ARCHITECTURAL DESIGN FOR A EUROPEAN SST SYSTEM

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ABSTRACT

The paper presents the results of a detailed design, evaluation and trade-off of a potential European Space Surveillance and Tracking (SST) system architecture. The results have been produced in study phase 1 of the on-going "CO-II SSA Architectural Design" project performed by the Astrium consortium as part of ESA's Space Situational Awareness Programme and are the baseline for further detailing and consolidation in study phase 2. The sensor network is comprised of both ground- and space-based assets and aims at being fully compliant with the ESA SST System Requirements. The proposed ground sensors include a surveillance radar, an optical surveillance system and a tracking network (radar and optical). A space-based telescope system provides significant performance and robustness for the surveillance and tracking of beyond-LEO target objects.

1 INTRODUCTION

Phase 1 of the CO-II project tackled the consolidation of the system requirements; the definition and trade off of potential sensor-networks and non-sensor infrastructure options and the selection of a baseline architecture design. In the following phase 2, this baseline architecture will be further detailed to include the development of a programmatic roadmap which will then be presented to the Agency. Although the top-down architectural design is also performed for the Space Weather (SWE) and Near Earth Objects (NEO) segments of the programme, this paper addresses only the SST segment. The activity is one of two ESA contracts running in parallel and it is anticipated that the results of the two contracts will be consolidated in order to obtain a final target architecture.

2 KEY DRIVERS AND METHODOLOGY FOR ARCHITECTURE DESIGN

Well before the start of the SSA Preparatory Programme, architecture studies to size and design the European Space Surveillance and Tracking (SST) were carried out within the framework of technological studies. Several sensor network architecture concepts with different levels of performances were proposed, see e.g. [1], [2], [3], [4], [5].

Within the scope of the SSA Preparatory Programme, the requirements for an SST system were elaborated, shaping the main features of the services it intends to offer with the associated expected level of performances. These requirements paved the way for the design activities.

A thorough review of these requirements was performed at the start of the study, bringing understanding, quantification and confirmation to the essential performance requirements and allowing the identification of key design drivers.

A 'lethality' study was included to assess the size of objects leading to a lethal collision. A lethal collision is defined to be a collision between any space object and an operational satellite which ends the satellite's mission. In order to reduce the probability of lethal collision by the required 90% compared with the probability without a system, the study concluded that LEO objects of the size of about 5.7 mm must be catalogued. Feasibility of mass cataloguing of the lethal debris was clearly questioned by the tremendous sensing sensitivity required and the subsequent amount of detections to be processed and further correlated. In consequence it was decided not to consider the lethal requirements in the design and sizing of the SST capabilities, but to aim at a full compliant system with respect to mitigation of the catastrophic collisions. A catastrophic collision is defined as a collision with Energy to Mass Ratio (EMR) greater than 40 J/g. This threshold allows to determine the collisions that could potentially produce a very high number of objects in orbit.

Simulations were performed to define the different key

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parameters leading to the reduction of the required catastrophic collision risk, i.e. by 90% compared to the natural collision probability without a system.

The key parameters were found to be the object size, orbit accuracy, the false alarm rate and the Accepted Collision Probability Level (ACPL, the collision alert threshold). Moreover, it was shown that various combinations of these parameters may lead to the relevant reduction of the collision probability in compliance with the SST requirements (Fig. 1).

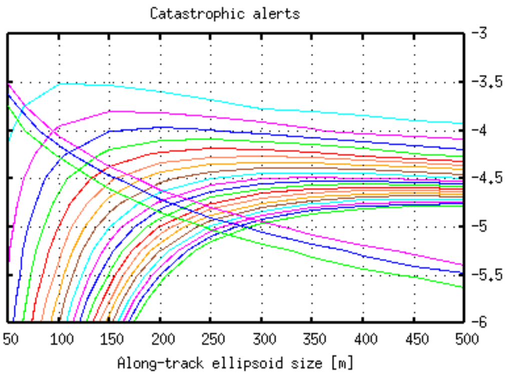


*Figure 1. Sample shape of LEO catastrophic alerts per sat*year (curve from 0.1 to 2) and risk reduction (90, 92, 94% - pink, blue and green lines superimposed) per envelope size (x-axis) and log10(ACPL) (y-axis)*

As the requirements on these parameters vary depending on the target populations and the orbital regimes, the most stringent criteria were selected to define the reference groups of population to be considered for performance simulation setting thereby the minimum size of the objects to be detected for each type of orbit.

