System Approach to Analyse the Performance of the current and future EU Space Surveillance and Tracking system at Service Provision level

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ABSTRACT

The "Decision of the European Parliament and the Council Establishing a Space Surveillance and Tracking Support Framework" was adopted on April 16, 2014. It established the European Space Surveillance and Tracking (EU SST) Support Framework at European level, which evolved into a fully-fledged component of the European Union Space Programme adopted on 28 April 2021. EU SST contributes to the global burden sharing of ensuring the 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 survey the in-orbit fragmentation of space objects. For that purpose, the design and the performance analysis of a global system architecture proving best value for money for the medium and long term has been established as one of the main activities of EU SST.

This paper presents the evolution of the system approach adopted for the simulation-based performance evaluation of the current and future EU SST system using observation and cataloguing capabilities [1], including an analysis of the service provision capabilities. Individual sensors, both existing and under development, are first modelled according to their performance and corresponding surveillance strategies. Different levels of performance can be considered for each sensor depending on potential future upgrades. Then, coverage and cataloguing simulations are performed, and each sensor's added value is assessed. Finally, sensor contribution to the services is evaluated to determine the overall EU SST network performance.

This work describes the simulation hypotheses and techniques adopted for the three main services currently provided by EU SST: collision avoidance (CA), re-entry analysis (RE), and fragmentation (FG) analysis. The simulation cases were developed and tested by two independent simulation benches: BAS3E, belonging to the CNES (France) and AS4/*Sassim*, under supervision of CDTI (Spain). In order to estimate the service provision performance of space surveillance and tracking systems, specific methodology for each one of the services together with a set of metrics have been developed. In the case of the CA, one of the main challenges has consisted of setting up a population set showing statistically representative conjunctions to be observed during the screening

period prior to TCA (Time to Closest Approach). The RE simulations focus on the coverage performance of the sensors, during the last days of the re-entering object's orbital lifetime. To this end, the major difficulty found has been how to model the tracking sensors (mount velocity, capacity to acquire the image, etc.), which can contribute to improve the observations, and therefore, the RE analyses during the last days before the re-entry. The FG service simulations show the capability to observe the clouds of fragments after the fragmentation event. The cataloguing performance results of the FG service are also provided with respect to the miscorrelation percentage, especially important during the initial days. In conclusion, the service provision simulations enhance the assessment methodology and tools used bv EU SST for system performance evaluation, moving one step further towards an end-to-end simulation environment for SST activities, adding the service provision layer simulation results to the previously existing ones, which dealt with coverage and cataloguing.

Key words: EU SST, simulation, architecture, coverage, cataloguing, service provision, SST, sensors

1 INTRODUCTION

1.1 The EU SST Support Framework

The EU SST Support Framework was established by the European Union in 2014 with the Decision 541/2014/EU of the European Parliament and the Council [2]. This Decision foresaw the creation of an SST Consortium (see the logo in Fig. 1. EU SST logo) currently composed of seven EU Member States – France, Germany, Italy, Poland, Portugal, Romania and Spain; in cooperation with EU Satellite Center (SatCen).

Fig. 1. EU SST logo

Since 2016, the SST Consortium and the SatCen, responsible for operating the EU SST Front Desk as interface to the users, have worked together to develop a European SST capability and formed the SST Cooperation. The enhancement of the SST capability has focused on, the integration of existing assets (sensor and operations centres) of the Consortium members assets to provide a set of SST services to all EU countries, EU institutions, spacecraft owners and operators, and civil protection authorities, and the design of architectural optimal network, following a best value for money approach, for the medium and long term. The EU SST services assess the risk of in-orbit collisions, uncontrolled re-entry of space debris into the Earth's atmosphere, and detect and characterise in-orbit fragmentations. The approach presented in this paper is generic and flexible enough to include assets from additional Member States that may join the EU SST partnership in the frame of the EU Space Regulation [3].

1.2 EUSST High Level Architecture

The functional SST high level architecture is composed of a sensor function, all the activities involving observations of space objects from sensors (telescopes, radars, lasers); a data processing function, in charge of the observations processing to build a catalogue and maintain a catalogue of objects; and a service provision function, committed to the generation and provision of SST information such as collision avoidance (CA) warning, re-entry (RE) warning or fragmentation (FG) detection (as identified in [2]) to the external user. The three functions map into a service provision model, as shown in Fig. 2, which are described in [1] and [4].

This paper focusses on the Service Provision chain (CA, RE and FG services), which is being simulated, and its impact on the overall EU SST system performance. Nowadays, EU SST is providing CA services to more than 270 satellites from 39 different organisations, and RE and FG services to more than 100 organisations. The SST services are provided upon request to all EU Member States, the European Council, the European Commission, the European Union's External Action Service, public and private spacecraft owners and operators, and public authorities concerned with civil protection. The three services consist of:

- The CA service provides risk assessment of collision between spacecraft and resident space objects (RSO), generates collision avoidance alerts and analyses all the available information in order to detect close approaches with different levels of risk.

- The RE analysis service provides risk assessment of the uncontrolled re-entry of manmade space objects into the Earth's atmosphere that may constitute a potential risk to the safety of EU citizens and to terrestrial infrastructure. All available information (data from sensors contributing to EU SST and other re-entry information from external sources) is analysed in order to carry out re-entry predictions.

- The FG analysis service provides detection and characterisation of in-orbit fragmentations. All available information is subjected to short, mid and long-term analysis, concluding with the provision of different FG products.

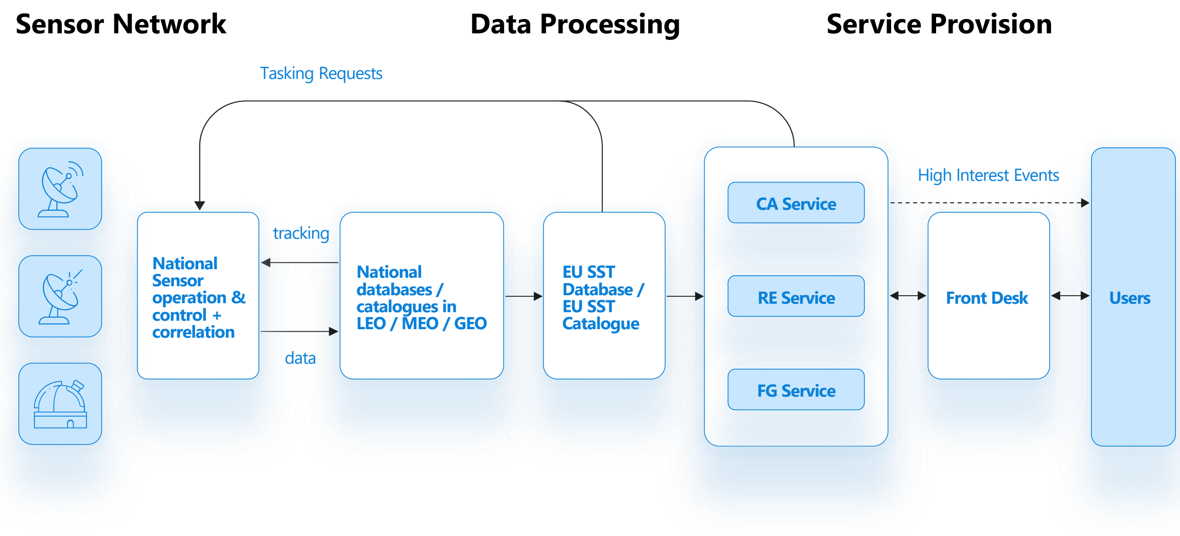

Fig. 2. Service Provision Model.

