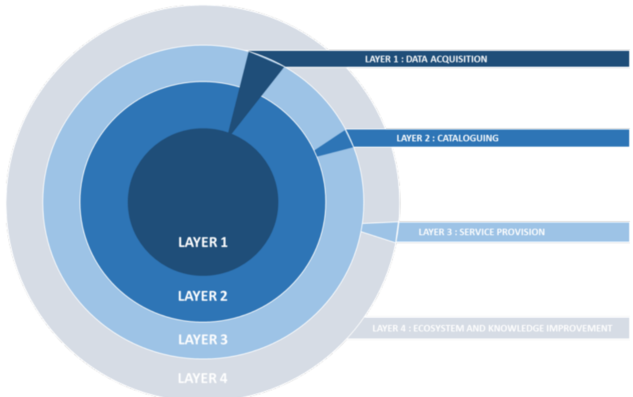


Fig. 5: EU SST R&D layers

- **Layer 1 - Data acquisition**: this is the primary layer, providing the EU SST with observations. Activities within this layer intend to improve the detectability and observability of overall objects orbiting the Earth.
- **Layer 2 - Cataloguing**: once the observations are made, one must build an extensive and up-to-date catalogue fueling the services. Activities within this layer intend to improve the current process to finally, increase the number of objects identified in the catalogue in one hand, but having a better assessment of uncertainties related to the current catalogue.
- **Layer 3 - Service provision**: activities within this layer intend to improve the process and scalability of the three main (core) services the EU SST is committed for.
- **Layer 4 - Ecosystem and knowledge improvement**: ensuring the safety of the space population means also being aware of the environement in the near-Earth space. Activities within this layer intend to improve the global space situational awareness of the EU SST and potentially provide new services. Besides, a large volume of data is exchanged between 15 different countries, securitizing and monitoring data is essential. Consequently, some activities are planned to improve the data governance process used to manage overall data shared internally to the EU SST.

## 2.1 Data acquisition

### 2.1.1 Patrimonial sensors improvement

As described in 1.1, the EU SST is based on a core dual network of sensors (civilian and military). Nowdays, this network is able to detect 90% of the objects bigger than 50 cm orbiting in LEO regime but only 20% of those over 7 cm, mostly through surveillance radars. In MEO regime, thanks to the contribution of the worldwide optical sensors, 50% to 70% of objects bigger than 35 cm are usually catalogued. Finally, in GEO regime, all objects above 35 cm of size are continuously observed and catalogued.

**Radar sensors upgrade** Despite these promising results, the EU SST ought to increase further its detection capabilities.

- **ES_S3TSR**: improvements will be made to be able to detect objects bigger than 12 cm (currently, around 25 cm). Besides, the deployment of two additional transmitters will lead to increase the field of regard, leading to observe more objects.
- **FR_GRAVES**: this surveillance radar will be to detect almost all object bigger than 1 m (2700 objects), 85% of the objects bigger than 50 cm (3900 objects), and 25% of objects bigger than 10 cm (4600 objects).
- **FR_GRAVES_NG**: a new enhanced radar system replacing the existing system, will be developed and deployed, aiming to detect almost all objects bigger than 50 cm (4400 objects) and 70% objects bigger than 10 cm (12500 objects) by 2030.[2]

In addition, as described in 1.1, some regions far for Europe are not covered. A new Portuguese surveillance radar will be deployed outside Europe able to detect objects bigger than 12 cm.

**Optical sensors upgrade**

- **CZ_SHOT**: thanks to a new CMOS camera, the number of observed objects overall the three main orbital regimes LEO, MEO and GEO will be significantly increased.
- **FR_TAROT***: composed of 3 telescopes (one in mainland France, the second in Chili and the third located in the French island ”La Réunion”), the complete system will be upgraded to perform real-time observation scheduling optimizations;
- **GR_KRYONERI**: funded by a national budget line, this sensor will be able to perform high quality observations of LEO, MEO and GEO satellites in a fully automated mode with minimal human interference;
- **GR_BAKER-NUNN**: funded by a national budget line, this sensor will be able to detect, 30% and 77% of objects bigger than 35cm, in GEO and MEO orbital regimes respectively;
- **PT_SURV-DEPLOY**: this already existing sensor will be reallocated to Oceania VLA, increasing then the detection capabilities of the EU SST into this area.

### 2.1.2 Innovative commercial sensors

As the EU SST is contributing to fostering and supporting the European industry, one of the planned activity to increase the overall performance of the network is to co-fund the development of innovative commercial solutions. The innovative aspect could be one of the following point (non exhaustive list):

- being deployed in poorly-covered VLA;
- being able to detect smaller objects;

[2] Simulations performed thanks to ESA Master population [8] and the EU SST simulation bench [6]

- producing accurate measurements;
- addressing current observation limitations (for example, enabling optical observations in daylight);
- decreasing the operative – and, in the end, the data – cost.

Finally, we target to improve the current cataloguing capabilities up to 50% and 70% of the objects bigger than 7 cm and 10 cm respectively, for objects orbiting in LEO, and all objects bigger than 35 cm for both MEO and GEO objects. Besides, as we plan to deploy sensors overall worldwide VLAs, we expect to get the capability to increase the sampling all along the orbit of objects, leading to increase the catalogue accuracy, and in the end, the quality of the three services products.