These five reference groups are defined as follows (Fig. 2):

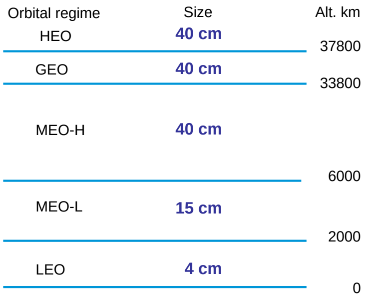


Figure 2. Minimum size of object to be detected as a function of the orbital regimes. The size of the objects to be detected increases with altitude in the LEO regime with a start value at 4cm.

Note that these groups were derived for simulation purposes. The actual requirements can differ, e.g. the MEO region is not divided in high and low but a size law is provided. For LEO, the size requirement is not fixed but needs to be traded between the other key parameters described above.

The other key requirements identified driving the SST architecture are the complete coverage of the above population groups and the timeframe during which the accuracy envelope (derived from the risk reduction analysis) must be maintained. An object orbit must be updated 48 hours before it violates this accuracy envelope.

The approach taken to design and to converge towards a baseline architecture was then a combination of a top-down and a bottom-up approach. A schematic of the process is shown in Fig. 3.

In the bottom-up approach, a thorough review of previous architecture studies was performed. It led to the identification of major building blocks for the design of an architecture that can be compliant with the driving system requirements.

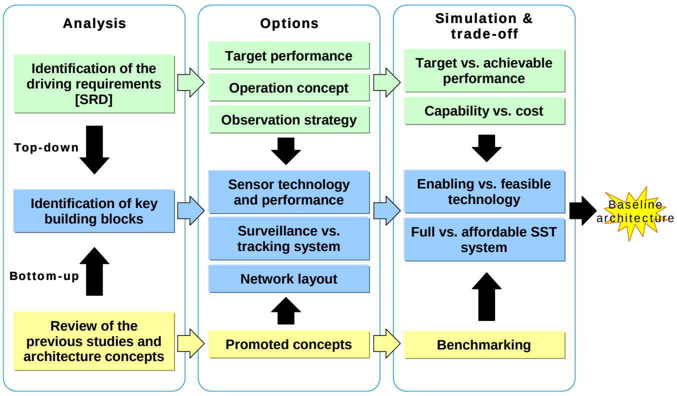


Figure 3. Schematic of the engineering approach

In the top-down approach, these building blocks were adapted to reach the best compromise for compliance with the key requirements (see section 3). Different options for sensor performance, observation patterns and strategies were assessed in order to meet the required coverage, detection sizes and availability. Simulations were carried out to validate these enhancements (see section 4).

Trade-offs between different options for one building block were carried out and finally, the assembly of the chosen building blocks lead to the proposed baseline sensor network architecture. Last but not least, given the high number of objects to be detected and tracked, an effective surveillance system within the SST segment is expected to:

- Detect new objects in space,
- Set-up a data base containing the orbit of all known objects,
- Re-detect already seen objects, and
- Maintain the objects orbital data base while meeting the accuracy envelope requirement.

3 SENSOR NETWORK ARCHITECTURE ELEMENTS

3.1 Ground-based Radar

In order to perform the surveillance of objects in LEO orbits (up to 2000 km), the most suitable option is to use ground-based radar. Radar assets are insensitive to weather outage effects and can be operated continuously on a 7d/24h basis (arguments that are later also key for space-based optical observations of beyond-LEO objects). However, the required transmitting power limits the range for reasonably sized surveillance radar to the LEO region.

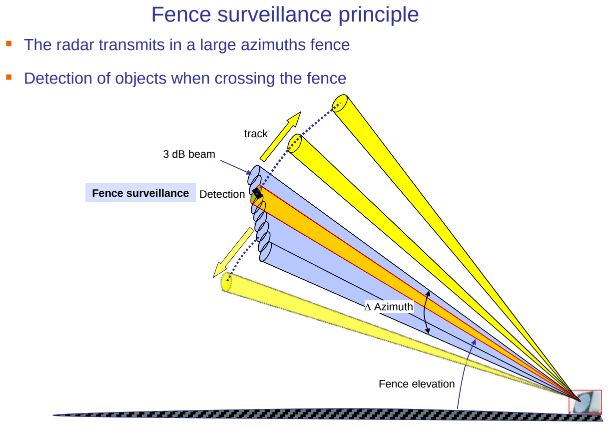
Different options for the surveillance radar were considered. The following trade-offs were made:

