THE EUROPEAN SPACE SURVEILLANCE SYSTEM – REQUIRED PERFORMANCE AND DESIGN CONCEPTS

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Europe is preparing for the development of an autonomous system for space situational awareness. One important segment of this new system will be dedicated to the surveillance and tracking of space objects in Earth orbits. First concept and capability analysis studies have led to a draft system proposal. This foresees, as a first deployment step, a ground-based system consisting of radar sensors and a network of optical telescopes. These sensors will be designed to have the capability of building-up and maintaining orbital elements and properties of space objects in a catalogue. Based on these capabilities, a number of related services will be provided including collision avoidance and the prediction of uncontrolled re-entry events. For the time being, user requirements; defining the various services and their required accuracy and timeliness, are being consolidated. Parameters such as the lower diameter limit above which catalogue coverage is to be achieved, the level of catalogue coverage in various orbital regions and the accuracy of the orbit data maintained in the catalogue are important design drivers for the number, location and performance of the various sensors. In this requirement consolidation process, the performance to be specified has to be based on a careful analysis, which takes into account accuracy constraints of the services to be provided, the technical feasibility, complexity and costs. User requirements cannot be defined without understanding the consequences they would pose on the system design.

This paper will outline the user requirement consolidation process for the surveillance and tracking segment. It will present the core user requirements and the definition of the services that are derived from them. The desired performance parameters are explained, together with the corresponding justification. This will be followed by an identification of the major design drivers. The influence of these drivers on the system design will be analysed, including limiting diameter, catalogue coverage, and orbit maintenance accuracy driven by the planned collision avoidance service. Finally, a first-pass compilation of settled performance parameters for the surveillance and tracking segment will be presented, and design solution concepts of a corresponding ground-based surveillance radar.

INTRODUCTION

Space-based systems have become indispensable for a wide spectrum of applications critical to key areas of society, and it can be anticipated that the dependency on space-based assets will grow rapidly in the short term. These dependencies raise concerns, since the degradation of this space infrastructure could considerably impair the economy, safety and security of government, industry and the general public. Currently, the EU does not possess any extended capability to monitor space and to identify potential man-made or natural threats to its security.

In response to these concerns, during the ESA Ministerial Council in November 2008, Europe initiated a 3-year Preparatory Programme for the development of a Space Situational Awareness (SSA) System. The overall aim of this initiative is “to support the independent European utilisation of, and access to, Space for research or services, through the provision of timely and quality data, services and knowledge regarding the environment, the threats and the sustainable exploitation of the outer space”[2].

Accurate, timely and comprehensive space situational awareness is instrumental for the protection of all critical European infrastructures in Space and for the secure and safe operation of its Space activities and services, as well as for the protection of the population in the case of re-entry events, or possible NEO impact threats [1].

The high-level users’ needs for the European SSA system, as expressed by the SSA user group during its meetings in the 2006-2008 timeframe, can be summarised as follows [2]:

- support the safe and secured operation of space assets and related services
- support risk management (on orbit and during re-entry) and liability assessment
- assess the status and basic characteristics of space objects (both human-made and natural).
- detect non-compliance with applicable international treaties and recommendations
- enable the allocation of responsibility for space objects (to launching State) or organisations (ESA, member states, etc.), and support confidence-building measures (identification of owner and/or operator)

The architecture of the future European SSA System will be based, on the federation of existing and available national assets, together with the newly developed and procured elements. This will be implemented through a progressive integration process. Hierarchically, the system will consist of 3 segments:

- Space Surveillance and Tracking (S&T)
- Space Weather (SWE) and
- Near-Earth Objects (NEO)

These segments are largely independent in terms of the services, availability needs and associated user groups. However, in terms of development, the S&T and NEO segments can potentially share (at least in some parts) the same design for the optical sensors, sensor network and the data processing software.

THE SURVEILLANCE AND TRACKING SEGMENT AND ITS SERVICES

Services

In response to the basic user needs [2] the system will have to provide services which result in one or more user products each. Performance, availability and constraints differ from among services and are addressed separately. The following services have been identified (see *Fig. 1* for an overview, products and expected user communities):

- **Catalogue of Man-made Objects:** space surveillance and detection of objects, cold start of a catalogue with defined coverage requirements, maintenance of a catalogue with given accuracy constraints
- **Collision Avoidance:** Conjunction analysis, refinement of the analysis and screening of user provided ephemerides
- **Detection and Characterisation of In-Orbit Fragmentations:** Screening of newly detected objects for those correlating from a common originator, identification of the originator objects and characterising the event, issuing warning bulletins
- **Re-entry Predictions for Risk Objects:** Identification of risk objects that are close to a natural uncontrolled re-entry, prediction of re-entry location and epoch (with uncertainty information), refinement of the analysis in order to achieve the required prediction accuracy
- **Object and Manoeuvre/Mission Characterisation:** Monitoring of objects to identify active spacecraft, data screening for orbit changes, characterisation of orbit changes
- **Special Mission Support:** Follow-up of the objects of concerns, highly-accurate orbit determination, observation of object release, Observation of orbit changes
- **Characterisation of sub-catalogue debris:** Use of a limited amount of sensor time to characterise the sub-catalogue debris environment, databases with derived statistical information