1.3 Architectural Analysis Objectives

The architectural analysis presented in this paper is intended to evaluate the performance of the EU SST systems expected by 2023, from the service provision perspective, once the on-going upgrades are expected to be completed. The sensor network is detailed in the Annex A. The main objective of the architecture studies is to provide decision makers with the system-engineering point of view on alternative design solutions, and to evaluate and rate, in terms of performance and best value for money, such different architectures. The system performance evaluation is based on five pillars from coverage, cataloguing to service provision (CA, RE and FG). These simulated studies do not, nor are they meant to, reflect the current status of the EU SST system. In fact, such analysis was provided to decision makers to help them select the upgrades of the EU SST system that are currently being performed.

2 DEFINITION OF PERFORMANCE EVALUATION

The evaluation of performance of a SST system is a complex task. While the relative performance of a given sensor can be determined considering its location and main features -- Field of View (FOV), detectable radar cross section (RCS), etc. -- its overall contribution within a larger network is not straightforward to evaluate. Some of the key elements to consider are, for example, the number of RSOs that can be observed by this sensor, which of them are already observed by the remainder of the network, or whether the additional observations brought by this sensor can improve the orbital estimation of the object. In the context of this paper, the evaluation of a SST system should also assess the delivery of services, a key feature of the EU SST architecture. As introduced above, the evaluation of the performance of the EU SST system lies on five different pillars: coverage performance, cataloguing performance, CA service performance, RE service performance and FG service performance. Those five pillars are dependent from one another: a good coverage performance contributes towards a good cataloguing performance, which in turns is a strong basis for an efficient service provision. At the opposite, targeting high performance in one of the five pillars can have negative consequences on the others, e.g., allocating significant sensing resources to follow a FG event might lead to a reduction of the coverage and cataloguing performances. In short, the estimation of the system's performance throughout the five pillars follows no easy rule of thumb.

2.1.1 Coverage performance

The coverage performance corresponds to the lower layer of evaluation of a SST system. The coverage simulations compute all the potential observations produced by the sensor layer and analyze them. It allows us to understand which objects of the population can be observed, how often, from which sensor(s), with what timeliness, etc.

A comprehensive set of indicators for the coverage performance have been defined, such as the percentage of observed by any given sensor, that of the “well-observed" objects – a figure of merit of the objects with limited observation gaps -- or an evaluation of the redundancy between the sensors' individual coverage of the reference population. The indicators are described in more details in [1].

2.1.2 Cataloguing performance

The cataloguing performance is a key feature of the system performance evaluation. Cataloguing simulations take benefit of the observations provided by the sensor layer, as computed in the coverage simulations, and simulate the data processing layer generating the catalogue of orbits. Note that, while a good coverage performance is a prerequisite for a good cataloguing performance, the relationship between the two pillars is not straightforward; as such, specific metrics have been derived for the latter.

A set of indicators of the cataloguing performance have been defined such as the number of objects in the catalogue and the accuracy of the catalogue. Some indicators (as described in [1]) have been used in the past such as whether the covariance was consistent with the error in the mean estimate. In this current simulation stage, a new metric is being adopted to assess whether the catalogue is *actionable*, that is, whether the information it contains is exploitable for service provision. An object in the catalogue is considered as *actionable* if, 48 hours after the end of the simulation, its covariance level (1-sigma) falls below the thresholds in QSW frame described in Table 2-1 of [1]. This covariance is computed through orbit determination and later on propagated numerically.

2.1.3 Collision avoidance performance

To evaluate the ability of a SST system to provide a CA service, several aspects need to be considered:

- What is the capacity of the system to detect a conjunction?
- When a conjunction is detected, how able is the system to follow the event and provide actionable information?
- When following an event, what is the added value of the system?
- What is the global performance of the system towards reducing the risk for on-orbit satellites?

Then, the performance evaluation has to address all the points above.

Regarding the capacity of the system to detect a conjunction, simulations are based on a comparison of two screenings. First, by screening the true population (available in the simulation test benches), the number of *true conjunctions* and their associated characteristics (such as Time to Close Approach (TCA), miss distance (MD), etc.) can be computed. Then, by screening the catalogue of objects that can be built from a simulated network, the number of *detected conjunctions* and their associated characteristics can be computed. Comparing the *true conjunctions* and the *detected conjunctions* allows us to analyse the performance of the CA service for conjunction detection.

Regarding the follow up of an event, one can borrow from coverage simulations and analyse how well the secondary objects can be observed by the network. Since any object of the population is likely to be involved as a secondary object in a conjunction (as it is explained in §3.1.1), this analysis basically consists in a coverage analysis of the whole population. The indicators defined for the coverage simulations [1] can be applied for the performance evaluation but are considered from a CA point of view to derive meaningful results.

Regarding the added value of the CA service, this service provision is simulated from the detection of the event to the computation of the Probability of Collision (PoC). This allows to assess the ability of the CA service to estimate the risk of a conjunction, to re-evaluate this risk frequently, to task tracking sensors and include their observations in the analysis. All of this with the final objective to alert satellite owners and operators in case the PoC remains above a given threshold in order to perform collision avoidance manoeuvres. The computation of the PoC is strongly affected by the covariance associated to the orbit estimates, and the covariances in the catalogue are not typically consistent with the error of these estimates. In order to mitigate the impact of this discrepancy the so called ‘Kpks method’, analysing the impact of covariance on the probability of collision, is implemented [5].

Finally, an evaluation of the global performance of the CA service can be performed considering the cataloguing performances (number of catalogued objects, accuracy of the catalogue) and using a statistical approach. Typical indicators are the level of risk reduction brought by the system, the residual risk (due to cataloguing performance and accepted level of risk from the operator), the expected number of collision avoidance manoeuvres to be performed and the expected number of false alarms [6].

Since this process can be followed for any SST system, it allows to identify the performance and shortcomings of the SST system from the perspective of collision avoidance, as well as to analyse system evolutions aiming to address these shortcomings.

2.1.4 Re-entry analysis performance

The RE service consists in being able to predict an upcoming re-entry, to follow the event especially during the last days prior re-entry, and to be able to estimate the re-entry date and location, with a particular focus on large objects over inhabited regions of the planet. The evaluation of the performance of a RE services are many similarities with the CA methodology. To evaluate the capacity to detect upcoming re-entries one can compare the propagated state of the true population, giving the number of *true re-entries,* and their associated characteristics (such as the re-entry date and location) with the propagation of the simulated catalogue giving the number of *detected re-entries* and their associated characteristics. To evaluate the follow up of an event also consists in performing a coverage simulation on objects close to re-entry. In addition, the estimated re-entry epoch of an object should be backed by a sequence of 'no-show' events, which ought to be implemented in the simulation framework. A 'no-show' event is recorded when a tracking sensor provides no measurement upon being pointed at an object's estimated position, either because the error on the object's position is large enough for the real object to lie outside of the sensor's FOV, or because the real object – unbeknownst to the current catalogue -- has already re-entered the atmosphere.

One important aspect is worth noting concerning the RE service simulation is the role of the tracking sensors. The mount capacities in term of angular velocities (and, presumably, acceleration) need to be consider when evaluating whether or not the sensor is able to track the objects close to re-entry. From other side, while the object from the population is propagated until re-entry, the object in the catalogue has its predicted lifetime and impact point updated regularly as long as new observations are provided by the sensors. However, one difficulty lies in the modelling of the atmospheric drag. Indeed, the sources of uncertainty considered as input for the dynamical model, as implemented in the simulator, has a direct impact on the accuracy of the estimated quantities as part of the RE assessment.