- Tracking concept: „1 surveillance radar + n tracking radars“ vs. „1 surveillance radar only“
- Radar type: „Monostatic“ vs. „True bi-static“ vs. „Quasi-monostatic“
- Sensitivity & altitude „4 cm at 2000 km altitude“ vs. „6 cm at 1600 km“ vs „…“
- Frequency Band: UHF vs. L-Band vs. S-Band
- Radar location, search volume, etc.

Tracking concept:

The surveillance radar shall provide data for both, initial and high precision orbit determination (OD) in order to set-up and maintain a database with orbital information of LEO objects satisfying all customer specified requirements. The proposed system is one joint surveillance and tracking phased array radar which meets the requirements for a fence based surveillance & track initialisation as well as the OD requirements of the tracking process.

Fig. 4 shows the operation principle of this fence based surveillance & tracking radar: An object is detected when it crosses the radar fence. Then, it is immediately tracked in order to support initial OD respectively the orbital parameters' refinement process.


Fence surveillance principle

- The radar transmits in a large azimuths fence
- Detection of objects when crossing the fence

Figure 4. LEO surveillance radar operation principle

Radar type and sizing:

To take advantage of bi-static configurations (separated transmitter and receiver: E.g. less complex cooling, less thermal noise) while omitting most of its contras (e.g. different TX and RX look angles), a radar system working in a quasi-monostatic configuration is proposed. Here, transmitter and receiver are separated but are in close vicinity.

Sensitivity & altitude:

In order to ensure the customer required reduction of catastrophic collisions by means of providing collision warning services, the complete system has to enable surveillance down to object sizes shown in Fig. 2. Several options were analysed (6 cm at 1200km, 4cm at 1200 km, 6 cm at 1600 km, 8 cm at 2000 km, 4 cm at 2000 km). As best compromise between detection/cataloguing performance and requirements on design and power budget, the 6 cm at 1600 km reference altitude was chosen.

Operating frequency:

The selection of the operating frequency band has far-reaching consequences, also because later-on changes are almost impossible for financial, legal and technical reasons. Thus, besides physical reasons, one has to assess preferably all relevant factors in the frame of the frequency selection. Relevant factors are

- Achievable radar cross section (RCS),
- Required operating power
- ITU frequency regulations,
- Properties w.r.t. object separation and characterisation,
- Technical readiness level (TRL) of the components and assemblies
- Costs, and Expandability options

As preliminary choice, S-Band (3085 MHz) has been selected due to compliance with derived accuracy requirement, minimum absolute size estimation errors in the regimes of interest, attitude rate and stabilisation state assessment capability, etc. However, the assessment if alternatively an L-Band solution can meet the requirements is on-going. Such a solution could mitigate complexity and cost of the radar design.

Location:

Previous studies have shown that a radar located at low to medium latitudes (e.g. Spain, Germany) provides good coverage of LEO orbits.

3.2 Ground-based Telescopes

The suitability of optical means for space surveillance is mainly linked to the ability to detect faint objects at rather large distances. The object brightness and respective detection capabilities are directly linked to its size, its range, its angular velocity and its illumination conditions. Moreover, observations are only possible during the night.

Because of these constraints, the optical surveillance of objects in LEO is quite challenging. In particular the projection of the Earth shadow at low altitudes spans a wide angle on the sky, and prevents objects to be illuminated during all the night. Typically the objects in LEO can be observed only during 1-2 hours after sunset or before sunrise. These restrained observation conditions along with the respective implications w.r.t. the complexity of the required telescope design and orbit determination procedures have led to the exclusion of optical surveillance for the LEO region (also for upper LEO e.g. as radar complement) within the study.

For higher altitudes, the most important requirement is the ability to detect objects with sizes of a few tens of centimetres. For instance, for low MEO objects (altitudes between 2000 and 6000 km), and assuming an elevation of 30°, objects with a size of 15 cm have apparent magnitudes between 14 and 17. For upper altitudes (upper MEO to GEO orbits), but assuming this time objects with a size of 40 cm, apparent magnitudes are between 15 and 18.