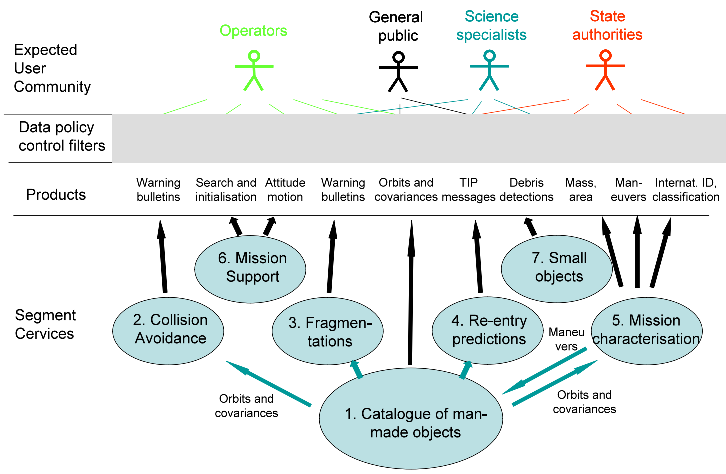


Fig. 1: Services and expected user communities

The services will lead to different outputs to the user communities. Internally however, they are not expected to be independent. The surveillance and tracking segment itself will make use of some services in order to derive data products from other services.

Performance

The required performance of the system in any of the seven services is currently under evaluation. With the cataloguing being the core of all services, the following parameters have been identified as being the key to the overall performance and the main system design and are thus considered as cost drivers:

- the lower diameter cut-off envelope above which catalogue coverage has to be provided, and the level of coverage above this diameter cut-off
- the accuracy of the orbit information provided
- the overall technical availability of the system

Guidance for the selection of the associated performance figures are given through the program declaration [2] which mandates that the system has to detect non-compliance with applicable international treaties and recommendations, to support liability assessment and to enable the allocation of responsibility for space objects to launching states or organisations. One of the most predominant international recommendations related to space debris mitigation are the guidelines of the IADC [3]. In this regard, a direct consequence of this request is the necessity to cover objects in the so-called protected regions (LEO 0 - 2000km altitude and GEO 35586 - 35986km) for which the guidelines prescribe particular mitigation measures. The objects to be covered are those that have the technical potential to cause a violation (payloads and rocket bodies) due to the way they are operated or abandoned, as well as those objects that result as a consequence of a violation (mission related objects, evidence for fragmentations). Evidence for fragmentations could be the existence of larger debris pieces or detected changes to the parent object (e.g. loss of object).

Secondly, the program declaration [2] requires that the system supports the safe and secure operation of space assets as well as an active risk management (on orbit and during re-entry). This translates into a requirement for the generation of warnings for manoeuvrable spacecraft regarding close conjunctions that would result in catastrophic collisions. Collisions between space objects are “catastrophic” when a certain energy/mass ratio is exceeded. This leads to a disintegration of the colliding objects and, thus, to a contamination of the environment that has the potential to trigger more catastrophic collisions. This requirement indicates that the system must be able to identify and issue timely warnings of catastrophic collisions involving European manoeuvrable space objects. This has two implications:

1. Objects with the potential to cause catastrophic collisions with European manoeuvrable payloads must be covered by the lower diameter cut-off envelope (which will include a significant share of fragments).
2. The accuracy of the orbit information (i.e. the final product after potential refinement actions) must be such that the number of hazardous conjunctions that would be missed is marginable.

REGIONS AND DIAMETER CUT-OFF ENVELOPES

A ground-based space surveillance system cannot and does not need to provide the same performance for all orbital regimes. Therefore, the performance requirements over certain regimes can feasibly be relaxed in comparison to others. While Low Earth Orbits (LEO) will, typically, be observed by radar means; in moderate orbital altitudes, comparably small objects can be covered and their orbits updated regularly. A high performance in detection sensitivity and orbit data accuracy is needed to cover the needs for collision avoidance (which are the most demanding in LEO).

