System Approach to Analyze the Performance of the EU Space Surveillance and Tracking system

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ABSTRACT

This paper presents the approach followed to evaluate the performance of the current and future architectures of the EU Space Surveillance and Tracking (EU SST) system. It provides a description of the tools and techniques, as well as the simulation hypotheses, used to evaluate the expected orbital regime coverage (observation capability) and cataloguing capability (with associated accuracy analysis of the resulting orbital information), as a function of the possible evolutions of the sensing architecture.

This study has been executed by two different engineering teams with independent tools, for validation purposes. The first analysis utilises the BAS3E tool, belonging to CNES; and the other one uses AS4/*Ssasim*, under supervision of CDTI. The two tools are presented, as well as the simulation hypotheses and techniques. The overall analysis is based on the underlying population of objects from ESA's MASTER-2009 reference population propagated to 2040. Both tools allow for the simulation of the observations generated by a network of sensors, the data processing of these observations to generate a catalogue of objects, and the assessment of the space surveillance and tracking system performance through key performance indicators.

These key indicators for architecture performance are also presented and discussed. Among them, the following aspects are considered for coverage: the number of observed objects, the number of so-called well observed objects, the total number of tracks, the mean track length, the mean number of observation opportunities, and the mean gap duration. For the cataloguing capability per orbital regime, the following aspects are considered: the number of catalogued objects, their averaged accuracy and the number of objects with orbital accuracy better than an imposed threshold, among others.

After the detailed presentation of the system engineering tools and techniques, this paper provides a few sample results to illustrate the architectural studies performed and to provide insight in the different architectural options, highlighting the benefit of having an architecture to be able to catalogue.

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

1 INTRODUCTION

1.1 The EU SST Support Framework

The EU SST Support Framework was established following the "Decision No 541/2014/EU of the European Parliament and of the Council establishing a Framework for Space Surveillance and Tracking Support" (2014) [1]. The Framework is implemented by the EU SST Consortium, in cooperation with the EU SatCen. At the time of the analysis, the EU SST Consortium member states are France, Germany, Italy, Poland, Portugal, Romania, Spain, and the UK.[1]

Figure 1-1 EU SST

Within the Framework, the EU SST Consortium members have undertaken, on one hand, the integration of existing assets (sensors and operations centres) of EU Member States and, on the other hand, the design of architectural options for the medium and long term. In order to prioritise upgrades and improvements following a best value for money approach while avoiding unnecessary duplication, it was required to analyse the performance of different architectural options in regard to the expected capability to observe objects in space, and to determine and predict their orbit to support the provision of services thereof (Collision Avoidance, Re-Entry Analysis, Fragmentation Analysis). 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 [2].

1.2 EU SST High Level Architecture

The functional SST high level architecture is composed of a sensor function, a data processing function, and a service provision function.

- The **Sensor function** covers all the activities related to obtaining measurements of space objects from the sensors of the SST system. Sensors include today radar and optical telescopes together with laser ranging based optical sensors. Both surveillance and tracking activities are within the scope of this function.
- The **Processing function** is dedicated to the processing of the measurements provided by the sensor function for the generation of the catalogue. It performs the association of measurements with existing objects in the catalogue, the orbit determination for correlated and new objects, and the update of the catalogue.
- The **Service Provision function** is committed to the generation and provision of SST information such as collision warning, re-entry warning or fragmentation detection (as identified in [1]) to the external users. This includes the reception and evaluation of service requests, the generation of acknowledgment messages, and the provision of SST information to users. It is also in charge of handling user registration and subscription, as well as the provision of user support. The service provision function has not yet been included in the simulation framework but will be in the near future.

The three functions maps into a service provision model, as shown in Fig. *1-2*, which describes the operational layer of EU SST.

[1] Since October 2020 the UK ceased to be an EU Member State and had to leave the Consortium as a consequence of the Brexit.

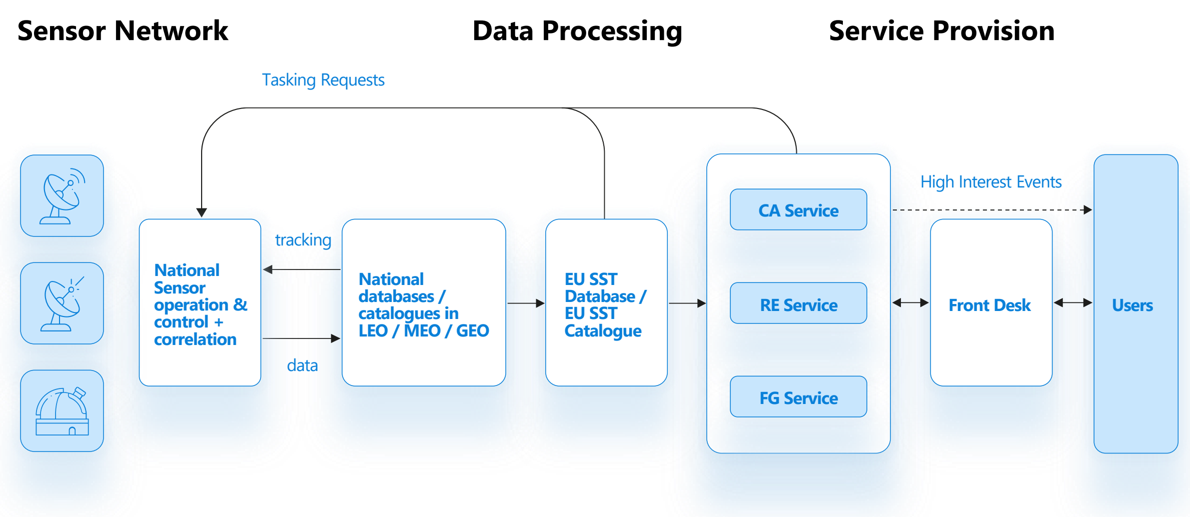


Fig. 1-2 Service Provision Model.

The service provision model depicted above has proved to be a success and EU SST is, at the time of writing (August 2021), providing CA services to more than 230 satellites from 32 different organisations, and RE and FG services to more than 100 organisations.

The services are currently restricted to European Union public and private organisations only, but in the short term, following the adoption of the EU Space Regulation [2], will be extended to non-European actors and will continue evolving and expanding towards mitigation and remediation objectives.

This paper focusses on the Sensor function only, and its impact on the potential cataloguing capabilities. The full service provision chain is being simulated and will be the topic of future publications.

1.3 Architectural Analysis Objectives

The architecture studies are a cornerstone for the definition of the evolution of the EU SST system at medium- and long-term. The main objective of the architecture studies is to provide decision makers with the system-engineering point of view on alternative design solutions, referred to as architectures, and to evaluate and rate, in terms of performance and best value for money, such architectures. To do so, architecture studies activities analyse the performance and added value of a particular sensor or upgrade, being part of a complete network. The performance from coverage, cataloguing and service provision point of view is therefore evaluated. The approach is in line with a bottom-up approach, with the objective to avoid unnecessary duplications and target best value for money, while integrating limitations such as budget constraints and time constraints.

The architectural analysis presented in this paper is intended to evaluate the performance of the EU SST systems in 2019 with respect to proposed future upgrades.[2] The simulated cases presented in this work include the analysis of four surveillance radars, nine tracking radars, and a total of 48 telescopes from France, Italy, Poland, Portugal, Romania, Spain and the UK. 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 ARCHITECTURE ANALYSIS FRAMEWORK

This section provides a description of the tools and techniques, the indicators used to evaluate the performance of the architectural solutions, as well as the simulation hypotheses.

[2] Not all the sensors included in the 2019 scenario are nowadays part of the current EU SST network and are considered for the future short-term scenario of 2023. Find comparison tables between 2019 and 2023 scenarios in Annex B.