#### 2.1.3 Space Based Surveillance System (SBSS)

This concept might be very beneficial to fill the gaps of ground-based architectures. In fact, the geometry of observations (smaller ranges, higher revisit, etc.) as well as various environment aspects (no atmosphere crossed by the signal, no weather impacts, etc.) might lead to higher detection performances, thus improving the sensor layer and consequently, the data processing and service provision layer performances.
During the 3 last years, internal studies have been conducted to assess the performance of an enhanced network composed of both ground- and space-based sensors to maintain a surveillance activity of the near-Earth space. On the space-based side, two constellations were considered:

- **SBSS_A** consisting of two satellites orbiting the Earth in a sun-synchronous orbit at an altitude close to 600 km. The satellites were both crossing the ascending node at 6 h (Mean Local Time) and separated by a 180°;
- **SBSS_B** consisting of six satellites orbiting the Earth also in a sun-synchronous orbit at an altitude close to 600 km but with different orbital plans, with 3 satellites each. Since the first plan crossed the ascending node at 6 h (Mean Local Time) , the second crossed the ascending node at 18 h (Mean Local Time). in the two planes, satellites are separated by 120°.

Despite the details of this study are classified, as mentioned in the table 1, complementing a ground-based network with a SBSS mission could increase significantly the detection capabilities of the EU SST in LEO orbital regime.

Table 1: Coverage simulation results – percentages of observed objects in LEO orbital regime

| Network | Percentage of observed objects with respect to simulated | | | | | |
|---|---|---|---|---|---|---|
| | $\geq$ 3 cm | $\geq$ 5 cm | $\geq$ 7 cm | $\geq$ 10 cm | $\geq$ 50 cm | $\geq$ 1 m |
| GROUND | 38 | 68 | 80 | 88 | 98 | 99 |
| GROUND + SBSS_A | 51 | 82 | 93 | 98 | 100 | 100 |
| GROUND + SBSS_B | 59 | 88 | 96 | 99 | 100 | 100 |

Although few missions are dedicated to SBSS (mainly led by the US), to this day, no operational mission provides a global capacity to observe different orbital regime allowing large-scale cataloguing. Some missions are dedicated to the observation of the "near environment" of the hosting satellite, but none focusses on a global mission for cataloguing objects. Nowdays, all SBSS missions use passive optical sensors in the visible spectrum. In addition, in the opposite of ground-based solutions, some technical challenges need to be solved to define and launch an appropriate SBSS mission involved in global space surveillance such as computing performances. Due to the number of objects in space and, thus, potentially in the field of view of the on-board sensor, identifying and cataloguing objects can be very time- and resource-consuming. Some compromises should be met to optimize performances by first, selecting best hardware, but also, sharing the burden between between on-board and on-ground computation.

**On-board autonomy for space surveillance and tracking** For the first, we plan to investigate, for every on-board key topic (such as image processing, on-board delegates computation and data compression), the compatibility between the algorithms and the on-board processing capabilities. Multiple kinds of on-board data processing hardware could be considered, among typical space grade and COTS data processing components. In addition, on-board data storage capacity and capability should be studied as well. Within this part, hardware development are expected over the three next years.

**SBSS optical payload design** For the second, based on optical solutions, we will analyse as well how SBSS payloads can be beneficial to self-monitor constellations (i.e for the future connectivity constellation) leading to a better knowledge on the nearby environment of the constellation with the advantages of the lower latency, lower timeliness, no dependency of the observation time and lower sizes of objects to detect, among others.

**Futurist mission design** For the third, we plan to assess the feasibility of non-passive optical sensors and we will investigate the potential of lower TRL technologies such as the use of space based infra-red sensors, lasers, radio-frequency sensors, e.g. The part will assess for all those techniques (plus potential new ones proposed by the subcontract) what kind of performance can be expected at instrument level, spacecraft or mission level. The benefit will be evaluated to demonstrate the potential of such new methods. The main impact on the spacecraft (power consumption, on board storage or CPU, AOC . . . ) or system (TM/TC link, ground control centers, . . . ) design will be assessed. In addition, the operational KPIs (such as contribution to catalogue, timeliness, accuracy, and detection capabilities) will be the starting requirements to shape the futurist SBSS missions.

### 2.2 Cataloguing

#### 2.2.1 Lasers contribution

As described in 1.2, 3 lasers stations are involved in the EU SST data provision layer. Despite promising results on cooperative targets (RMS $\leq 20\,\mathrm{m}$), exploiting data coming from this technology is apparently limited by the nature of the target. In fact, even if the accuracy of measurements is compliant with EU SST thresholds for space surveillance, the accuracy is falling down significantly for non-cooperative targets, such as debris or spacecrafts without retroreflector on-board (non exhaustive list). With less than 1.2% of overall objects orbiting the Earth ([24] and [9]), the number of good targets for this technology is extremely limited. Besides, considering cooperative objects, accurate measurements are solely possible in full-night, reinforcing the limit of that technology to contribute to space surveillance activities. As the result, those sensors are not considered for the building-up of an exhaustive and accurate catalogue. However, because of the encouraging results obtained on cooperative targets, we plan to improve internal process to tackle the issue regarding non-cooperative objects.

**Observation campaigns** Based on observations campaigns, this activity intends first to improve algorithms to deal with non-cooperative objects, potentially including multi-static observations. The main aim of that part is to improve the Orbit Determination (OD) chain for a catalogue maintenance scenario including laser measurements.

**Daylight tracking** The second part of this activity will be dedicated to tackle the challenge of daylight tracking, increasing the operative time of these sensors, increasing consequently the contribution to catalogue and service provision.

**Automated scheduler** The last part of that activity will be to develop an operational software to pilot the stations to schedule automatically observations using an optimized strategy.

#### 2.2.2 Cataloguing algorithms

Once measurements gathered by the network of sensors are available, they are post-processed to build-up a catalogue containing the orbit estimate for catalogued objects. This catalogue is then the entry point to provide services. Because of this, it must be accurate, complete, and up-to-date. The catalogue processing chain consists of a high-performance software library, used for orbit association, determination and propagation.

**Responsiveness to physical model** We plan to determine the impacts of different orbit propagation and determination algorithms as well as perturbation models on the catalogue's performance and accuracy. In addition, this activity will evaluate the sensitivity of the chain regarding the system configuration and the volume or nature of the data ingested to estimate orbital parameters. Depending on the case (such as orbital regime, nature of measurements,...), recommendations will be established, ensuring the highest gain over constraints ratio.