Since this process can be followed for any SST system, it allows to identify the performance and shortcomings of the SST system from the perspective of re-entry analysis, as well as to analyse system evolutions aiming to address these shortcomings.

2.1.5 Fragmentation follow up performance

The evaluation of performance of the FG service lies mainly in the capacity of the system to detect as soon as possible a fragmentation, and then to be able to track and catalogue as many resulting fragments as possible. In a simulation framework, a given number of *true fragmentations* and their associated characteristics (such as time of fragmentation, relevant object, number of generated fragments, etc.) can be introduced, in different orbital regimes. Then, the number of *detected fragmentations* and their associated characteristics can be computed. Comparing the *true fragmentations* and the *detected fragmentations* allows to analyse the performance of the FG service for fragmentation detection. Two main challenges lie in the sensor and data-processing layers. On the sensor part, the generation of measurements from a cloud of nearby objects may require a knowledge of the sensor and raw data processing beyond the scope of a simulator aiming to analyse a complete network. On the data-processing part, a fragmentation is detected when there is an important increase of un-correlated measurements from the new fragments (or an increase in the number of objects in the catalogue if IOD (Initial Orbit Determination) is directly performed), meaning that the correlation algorithms and the monitoring of non-correlated measurements need to be adequately tuned to allow such detection. If a human-in-the-loop confirmation is needed, this complicates the evaluation of the timeliness of the detection which is a key feature of FG service performance.

The capacity of the FG service to follow and catalogue as many fragments as possible can be evaluated following the coverage and cataloguing simulation process, including extra features such as the capacity to identify date of fragmentation and parent(s) object(s) through back propagation of the fragment cloud and comparison with the catalogue.

Since this process can be followed for any SST system, it allows to identify the performance and shortcomings of the SST system from the perspective of fragmentation detection, as well as to analyse system evolutions aiming to address these shortcomings.

3 ARCHITECTURE ANALYSIS FRAMEWORK

3.1 Simulations assumptions

The following elements give a high-level overview of the simulation process shaping the two test benches:

- The ESA MASTER-2009 [7], [8] reference population evolved to 2040 was used as the baseline population for the simulation. The main assumptions regarding this population are described in [1].
- The following force models are taken into account:
  - WGS84 Earth model with 12x12 development;
  - Atmospheric drag, with constant solar activity (F10.7 = 140 and Ap = 9). AS4/SSIM consider Jacchia Lineberry model, while BASE3E uses MSIS00 model;
  - Solar Radiation pressure force, based on Cannon-ball model;
  - Third body perturbations.
- Sensors are considered to be partially or fully available based on declared constraints. Individual sensor detection performances are given as input to the simulation tool to estimate the global performance of the sensor network. Some details are provided in [1].
- It is assumed that initially the whole population is known, i.e., the composition of the catalogue mirrors the real population (i.e. hot start). As a consequence, the simulations address the question of the catalogue maintenance, instead of the catalogue build-up. While 100% of the population is in the initial catalogue, it is not assumed that the catalogue has a perfect knowledge of the state of each object in the population. Further description is provided in [1]. The following uncertainties are considered:
  - Uncertainty on the area-to-mass ratio: the design choice is 10% uncertainty (1σ, Gaussian uncertainty) based on consortium experience.
  - Uncertainty on the initial orbit: typical uncertainties on Two-Line Elements (TLEs) are considered [9]. Initial position components are Gaussian distributed, while no dispersion on initial velocity is considered.
  - Initial uncertainties on position and area-to-mass ratio are assumed independent.

3.1.1 CA service simulations assumptions

The main assumption of the CA simulation concerns the choice of the population. Indeed, considering a realistic population such as TLEs or MASTER population would lead to the following:

- Very few, if not zero, conjunctions in MEO and in GEO during the days of simulation (typical duration of a simulation is one or two weeks).
- Thousands of conjunctions in LEO, but few with very short MD or high PoC.

To cope with those difficulties, a synthetic population is generated to allow a total control on the number of conjunctions occurring in the simulation duration as well as the geometry of the conjunction. Once the number of desired conjunctions is chosen and the associated primaries are selected, the orbits of the primaries are propagated until a randomly chosen TCA. Then, an artificial secondary object is created at TCA, with a random MD among a distribution tuned to ensure interesting subsequent analysis. Very small MD values (even a zero) are introduced. A high number of MDs lying into the safety volume are considered but also missed distance outside the safety volume are introduced to allow false detection of conjunction to happen. The relative position and velocity of the secondary is selected from a historical dataset of CDMs (Conjunction Data Message) to ensure that realistic and representative geometries are considered. Once the orbit of the secondary at TCA is set, it can be back-propagated to the start date of the simulation. As an example, the synthetic population built for LEO is composed by around 2500 pairs of primary and secondary objects creating more than 3000 conjunctions in the two weeks simulation duration, with MDs ranging from 0 to 40 km as shown in Fig. 3.

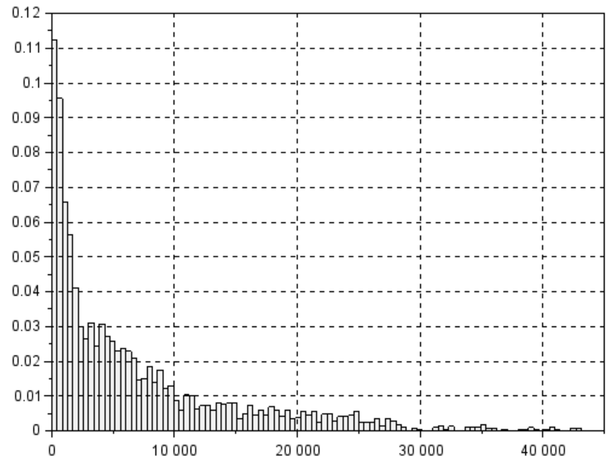

Fig. 3. Missed distance (m) histogram for synthetic population in LEO

The procedure to compute the penetration factor is as follows:

1. The relative position vector w.r.t. the primary at TCA is computed.

$$\vec{R}_{relative} = \vec{R}_{primary} - \vec{R}_{secondary}$$

2. The normalized distance is computed using the safety shape (Ellipsoid in this case)

$$X_{dist} = \frac{R_{relative}[x]}{Semimajor\ axis\ A}, \quad Y_{dist} = \frac{R_{relative}[y]}{Semimajor\ axis\ B}, \quad Z_{dist} = \frac{R_{relative}[z]}{Semimajor\ axis\ C}$$

3. The penetration factor is 1 – normalized distance.

$$P_f = 1 - \sqrt{X_{dist}^2 + Y_{dist}^2 + Z_{dist}^2}$$

The conjunction screening is performed in the simulation considering the JSPOC (Joint Space Operations Center) definition for safety volumes [10]. In the conjunction risk process, objects are divided into pairs, and each pair is screened for a conjunction detection. The objects trajectory is propagated during the screening interval and the distance between the two objects is monitored to identify local minima, retrieving a list of MD and TCA. For each local minimum, a check is made if the MD is smaller than a threshold. This threshold is defined by the size of the longest dimension of the safety shape. For conjunctions violating this initial filter, the penetration factor is computed. Conjunctions with penetration factor greater than zero represent close approaches in which the secondary object enters the safety shape of the primary. Additionally, the penetration factor also provides a normalized way to evaluate conjunctions based on MD. The penetration factor values between zero and one are normalized distances from the center of the safety shape. Thus, for two objects with the same safety shape, a conjunction with penetration factor of 0.85 would represent a much closer approach than 0.05. A penetration factor of one represents a ‘zero miss’ collision.