2.1 Definition of the Simulation Performance Indicators

The analysis of the different EU SST architectures is based on a number of simulation performance indicators gauging the coverage and cataloguing capabilities of a given architecture applied to a given population.

Coverage analyses provide a series of fast indicators, which allow identifying a limited set of architectural options to be simulated in cataloguing studies. This is of great advantage given the computational complexity of cataloguing studies when compared with coverage analyses. The detailed cataloguing studies are then performed, resulting in a series of cataloguing performance indicators, which allow evaluating the ability of a given architecture to catalogue a given population. Furthermore, they allow quantifying the accuracy of the catalogued orbits, which is expected to have a major impact on the quality of the services provided by the system.

The indicators are computed as a function of object size, with different reference levels depending on the orbital regime (≥ 7cm, ≥10cm, ≥50cm and ≥1m for LEO, and ≥35cm, ≥50cm, ≥1m and ≥5m for GEO/MEO). Some examples of the outputs (tables and diagrams) are shown in Annex A.

2.1.1 Fast indicators for coverage analysis

The fast indicators of interest for the coverage analysis are:

- The total number and percentages of objects observed at least once during the simulation period by each sensor, by each sensor network as well as by the overall EU SST network.
- The total number and percentages of objects considered as "well observed", which is intended as a figure of merit of the objects that might be sufficiently observed to be catalogued. Criteria for "well observed" objects are:
  - For GEO/MEO objects: observation gap may not exceed 72 hours.
  - For LEO objects: observation gap may not exceed 24 hours.
- The total number and percentages of observed and well observed objects as a function of size and orbital regimes / altitude bands. The size categories depend on the orbital regime considered, as the technology to observe space objects may change from one orbital regime to the other.
- The redundancy between sensors, which analyses how many sensors can observe the same group of objects.
- The fast indicators also include a set of additional indicators aiming at providing more details to the analysis.

For Radar sensors, the indicators are:

- The total number of tracks provided during the simulation for each sensor.
- Tracks mean duration.
- The mean number of observation opportunities per day considering all the observed objects (it counts the number of times they have been observed, divided by the simulation duration and computes the average for all observed objects).
  The mean gap duration for all observed objects (computes the gap duration and the average of all of them).

For Optical sensors, these indicators are:

- The total number of tracks provided during the simulation for each sensor. Track is defined as a set of observations of a unique object from a unique sensor, obtained during a period of time, of continuous observation of the object.
- The track accuracy computed with the following formula (where σ_{meas} is the standard deviation of the sensor's noise model or accuracy of the measurements, and nb_{obs_mean} is the number of measurements).
  - $Track_{Mean\_Accuracy} = \frac{\sigma_{meas}}{\sqrt{nb_{obs\_mean}}}$
  - This formula is adapted to the comparison of individual sensors.
- The mean number of observation opportunities per day considering all the observed objects (i.e., the number of times they have been observed, divided by the simulation duration, and averaged over all observed objects).
- The mean gap duration for all observed objects.

2.1.2 Performance indicators for Cataloguing Simulations

The performance indicators that are of interest for the cataloguing analysis are the total number (and percentages) of objects which can be catalogued, as a function of size and orbital regimes / altitude bands. The main difficulty for this type of simulation lies in the definition of a "catalogued object", as it depends on the orbital precision required to deliver SST services. In a classic top-down approach, the user's requirements attached to services would be available and, derived from those requirements, the systems requirements would give the thresholds needed to define what is a "catalogued object" in terms of, for example, the required accuracy for a given timeliness.

Since a bottom-up approach has been followed within the EU SST projects, high-level user requirements are not available.

It was decided in 2019 that, within the architecture analysis, the definition of "catalogued object" would follow that of [3] i.e., an object is considered as catalogued if its accuracy (defined as the difference between true object and catalogued object) 48 hours after the end of the simulation is within the envelope defined Table 2-1 below.

Table 2-1. Required accuracy envelope after 48h for catalogued object (QSW local orbital frame; Q = radial; W = out of plane; S completes the frame).

Orbit Type	Threshold in QSW frame (m)
LEO	[40; 200; 100]
MEO	[600; 3000; 1500]
GEO	[2500; 2500; 2500]

One should be aware that the chosen criteria influence the results, especially in LEO where the drag perturbation complicates the maintenance of a catalogue within the above accuracy requirements.

Another indicator called "Catalogue Accuracy" is also provided by the cataloguing simulations. This indicator provides an idea of the quality of the orbit after the execution of the orbital determination and correlation algorithms. It is the median values in radial, tangential and out of the plane of the orbits errors for the objects that have been catalogued under the accuracy threshold.

2.2 Tools & Techniques

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

Both tools, with slightly different assumptions, allow simulating the observations generated by a network of sensors and provide the key indicators to estimate the performance of space surveillance and tracking systems.

2.2.1 BAS3E

The BAS3E space surveillance system simulation bench is composed of several stages, which allow performing a set of computations 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 (field of regard (FOR), limiting magnitude or radar cross section (RCS), etc.) as well as implementing surveillances strategies to position the sensors' field of view (FOV). The observation stage generates the measurements provided by such 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 Initial Orbit Determination 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 [4].

More details about the algorithms implemented in BAS3E are given in [5].

2.2.2 AS4/*Ssasim*

A combination of two different tools, AS4 and *Ssasim*, is used to perform the simulations.

AS4 is a DEIMOS proprietary tool, made available to CDTI for EU SST activities. The Advanced Space Surveillance System Simulator (AS4) is a simulation tool conceived as a simulation for space surveillance, comprising a full set of simulation capabilities. It includes space objects population environment, sensors measurements 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 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.

Once the measurements are generated, they will be processed in the Post-processing tool. This tool is based on data treatment and analysis, which provides statistical information from the objects. It allows analysing the measurements in regards to frequency of observations, gaps, duration of tracks, number of observed objects, type of observed, among others. This tool has grown in flexibility and it has been updated during the project in order to address the objectives and needs of the study.

Ssasim is a GMV's COTS (Commercial Off-The-Shelf) software tool capable of maintaining a catalogue of man-made, 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), 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 [6].

Ssasim is composed of a measurements pre-processor module, a synthetic measurements generator, an objects 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 preliminary 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 whose precise orbit is unknown and thus needs to be derived from the few measurements available. 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.

2.3 Simulation Assumptions

2.3.1 Space Population Assumptions

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:

- The definitions of the orbital regimes within this document are:
  - LEO: altitude of apogee under 2000 km (with a total number of objects of 25313).
  - MEO: number of revolutions per day in [1.5; 2.5] and eccentricity under 0.2 (with a total number of objects of 271). This definition is under revision at consortium level.
  - GEO: altitude of perigee and apogee within the GEO altitude +/- 2000 km (with a total number of objects of 2210)
  - OTHER: anything that does not lie in LEO/MEO/GEO. These objects are not considered in the current analysis, and will be analysed in future work.
- Only space objects resident in LEO, MEO and GEO are simulated, which form the primary regimes of interest.
- OTHER objects (primarily those in Geostationary Transfer Orbit (GTO), Molniya orbits and others in eccentric orbits) are omitted in this study but will be considered in future work.
- For LEO, the population is clipped at 7 cm, while for MEO and GEO, the population is clipped at 35 cm.

In order to reduce the execution time of the simulation, a reduced LEO population of 2500 representative objects is sampled for the cataloguing simulations. Such reduction has little impact on the overall estimation of the system performance as have been verified by our analysis and simulations.

In addition to those baseline assumptions, it is worth mentioning that no new objects are considered during the simulation (no launches or fragmentations occur). These aspects may be analysed in future work.

The population is propagated using numerical propagators with full dynamical models (all relevant perturbations are considered). All objects are considered as non-manoeuvring (no station keeping or collision avoidance manoeuvres are considered).

Considering that all objects are non-manoeuvring makes the correlation process easier than in reality. However, it can be assumed that it does not strongly impact the architecture trade-off since most of the space objects are debris, or do not manoeuvre on a daily basis.