**Responsiveness to space weather** Speaking about perturbation model, for LEO objects, the main dissipative force stems from the effect of the atmosphere on the spacecraft. However, this effect is highly driven by space weather. A second activity will focus on investigating in more detail the impacts of spae weather events on the cataloguing capabilities. In detail, the recovery of catalogue accuracy and information after major space weather events shall be evaluated. Recommendations to enhance the operational system's capabilities, and operational routine to be followed following adverse events is expected.

**Bi-frequency radar tracking approach** Thanks to the EU SST sensor network, radars are contributing to the catalogue with accurate measurements (RMS $\leq 50\,\mathrm{m}$ and RMS $\leq 2\,\mathrm{m\,s^{-1}}$ for ranging and Doppler systems, respectively). Recently, some external studies showed the interest to use during a ground-pass, measurements using two different

frequencies, to increase the accuracy of measurements. The performance gain demonstrated in is an order of magnitude thanks to that procedure.
Consequently, the processing and correction of the dual frequency measurements will be implemented and tested. In addition, the benefit and longevity of the highly accurate measurements will be evaluated, also respecting cost-for-value aspects with focus on the direct impact on the services. A simulation test bench will be implemented to generate the data used to test this approach.

### 2.2.3 Long-term processing

On the operational side, numerical propagators are typically used to predict the trajectory of any objects orbiting the Earth. Based on numerical integration schema (such as Runge-Kutta, Dormand-Prince...) these propagators are preferred because all forces involved (conservative and dissipative) are computed with reasonable accuracy (depending on the fidelity of the both spacecraft and environment subjacent models). Despite they can be accurate, due to their inherent complexity, running these propagators is time-consuming [14]. In addition, the error comes first from the integration schema itself, that can be managed by fine-tuning the algorithm parameters (such as convergence value, integration step...). Secondly, the predicted trajectory will diverge from the real one because of the dissipative force model involved. For instance, in LEO, one of the main dissipative force is the drag, that the effect depends on the shape and attitude of the object, and the space weather as well. Despite the trend of space weather can be predicted, non-negligible variations occurs systematically, and especially in long-term propagation (Fig. 6 [3]), leading to theoretical trajectories highly diverging from the real ones within a few weeks.

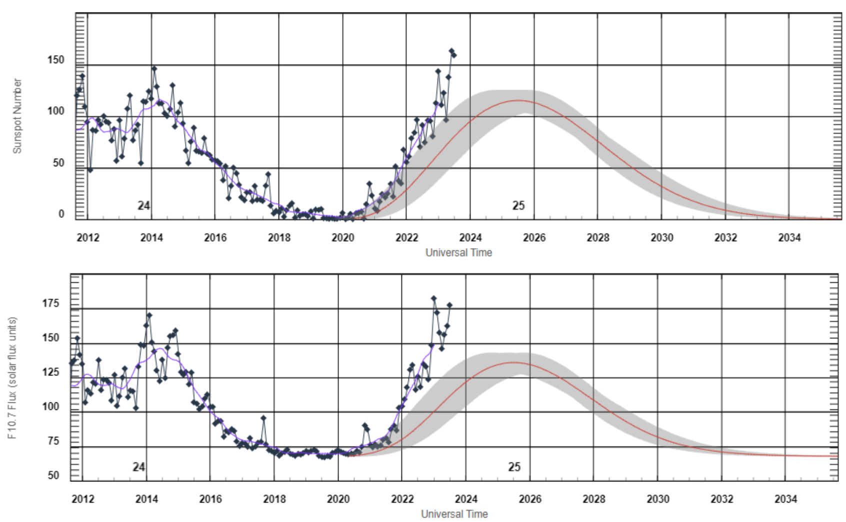


Fig. 6: On the top, the evolution of predicted sun spot number (in red) with uncertainties (in grey) as function of time, and the observed one (in black). On the bottom, the 10.7 cm predicted flux (in red), with uncertainties (in grey) and the observed one (in black) [3].

Alternatively, analytical models are of interest to perform fast computation as they are based on analytical equations and mean effects. However, nowdays, these models are not propagating covariances. The main aim of this activity will be to design a new propagation model enabling the uncertainties propagation in one and, and trying to increase the accuracy of predictions in the other end. Such a model would be beneficial to existing services (CA, FG), but also potential new ones. The use of artificial intelligence can be considered but it is not a solution to be imposed *a priori* .

### 2.3 Service provision

#### 2.3.1 Collision Avoidance service improvement

As seen in Section 1.2, ensuring that algorithms and methods backing up CA are scalable to the evolution of the space population is essential. For CA assessment purposes, it means being able to assess the collision risk for all catalogued objects in a short time frame (no more than 24 hour). This problem is driven by two main factors, the involved optimization method in one hand (reducing the number of possible combinations), and the collision risk computation method in the other hand.

**Optimization process** For the first one, the internal library currently used is based on four filters (*radius*, *inter-orbit distance*, *time* and *modified time* filters). However, previous works gave promising results by reducing the number of interaction thanks to the nature of the orbit itself through a *semi-major axis based* filter (based on Smart Sieve filter[2]). As shown in Fig. 7, the object interaction is located in the vicinity of the diagonal, allowing in the same time multi-node computation and, in the end, multi-threading.