Passive optical sensors (possibly in combination with radars) are considered to be used to cover the higher altitude regions, since they are more effective for the observation of objects with low angular rates, and under more constant illumination conditions. The smallest coverable object sizes will likely be larger compared to LEO when reasonable efforts are assumed. A LEO-equivalent detection performance would be advantageous for these regimes, but is found to be less critical for collision avoidance as we will show later. The achievable orbit accuracies are a function of the dimensions of the telescope network, however expectations are moderate, since surveillance data will be only sparsely used for critical operation phases.

Orbital regions

The considerations above lead to the definition of separate orbital regions with individual performance requirements, which are analysed below.

The orbital regions are defined in order to reflect the system users' requirements for spacecraft protection, the monitoring of compliance with international ordinances as well as the seven user services that were defined previously. Where user requirements allow, regions are limited to the minimum possible extent in order to keep the survey efforts within a manageable level. In addition, for the network of passive optical telescopes, the altitude range in a region should be small in order to reasonably limit the range of possible angular velocities for an optimised detection. Further drivers for the definition of regions are a functional split of observation tasks between sensor types, object sizes and the actual distribution of the objects. As a result of this the following regions have been defined:

LEO: 0 -2000km altitude
- covers the IADC's definition of the LEO protected region
- covers the major density peaks in spatial density (vis-à-vis the collision avoidance needs)
- contains the majority of cases for which LEOP support might be required, re-entry prediction support and the characterisation of in-orbit fragmentations (more than 80% of all historical detected fragmentation has occurred here)

GEO: 33786 - 37786km altitude
- covers the IADC's definition of the GEO protected region including the graveyard orbits, but also typical disposal orbits of GEO insertion stages as well as the apogees of "fresh" GTOs
- contains ca. 400 operational payloads - which presents higher density than other areas for manoeuvre detection
- has a small range in inclination and angular velocities that allows for leak-proof surveys and accurate orbit determination results

MEO: 12846km - 33786km altitude
- has a high percentage of operational payloads when compared against the number of inactive satellites or fragmentary debris
- orbits in this region are concentrated in limited inclination bands with altitude boundaries that lend themselves well to optical detection

Gap (Lower MEO): 2000-12846km altitude
- contains a low number of resident objects with a high range of angular velocities. Relatively difficult to acquire with cost-effective radar or optical sensors.

Fig. 2 illustrates the selected regions in comparison to the spatial density distribution of objects > 10cm and > 1cm according to the ESA MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model [5] of the epoch May 2005.

Orbits are considered to be resident in a region when no part of the orbit transects the defined region boundaries. Orbits are taken to be transient with respect to a region when part of the orbit passes beyond or below the regional boundaries (irrespective of the distance).

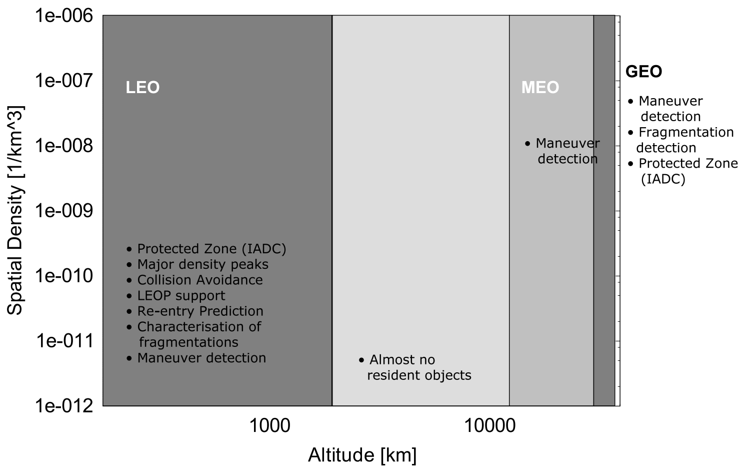


Fig. 2: Orbital regions and spatial object densities according to MASTER-2005 [5]

Diameter cut-off envelopes

In order to create a cost effective system that can meet the user requirements, the definition of the smallest diameter of an object that can be detected – for each region – should be defined and quantified. The needs derived for collision avoidance are, because of the relevant object sizes and high precision requirements, considered to be the most demanding. They are, therefore, used as a starting point for the definition of the minimum diameter cut-off. The corresponding requirement is to detect potential catastrophic collisions with manoeuvrable spacecraft. Catastrophic collisions have severe impacts on the environment. According to [4], they occur when the resulting energy-to-mass ratio (EMR) exceeds a certain level. The value, which is consistently used for environment evolution studies (by various space agencies including ESA), is 40J/g. The EMR is defined as follows **(1)**:

$$EMR = \frac{0.5 M_p v_{imp}^2}{M_t} \quad (1)$$

Where M_p is the mass of the chaser
M_t is the mass of the target
v_{imp} is the impact velocity

For the analysis, 231 European payloads (EU states) above 100kg mass have been selected as targets. A mass threshold of 100kg was selected in order to account for the fact that smaller payloads tend to have limited or non-existent manoeuvring capabilities and, therefore, do not belong to the group of potential users of a collision avoidance service. Secondly, very small targets would, on average, lead to larger energy-to-mass ratios and, therefore, more likely to catastrophic collisions, but any such events will generate a less significant amount of debris when compared to larger satellites.