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.

2.3.2 Sensors Performance Assumptions

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 the architecture analysis section.

The main general limitations of the sensor modelling are:

- The Signal-to-Noise Ratio (SNR) is not computed during the simulation.
- For radars, detection is based on the radar equation and a reference performance point (RCS value provided at a given range), which simplifies the radar behaviour for the simulations. Probability of detection and false alarm rates are not considered.
- For telescopes, detection is based on magnitude computation, the limiting magnitude value that can be detected by the telescope being an input of the simulation. Probability of detection is equal to 1 if the object is visible, as in the case of radars.

2.3.2.1 Radar performance

The NASA SEM model [9] is used in our simulation to compute the RCS of the object, given the object size (i.e., diameter) and signal wavelength.

2.3.2.2 Telescope performance

Telescope performances are described with the FOV size, the limiting magnitude (which may differ for each orbital regime, in order to account for the different exposure times) and the angular accuracy of the observations.

The magnitude model used in BAS3E tool is the following one:

$$m_{obj} = m_{sun} - 2.5log_{10}(\frac{A}{R^2}(\rho_{diff}F_{diff} + \rho_{spec}F_{spec}))$$

With:

- m_{Sun}: sun magnitude
- A: object cross sectional area
- R: range between the sensor and the object
- ρ_{diff}: diffuse reflection coefficient
- ρ_{spec}: specular reflection coefficient
- F_{diff}: diffuse reflection function
- F_{spec}: specular reflection function

Diffuse and specular reflection functions are given by:

$$F_{diff} = \frac{2}{3\pi^2}[\sin(\varphi) + (\pi - \varphi)\cos(\varphi)]$$

$$F_{spec} = \frac{1}{4\pi}$$

With φ being the phase angle.

The objects are assumed spherical; the absorption, specular, and diffuse coefficients are set to 0.8, 0.1, and 0.1, respectively.

The AS4 magnitude model is very similar, except that the specular term is not considered.

Trailing losses are not directly considered in the simulation since the SNR is not computed. However, they have been considered when establishing the limiting magnitude values for optical sensors.

2.3.3 Cataloguing Analysis Assumptions

2.3.3.1 Initial Catalogue, update and propagation

It is assumed that initially the whole population is known: 100% of the real population is inside the catalogue (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 population. 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 [10]. Initial position components are Gaussian distributed, while no dispersion on initial velocity is considered. It is acknowledged than in LEO real uncertainties depend on the altitude of perigee: orbits at low altitude have greater uncertainties, which is neglected here.
- Initial uncertainties on position and area-to-mass ratio are assumed independent.

The catalogue is propagated using numerical propagators with a full dynamical model (all relevant perturbations are considered) different from the one used to propagate the population, to account for various sources of uncertainty in the dynamical model (atmospheric drag force being the strongest one). This is a key feature for this study: a perfect knowledge of the orbital dynamics is not assumed.

Two different approaches for the update of the catalogue are used by the two tools in use:

- For BAS3E, orbit determination is performed each day of the simulation (using a batch least square method).
- For AS4/*Ssasim*, the sequential filter SRIF updates the orbit whenever a new measurement is available.
- To decide whether or not an object can be considered as catalogued, its orbit is compared with the real one (perfectly known in the simulation process): if the mean error is under a given threshold, then the object is considered as catalogued (see §2.1.2).

- The mean error between the orbit of the catalogue and the real one is obtained by computing the position of the catalogued object in the local orbital frame of the reference one. An averaging over several point spread over one orbit is performed to remove the influence of anomalies (errors being larger or smaller at the perigee/apogee). This evaluation of the error is being revisited at Consortium level to consider the estimated orbit covariance instead.

2.3.3.2 Correlation and Orbit Determination algorithms

In BAS3E, the correlation between measurements and objects of the catalogue is performed using a correlator based on a weighted Euclidean distance. The discrepancies between real and theoretical measurements (built from the catalogue) are computed and normalised by the sensor accuracy so that the different components (angular, range, etc.) of the measurements can be summed up. A root mean square summation is performed to compute the distance between the processed object and measurement, and a "nearest neighbour" algorithm is then used to associate each measurement to its closest object.

In AS4/*Ssasim* the correlation is performed by comparing the real measurements against the synthetic ones. This process starts by synchronising the real measurements to common epochs – imposed by the synthetic ones. To do so, the real measurements are interpolated to the synthetic measurements' epochs. Once both real and synthetic measurements are at the same epochs, the synthetic tracks are attempted to be correlated with each of the real tracks. For each correlation candidate (track) the residuals are obtained as the difference between the real and the synthetic measurements and are processed to obtain different metrics (for example, root-mean-square (RMS) of all the residuals of the track). These metrics are used to determine the best candidate for a given real track, and the correlation status can either be correlated or uncorrelated depending on if these metrics are within given thresholds.

In both tools, miscorrelation (association of a measurement to the wrong object) can happen, as in real life, but will hopefully be ruled out by the orbit determination filter. Nevertheless, due to previous assumptions (in particular, objects do not manoeuvre), the risk of miscorrelation is reduced.

Once the correlation step is executed, correlated measurements are used for orbit determination. The two simulation tools do not apply the same filter. BAS3E uses a Least-Squares filter with the following settings: observation filters based on measurement errors as well as Weighted Root Mean Square are used, the typical arc duration is 4 days. On the contrary, AS4/*Ssasim* uses SRIF tool as the orbit determination tool that will be executed for all the passes processed in AS4*/Ssasim* simulations. It is executed when the pre-processed tracking data is correlated to an existing catalogue object.

3 ARCHITECTURE ANALYSIS PROCESS

This section summarises the process followed for different architectural options.

The simulations aim, firstly, to analyse the direct impact of each upgrade on the sensor, so that each sensor/upgrade is simulated on its own. Then, we proceed to analyse the impact of the upgrade on the network. For this, initially a simulation of the full network without any upgrade is executed: it represents the performance of the current network fully connected and operational but not upgraded. Then, a scenario of the full network with all upgrades is simulated: it represents the maximum performance if all upgraded were completed.

3.1 Radar Architectures: Survey and Tracking Sensor

Simulations executed for the analysis include the following steps:

- First, to analyse the direct impact of the upgrade on the sensor, each sensor/upgrade is simulated on its own
- Then, to analyse the impact of the upgrade on the network, the following is considered:
  - Simulation of the full network without any upgrade: it represents the performance of the current network fully connected and operational but not upgraded.
  - Simulation of the full network with all upgrades performed: it represents the maximum performance if all upgrades were completed.
  - Then, to analyse the impact of each upgrade on every possible network assuming that all sensors remain operational.
  - Networks assuming that at least one of the sensors are not operational anymore are not considered in the added value analysis.

Finally, a redundancy analysis is performed on the objects that can be observed.

3.2 Optical Architectures: Survey Sensors

The sensors are classified by Very Large Area (VLA) criteria to ease the analysis of the geographical repartition of the sensors around the globe. The VLA concept consists in defining geographical regions allowing to group sensors by same geographical area. The underlying idea is that, at first order, the same sensor placed in locations in different VLAs will show different performance and added value. There are 7 VLA analysed: Europe, Asia, North America, South America, South of Africa, Pacific and Oceania (see Fig. 4-3).

The objective with the survey telescopes simulations is:

- To analyse the direct impact of the upgrade on the sensor, each sensor/upgrade is simulated on its own.
- To execute a redundancy analysis to estimate the amount of the observed objects by the sensor, that are already seen by other sensors within the VLA as well as the percentage of objects observed by a given number of sensors.

3.3 Optical Architectures: Tracking Sensors

The analysis of the tracking telescopes closely follows that of the tracking radars (see §3.1) though the process is partitioned across the VLA regions. That is, the configuration without the upgrades and the impact of the upgrades are assessed upon the computation of the performance metrics (coverage, redundancy across sensors, etc.) across all the sensors sharing a common VLA region.