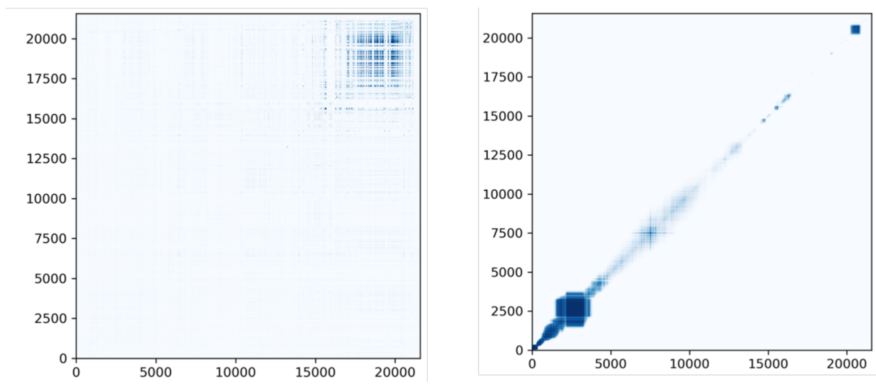


Fig. 7: $N$ vs $N$ problem without sorting (on the left) and using a semi-major axis based Smart Sieve sorting approach (on the right).

Besides, this library is using the classical *Alfano-Negron Close Approach Software* approach (ANCAS) [22] to compute extrema of the distance functions using the first and seconds derivatives and in the end, computing the Time to Closest Approach (TCA) and Distance to Closest Approach (DCA). Because this method is numerical, it is highly time-consuming. Over the past three years, two major improvements have been studied and made to decrease the computational time. The first one was to deal with binary ephemeris instead of "text plain" files. Decreasing the overhead due to the nature of the data, this change led to make the reading phase 7 times faster than before. The second major improvement was about the distance computation process used. Since the *ANCAS* is numerical as said previously, the *CATCH* method [5] implemented during these studies is based on Chebychev Proxy Polynomial method to fit derivative of distance function. The roots are extracted then using a linear algebra methods, i.e calculating the companion matrix's eigenvalues. As this method is purely analytical, in the end, it should be more efficient than the current one. Based on a set of 21178 objects in the catalogue (TLEs) between June 13, 2021 and June 18, 2021, more than 83400 conjunctions have been identified with an average error of 1 cm, in less than 1.5 h against around 11 h using the *ANCAS* approach, which is a gain of a factor 8. The planned activities on this topic concerns the demonstration of the previous work added-value on an operational context, meaning, the use of SP and O/O orbits to confirm the previous results in terms of computation time and accuracy. Recommendations will be provided to fine-tune algorithms in order to be used operationally to provideCA service.

**Risk estimation method** As described above, being scalable to both space population evolution and space traffic management, means being able to anticipate accurately all possible situations. Most of the risks are "fast-encounters" enabling assumptions on the encounter geometry leading in the end, to simplify equations of the probability of collision. For instance, in that case, the fundamental hypothesis is the relative motion is uniform and rectilinear while the encounter duration is short enough. However, these assumptions may not be met for other situations such as low relative velocity cases.

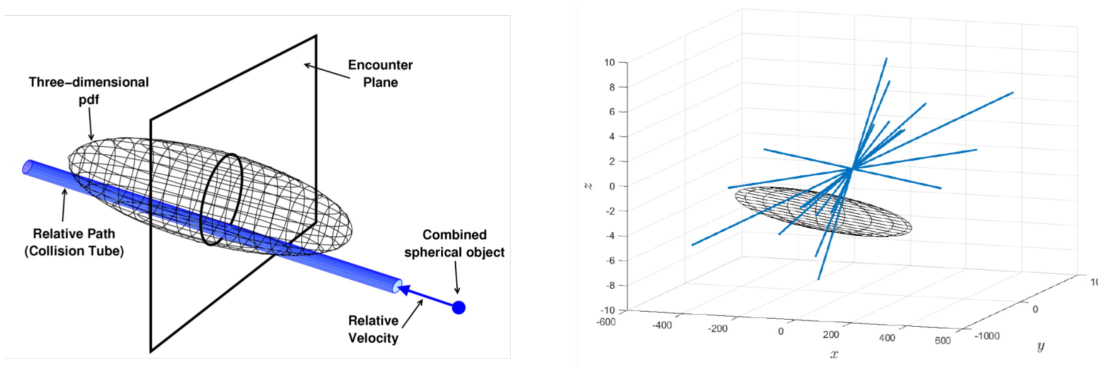


Fig. 8: Short-term encounter geometry without velocity uncertainty (left) and considering velocity uncertainties (right).

Hopefully, thanks to collective experience in the EU SST, plenty of historical CDMs are available. The first step of the study will be to construct a database of interesting, so called non-standard cases. New methods will be drafted and implemented to design a new probability of collision algorithm.

**Space mission Lifecycle involvement** Providing collision avoidance service means also being able to ensure the safety of the object all along the mission. Obviously, it means while the spacecraft is orbiting the Earth (LEOP, active and EOL activities), but also, at launch. Being efficient when the object is orbiting the Earth leads to being able to compute quickly maneuver recommendations. Since most spacecrafts use chemical thrust leading to short maneuvers slots with low impact on the mission, the number of low-thrust based spacecrafts is continuously increasing. Due to the nature of the thrust, slots are quite long (more than 1 orbit) leading to make the mission standing by for a long time (best scenario) in one hand, and increasing the probability to destabilize the environment by creating cascading risks (worst scenario). Despite previous works on that part which led to the description of the algorithm to use (such as *Semi-Definite Random* or *Branch & Bound* algorithms[16]) and providing the automated collision risk management decision tree, this work is still at an early stage. The planned activities on this topic concern the validation of the algorithms for automation and optimization of the maneuver estimation based on various constraints. In addition, other constraints such as window station keeping, maneuvers positioning (attitude rallying, mission planning, maximum increment based on thrust duration or thrust magnitude, etc) will be addressed.
As it is planned to cover all the mission stages, the last operational phase is during the launch, prior to the mission itself.
The planned activities are the estimations of the needed threshold considering the type of secondary objects (manned objects, operational satellites, debris, ...) and the chosen criteria that can be secondary dependent. The target orbits of the primary objects are also an important parameter because it defines the Mission Elapsed Time (MET) conditioning the time horizon for the surveillance and amplitude of uncertainties. A compromise between safety and operational constraints must be met. To do so, the CNES tool LEOPARD dedicated to the risk assessment during this stage will be used and improved to provide, in addition, recommendations about risk criteria thresholds and, finally, mission oriented guidelines.