ESA's software for the assessment of collision flux on user-defined target orbits, MASTER, has been used as the basis for this analysis. MASTER results are developed from a space debris population model that has been derived from the simulation of historical debris release events (including more than 250 on-orbit fragmentations). The model considers objects larger than 1μm and makes use of a launch and debris release traffic model to predict fluxes 50 years ahead. A total of 231 MASTER-runs have been performed to characterise the flux of objects > 1cm for all European payloads. The analysis has been performed for the epoch 01/01/2020. This epoch is at the beginning of the proposed SSA system life of 20 years, assumed to represent the worst case environmental conditions. The results of the MASTER runs have been filtered according to equation **(1)** in order to separate the overall catastrophic collision flux for the European payloads. Fig. 3 analyses the catastrophic collision flux as a function of chaser diameter and semi-major axis for chasers in LEO. It shows that at 800km altitude, objects as small as 5cm contribute to the catastrophic collision risk. The lowest critical chaser diameter increases with semi-major axis, since the impact velocities decrease with altitude.

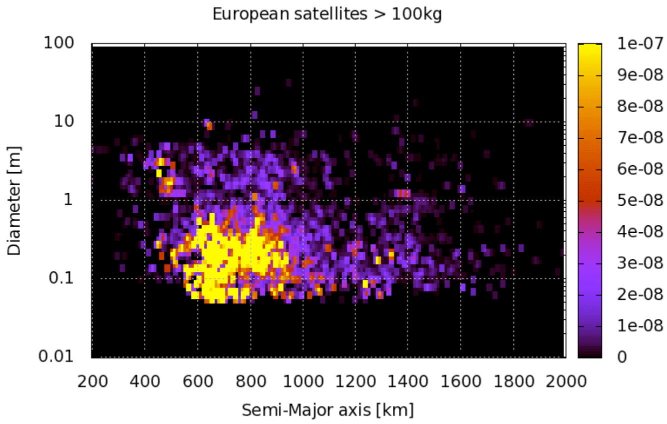


Fig. 3: Distribution of the catastrophic collision flux for European satellites > 100kg

These results can then be used to dimension the diameter envelope in each orbital region. For this, a software tool has been developed that varies the lower diameter cut-off for each region. It then cumulates the catastrophic collision flux generated by objects that fall above the thresholds and compares this accumulated catastrophic collision flux to the overall collision flux. A result of this exercise is that the diameter threshold for objects in the MEO and GEO regions (and for those that transit these regions) can be ignored. This is due to the generally short dwell times of objects in transient orbits, the lower encounter velocities as well as the generally lower spatial density. This means that the lower diameter threshold will be driven by other requirements, independent from the catastrophic collision flux. For LEO, an altitude dependent diameter cut-off has been derived. Since this region is expected to be observed by radar, the radar-range equation has been accounted for in the following definition of the diameter cut-off envelope (2):

$$d_{\min} = \sqrt{\frac{h_p^4}{h_{ref}^4} d_{ref}^2} \tag{2}$$

Where d_{min} is the lower cut-off diameter above which 98% coverage probability has to be achieved

h_p the perigee altitude of the to-be-observed orbit

h_{ref} is a reference altitude of 2000km

d_{ref} is a reference diameter at the reference altitude

The diameter d_{ref} needs to be defined such that the curve is calibrated in a way that all catastrophic collision fluxes are just contained therein. The a-priori defined coverage probability of 98% takes into account that when using radar, the detection has a probabilistic element. The variation of d_{ref} has a dramatic effect on the coverage level as Fig. 4 shows. The expected saturation level of 98% is achieved for a d_{ref} of about 32cm, which corresponds to about 8cm at 1000km and about 5cm at 800km.

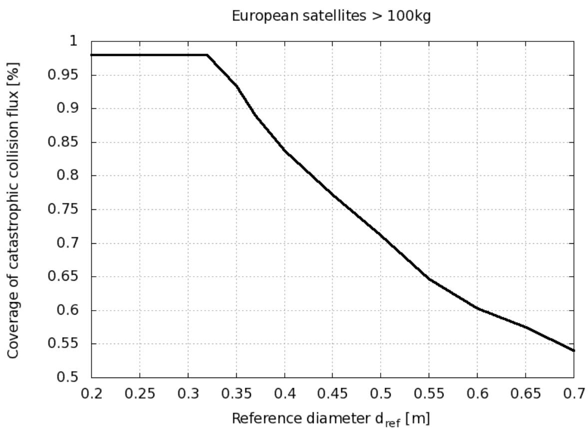


Fig. 4: Simulated SSA coverage of the catastrophic collision flux of the system as a function of the reference diameter for the LEO region