The PoC is computed using state-of-the-art techniques in use in operational centers, including the ‘KpKs method’ for covariance dilatation [5]. The process involves computing a PoC value using a scale factor Kp on the primary object covariance and Ks on the secondary object covariance. This grid is then searched with an optimizer to identify a local maxima value. The final computed PoC returned by the process is this maximum PoC from the optimizer. All intermediate probability values for each KpKs pair can be stored for further analysis. The values of Kp and Ks varies from 0.25 to 4.0 using 16 steps.

3.1.2 RE service simulations assumptions

The re-entry events followed by the RE service are relatively scarce (a few objects per month), such that a population reflecting the general makeup of the LEO orbital regime does not offer enough re-entry opportunities to build reliable statistics during a typical scenario (14/15 days). For the sake of simulation, then, a reference population is built in which every object re-enters the atmosphere within the 15-day-long span of the scenario, and to which the full processing chain (cataloguing, then service provision) is applied while disregarding scheduling conflicts among sensors -- that is, a tracking sensor may be tasked simultaneously towards different objects in the catalogue, The RE service is then evaluated for each object, and statistics are averaged across the whole population.

The construction of the reference population for RE studies balances two key features: first, as explained above, the lifetime of the objects is tuned such that the re-entry epochs of the all the follows a targeted distribution; second, the makeup of the population is based on historical events, to ensure a realistic statistical distribution of the re-entering objects.

The reference population was built from around 2000 historical re-entries identified from the SpaceTrack's decay table. An initial kinematic state was supplied for each object from the SpaceTrack's TLEs, while area/mass data was sampled from historical database for re-entering objects. Using BAS3E's high-fidelity propagator, each object was then propagated, until re-entry point (triggered at 80km altitude), then back-propagated for a random duration, dispersed around an averaged value of 12 days across the objects. Overall, the reference population is composed of 1559 SATs & DEBs (satellites or debris) and 482 R/Bs (rocket bodies), ensuring some diversity in the representation of re-entering objects (see Fig. 4).

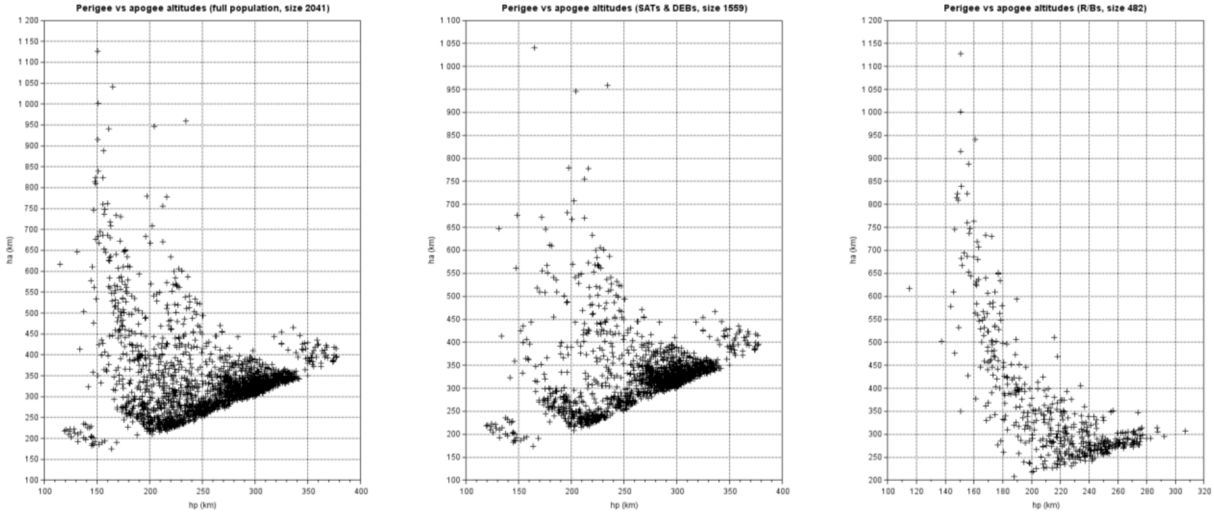

Fig. 4. Perigee vs apogee altitude for full population (left), satellites and debris (middle), and rocket bodies (left).

3.1.3 FG service simulations assumptions

The generation of population of fragments is based on three steps: one, analysis of historical events recorded by EU SST system in order to know the type of orbits, sizes of objects involved in a collision (or explosion), and their consequences most frequent; two, execution of Fragmentation Generation tool (AS4) with a set of cases with different collision angles, parent masses and orbits; and three, Monte Carlo execution with the selected parents in the previous steps.

The MASTER 2009 NASA Breakup Model [16] has been used to create the synthetic population, see an example in Fig. 5. It is a statistical model based on space surveillance data and a few ground-based test data with additional mathematical and statistical functions in order to improve the fragmentation model, which increases the complexity of the algorithm.

The model is based on three key points to correctly generate the distribution of fragments (in addition, differentiating between collision and explosion):

- Area-to-mass ratio distribution: The computation of the area-to-mass ratio distributions needs the computation of the normal distributions or cumulative distribution function (CDF), the formula for the average cross-sectional area as a function of diameter and the formula that computes the mass fragments. These computations are based on a pseudo-random number and probability. For this reason, once the parents are selected a set of iterations of the tool are executed to generate the synthetic population. The model uses two bi-modal normal distributions to assign an area-to-mass ratio to generated large fragments and a simple normal distribution for small fragments.

- Size distribution and number of fragments: The size distribution established by the NASA Breakup Model [16] is employed by the Fragmentation Generation tool with some variations for the case of collisions. The difference is that a new variable is added to the formula for the size distribution, the ejecta mass. The ejecta mass depends on the specific kinetic energy, which defines whether the collision is catastrophic or non-catastrophic. Moreover, the algorithm uses an update of the formulas in order to get two different clouds.

- Velocity distribution: The normal distribution is employed for the additional velocities acquired by the fragmentation. In the Fragmentation Generation tool, the conservation of momentum is used to determine fragment directions, following physical laws to satisfy the conservation of lineal momentum. The technique is based on distributing the delta-velocities vectors uniformly around the center of mass of each parent object. Another physical aspect taken into account is the conservation of the kinetic energy, but it is not exactly conserved since a hypervelocity impact and part of the energy is dissipated during the impact. Therefore, once the conservation of momentum and mass consistency are applied, if the total energy is greater than the initial energy, then all additional velocities are scaled downward until energy is conserved, assuming the loss energy is null. On the other hand, if the total energy is lower than the initial energy, the difference is assumed to be the loss of energy and no scaling actions are applied.

In the case of LEO synthetic population, a frontal collision, at 800km with the parent's objects mass of 1190kg and 500kg has been selected. The fragmentation event simulation provides a cloud of 2459 objects bigger than 7cm, which in term of simulation load is equivalent to the LEO reduced population usually considered. For MEO and GEO, explosion of several satellites with mass close to 2000kg (NSO, Navigation Satellite Orbit, in case of MEO) globally distributed has been selected as parents.