The other main requirement of optical systems for space surveillance is the ability to survey a large portion of the sky, which allows detecting new objects, observing steady and transient phenomena, and performing observations of catalogued objects to achieve and maintain the required orbital accuracy. This means that optical telescopes with a large FoV are needed in order to optimise the observation time. Following trades w.r.t. technical complexity, abberations, etc., it has been decided to use telescopes with a moderate FoV (2°) in order to reduce the risks associated to a complex optical design, and then follow a “*scanning fence*” approach. In that case the telescope is moved in a step-and-stare fashion to cover a stripe in a particular direction. In that case the mount of the telescope becomes very critical, as requirements are quite demanding in terms of slewing rate (≥2 deg/s) as well as stabilisation duration (≤1 second), but still with the ability to move a telescope with a diameter of around one meter.

This approach is particularly suited for the observation of GEO and to less extent MEO orbits, as the field-of-view crossing times are long, which allows observing the same object several times with the same telescope. For such orbits, the coverage of a fence in declination ensures even the coverage of objects with large inclinations. Fig. 5 shows the concept that has been retained, where four telescopes are used to each scan ±17 degrees declination stripes, located respectively at right ascension of -30°, -15°, +15° and +30° from the anti-sun direction. Each individual strip is made of 17 patches of size 2.5° x 2.5°, scanned in a step-and-stare fashion. The time in each frame is equal to 10 seconds (allowing three measurements of an object per revisit), and the time to slew between frames, including field stabilisation) is equal to 5 seconds.

The derived telescope parameters are the following:

- An aperture of 1.0 m, with a collecting area equivalent to a 0.8 m diameter full aperture telescope and an overall length of 3.5 m

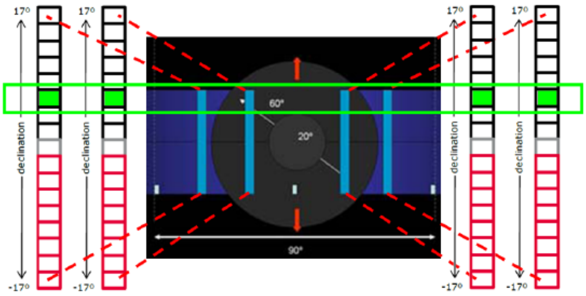


Figure 5. Observation strategy retained for the surveillance of high altitude orbits (MEO/GEO).

- A folded Schmidt optical design, providing a FoV of 2.5° x 2.5°
- A 4k x 4k detector, with a pixel size of 15 µm (equivalent to 2.5 arcsec/pixel)

The limiting magnitude for a given sensor/site depends on the relative angular velocity of the object. Fig. 6 provides the achievable detection performance in GEO (top) and MEO (bottom), where it can be seen that objects with apparent magnitude up to 18 (40 cm from 6000 km upwards), 14.25 (15 cm at 2000 km) or 15.5 (22 cm at 6000 km) can be detected.

However above approach may have some gaps in the observability of specific orbits. Depending on timeliness and revisit requirements, additional telescopes could be required for the surveillance of non-GEO orbits (e.g. MEO). Additional tracking telescopes may also be required to improve the catalogue accuracy of such orbits. The specification of these extra telescopes will be part of the architectural detailing.

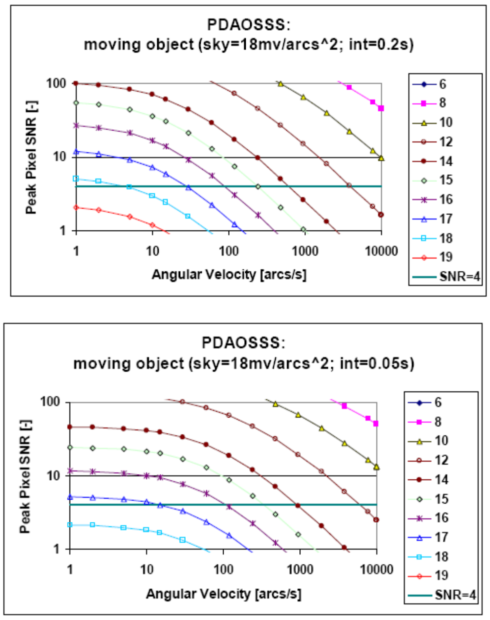


Figure 6. Limiting magnitude of a telescope as a function of the apparent angular velocity. Exposure time optimised for GEO (15 arcsec/s, top) and MEO (50 arcsec/s, bottom).