4 ARCHITECTURE ANALYSIS CASES

4.1 Radar Architectures

The analysis is performed for several surveillance radars (GESTRA, GRAVES, S3TSR and BIRALES, see Fig. 4-2) and tracking radars (TIRA, SATAM1/2/3, BIRALET, MFDR, Pampilhosa, Cheia C, and CASTR), see Fig. 4-1. For all of them several configurations per sensor have been assumed, i.e., one base configuration free of any upgrade and others applying a range of different upgrades (hardware, software, etc.) proposed by the relevant member states. The goal is to evaluate the added value of the sensor and upgrades to the architecture, in order to select the ones showing best value for money. The same approach has been followed with the optical telescopes.

Radar performances in the form of limiting RCS vs range has been considered for the simulation, however no detailed information is provided in the paper as this information has not been released to the public.

The revisit period or the image acquisition period is also configured for each sensor according to some specific parameters.

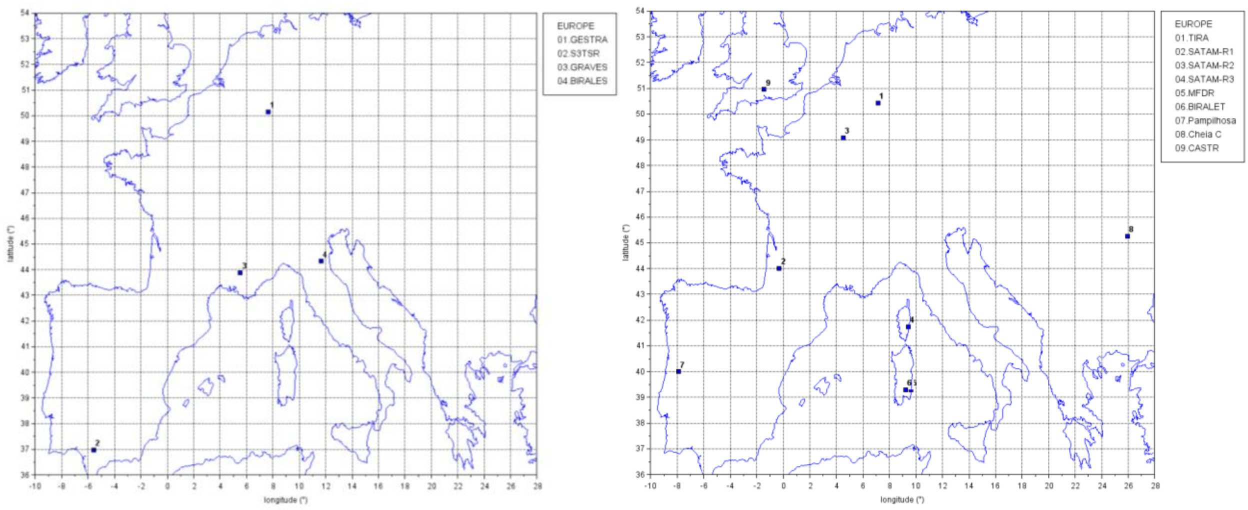
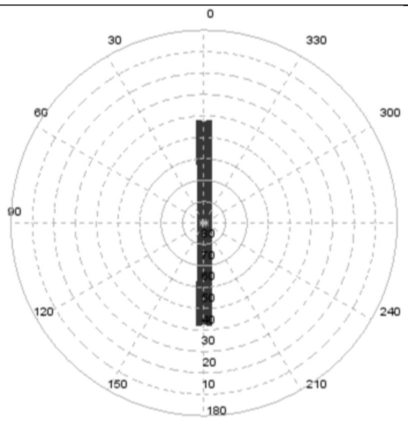
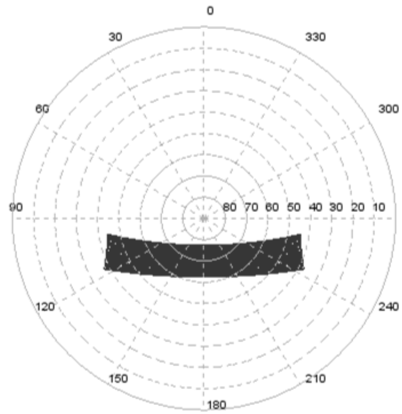


Fig. 4-1. Survey radars (left) and tracking radars (right).

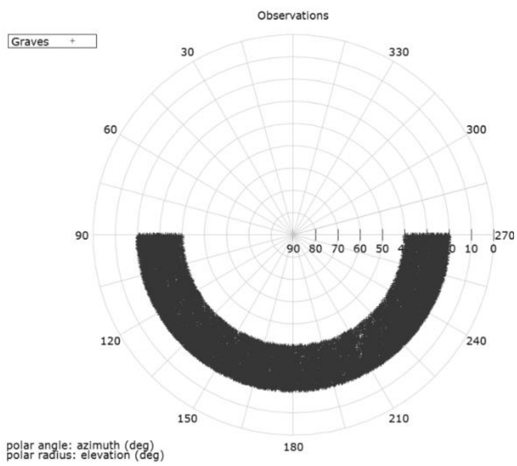
BIRALES (BIR)



GESTRA (GES)



GRAVES (GRA)



S3TSR (S3T)

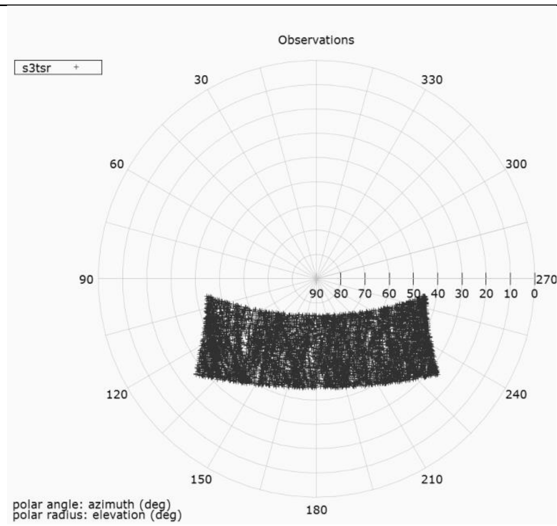


Fig. 4-2. Surveillance radars FOR.

4.2 Optical System Architectures

A total of 48 telescopes from France, Italy, Poland, Portugal, Romania, Spain and the UK have been simulated, with and without the upgrades proposed by the relevant member states. The telescopes are subdivided in the so-called VLA regions. The VLA concept refers to large areas over the Earth where sensors can observe similar objects in space (in particular those close to the GEO region).

One of the objectives of the simulations is to optimise the use of such a large number of sensors divided per VLAs, considering also redundancy aspects.

The optical architectures presented in the paper only relate to passive optical telescopes. Laser sensors are additionally used for tracking activities, but their analysis is not presented in this paper.

One of the main requirements of the telescope architecture is to allow complete coverage of the GEO ring, with at least three sites in redundancy and good site repartition to avoid seasonal effects.

In order to highlight the fact that detailed locations are not a critical specification, the sites are gathered within the VLAs (Pacific, North America, South America, Europe, South of Africa, Asia, Oceania) as shown in Figure 4-3 below.