Object diameters smaller than 5cm are difficult to detect, as they would fall in the Rayleigh region of the envisaged L-Band solution of the ground-based surveillance radar. In the Rayleigh region, the RCS drops more rapidly with the diameter. In order to take this into account, a constant diameter cut-off value of 5cm has been introduced from 800km down to 400km and 3cm from 400km down to the lowest orbital altitudes (see Fig. 5). This limitation, due to the already small diameters, has no effect on the coverage level of the catastrophic collision flux. While only European satellites have been selected for this analysis, it has been verified that these settings would as well satisfy the needs of a service aimed at all payload operators.

Coverage of intact objects

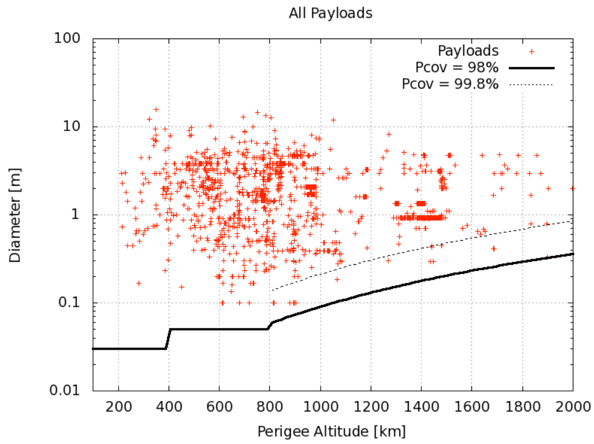


Fig. 5: LEO cut-off diameter envelope and all payloads as of 2008 [6]

Further on it remains to be analysed whether the selected cut-off diameter envelope for LEO and the to-be-selected cut-off diameters for the remaining regions satisfy the needs for the monitoring of intact objects (payloads, rocket-bodies and mission related objects) in response to all services related to LEOP support, monitoring of legal compliances, re-entry predictions and mission characterization. Fig. 5 shows the cut-off diameter envelope combined with the characteristic length of the payloads in LEO at the beginning of 2008. The data originates from ESA's DISCOS[6] database. The characteristic length is the average of the three principle dimensions of a body. In cases, where no dimensions are available, the value has been derived from the average cross-section (or even the Radar Cross Section if no other data are available) by assuming a spherical shape.

All LEO payloads are covered by the selected scheme. For MEO and GEO resident and transient objects constant cut-off diameters of 50cm and 70cm have been selected respectively, which will be verified in the following. Like for the LEO region a coverage level of 98% is associated with these regions. For LEO transient objects a d_{ref} of 50cm and a coverage level of 50% is assumed. Tab. 1 shows, for a population in 2005, the respective numbers and coverage level per region for the identified specification of the regions. This gives a total coverage of about 93% across all object types, which is well within the target range of 90%-99% given by the users [10]. It should be noted that this analysis is based on information from the US surveillance network. Therefore, potential limitations of that catalogue in this regard would flow in here as well.

Tab. 1: Number of Payloads, Rocket-Bodies and MROs (as of 2005) and coverage performance [6]

Region type	Payloads	Covered	Rocket-bodies	Covered	Mission related	Covered

		[%]		[%]	objects	[%]
LEO resident	1851	98.0	823	98.0	637	97.5
MEO resident	179	98.0	42	98.0	2	50.0
GEO resident	831	97.8	192	95.3	13	46.2
LEO/MEO/GEO transient	89	96.6	245	97.1	43	69.8
LEO/MEO transient	32	98.0	204	98.0	64	90.6
LEO transient	59	50.0	87	50.0	143	50.0
MEO/GEO transient	135	98.0	141	96.5	3	66.7
MEO transient	3	98.0	3	98.0	1	98.0
GEO transient	1	98.0	7	71.4	0	98.0
Objects outside regions	31		18		69	
Objects in region but not covered	95		87		115	
Objects in regions	3180	97.0	1744	95.0	931	87.7
Objects in general	3211	96.1	1762	94.0	1000	81.6

Another uncertainty in this analysis is the age of the information used. In 2009 the catalogue would contain 36,131 objects, 25,392 would be LEO resident (70.3%), 3308 of them would be intacts (payloads / rocket bodies, MROs), 22,084 of them would be debris (86.9%). Since users expect the system to provide full service for a 20 year lifetime (assuming system acceptance in 2020), the situation in 2040 will have to be analysed as well. Assuming a business as usual scenario [4], in 2040 the catalogue will contain 127,884 objects, 79,549 will be LEO resident (63.3%), 8,003 of them will be intacts (payloads / rocket bodies, MROs), 71,546 of them will be debris (89.9%). For the coverage of intact objects, no major changes are expected for 2040, since the sizing of payloads and the preferred operational orbits are assumed not to differ much in 30 years. A large number of debris may, however, accumulate in altitudes with longer orbital lifetimes, thus in larger ranges which in turn might challenge the radar design.