3.3 Space-based Telescopes

Space-based telescopes are especially suitable for the surveillance and tracking of beyond-LEO objects. Especially for GEO, an SBSS (Space-Based Space Surveillance) satellite can play out its advantages just as radar does for the LEO population:

- An SBSS makes the optical SST system robust, as it is insensitive to weather, atmospheric conditions and the day/night cycle.
- Full longitudinal GEO belt coverage and high availability are obtained along with
- Favourable properties w.r.t. catalogue generation and maintenance due to very good observation timeliness and re-visit times.
- And: no geographical and geopolitical restrictions as for multiple ground-based optical sites have to be considered.

During the study, different possible orbits and observation strategies for a space-based telescope have been discussed. The outcome of these trades point strongly towards a telescope in sun-synchronous LEO for comprehensive GEO surveillance and significant collateral detections and cataloguing of objects in other orbital regimes such as MEO.

By employing active pointing close to the Earth shadow for minimized phase angles in a step-and-stare fashion similar to the ground-based fence concept, the complete GEO belt can be covered with frequent follow-ups. The orbital dynamics of the GEO population carries the objects through SBSS' observation fence within 24 hours, just as the Earth carries the surveillance radar fence through the LEO population once per day. This is at the same time the reason why only one sensor can achieve comprehensive GEO coverage, with enhanced follow-up performance and thus orbit determination accuracy via an optional second s/c. As an alternative, only one s/c could be used for performing both observation and follow-up, resulting in a somewhat reduced total coverage but higher accuracy.

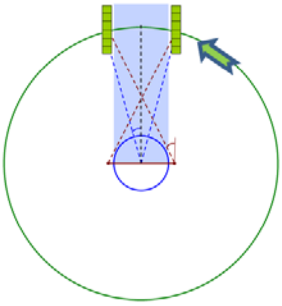


Figure 7. GEO surveillance fence strategy via step-and-stare pattern. Fences should be located close to the Earth shadow (blue) for low phase angles. Two fences are shown, which could be covered either by a constellation of two s/c or by one s/c only with reduced declination coverage. While the s/c orbit (red horizontal line) remains inertial, the objects in the GEO belt (green circle) drift through the fence (arrow).

Besides the nominal surveillance mode, the tasked tracking of specific objects is possible. The operational flexibility of the SBSS will also allow a significant contribution w.r.t. other mission goals such as the detection of manoeuvres and break-up events, object characterisation, special mission support (e.g. for LEOP), timely reaction w.r.t. collision risk assessment and will also potentially contribute to the characterisation of the sub-catalogue small debris population. In addition, an SBSS could host further secondary payloads, e.g. Space Weather sensors.

The early deployment of an SBSS demonstrator could provide substantial initial operating capability for the SST system. While the technologies themselves which are required for an operational SBSS are considered mature and have been mostly demonstrated already by other missions, the goal is the demonstration of the complex end-to-end chain of mission functions from planning, tasking, acquisition of measurements via different observation strategies, image processing to finally the generation of the product. Therefore, the demonstrator will show degraded performance only for a few requirements (e.g. sensitivity) while being compliant to the functional and most other performance requirements (e.g. metric accuracy). The combination of the demonstrator with an operational SBSS deployed later on (constellation of two s/c as mentioned above) can lead to increased performance.

Table 1: Baseline mission parameters for SBSS

Parameter	Mission Baseline
# telescope s/c	1 (operational) + 1 (demonstrator)
Detection principle	Visible spectrum, passive optical detection
Telescope orbit	LEO, 750 km reference altitude (600–900 km), SSO; LTAN 18:00–20:00
Operational modes	Surveillance; Tracking; Small Debris
Orbital regions for surveillance	Emphasis on GSO objects; plus: beyond-LEO (GTO, MEO, HEO, Molniya)
Orbital regions for tracking	Emphasis on MEO objects; plus GSO, GTO, HEO, Molniya, LEO (tbc)
Other regions	Detection of small debris in LEO
Pointing modes	Active pointing of telescope via platform
Observation strategies	For GEO/GSO belt: GEO Fence; phase-angle optimized close to the Earth shadow Non-GEO: Tasked tracking;

Although the SBSS can provide significant performance, a jointly and complementarily operated ground-based optical system is deemed favourable in order to achieve full compliance to the ESA SST system requirements. First of all, SBSS concentrates on the coverage of the GEO belt. Possible remaining accuracy or coverage gaps can be closed from ground along with more frequent follow-ups. Of course, larger apertures for higher detection sensitivity (smaller objects) can be implemented more cost efficient on ground.