### 2.3.2 Fragmentation service improvement

**Realistic fragmentation model** As shown in the paragraph 1.2, according to the current trend, the number of objects orbiting the Earth is increasing. Despite efforts involved by all worldwide countries to avoid a situation akin to the Kessler syndrome [11][10], there is a non-negligible risk that the number of fragmentation will increase consequently. Models and process currently used in the EU SST will be improved during the next 3 years to tackle this situation, preventing as best as we can this critical situation from happening. Regarding the model, we plan to merge current analytical models with real data from already existing fragments. This hybrid model is meant to improve continuously the realism of analyses provided by the EU SST. This will be done by improving two main parts of this service:

- the software used internally to provide Early Impact Risk Analysis.
- evaluating the impact of a fragmentation event due to a Large vs Large collision occurs.

### 2.3.3 Reentry service improvement

As mentioned in 2.3.2, almost all countries involved in the space operations are strongly working on solutions to limit the number of uncontrolled (debris and passivate satellites) objects orbiting the Earth, meaning limit the probability to create debris, but also ensuring controlled reentries. Consequently, the number of re-entry events will increase continuously. Because of the potential consequences of a such event on the air traffic, but also if there is a risk a debris hits the surface of the Earth, the EU SST aims to predict accurately the reentry trajectory. Mainly, three factors drive the accuracy of the trajectory of a reentry objects:

- The effect of the atmosphere (main dissipative force for these objects) on the dynamics;
- The physical model of the object;
- The accuracy for the last estimated orbital parameters.

Since the third point is limited by the data used to perform the orbit determination and already covered by other activities (see 2.2, 2.1), the first two points can be improved.
Regarding the effect of the atmosphere effect throughoutl a re-entry, the ballistic coefficient of the object can widely vary, depending mostly on the solar activity variations and the real orientation of the object (shape and attitude). Since the predicted solar activity accuracy can't be improved by the EU SST, in the most cases, the shape and the attitude are considered to be unknown. Hopefully, we are able to assess the error we make on the ballistic coefficient by monitoring the variations all along the orbit determinations, but also thanks to the covariance produced by the orbit determination process. Consequently, to improve the consistency and realism of the time window provided during these predictions, a scaled ballistic coefficient exploiting the orbital covariance will be used. Regarding the physical model of the object, as mentioned, the shape is unknown in most cases. However, during the re-entry, we expect the object to blow-up with a pattern shaped by some constraints. A Monte Carlo break-up simulation will be implemented and used to evaluate the fragments spread and, in the end, the width of the footprint corridor.

### 2.4 Ecosystem and knowledge improvement

#### 2.4.1 Space situational awareness

**Space population evolution and potential hazardous objects** The space environment on which the EU SST system performs its mission is in constant evolution. In order to provide relevant services, we need to be perfectly aware of the trend for the future space population evolution. Nowdays, for space debris purposes, the ESA Master catalogue [8] is commonly used. As a point of reference, we plan to build-up an internal catalogue to:

- Evaluate future orbital environment scenarios;
- Derive orbital populations of any given minimum size to be considered by the architecture simulation and system design task;
- Further develop space environmental indexes allowing analysing the impact of space missions on the environment.

The outputs of this activity will be used to identify the needs in terms of strategies, resources, and means, shaping the future of the EU SST. We plan to acquiring knowledge about the orbital environment while reaching a common understanding of the mechanisms behind the medium- and long-term evolution of the orbital environment and their effects. In addition, this task will allow us to reach a common understanding of the future space environment (e.g. impact of small satellites and large constellations in the medium-term orbital evolution). Besides, we plan to develop novel space environmental indexes, allowing the evaluation of the impact of a given mission (composed by any number of satellites, from single satellite to large constellation) on the environment. The space environmental indexes are a mechanism discussed at international level that will support future mitigation and remediation services by quantifying the potential of any mission to degrade the orbital environment. A way to quantify the environmental capacity of space, simply stated "how much activity can we afford before triggering catastrophic consequences such as the Kessler syndrome ([11], [10])", will also be investigated, using for example a threshold based approach based on the environmental indexes.

**Environmental index** Environmental indexes (see [13], [21]) represent an effective and efficient way to evaluate the impact of a given mission on the environment. Such evaluation represents an interesting and valuable tool to have additional insights that can be used in the frame of existing services as well as in the framework of the development of future services, and will have a key role in the development of STM systems. These indexes are powerful tool to identity the most concerning objects in all orbital regimes contributing to the monitoring of the long-term sustainability of the orbital environment. The development of indexes is an activity that has been tackled by several actors in the past and reported during the IADC forum. During the three last years, EU SST progressed on the development and improvement of these indexes focusing mainly on the Fragmentation Environmental Index (FEI) and identifying the 50 most concerning objects in LEO. In order to carry on the work achieved, this task intends to develop further indexes based on two different aspects:

- Subjective weights of mission duration, collision assessment, SST services used, post mission disposal activities ans size/mass of the satellite;
- Objective analysis thanks to Monte Carlo simulations to compute the overall accumlated collision risk for the mission in one hand, and the overall induced risk from the mission in the other hand.

In addition to the long term propagation improvement already planned (see 2.2.3), statistical or stochastic approach will be assessed such as the Acciarini and Vasile network model [1], or density propagation methods ([17], [12],...). In the end, we plan to foster the international cooperation and study synergies with other indexes.