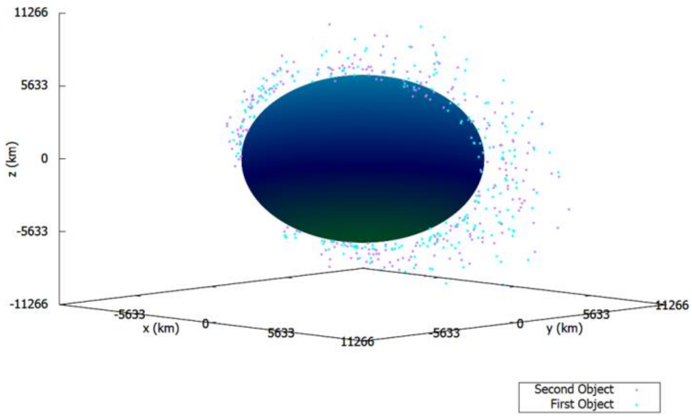

Fig. 5. Synthetic population in LEO.

3.2 Tools & Techniques

This study has been executed by two engineering teams with different simulation tools, for validation purposes. One analysis utilises the BAS3E tool, belonging to the CNES; and the other uses AS4/*Ssasim*, under supervision of CDTI.

3.2.1 BAS3E

The BAS3E test bench is composed of several stages, which allows performing a sequence of computational steps for fulfilling a higher-level functionality (e.g. system architecture performance or cataloguing).

The visibility stage computes the visibility of all space objects from all sensors in the network, considering a set of user-defined constraints -- e.g., the field of regard (FOR), the limiting magnitude, the RCS -- as well as implementing surveillances strategies to position the sensors' FOV. The observation stage generates the observations provided by the sensors as a function of the user-defined noise parameters (accuracy of measurements).

Observations are associated to objects with a nearest neighbour approach. First, unlikely associations are filtered out through a maximum admissible object-to-observation distance; then, each object is associated to the closest observation among the admissible candidates (if any). The association method can accommodate a range of object-to-measurement distance metrics; in its current form, it is implemented with a Mahalanobis distance.

The orbit determination is performed with a numerical propagator, with the option to estimate dynamic parameters (drag force coefficient and/or solar radiation pressure coefficient). Measurement-related parameters (observation bias, date bias, sensor position offset, etc.) can also be estimated upon request. The tool includes several OD filters but only the least mean squares method is used within this study.

The tool also implements observation-to-observation association and IOD algorithms, in order to deal with the observations that have not been associated yet following the nearest neighbour approach. The method employed borrows from the concepts of admissible regions and clustering algorithm [11].

With respect to the collision avoidance simulation, BAS3E is able to perform a screening of the catalogue (list of primary satellites against all, or all versus all) to detect conjunctions considering different safety shapes (sphere, box, ellipsoid…). The PoC is computed with the LAAS method [12], also used in the French operational center. Note that this method is adequate for short-term space encounters in single conjunction, and other conjunction geometries are yet to be handled in BAS3E. A covariance dilatation strategy is used to identify the highest PoC value for each conjunction. BAS3E tool uses the state of the art 'KpKs method' [5]. The process involves computing a PoC value using a scale factor Kp on the primary object covariance and Ks on the secondary object covariance. This grid is then searched with an optimizer to identify a local maxima value. The final computed PoC returned by the process is the maximum PoC value yielded by the optimizer.

The simulation of the re-entry service provision entails the estimation of the epoch and position of the re-entry events, once identified from the catalogue. The tracking sensors play a significant role in the process, as they may be tasked to follow upcoming re-entry events in order to refine the estimate delivered by the service. A tracking sensor tasked towards a new object is pointed at the object's estimated position in the catalogue; if the object's *real* position in the reference population does not lie in the sensor FOV, no measurements are generated and a 'no show' event occurs. In the context of the re-entry simulations, 'no show' events may also occur when the object pointed at still exists in the catalogue but has already re-entered in the reference population. In either case, a 'no show' event does not prevent further tasking towards the missing object. A stream of 'no show' events, however, may hint at a catalogued object surviving past its *real* re-entry epoch; while this information is not currently exploited.

More details about the algorithms implemented in BAS3E are given in [13].

3.2.2 AS4/*Ssasim*

A combination of two different tools, AS4 and *Ssasim*, is used to perform the simulations. These tools are propriety of DEIMOS and GMV, respectively, and they are available to CDTI for EU SST activities.

The Advanced Space Surveillance System Simulator (AS4) has been designed as an end-to-end simulation environment for space surveillance system comprising a full set of simulations capabilities. It includes a module for the generation of space debris population, sensor measurement generation, initial and routine orbit determination tasks, correlation and cataloguing activities (for radar and optical measurements, both tracking or surveillance, accounting also for space-based sensors). It also provides product delivery (collision risk computation, re-entry events reporting, fragmentation analysis and launch detection and ephemerides generation).

The Measurements Generation Module is a core part of the AS4 and provides large flexibility regarding to sensors configuration and strategies, taking into account a large set of constraints that allow generating realistic observations. The generation of observations is executed prior to the evaluation of performance of all services. The concept of simulated measurements consists in determining the difference between true objects and catalogued. For each object, the visibility determination algorithm is executed in several steps following a configured observation strategy, with filters and discarding criteria, such as moon distance or minimum visual magnitude, that allow generating measurements when the object is observed by the sensor.

Ssasim is a COTS (Commercial Off-The-Shelf) software tool capable of maintaining a catalogue of Earth orbiting objects and their orbital information through the processing of measurements from a pre-defined space surveillance network of sensors. This SST Catalogue Maintainer Software does not depend on any other system (except for the provision of inputs, measurements, and sensor configuration), and thus can be used as a standalone product. The SST Catalogue Maintainer Software is based on the orbit determination and propagation capabilities in ESA's NAPEOS [14].

Ssasim is composed of the following integrated elements: a measurement pre-processor module, a synthetic measurement generator, an object correlator, a preliminary orbit determination tool, a sequential orbit determination module, and a catalogue post-processing component for the analysis of the cataloguing performances. Thanks to this last module, it can evaluate the cataloguing capabilities of a space surveillance network. The synthetic measurements generator is used to generate simulated measurements that are then compared against the real measurements during the correlation process. The initial orbit determination module is only used when a set of measurements are not correlated to an existing object and thus are assumed to correspond to a new object. The sequential orbital determination module, based on SRIF (Square Root Information Filter) algorithm, is in charge of performing the routine orbit determination task of the known objects based on the available measurements. It is executed when the tracks are correlated to an existing catalogue object, in case of issues with the convergence of SRIF filter, the module can use the Batch Least Squares estimation.

The AS4 Collision module, the software analyses the collision risk between two objects based on the closest distance at the time of the closest approach. The software can analyse an identified conjunction event, or can be configured to search for all close encounters of a target-chaser pair in a given time interval (screening), it computes the conjunctions considering a safety shape (input parameters) and provides the PoC with algorithms using nominal covariance or scaled covariance for maximum collision probability. The PoC algorithm in the simulations is computed using the scaled PoC method, known as 'KpKs method' [5] and Alfriend&Akella algorithm [15] or a short-term encounter between spherical objects algorithm [12].

With respect to re-entry module produces a report of objects with the prediction of the re-entry epoch and location. The tool makes use of the initial catalogue where the measurement data was generated (real world) and the estimated catalogue provided after the cataloguing process (estimated world). Both are propagated using a long-term numerical propagator and compare the predicted re-entry for the estimated world and the real world. An object is assumed to re-enter when its altitude drops below a threshold value. The tool is also capable of detecting 'no-shows' events, that is, objects that exist in the estimated catalogue but have already re-entered the reference population. This can also help us to identify the quality or validity of the estimated catalogue based on the objects (orbit characteristics, A/M, etc).