The proposed 30 cm telescope with 5° field-of-view (compact TMA design for large FOV and aperture) for the operational SBSS has been derived in order to catalogue GEO objects down to 70 cm in nominal operations. This includes the “catastrophic” object population > 1 m and parts of the “Mission Related Object” (MRO) population. However, sensitivity can be improved for adapted observation strategies which aim at decreased observed angular rates of the target objects. The 40 cm sizes threshold of the ESA SST requirements could therefore be achieved.

For other orbit regimes like GTO, Molniya, and in particular MEO, one SBSS can detect and catalogue only parts of the population. The remainder should be covered by telescopes on ground, as a larger number of sensors might be required in order to implement an efficient strategy (which might still remain challenging for some populations).

Table 2: Main SBSS s/c characteristics

Main characteristics	Parameter
Telescope aperture	30 cm (operational) 20 cm (demonstrator)
Telescope Field-of-View	5°x5° (operational) 3°x3° (demonstrator)
Optical design	TMA (Three-Mirror-Anastigmat)
Platform	3-axis stabilized Launch mass ≥ 500 kg (operational) Launch mass ≤ 200 kg (demonstrator)

4 PERFORMANCE ASSESSMENTS

A preliminary assessment of the different sub-architectures in terms of detectability and cataloguing is provided in the following. It has been done by simulating the observations of a given sensor network for a given object population. The simulations are evaluated afterwards to provide two different indicators, the number of objects detected as a function of time, and the number of objects revisited at a given rate (e.g. every 24 h), as a function of time:

1. An object is considered *detected* by an optical device if its apparent magnitude (computed as a function of albedo, distance and phase angle) is brighter than the threshold of the telescope (which is a function of the relative velocity). This definition ignores important effects like the identification of the object in a star field, correlation between consecutive images, etc.
   Detectability with radar is fulfilled if the RCS of the object is bigger than the radar´s minimum RCS at the object´s distance (radar *power-four* law is applied to computed the detectable RCS at a given distance).
2. *Cataloguing* means that it is possible to perform an orbit determination that fulfils the required accuracy. The simplification applied in the simulations is by means of *re-visiting*: If an object is observed every some hours, it should be possible to catalogue it. This approach ignores a number of real-world issues, in particular correlation and the initial orbit determination.

For the purposes of this initial analysis, the following re-visiting criteria have been used:

Table 3: Cataloguing criteria

Orbital Regime	Maximum re-visiting period
LEO	24 hours
Low MEO	30 hours
High MEO	30 hours
GEO	36 hours
HEO	36 hours

Three different sub-systems will be analysed: The ground-based network of telescopes, the space-based network of telescopes, and the ground-based radar.

For the *ground-based network* two different options were evaluated. Both uses the same network of sites (*Tenerife, Marquises Island, Cyprus* and *Perth*), but differ in the number of telescopes per site, and the characteristics of the telescopes.

Table 4: Characteristics of ground-based telescopes

	4 fences	**2 fences**
Number of telescopes per site	4	2
Field of view of the telescopes	2.5˚	6.67˚
Declination stripes surveyed (phase angles)	-30˚, -15˚, +15˚, +30˚	-25˚, +25˚

For the *space-based network*, Two different options were evaluated: Either to use one or two Sun-synchronous satellites at 750 km altitude. They are continuously scanning a declination stripe in the GEO ring, a strategy similar to that used by the ground-based telescopes. The angular separation between the declination strips is ±11.5˚ w.r.t. the centre of the Earth shadow, and the field of view of the telescopes is 5 degrees.

Finally, for the radar system, five different designs were tested, which differ in its capabilities defined in Table 5. The radar is located in Spain and it is scanning a fence between 20˚ to 40˚ in elevation and 120˚ and 240˚ in azimuth.