**Manoeuvre detection from data fusion** Among all active satellites already orbiting the Earth and those scheduled to be launched, the majority of them are able to perform maneuver for station keeping, collision avoidance or the mission itself. Since plenty of operators have already subscribed to EU SST services, enabling consequently the free-trade of information related to maneuvers internally, some did not, creating a gray zone where information are missing. However, the detection and magnitude of the maneuver is important in the nominal CA estimations, and critical in phases like LEOP and EOR where the maneuvers can have a big influence obviously on the mission itself, but also on the space population. In order to shape the future space traffic management, a better knowledge of the situation in space is needed, meaning for instance being able to detect manoeuvres even for non-cooperative satellites. Thanks to the data gathered by both patrimonial and commercial providers on board, we plan to develop methods and algorithms to be able to detect maneuvers based on measurements (radar, optical, laser, passive-ranging). As this problem is also an identification problem bounded by logical spatial criteria (such as semi-major axis discontinuity, inclination discontinuity...) and patterns (such as periodic manoeuvres for station keeping...), artificial intelligence approach involving potentially stochastic methods will be assessed alternatively to statistical methods.

**Attitude mode detection from data fusion** During the lifecycle of a space mission, for many reasons, some trouble occurs, e.g., loosing the TM/TC link between on-board equipment and the ground segment, or loosing the control of the spacecraft itself. In such cases, being able to estimate the behavior of the spacecraft is essential, the attitude mode among other things to recover if possible, the satellite. Besides, nowdays, in order to limit the number of debris orbiting the Earth, plenty of On-Orbit Servicing (OOS) and ADR projects are planned to be conducted. For most of these projects, estimating the attitude is mandatory to dock to the target and provide the service. Thanks to the data gathered by both patrimonial and commercial providers on board, we plan to carry on internal studies achieved during these 3 last years, to be able to estimate the attitude mode of any targets using light or RCS curves thanks to different methods such as Lomb-Scargle periodogram ([15] [23]), or multi-model Least-Square Method (LSM) filter.

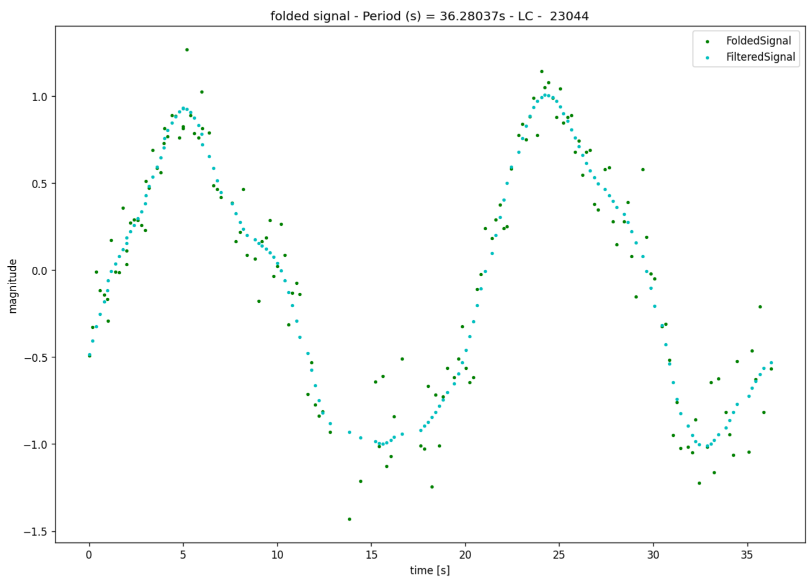


Fig. 9: Detrended light curve of COSMOS 2277 satellite in tumbling at 36.28 s and epoch folding showing mean folded data obtained.

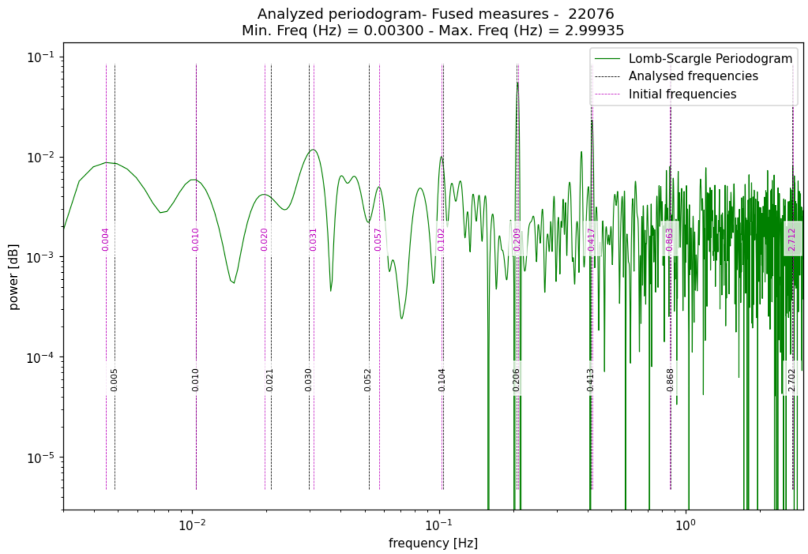


Fig. 10: Exemple of selected candidates (initial frequencies in plot) and optimized candidates (analysed frequencies in plot) in a periodogram of Topex (in tumbling at 10 s, reference) obtained with a classic light curve.

In addition, artificial intelligence will be considered to match shape models, attitude laws and identify signal patterns in light and RCS curves to determine the roto-translational state of space objects. Alternatively, adaptative optics is a well-known technology in astronomy improving the performance of optical sensors by correcting wave-front distortions induced by the atmosphere. This approach will be considered too.