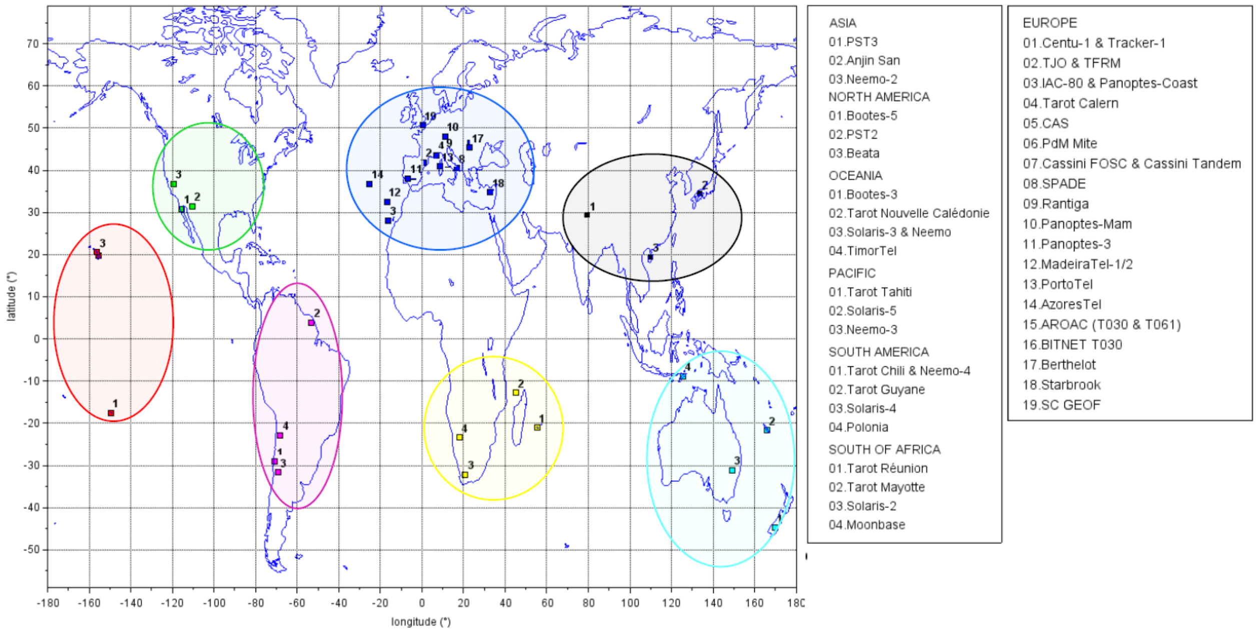


Fig. 4-3. Very Large Areas: Pacific (red), North America (green), South America (pink), Europe (blue), South of Africa (yellow), Asia (black) and Oceania (cyan).

The detailed results of each sensor networks for the simulations of 2019 are detailed in Annex A.

5 CONCLUSIONS

This paper has presented system engineering tools to support the definition of the evolution roadmap of a Space Surveillance System at short, medium and long term. Such system engineering tools, together with an associated methodology, are used to assess the performance of a sensor network, composed by a heterogeneous network of sensors, to observe and catalogue an orbital population of an arbitrary minimal size, spanning from LEO to GEO. In the framework of EU SST, the presented system engineering tools, with the associated methodology, have 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 while avoiding unnecessary duplication.

The architecture study presented here includes a total of 46 architectural scenarios involving surveillance radars (individual sensors and different combinations among them, considering configurations before the upgrades and future improvements). For the case of telescope architectures, the study has supported the analysis of the impact of each sensor upgrade to assess the redundancy among them and to estimate the number of objects (MEO and GEO population) observed by the different sensors in each VLA region. In the analysis of optical systems, adequate observation strategies have been defined considering both the objective of cataloguing GEO objects (and MEO objects for which a suitable surveillance strategy is being studied) and the main constraints of the sensors (mainly minimum visual magnitude, observation quality and revisit time according to their features).

There are a few interesting points that could be tackled in the following stages of the simulations:

- The behaviour of the EU SST system has been assessed with respect to what could be considered ‘normal operating circumstances’; however, a number of highly challenging events have been identified that could impact on the system performance. This includes discrete events such as fragmentations, as well as trends in the future on-orbit population following the introduction of ‘new space’ concepts such as large constellations and small satellites.
- The inclusion of tracking sensors (radar and optical) in end-to-end simulations, including scheduling of these sensors and the service provision layer, can show how they can contribute to the cataloguing results, but also in the case of high interest events.
- The evolution of the analysis from the sensor network to the full service provision chain, in order to measure the impact of the sensor network on service products.

6 ACKNOWLEDGEMENTS

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8 ANNEX A: DETAILED ARCHITECTURE ANALYSIS RESULTS

This section presents the detailed results for the different architecture scenarios studied in 2019. Some scenarios were provided to decision makers to select the sensors and upgrades of the current EU SST architecture.

8.1 Radar Architectures Results: Survey Sensors

The following radars and proposed upgrades were considered:

- GESTRA (GES) is considered by three configurations: current, upgrade 1 (UP1), upgrade 2 (UP2)
- GRAVES (GRA) has two configurations: current and after upgrade (UP)
- S3TSR (S3T) has two configurations: current and after upgrade (UP)
- BIRALES (BIR) has three configurations: current, upgrade 1 (UP1), upgrade 2 (UP2)

In total, 46 coverage and cataloguing simulations for survey radars were performed. The following tables summarise some results from these simulations (not including the 46 cases for the sake of simplicity). Note that ALL_UP1 and ALL_UP2 simulations include the upgrades for GESTRA, GRAVES and S3TSR with the upgrade 1 and 2 of BIRALES respectively. Table 8-1 and Table 8-2show that 45% of the objects with a size bigger or equal to 7cm are observed and 16% of them are well-observed by the whole architecture with the current configuration (ALL_2019), and that after the upgrades these values increase to 66% observed and 27% well-observed with size ≥ 7cm.

Table 8-1. Percentage of Observed Objects in LEO population for various architectures.

	Coverage (%)			
	≥7cm	≥10cm	≥50cm	≥100cm
ALL_2019	45	62	93	99
ALL_UP1	57	78	98	99
ALL_UP2	65	83	98	99

Table 8-2. Percentage of Well-Observed Objects with respect to Observed Objects in LEO.

	Well-Observed with respect to Simulated Objects (%)			
	≥7cm	≥10cm	≥50cm	>=100cm
ALL_2019	16	22	79	97
ALL_UP1	20	28	90	98
ALL_UP2	27	37	95	98

The percentage of catalogued objects for all upgraded sensors operating together (25%), is lower than the percentage of well-observed objects (27%) computed by the coverage simulations, as expected. This is more obvious for large objects with 77% of the objects ≥50cm than can be catalogued, versus 95% well observed. This highlights the fact that some objects are hard to maintain in the catalogue even if they are well observed. It can be the case for objects with a low perigee altitude or a high area to mass ratio, that are submitted to strong drag perturbation.

A set of indicators have been analysed for all radar architectures in order to evaluate the differences between them, see Table 7-3 and 7-4.

Table 8-3. LEO architectures fast indicators.

	Indicators			
	Number of tracks	Mean track length (s)	Mean number of observations opportunities per day	Mean Gap Duration (h)
ALL_2019	13145	76	1,72	54
ALL_UP1	20733	84	2,1	30
ALL_UP2	28519	82	2,5	21

Table 8-4. Percentage of Catalogued Objects with respect to Simulated Objects in LEO.