Table 5: Characteristics of the radar

	1200 km-6cm	1200 km-4cm	1600 km-6cm	2000 km-8cm	2000 km-4cm
Minimum size (cm)	6	4	6	8	4
RCS (m^2)	2.21E3	7.19E4	2.21E3	3.3E3	6.47E4
Reference distance (slant range) (km)	2455	2455	3084	3672	3672

Fig 8 and Fig 9 show the coverage obtained by the *ground-based telescopes* after simulating 15 days around March´s equinox and June´s solstice. The blue bars correspond to the first system, which have four telescopes per site with smaller field of view, while the red bars correspond to the system with two telescopes per site with higher field of view. This higher field of view can be seen in the higher detectability and re-visiting in MEO and HEO.

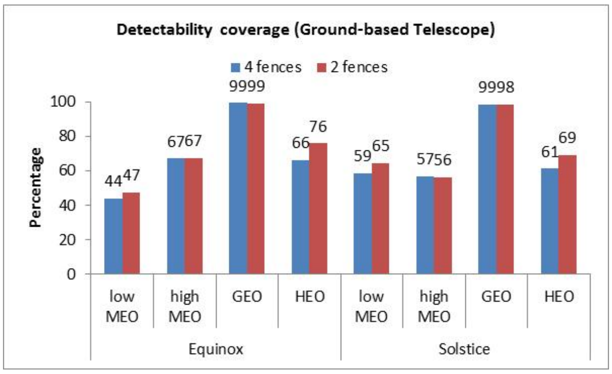


Figure 8: Detectability coverage of g-b telescopes

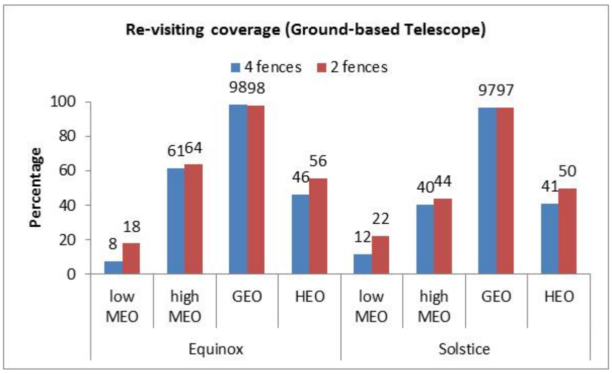


Figure 9: Re-visiting coverage of g-b telescopes

Fig 10 and Fig 11 show the results of the *space-based telescopes* after simulating 15 days around March´s equinox and June´s solstice. Blue bars correspond to one satellite while red bars to two satellites. The clear advantage seen with the two satellites is the re-visiting where in some cases is significantly higher.

It is emphasised, that the reference population included objects down to 40 cm size, which cannot be detected by the SBSS in nominal mode as explained above. This explains why 100% coverage is not reached. Moreover, the simulated FOV has been simulated not rectangular but circular (but same area), hence some “leakage” is expected between observation fields.

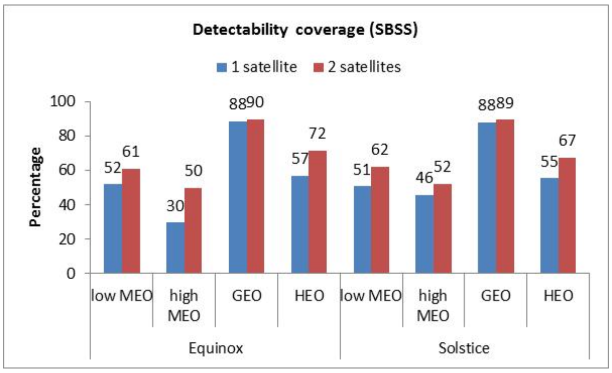


Figure 10: Detectability coverage of SBSS

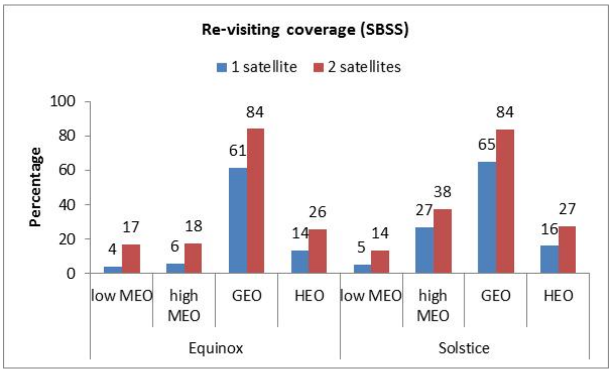


Figure 11: Re-visiting coverage of SBSS

Finally Fig 12 and Fig 13 show the results of the different radar systems after simulating. The main differences are clearly seen in the high MEO region, where obviously the more powerful is the radar, the more objects it can detect.