Fragmentation events are also another service evaluated and analysed under simulations. A specific population with fragments is generated using the Fragmentation Generation Tool. The MASTER 2009 NASA Breakup Model [16] is used to create the synthetic population. It is a statistical model based on space surveillance data and a few ground-based test data with additional mathematical and statistical functions in order to improve the fragmentation model, which increases the complexity of the algorithm. A fragmentation event can be generated by either a collision or an explosion in any orbital regime. Moreover, a Monte Carlo execution is performed with the population to increase the randomness of the number of fragments in the algorithm. The main objective of this activity is to evaluate the capacity of the EU SST system to detect a fragmentation event and the capacity to follow the new objects.

4 EU SST SYSTEM PRELIMINARY PERFORMANCES

This section presents several examples of the results and estimation of EU SST system performances derived from the simulations and methodology described in previous sections for the three services: CA, RE and FG services. Note that the system is evolving continuously, therefore, the expected performance will improve accordingly with respect the results presented next.

Regarding CA service performance, results are given in terms of percentage of secondary objects that can be observed during the last 7 days, which is a typical screening period to detect a conjunction, prior TCA as a function of the secondary size. These sizes are split into three categories, following classical terminology used by CA service providers: small, RCS < 0.1m²; medium, 0,1 < RCS < 1.0m²; and large, RCS >1.0m². The following Table 1 shows an example of the performance of the radar survey network in LEO for the collisions follow-up.

	Percentage of event followed		
Secondary size	SMALL	MEDIUM	LARGE
	10	79	98

Table 1. Follow-up performance in LEO for survey radars.

Note that the follow up performance is evaluated on all conjunctions of the synthetic population, not only the ones detected by the system, since external sources can send a warning about the conjunction. While this preliminary study suggests that survey radars are able to follow conjunctions involving medium and large objects, tracking sensors are expected to complement the survey units in their ability to observe smaller objects. The EU SST tracking network has shown the capability of observing all secondaries objects, although higher sensor redundancy for small objects is suggested. This performance for small secondary objects is very consistent with the coverage and cataloguing performance described in [1]. The challenge for the small objects comes from the technical limitation of the survey sensors included in the network.

In addition, our simulation tools are able to provide a baseline performance for the coverage of conjunction events. This is evaluated through the percentage of observed objects, computed on a daily basis, and aggregated throughout the last days prior to TCA. Fig. Fig. 6 shows the survey and tracking performances for CA events in GEO showing that the events can be monitored on a daily basis. Finally, preliminary results tend to indicate that the probability of collision is computed well, with a clear relationship between the true missed distance (available to the simulation test benches) and the estimated probability of collision (see Fig. *7*).

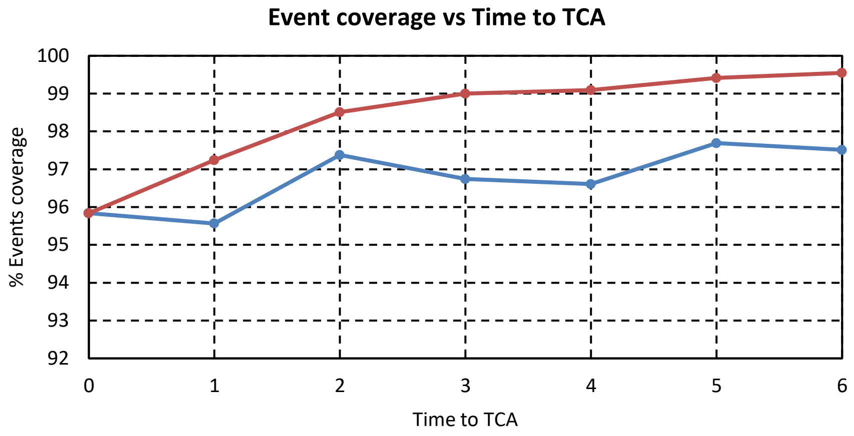

Fig. 6. GEO CA events observation rates on daily basis (blue) and cumulative (red).

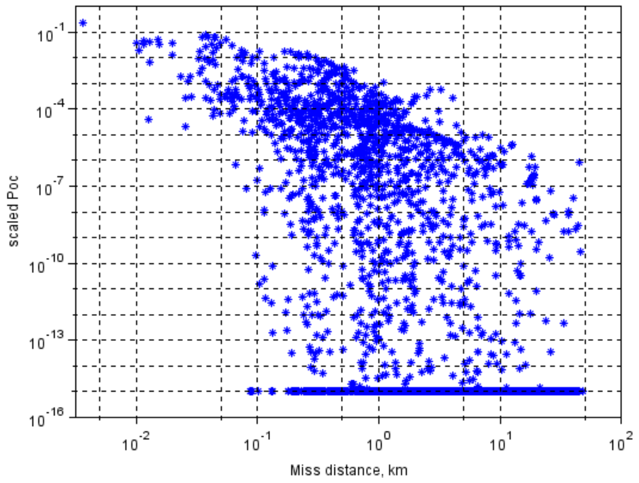

Fig. 7. Scaled PoC vs MD for LEO CA events.

In the context of the RE service provision, the evolution of the sensor coverage throughout an object's last days in orbit is deemed as a key component of the system performance. To this end, we designed a metric computing the percentage of objects (among the whole re-entry population) that are visible at least once during their last *n* days of their orbital lifetime, and it was evaluated every day in the last 7 days until re-entry. The following table shows the values for EU SST survey and tracking radar system. About 90% of the re-entries are covered by the survey radars, while the remaining ones relate to low-inclination (< 30°) objects.

	Percentage of observed objects, on a daily basis, until re-entry						
	RE - 6d	**RE- 5d**	**RE - 4d**	**RE - 3d**	**RE - 2d**	**RE - 1d**	**RE**
Survey and tracking radars	98	97	97	97	97	96	71

Table 2. RE simulation results – radars – percentage of observed objects until re-entry.

Overall, the survey radars provide a stable coverage of the re-entering objects, save on the last day where the performance steadily drops; yet, observing the last stages before re-entry is critical to establishing a robust estimate of the characteristics (date and location) of the re-entry event as well as to confirm the re-entry as soon as possible. Since tracking radars are typically nimbler and naturally adapted to follow objects until the re-entry point, they are likely to be an invaluable supplement to the survey radars for the re-entry service, provided that an adequate cueing strategy can be designed. It is important to notice that a tasking strategy has not been implemented yet for the tracking radars: in the table above, an *observable* object is one that could be followed by a radar if tasked to do so, rather than one that is effectively *observed* under specific tasking instructions.

Simulations integrate the cataloguing and the service provision, in order to assess the ability of the network to provide an estimate of the re-entry epoch and location for each identified re-entry event. To this end, the simulation run involving the survey radar network provides a baseline performance (see Fig. 8). Upcoming improvements will include a daily evolution of the re-entry epoch estimation and the addition of the tracking sensors as well. It will assess the added value of sensor tasking towards obtaining a refined estimate of the re-entry parameters.