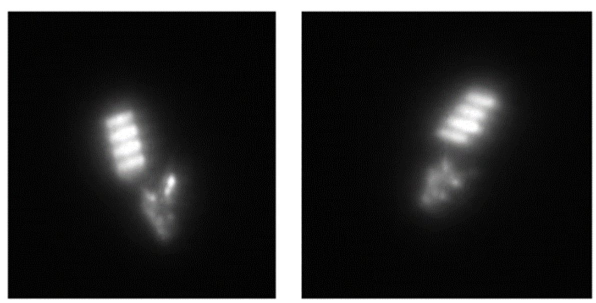

Fig. 11: METOP-B and METOP-C images where it can be clearly identify the geometry of the satellite and its main appendages.

**Interference prediction** As the number of satellites orbiting the Earth, the number of ground stations is continuously increasing as well as their concentration at some specific locations (such as polar regions). Besides, some RF bands are more and more congested (X-band for example) leading to increase the interference events. In order to anticipate this situation and to be prepared to propose some mitigations solutions, some preparatory studies are needed mainly related to the knowledge of the actual emission frequencies used by third party satellites (by opposition to the ones declared at ITU). Because of the consequences on space mission, this is of the main topic related to the next space traffic management concept.
The first part of the activity will consist in building up a real data based catalogue thanks to the development of algorithm dedicated to extracting third party emissions from ground station antenna logs. The expected outcomes of this algorithm would be the exact times of the emission, level and RF channel. Then, the development of an algorithm to predict the future RF emissions based on observations of some past emissions will be achieved. This prediction software will be used in the end to prevent further interference.

#### 2.4.2 Scalability assessment

**Simulation bench and digital twin concept** In the current frame of work of the EU SST, the components of the overall system are assessed either through operational performance tools on a regular basis (e.g. calibration campaigns), or through architecture studies simulating the system's projected performance point at a specific date, often in the future (e.g. analysis of the operational network at the outset of the Partnership). These tools operate, for the most part, independently from one another; in particular, the architecture studies typically consider a synthetic population of orbital objectives, from which synthetic observations are produced following sensors' statistical models replicating the real assets, then fed to OD algorithms to produce a synthetic catalogue.
The objective of this activity is to tap into the resources of the simulation test bench to design numerical twins of various components of the real system, able to process real input data (e.g,. measurements) and replicate as faithfully as possible the tested component (e.g., a sensor) under more realistic operating conditions. This lends itself to the close study of a genuine problem drawn from real events built from projected events and trends, complementing the current role of architecture studies addressing simulated problems.

#### 2.4.3 Infrastructure

**Data governance process** In 2022, more than 200 million measurements were shared internally to the EU SST thanks to more than 30 sensors, through the database. Compared to the previous year, the amount of shared data has increased twofold. Besides, as mentioned within the European Union Industry and Start-ups Forum (EISF), we plan to increase data coming from commercial providers from 5% to 50%, acting as anchor customer for the industry. Because there is plenty of commercial providers and taking into account the expected volume of data to deal with, the current data governance method shall be upgraded. It requires us to define the best way to manage transactions that can be internally to the EU SST in one hand, but also between the EU SST, the operators and the industry in the other hands to provide their commercial services.
Inspired by financial markets, we plan to set up such appropriate exchange media and communication channels for the task at hand through a secure environment backed by the DLT technologies (e.g. block chain). We obtained already promising results especially for block chain technology (hybrid on-chain/off-chain implementation), thanks to a Proof of Concept (PoC) emulating a marketplace for CCSDS-TDM [4] files. Nevertheless, we want to test other DLT solutions.
The first part of this activity will be to assess the best way among currentl DLT solutions, to reach our target which is implementing a viable, reactive and efficient way to monitor and manage data transaction in the EU SST. Then we plan to identify the best solution to enhance the current PoC to manage the data sharing protocol of EU SST.

**Secured network** Nowdays, overall data gathered by the EU SST network of sensors is freely shared between the 15 member states. However, among all the spacecrafts orbiting the Earth, some of them are military, meaning, overall data related to those objects is classified. For obvious security reasons, rules and procedures must be identified, compromising between the catalogue and service provisions on one hand, but abiding by the "right to know" principle on the other hand. Besides, once the strategy to deal with classified information is established, the infrastructure (meaning communication protocols, encryption method, data transfer and storage system) will be adapted, accordingly to the strategy once defined.
Since the rules are established internally by the Security Committee (SEC) hosting security experts and delegates from Ministry of Defense of the 15 member states, we plan to conduct R&D activities to implement the security strategy upon its design. Among the multiple challenge to address here, the most important will be:

- Maintain the security level of informations from end to end;
- Develop appropriate mechanisms to deal with the "right to know" principle, especially once measurements related to classified objects are gathered thanks to surveillance sensors;

## 3. CONCLUSION

Since its creation, the European Union Space Surveillance and Tracking (EU SST) has built a reputation as the main civilian stakeholder to achieve space surveillance and tracking first, but also to deliver on three key services : collision avoidance, reentry prediction, and fragmentation detection.
The catalogue, which is the entry point for those services is built thanks to a cross-technology based network of sensors deployed around the world. Nowdays, the EU SST is able to detect 90% of the objects bigger than 50 cm in orbiting in LEO regime but only 20% of objects over 7 cm, mostly through the surveillance radars involved. In MEO regime, thanks to the contribution of the worldwide optical sensors, 50% to 70% of objects bigger than 35 cm are usually catalogued. Finally, in GEO regime, all objects above 35 cm are continuously observed and catalogued.
Nowdays, the catalogue is currently maintaining 35% overall known objects (active or passivate satellites, debris, rocket-body...).

First, to civilian sensors upgrades, commercial providers on board and sponsoring new innovative commercial sensors (such as SBSS solutions), we aim to improve by 2026 the current cataloguing capabilities up to 50% and 70% of the objects bigger than 7 cm and 10 cm, respectively, for objects orbiting in LEO, and all objects bigger than 35 cm for both MEO and GEO objects.
We plan also to deploy more sensors in remote area (such as Oceania, or southern Africa) to increase the quality of the catalogue by increasing the capability to observe at different point on the orbit, all-along the sampling of the trajectory of objects orbiting the Earth.