	Catalogued (% with respect to simulated objects)			
	>= 7cm	>= 10cm	>= 50cm	>= 100cm
ALL _2019	11	16	58	75
ALL_ UP1	17	24	71	76
ALL_ UP2	25	35	75	76

To help the radar architecture comparison, the following charts are used to represent the most meaningful indicators for the 46 analysed cases. As an example, the results for ALL_2019 (current radar configurations) and ALL_UP2 configurations with the upgrades are included. All upgrades together would impact the network performance in the following way:

- Number of observed objects above 7 cm increases from 11300 to 16200
- Number of well observed objects increases from 3900 to 6700
- Number of catalogued objects improves from 2800 to 6300, including 2000 objects larger than 1m. No objects under 10cm are catalogued
- The catalog accuracy is globally kept, except the out of plane component which is improved
- Daily number of tracks provided by the network goes from 18800 to 40700, with an average duration of 82 seconds
- Mean gap duration is reduced from 54H to 21H

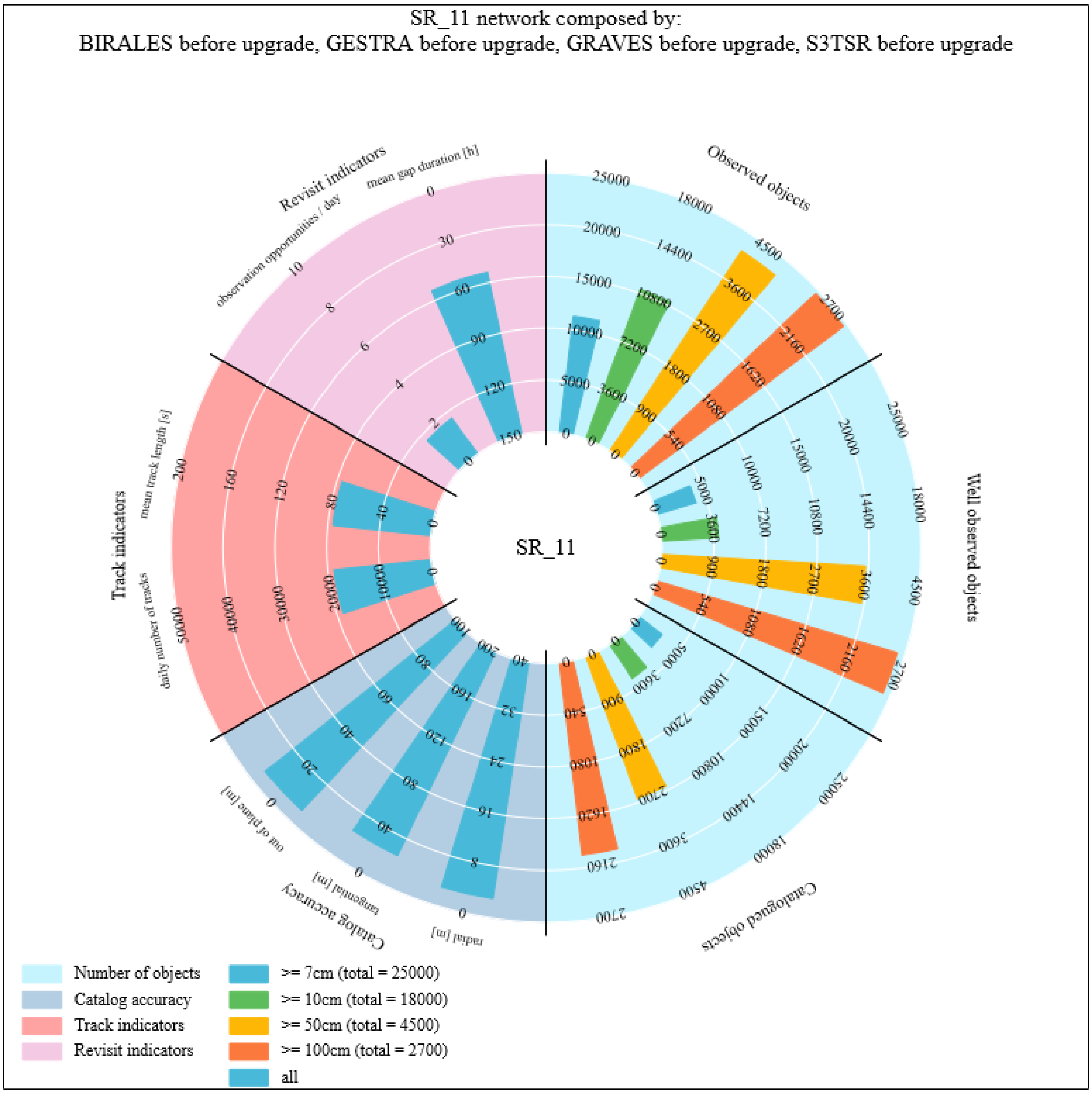

Fig. 8-1. Survey radar network performance before upgrades.

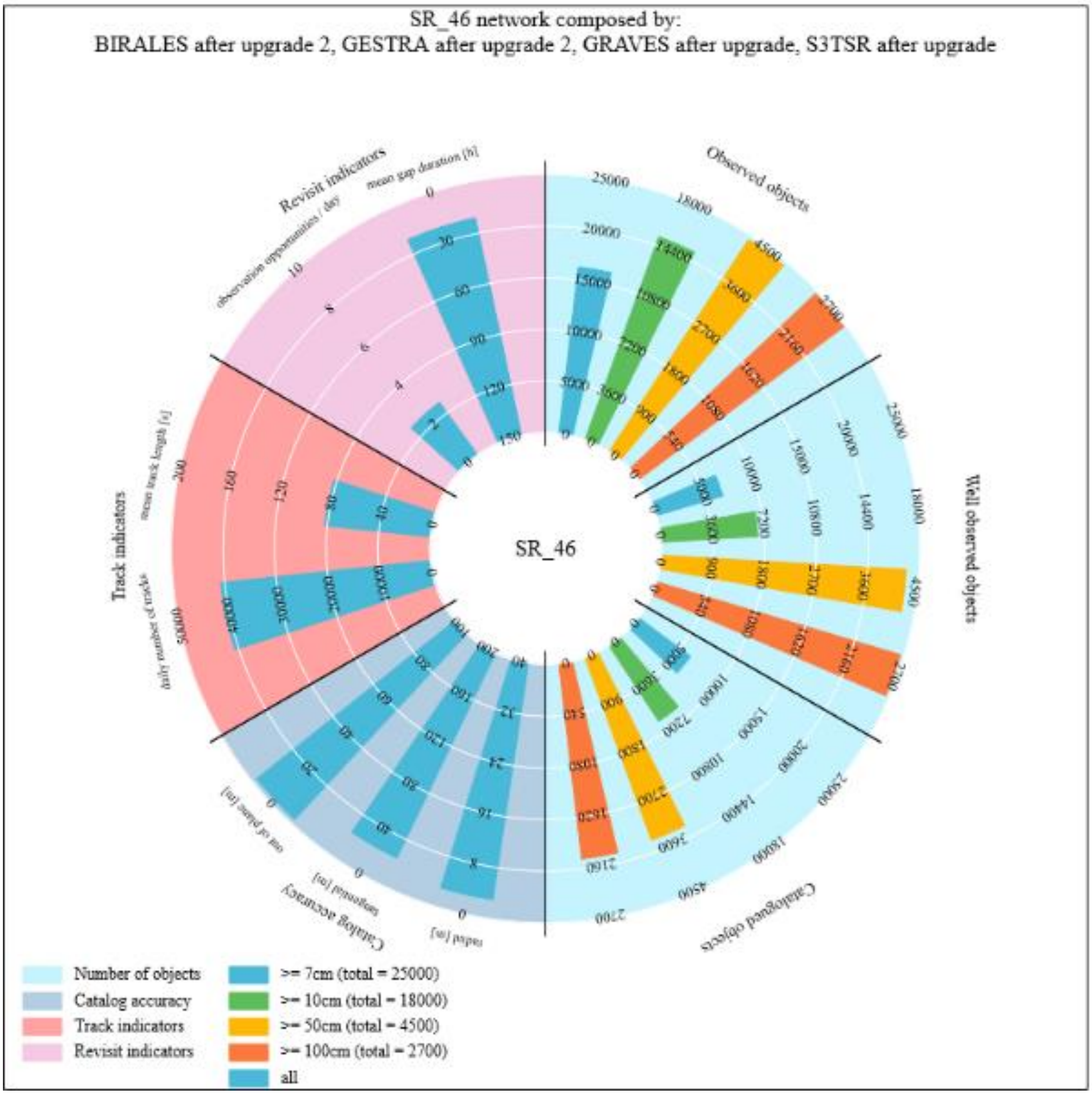

Fig. 8-2. Survey radar network performance after upgrades.