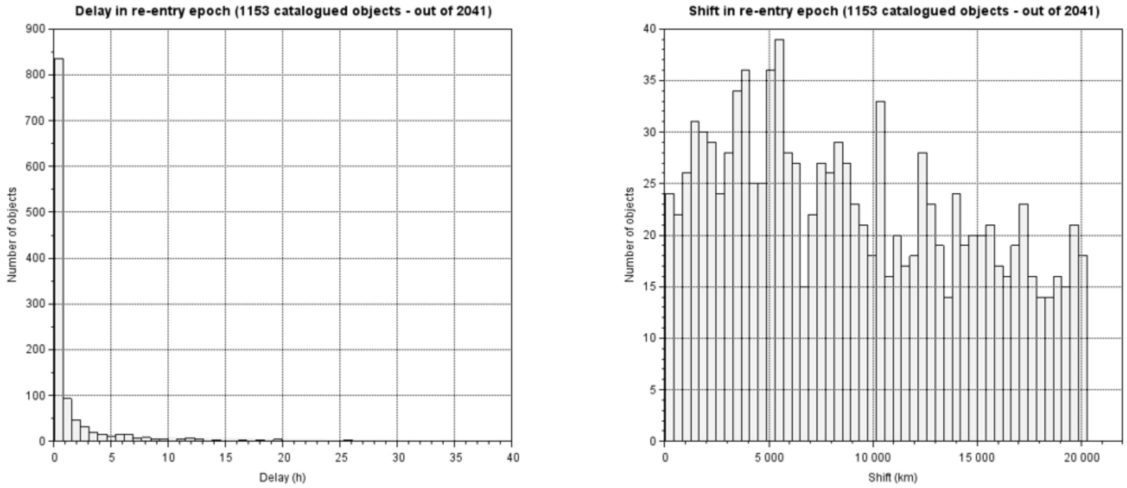

Fig. 8. Estimation of the re-entry epoch and location for catalogued objects.

The FG service provision performance results are given in terms of the percentage of objects that can be observed during the 14 days after TFG (time of fragmentation event) for the objects bigger or equal to 7 cm of diameter per day of simulation and the cumulative percentage of observed fragments. An example of the EU SST survey sensors performance for an FG event in LEO is shown in Fig. 9.

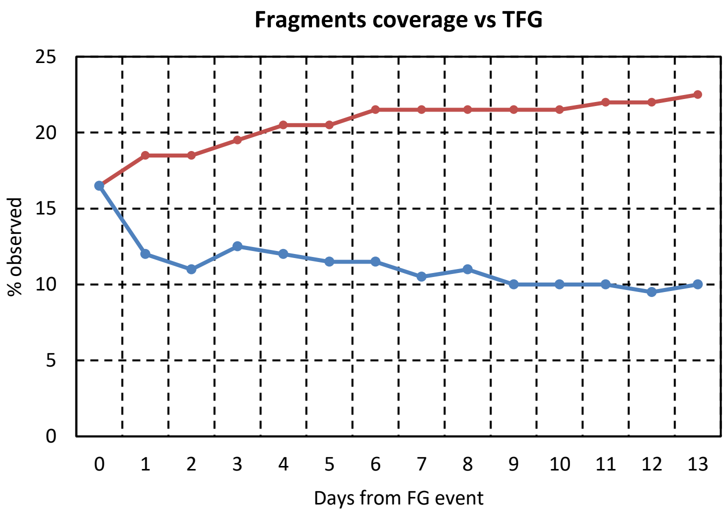

Fig. 9. LEO FG events observation rates on daily basis (blue) and cumulative (red).

As for the evaluation of the CA service, the total percentage of observed objects during the first 14 days can be split into three categories depending on the object size. An example for the follow-up of a FG event in LEO can be seen in the following table:

	Percentage of fragments followed		
Fragments size	SMALL	MEDIUM	LARGE
	17	98	100

Table 3. Follow-up performance in FG LEO event for survey radars.

In this particular case, the simulations show that survey radars are capable of observing mainly large fragments (medium or large sizes are observed in more than the 90% of the cases). The best coverage occurs at the time of the fragmentation, after which the cloud disperses, and the coverage performance decreases throughout time. After a few days, the performance becomes stable. Upcoming simulations will provide the capacity of sensor tasking and asses the added value of the tracking sensors. Initial simulations for FG LEO event suggest that the current EU SST tracking network is very performant and has the capacity to follow even small size fragments.

5 CONCLUSIONS

This paper presents a methodology, and a system engineering tool, to assess the performance of the current and future EU SST network from the perspective of service provision (collision avoidance, re-entry and fragmentation). The main challenges to perform such simulations are discussed, and details about the implementation are also provided. The described system engineering tool evolution towards the service provision completes the five pillars for the end-to-end system evaluation of a sensor network, to observe, catalogue and provide the main three services from LEO to GEO orbital regimes. This process aims to provide decision makers with a system-engineering point of view on alternative design solutions. Moreover, in the framework of EU SST the simulation tools confirmed their role as a cornerstone element to guide the system evolution activities at short, medium and long-term in order to guarantee a best value for money approach when evolving the system through a higher level of performance.

The simulation cases have been developed and tested through two independent simulation benches: BAS3E, belonging to the CNES (France) and AS4/*Ssasim*, under supervision of CDTI (Spain). There are still some improvements to be implemented in the upcoming stages of the simulations as, for example, the inclusion of tracking sensors with the corresponding scheduling and tasking strategy, especially for high interest events, which could improve the accuracy and performances of the estimates. Another interesting update will be the integration on the EU SST system engineering tool of state-of-the-art sensors as the passive RF system that offers good potential for the support to services; the infrared sensors, thought to increase the telescope availability for observation; or the space based sensors, very beneficial to fill the gaps of ground based architectures; among others.

6 ACKNOWLEDGEMENTS

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8 ANNEX A: REFERENCE SENSOR NETWORK

The reference network is composed of radars, telescopes, and lasers. An important distinction is made between surveillance and tracking units, covering complementary functions in the operations run by the consortium; some telescopes are designed to perform both roles, under distinct performance points, and are exploited as such.

In order to gauge the geographical repartition of the assets, and to provide a rough picture of the areas where the effort of the consortium is lacking or redundant, the globe is split into Very Large Areas (VLAs) and each sensor contributes to the performance statistics of the region it belongs to. The approximate locations of the VLAs are illustrated in the figure below:

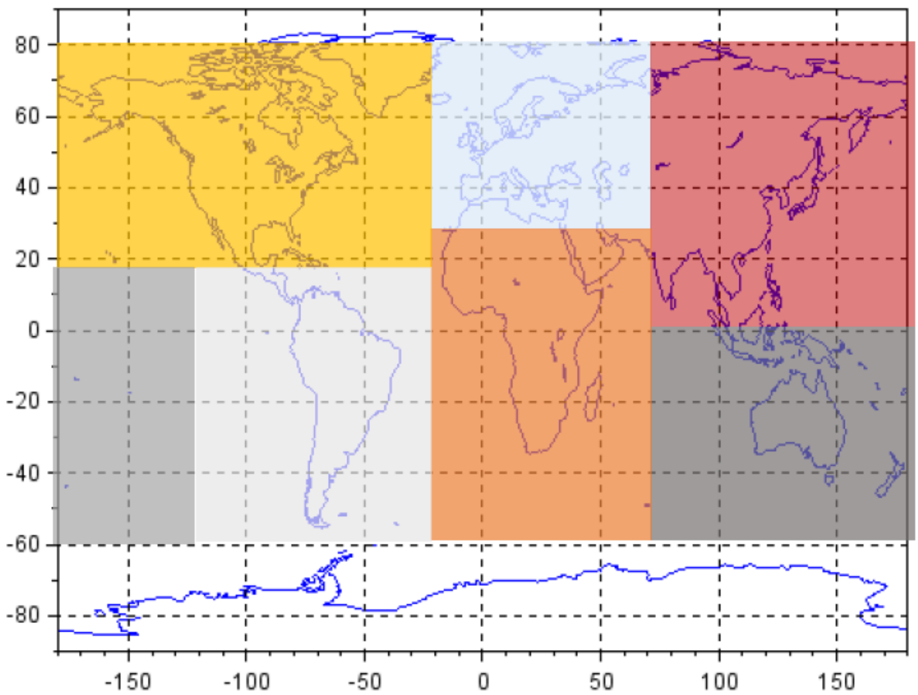

Fig. 10. Geographical layout of the VLAs: North America in yellow, Pacific Ocean in light gray, South America in white, Europe in light blue, South of Africa in orange, Asia in red, and Oceania in dark gray