ACCURACY OF THE ORBIT INFORMATION

The second major system design driver is the required accuracy that the orbit information shall be provided with. Accuracy of orbit information always needs to be looked at as a function of time. Depending on the orbit type and the initial covariance, hence the uncertainty estimate for the state at orbit determination epoch, the orbit accuracy evolves over time. Most applications (in particular collision avoidance) require the orbit information to be accurate for a period of a few days, which corresponds to the time to plan, verify, implement, upload and execute a maneuver. For this reason, the concept of the so-called accuracy envelope has been introduced. It foresees a limit for the 1-sigma error in the three OCRF positional and the three OCRF velocity components (i.e. the envelope).

The orbit information is expected to come with its own 1-sigma uncertainty estimates for the same parameters. The user will be notified once the uncertainty estimates violate the envelope. The segment is expected to provide a new data set at least 48h before the envelope is violated for the first time (see Fig. 6).

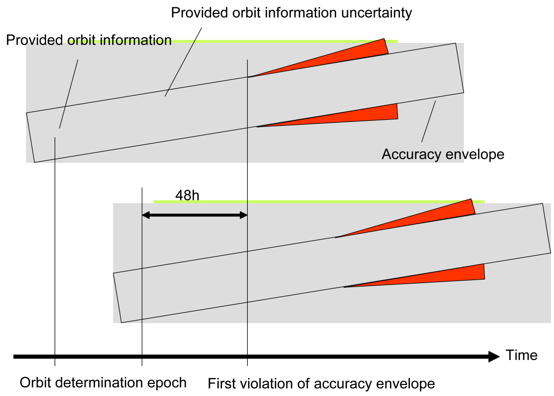


Fig. 6: Concept of the accuracy envelope

This concept gives the system designers the necessary room to trade-off between frequent updates of refreshed but less accurate orbit information, or rare updates of very precise data (with corresponding long validity). For certain objects, however, requirements on the timeliness with respect to the detection of maneuvers or fragmentation events will impose a re-observation schedule. What remains to be defined is the accuracy envelope itself. Again, collision avoidance seems to be the most demanding service for this, as the experience at ESA described in the following shows:

Collision avoidance activities at ESA as a source of expertise

ESA provides a collision avoidance service for their Earth Observation Satellites ERS-2 and Envisat both orbiting in 800km altitude. The service makes use of USSTRATCOM TLEs for the chasers, which are refreshed approximately once per day and the operational S-Band ranging orbits for the two targets. The orbits are screened for possible conjunctions once per day for 7 days ahead. A collision probability is computed for any of the conjunctions with geometric miss distance shorter than 10km in radial and cross-track direction and 25km in along-track direction [7]. The computation of the collision probability requires knowledge of the covariance of TLE orbits. As this information is not published an estimate has been made by comparing the TLE orbits with a numerically propagated orbit that has been fitted to the TLE [7], [8]. Tab. 2 shows the result for chaser orbits which are relevant for Envisat and ERS-2, revealing the considerable impact of inclination and eccentricity on the quality of the information.

Most chasers for Envisat and ERS-2 have near circular orbits and high inclinations. Uncertainties in the chaser orbit of a few hundreds of meters are not suitable to conduct collision avoidance, given that the target orbit is about 10 times more accurate. Although the most typical scenario is a head-on geometry, where the radial component is the critical one onto which an avoidance maneuver would add additional separation, the uncertainties are still so large that unacceptably large avoidance maneuvers have to be planned, with a few hundreds of meters altitude increase (200m is the maximum that can be achieved for Envisat in the attitude control mode). ESA encounters this problem by refining the accuracy of the chaser orbit information to approx. the level of the target orbit by requesting and processing additional radar tracks [7], whenever a given collision probability threshold is exceeded.

Tab. 2: TLE initial covariance estimates for chaser orbits with perigee altitude <800km

		Eccentricity	
Inclination	**Parameter**	**<0.1**	**>0.1**
0°-30°	RAD (m)	103	4989
	A-T (m)	419	6247
	C-T (m)	123	705
30°-60°	RAD (m)	129	2920
	A-T (m)	434	3747
	C-T (m)	163	2907
>60°	RAD (m)	104	691
	A-T (m)	556	699
	C-T (m)	139	2103

A comparison of TLE orbits with accurate reference orbits (e.g. generated from dedicated tracking) reveals that the real initial covariance is often considerably larger than the estimate. This method can only assess the theory error of the SGP4 theory behind the TLEs with respect to a numerical orbit propagation theory. Additional errors, like a general TLE inconsistencies, biases or measurement insufficiencies for orbits with unfavorable observation geometries or for small objects (fragments), where the observation goes along with a loss in the range accuracy.