8.2 Radar Architectures Results: Tracking Sensors

All tracking radars considered in this analysis are located in Europe. They include, together with their proposed upgrades:

- TIRA with no foreseen upgrade
- SATAM 1,2 3 with no expected upgrade
- BIRALET has two upgrades (2019 and UP)
- MFDR has three upgrades (UP1, UP2 and UP3)
- Pampilhosa has one upgrade
- CHEIA C band has one upgrade and new X band (CHEIA 2019, UP and FAST)
- CASTR has one upgrade and one ISAR (CASTR 2019 and UP)

For tracking radars, only coverage simulation with FOV = FOR are performed in order to analyse what objects can be tracked. Tracking radars are simulated with 100% availability: when the actual availability is lower than 100%, it is considered in the workload estimation (post processing of simulation results).

Table 8-5. Tracking Radars coverage results.

	Coverage (%)			
	>=7cm	>=10cm	>=50cm	>=100cm
ALL 2019	99	99	99	99
ALL UP	99	99	99	99

Table 8-6. Tracking Radar well-observed results.

	Well-Observed Objects with respect to Simulated Objects (%)			
	>=7cm	>=10cm	>=50cm	>=100cm
ALL 2019	99	98	99	99
ALL UP	99	98	99	99

Finally, a redundancy analysis was performed on the objects that can be observed (keeping in mind that the simulations for tracking sensors are performed using a field of view equal to a field of regard). Fig. 7.3 below shows that only around 60% of the objects can be observed by at least two tracking radars before the upgrade. On the contrary, after the upgrade all the population could be observed by at least three tracking radars.

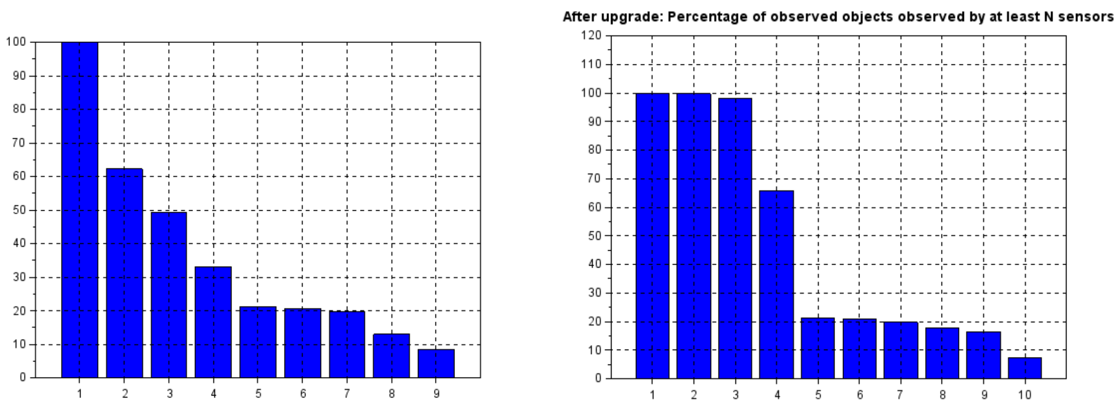

Fig. 8-3. Tracking network redundancy before (left) and after (right) the upgrade.

8.3 Optical Architectures Results: Survey Sensors

Here GEO coverage simulations are presented, lasting 14 days and considering a total of 2210 GEO objects bigger than 35 cm in the initial catalogue. Results are presented for the whole population and subgroups with >50, >100 and >500 cm diameter.

Table 7-7 lists the survey telescopes included in the simulations.

Table 8-7. Survey Telescopes List (before and after the upgrade).

VLA Region	**Survey telescopes**	
	Before Upgrade	**After Upgrade**
Asia	ANJIN SAN-A	ANJIN SAN-B PST3-D PST3-E NEEMO2_35
Europe	Tarot Calern SPADE CENTU1 TFRM PST3-D PST3-E RANTIGA-A PANOPTES-3 PANOPTES-COAST-A PANOPTES-MAM MadeiraTel1 PortoTel NEEMO 35 Starbrook	Tarot Calern SPADE CassiniFOSC CassiniTANDEM CENTU1 TFRM RANTIGA-B PANOPTES-3 PANOPTES-COAST-B PANOPTES-MAM MadeiraTel1 PortoTel Berthelot-S Starbrook
North America	BEATA	PST2-B BEATA
Oceania	SOLARIS-3B TIMORTEL	SOLARIS-3B SOLARIS-3C NEEMO 35 TAROT CALEDONIA TIMORTEL
Pacific Ocean	SOLARIS-5A	SOLARIS-5B NEEMO3_35 TAROT_TAHITI
South America	Tarot Chili POLONIA-A	Tarot Chili SOLARIS-4B POLONIA-B NEEMO4_35 TAROT_GUIANA
South of Africa	Tarot Réunion MOONBASE-A	Tarot Réunion SOLARIS-2B MOONBASE-B TAROT_MAYOTTE

The following figures show a summary of the coverage and well-observed objects for all the survey telescopes and for the four minimum object diameters analysed. The aim is to show at a glance a comparison of the more than 50 sensors, by VLA.

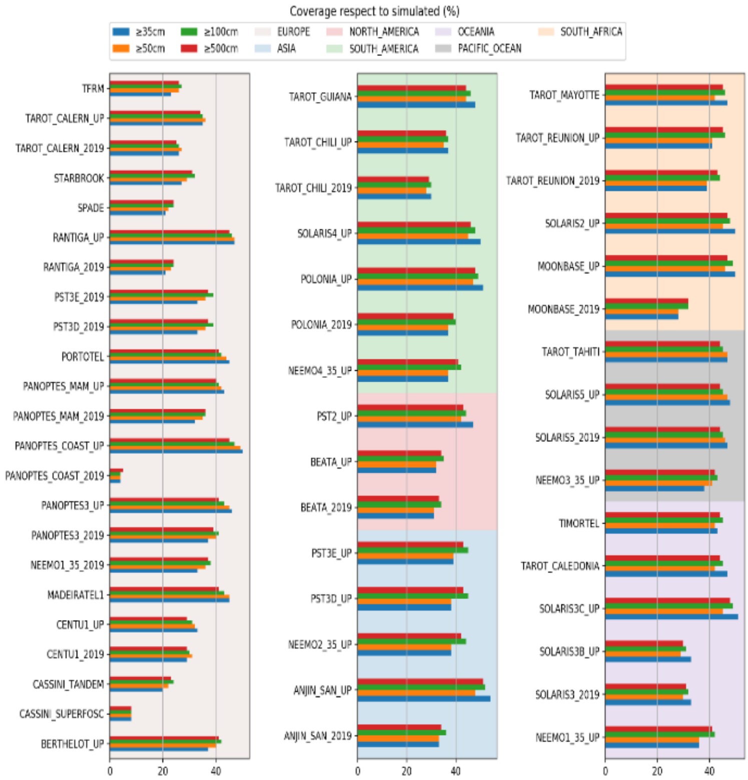

Fig. 8-4. Coverage (%) of all survey telescopes by VLA.