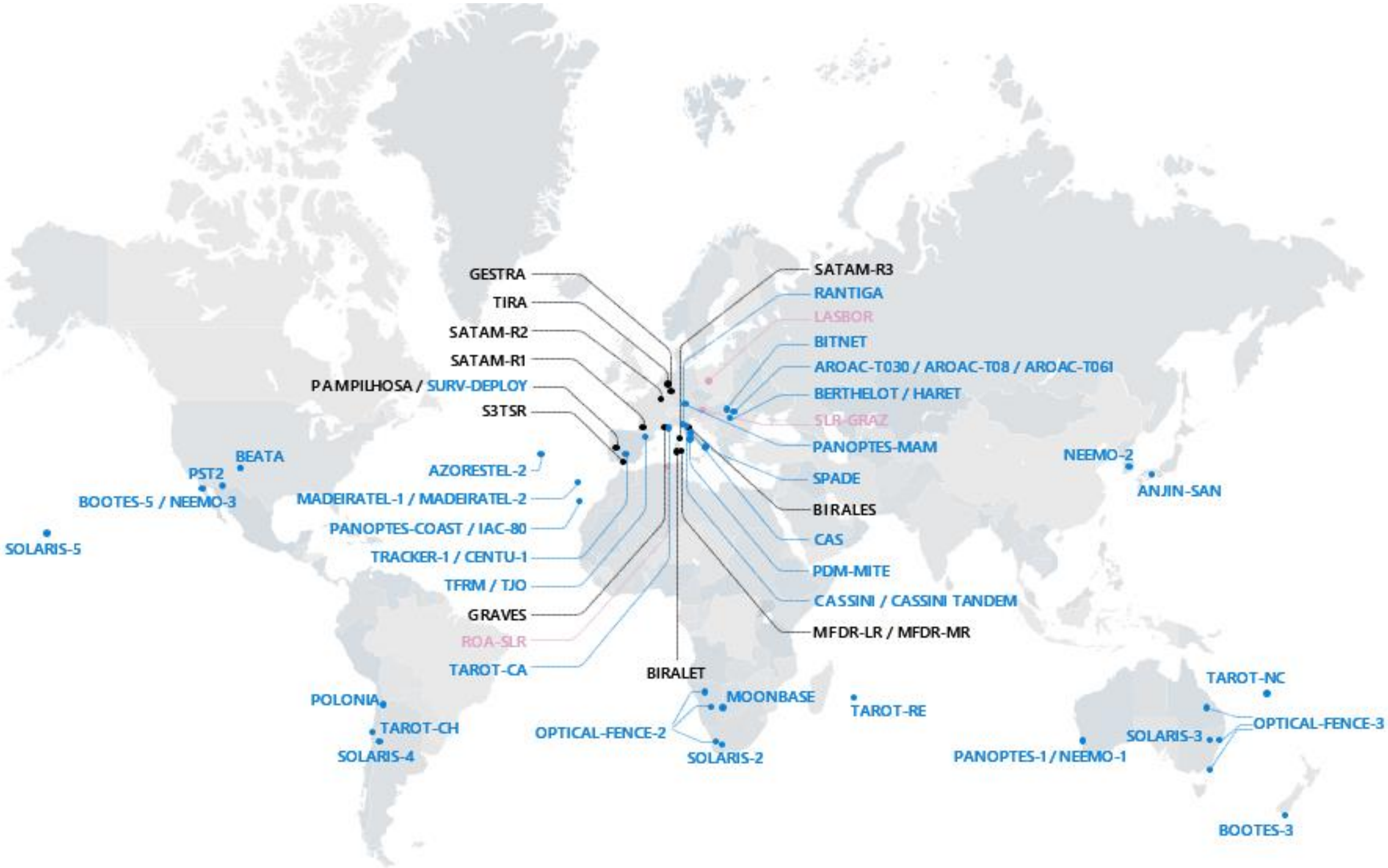

Fig. 11. Geographical layout of the reference network: radars (black), telescopes (blue) and lasers (pink).

The three tables below list the sensing assets composing the reference network
Table 4 for radars,
Table 5 for telescopes, and Table 6 for lasers.

Member state	Sensor	Role	VLA
DE	GESTRA	Survey	Europe
FR	GRAVES	Survey	Europe
ES	S3TSR	Survey	Europe
DE	TIRA	racking	Europe
FR	SATAM-R1	Tracking	Europe
FR	SATAM-R2	Tracking	Europe
FR	SATAM-R3	Tracking	Europe
IT	MFDR-LR	Tracking	Europe
IT	MFDR-MR	Tracking	Europe
IT	BIRALET	Tracking	Europe
IT	BIRALES	Tracking	Europe
PT	PAMPILHOSA	Tracking	Europe

Table 4. Radar assets in the reference network.

Member state	Sensor	Main role	VLA
ES	CENTU-1	Survey	Europe
ES	TRACKER-1	Tracking	Europe
ES	TJO	Tracking	Europe
ES	TFRM	Survey	Europe
ES	IAC-80	Tracking	Europe
ES	BOOTES-3	Tracking	Oceania
ES	BOOTES-5	Tracking	North America
FR	TAROT-CH	Survey	South America
FR	TAROT-CA	Survey	Europe
FR	TAROT-RE	Survey	South of Africa
FR	TAROT-NC	Survey	Oceania
IT	PDM-MITE	Tracking	Europe
IT	CAS	Tracking	Europe
IT	SPADE	Survey	Europe
IT	CASSINI	Survey	Europe
IT	CASSINI-TANDEM	Survey	Europe
PL	PST2	Survey	North America
PL	SOLARIS-2	Survey	South of Africa
PL	SOLARIS-3	Survey	Oceania
PL	SOLARIS-4	Survey	South America
PL	SOLARIS-5	Survey	Pacific Ocean
PL	OPTICAL-FENCE-2	Survey	South of Africa
PL	OPTICAL-FENCE-3	Survey	Oceania
PL	POLONIA	Survey	South America
PL	RATINGA	Survey	Europe

Member state	Sensor	Main role	VLA
PL	ANJIN-SAN	Survey	Asia
PL	MOONBASE	Survey	South of Africa
PL	BEATA	Survey	North America
PL	PANOPTES-COAST	Tracking	Europe
PL	PANOPTES-MAM	Survey	Europe
PL	PANOPTES-1	Survey	Oceania
PT	MADEIRATel1	Survey	Europe
PT	MADEIRATel2	Tracking	Europe
PT	SURV-DEPLOY	Survey	Europe
PT	AZORESTel2	Tracking	Europe
RO	AROAC-T030	Tracking	Europe
RO	AROAC-T08	Tracking	Europe
RO	AROAC-T061	Tracking	Europe
RO	BERTHELOT	Tracking	Europe
RO	HARET	Survey	Europe
RO	NEEMO-1	Survey	Oceania
RO	NEEMO-2	Survey	Asia
RO	NEEMO-3	Survey	North America
RO	BITNET	Tracking	Europe

Table 5. Telescopes assets in the reference network.

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Member state	Sensor	Role	VLA
DE	SLR-GRAZ	Tracking	Europe
ES	ROA-SLR	Tracking	Europe
PL	LASBOR	Tracking	Europe

Table 6. Laser assets in the reference network.