Besides the consequences for maneuvers, the limited accuracy of the TLEs leads to a considerable false alarm rate, and even worse, to a considerable background risk. This background risk is a consequence of the fact that the limited accuracy of TLEs forces the usage of a probabilistic criterion, a collision probability threshold. Conjunctions generating high collision probabilities will be analysed through an orbit refinement process and possibly encountered with avoidance maneuvers, while conjunctions with low collision probabilities are simply ignored. Such a selection has to be made, since the number of conjunctions per day in the screening volume of Envisat, for example, is about 38 per day, of which about 1 per day exceeds the collision probability of 10^{-6}. The problem is that the high number of ignored lower-risk conjunctions can accumulate to a considerable background risk as Fig. 7 shows. This means that the background risk exceeds the actual avoided risk when the reaction thresholds exceeds 1:5000.

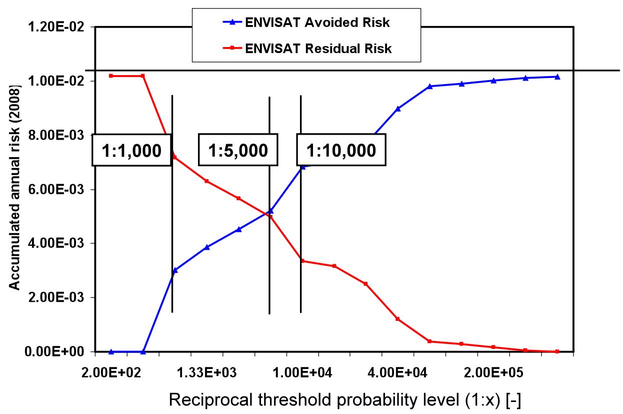
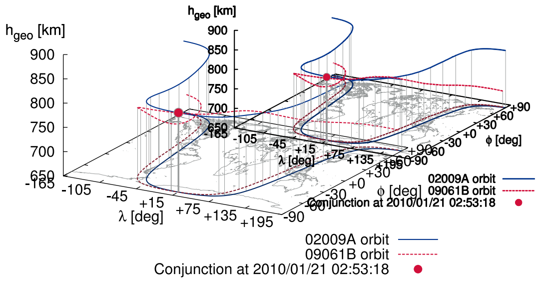


Fig. 7: Avoided and residual risk for Envisat in 2008

This problem becomes evident with time and was recently underlined by a very drastic example: On Jan. 21, 2010, 02:53 UTC, Envisat (COSPAR 02009A) would have had a close conjunction with a 3.8 ton Chinese CZ-2 2nd stage (COSPAR 09061B) at a distance of 48m. Due to the slightly eccentric CZ-2 orbit, with correspondingly high uncertainties in its TLE data, the risk potential of the event was only detected by the US JSpOC (Joint Space Operations Center), who have access to precise orbit data and alerted ESA on Jan.18. The highest risk predicted with ESA's means described above using the TLE information was only 1/365096 due to a radial separation of -346m, hence far below any reaction threshold. Based on 5 passes of the TIRA radar, ESA assessed a fly-by geometry at a total distance of 48m, with 15m in radial and 7m in cross-track direction (see Fig. 8). This result closely matched the JSpOC forecast. This improved assessment results in a probability of collision exceeding 1 in 80. This was the highest risk that ESA had noted in 15 years of conjunction assessments. At the same time, it was the event with the largest combined masses (8 tons + 3.8 tons), exceeding the Cosmos-2251/Iridium-33 mass (that led to 1,500 tracked catalog objects) by a factor of 7.6. Two maneuvers with a Δv of 4 cm/s each were agreed and implemented at -0.5 and + 0.5 orbital revolutions before and



after the conjunction.