Additionally, plenty of activities are planned to increase the accuracy of the catalogue on one hand, and helping to making the three main services provided by EU SST more exhaustive such as tackling limitations regarding laser stations, improving the accuracy of estimation and propagation models, or improving computation methods for the probability of collision.

Besides, to prepare the space traffic management concept and supporting new activities such as OOS, End Of Life (EOL) or ADR, some planned R&D activities aim to develop methods based on measurements gathered by the network of sensors, such as estimating the attitude using light or RCS curves. Artificial intelligence may be involved in some way.

Many works are also planned to enhance the reaslism of models and analyses, through the improvement of current break-up model or space population evolution predictions with real and up-to-date data. Besides, realism will be put in the foreground on the long-term as well as strategic analyses, by introducing the digital twin concept in the simulation bench[6], assessing the scalability of the EU SST.
Then, to deal with classified data and monitoring transactions, additional work is planned for building-up a secured, responsive and scalable infrastructure based on DLT solutions.

Finally, this ambitious R&D plan intends to tackle plenty of challenges by fostering civilian agencies involved in one hand, but also the European industry to continuously heighten completeness, accuracy, quality and responsiveness of the European space program towards achieving a safe and secure near-Earth space for the benefit of all.

## 4. REFERENCES


[1] G. Acciarini and M. Vasile. A network-based evolutionary model of the space environment. volume 8. European Space Agency (ESA), ESA Space Debris Office, 2021. 8th European Conference on Space Debris.

[2] J. R. Alarcón Rodríguez, F. Martínez Fadrique, and H. Klinkrad. Collision Risk Assessment with a 'Smart Sieve' Method. In B. Battrick and C. Preyssi, editors, *Joint ESA-NASA Space-Flight Safety Conference*, volume 486 of *ESA Special Publication*, page 159, August 2002.

[3] Space Weather Prediction Center. Solar cycle progression. `https://www.swpc.noaa.gov/products/solar-cycle-progression`, 2023.

[4] The Consultative Committee for Space Data Systems (CCSDS). *Tracking Data Message*, 2020. Recommendation for Space Data Systems Standards (Blue Book) - CCSDS 503.0-B-2.

[5] E. Denenberg. Satellite closest approach calculation through chebyshev proxy polynomials. *Acta Astronautica*, 2020.

[6] J. C. Dolado, V. Morand, and C. Yanez. BAS3E: A framework to Conceive, Design, and Validate Present and Future SST Architectures. In *First International Orbital Debris Conference*, volume 2109 of *LPI Contributions*, page 6154, December 2019.

[7] The European Commission. *Decision No 541/2014/EU of the European Parliament and of the Council*, 2014.

[8] Sven Kevin Flegel, Paula Krisko, Johannes Gelhaus, Carsten Wiedemann, Marek Moeckel, Holger Krag, Heiner Klinkrad, Yu-Lin Xu, Matthew Horstman, Mark Matney, and Peter Vörsmann. Modeling the space debris environment with MASTER-2009 and ORDEM2010. In *38th COSPAR Scientific Assembly*, volume 38, page 12, January 2010.

[9] International Laser Ranging Service (ILRS). Satellite names. `https://ilrs.gsfc.nasa.gov/missions/satellite_names.html`, 2023.

[10] D.J. Kessler. Critical density of spacecraft in low earth orbit: Using fragmentation data to evaluate the stability of the orbital debris environment. *JSC#28949 and LMSEAT #33303*, 2000.

[11] D.J. Kessler and B.G. Cour-Palais. Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Reseach*, 83:2637–2646, 1978.

[12] F. Letizia. Extension of the density approach for debris cloud propagation. *Journal of Guidance, Control and Dynamics*, 41(12), 2018.

[13] Francesca Letizia, Stijn Lemmens, Benjamin Bastida Virgili, and Holger Krag. Application of a debris index for global evaluation of mitigation strategies. *Acta Astronautica*, 161:348–362, 2019.

[14] Baohe Li, Jizhang Sang, and J.-S Ning. Comparison of orbit propagation methods for space debris. *Journal of Beijing Institue of Technology*, 24:87–92, 12 2015.

[15] N.R. Lomb. Least-squares frequency analysis of unequally spaced data. *Astrophysics and Space Science*, 39:447–462, 1976.

[16] Matthieu Masson, Denis Arzelier, Mioara Joldes, Bruno Revelin, and Jérôme Thomassin. Multi-maneuvers algorithms for multi-risk collision avoidance via nonconvex quadratic optimization. working paper or preprint, November 2022.

[17] C.R. McInnes. An analytical model for the catastrophic production of orbital debris. *ESA Journal*, 1993.

[18] ESA Space Debris Office. Esa's annual space environment report, 2023.

[19] NASA Orbital Debris Program Office. An update of the fy 1c, iridium 33, and cosmos 2251 fragments. *Orbital Debris Quarterly News*, 17:4–5, 2013.

[20] NASA Orbital Debris Program Office. The intentional destruction of cosmos 1408. *Orbital Debris Quarterly News*, 16, 2022.

[21] A. Rossi, E. Vellutini, E.M. Alessi, G. Schettino, V. Ruch, and J.C. Dolado Perez. Environmental index for fragmentation impact and environment evolution analysis. *Journal of Space Safety Engineering*, 9(2):269–273, 2022.

[22] Negron D. Salvatore A. Determining satellite close approaches. *Journal of the Astronautical Sciences*, 41:217–225, 1993.

[23] J.D. Scargle. Studies in astronomical time series analysis. ii - statistical aspects of spectral analysis of unevenly spaced data. *The Astrophysical Journal*, 263:835–853, 1982.

[24] Space-track. Satellite catalog. `https://www.space-track.org/#catalog`, 2023.