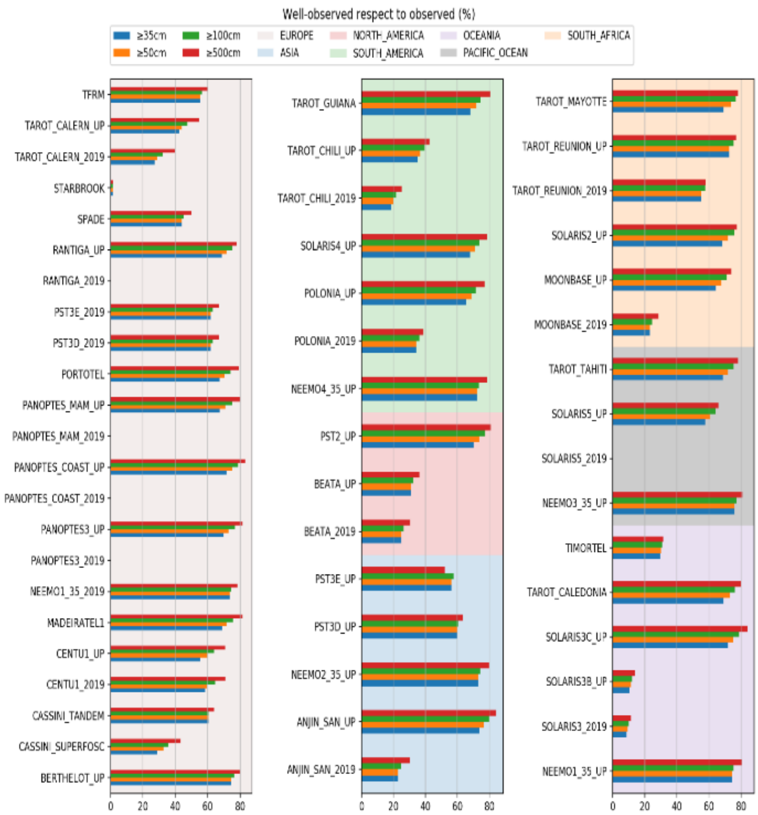

Fig. 8-5. Well-observed objects (%) of all survey telescopes by VLA.

From the added-value analysis simulations, it is also interesting to show the results of the redundancy analysis, that is, the percentage of objects that are observed by N sensors (observed by only one telescopes, observed by two, three, and so on). This indicates the overall redundancy capacity of the system. The redundancy comparison has been computed using the current configuration and the upgrade by each VLA.

8.4 Optical Architectures Results: Tracking Sensors

Only coverage simulations with FOV = FOR are performed with tracking telescopes for MEO and GEO population. As a consequence, simulation results provide the list of objects that could be tracked by the sensor: the number of objects instantaneously in the FOR is an indicator that illustrates the complexity of the tasking (minimum, mean and maximum values are of interest). This list can then be compared with the list of objects that that require tracking needs (in the basis of number of service-driven events & cataloguing needs).

Table 8-8. Tracking Telescopes List (before and after the upgrade).

VLA Region	**Tracking telescopes**	
	Before Upgrade	**After Upgrade**
Asia		ANJIN SAN-A PST3-A PST3-B PST3-C NEEMO2_50
Europe	CAS Cassini PdM-Mite Tracker 1 TJO IAC-80 PST3-A PST3-B PST3-C MadeiraTel2 AzoresTel Berthelot AROAC-T030 BITNET-T030 NEEMO_50 SGF GEOF	CAS PdM-Mite Tracker 1 TJO IAC-80 RANTIGA-A PANOPTES- COAST-A MadeiraTel2 AzoresTel Berthelot-T AROAC-T030 AROAC-T061 BITNET-T030 SGF GEOF
North America	Bootes 5 PST2-A	Bootes 5 PST2-A
Oceania	Bootes 3 SOLARIS-3A	Bootes 3 SOLARIS-3A NEEMO_50
Pacific Ocean		SOLARIS-5A NEEMO3_50
South America	SOLARIS-4	SOLARIS-4° POLONIA-A NEEMO4_50
South of Africa	SOLARIS-2	SOLARIS-2B MOONBASE-A

9 ANNEX B: SENSOR NETWORK 2019 vs 2023

As it has been explained in §1, the architecture studies presented in this paper include the sensor network under study on 2019. Not all the sensors included in the 2019 scenario are nowadays part of the current EU SST network and are considered for the future short-term scenario of 2023. Please find below the tables comparing the sensor network in 2019 and 2023.

9.1 Survey and tracking radars

Table 9-1 Survey and tracking radars 2019 vs 2023.

Survey radars		Tracking radars	
2019	**2023**	**2019**	**2023**
BIRALES GRAVES GESTRA S3TSR	GRAVES GESTRA S3TSR	TIRA SATAM 1,2,3 BIRALET MFDR Pampilhosa CHEIA C CAST	TIRA SATAM 1,2,3 BIRALET BIRALES MFDR-LR,MR Pampilhosa

9.2 Survey and tracking telescopes

Table 9-2 Survey and tracking telescopes 2019 vs 2023.

VLA Region	Survey telescopes			Tracking telescopes		
	Before Upgrade 2019	**After Upgrade 2019**	**2023**	**Before Upgrade 2019**	**After Upgrade 2019**	**2023**
Asia	ANJIN SAN-A	ANJIN SAN-B PST3-D PST3-E NEEMO2_35	ANJIN SAN-B NEEMO2_35		ANJIN SAN-A PST3-A PST3-B PST3-C NEEMO2_50	ANJIN SAN-A NEEMO2_50
Europe	Tarot Calern SPADE CENTU1 TFRM PST3-D PST3-E RANTIGA-A PANOPTES-3 PANOPTES-COAST-A PANOPTES-MAM MadeiraTel1 PortoTel NEEMO_35 Starbrook	Tarot Calern SPADE CassiniFOSC CassiniTANDEM CENTU1 TFRM RANTIGA-B PANOPTES-3 PANOPTES-COAST-B PANOPTES-MAM MadeiraTel1 PortoTel Berthelot-S Starbrook	Tarot Calern SPADE CassiniFOSC CassiniTANDEM CENTU1 TFRM RANTIGA-B PANOPTES-COAST-B PANOPTES-MAM MadeiraTel1 Berthelot-S AzoresTel1	CAS Cassini PdM-Mite Tracker 1 TJO IAC-80 PST3-A PST3-B PST3-C MadeiraTel2 AzoresTel Berthelot AROAC-T030 BITNET-T030 NEEMO_50 SGF GEOF	CAS PdM-Mite Tracker 1 TJO IAC-80 RANTIGA-A PANOPTES-COAST-A MadeiraTel2 AzoresTel Berthelot-T AROAC-T030 AROAC-T061 BITNET-T030 SGF GEOF	PdM-Mite Tracker 1 TJO IAC-80 RANTIGA-A PANOPTES-COAST-A PANOPTES-MAM MadeiraTel2 AzoresTel2 AROAC-T030 AROAC-T061 Berthelot-T
North America	BEATA	PST2-B BEATA	PST2-B BEATA NEEMO3	Bootes 5 PST2-A	Bootes 5 PST2-A	Bootes 5 PST2-A BEATA NEEMO3
Oceania	SOLARIS-3B TIMORTEL	SOLARIS-3B SOLARIS-3C NEEMO_35 TAROT CALEDONIA TIMORTEL	SOLARIS-3B SOLARIS-3C NEEMO_35 TAROT CALEDONIA PANOPTES-1	Bootes 3 SOLARIS-3A	Bootes 3 SOLARIS-3A NEEMO_50	Bootes 3 SOLARIS-3A NEEMO_50 TAROT CALEDONIA PANOPTES-1
Pacific Ocean	SOLARIS-5A	SOLARIS-5B NEEMO3_35 TAROT_TAHITI	SOLARIS-5B		SOLARIS-5A NEEMO3_50	SOLARIS-5A
South America	Tarot Chili POLONIA-A	Tarot Chili SOLARIS-4B POLONIA-B NEEMO4_35 TAROT_GUIANA	Tarot Chili SOLARIS-4B POLONIA-B	SOLARIS-4	SOLARIS-4° POLONIA-A NEEMO4_50	Tarot Chili SOLARIS-4A POLONIA-A
South of Africa	Tarot Réunion MOONBASE-A	Tarot Réunion SOLARIS-2B MOONBASE-B TAROT_MAYOTTE	Tarot Réunion SOLARIS-2B MOONBASE-B	SOLARIS-2	SOLARIS-2B MOONBASE-A	Tarot Réunion SOLARIS-2B MOONBASE-A