It is important to note that for the radar simulation, the population of objects used included objects in LEO with sizes bigger than 4 cm, so the effect on smaller objects cannot be assessed in these figures.

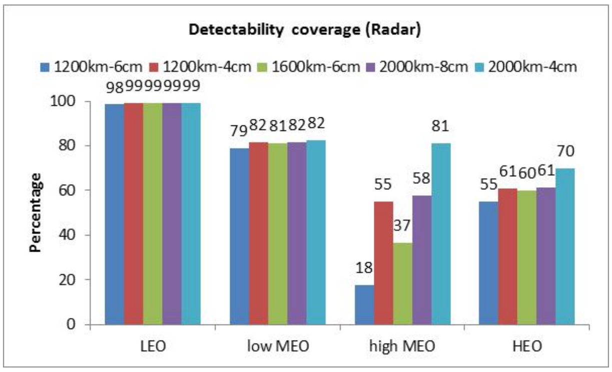


Figure 12: Detectability coverage of radar

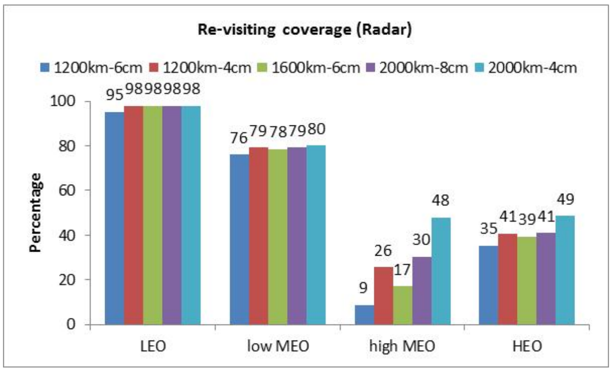


Figure 13: Re-visiting coverage of radar

This preliminary results shows that it is possible to detect 99% of all LEO/GEO objects with very high re-visiting characteristics. In MEO the results are more complex to assess, indicating that it would be needed to combine optical and radar measurements.

These results are being refined to include other effects, like realistic conditions under which an object can be said to be pre-catalogued and then accurately catalogued. Also it is expected to include degradation factors like weather conditions on the *ground-based telescopes*, failures on the detection and correlation of the objects, etc. This additional constrains will have significant effects in the final system.

5 TRADE-OFF CRITERIA AND METHOD

In order to further compare the potential architecture options against each other, a set of trade-off criteria was identified and applied. These criteria were chosen in order to support a decision that takes both technical and programmatic aspects into account and include amongst others performance compliance and scalability, robustness, development, programmatic and political risks, system autonomy and cost. Besides the sensor network but beyond the scope of this paper, the data centre and processing infrastructure has been traded and baselined in a similar fashion.

6 CONCLUSION

A baseline architecture for the sensor network of a European SST system has been derived during Phase 1 of the CO-II study with the goal of enabling a system design that is fully compliant with the ESA SST requirements. For all orbital regimes the main sensor system characteristics and associated performances were preliminarily defined and assessed via simulation.

The evaluation of the trades-offs and the performance simulations lead to the following baseline configuration:

- A radar surveillance system (1 site at low-medium latitudes) with extended range capability enables full coverage of the LEO population.

- An optical surveillance system (4 sites distributed at different longitudes near the equator) to cover beyond-LEO orbits.
- A space-based surveillance and tracking system (1 SBSS demonstrator, 1 operational SBSS) to cover beyond-LEO orbits. It significantly enhances robustness and operational flexibility.
- The space-based and ground-based components of the optical surveillance system are operated jointly and complementarily in fulfilment of the mission.
- A follow-up and tracking system (radars and telescopes) is needed to complete coverage, timeliness and accuracy, as well as support high fidelity screening of all orbit regions.

During the second phase of the study, the performance of the proposed architecture will be confirmed and detailed, with the final goal of demonstrating the required collision risk reduction (along with other key requirements). Sensor characteristics and locations will be iterated accordingly. Simulations will be refined in order to include real-world effects like weather conditions.

7 REFERENCES

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