Sizing the catalogue accuracy envelopes

In order to reduce the critical background risk, the collision probability reaction threshold must be set very low. In order to prevent an enormous amount of dedicated tracking campaigns for orbit refinement, the false alarm rate must be very low. Both lead to a minimum required accuracy. In the following, the accuracy of LEO orbits (as analysed before these comprise nearly all critical chasers) in the timeframe 24h after the orbit determination epoch are analysed. For this purpose an exemplary satellite in the Envisat operational orbit with an average radius of the cross sectional area of 1.848m is considered. The ESA DRAMA/ARES [9] tool has been used for the epoch 01/01/2040 (business as usual scenario) to determine the residual (i.e. background) risk as a function of the accuracy of the orbit information for both, target and chaser,

Fig. 8: Conjunction geometry between Envisat and CZ-2 upper stage on Jan 21st, 2010

and the collision probability reaction threshold. Fig. 9 shows that for an accuracy of 20m x 100m x 20m (radial, along-track, cross-track) at orbit determination epoch and a reaction threshold of 10^{-7}, the residual risk per satellite and year is on the order of $6*10^{-6}$. Fig. 10 shows the number of dedicated tracking campaigns that are required per year as a function of the same parameters. It can be depicted that for the selected reaction threshold, the number of campaigns per satellite and year would be around 20. Assuming the maximum number of maneuverable payloads requesting the service is 250 and assuming the number of passages to be tracked per campaign to be 4 (ESA experience), this will give 20,000 passages per year or 55 per day. This amount seems to be managable by 2 to 3 collaborating tracking stations operating 7/24. Also some satellite operators might find the original accuracy already sufficient to plan a maneuver.

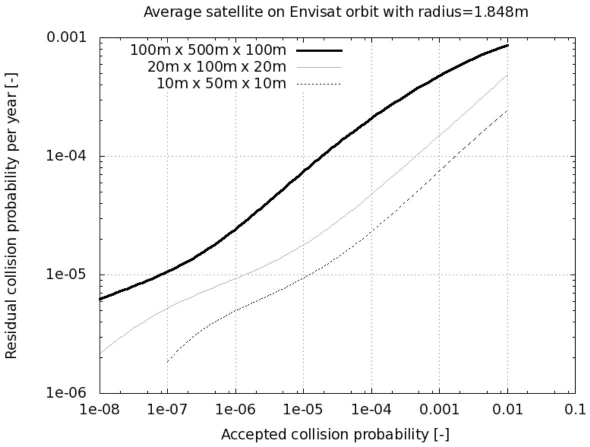


Fig. 9: Residual risk for a sample satellite as a function of the probability threshold and the initial orbit accuracy

The overall background risk would accumulate to 6% for all satellites over the 20 years of SSA system life. In other words, the success rate of the system to independently identify all conjunctions among the objects in the catalogue leading to potential catastrophic collision would be 96%. As only 98% of the catastrophic collision flux is covered and the overall availability of the system is limited (say 99% [10]), the success rate of the system to independently identify all conjunctions leading to potential catastrophic collision would be about 93%. This preliminary figure will

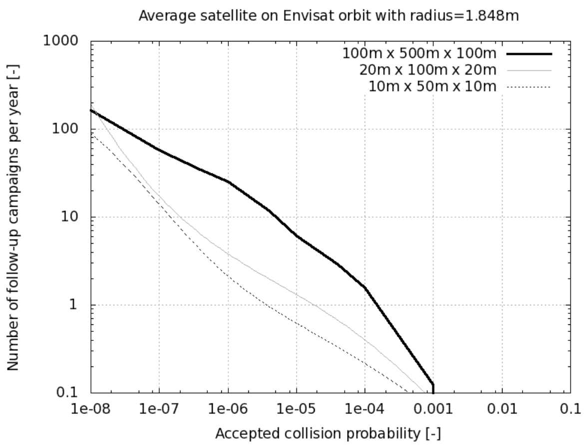


Fig. 10: Number of follow-up campaigns per year for a sample satellite as a function of the probability threshold and the initial orbit accuracy

have to be subject to the approval of the program initiators and the future system users.

DESIGN SOLUTION CONCEPTS

A very preliminary outlook on design options in response to these demanding user requirements shall be given in this section. It will concentrate on the more challenging LEO surveillance and tracking, for which large ground-based phased arrays radars are required. The LIS^4A tool has been used [10] to assess the population coverage by such a radar. LIS^4A uses the MASTER model population for selectable epochs and assumes that objects can be successfully maintained in a catalogue when they are detected at least once every 24hours, and observed for at least 10 seconds. This simulation does not yet check for the validity of the orbit accuracy criterion. To consider the limitation of radar sensitivity, the software makes use of the principle of a detection range, which is the maximum range at which a spherical object with a radar cross section of -20dBm^2 (0.01m^2) can still be detected. For that purpose, LIS^4A implements a formulation for the radar cross section that assumes all objects to be perfectly conducting spheres. In Fig. 11 the coverage performance of a phased array radar, building up a fence stretching from East to West over the zenith with 40^o of thickness is shown as a function of the radar latitude and the detection range. It can be seen that such a radar would achieve the required coverage level of 98%. This, obviously, is most efficiently done at high latitude. The reason for this is that the majority of the objects are on highly inclined orbits, with concentrated residence probability in high latitudes, thus generating many high elevation passages over the

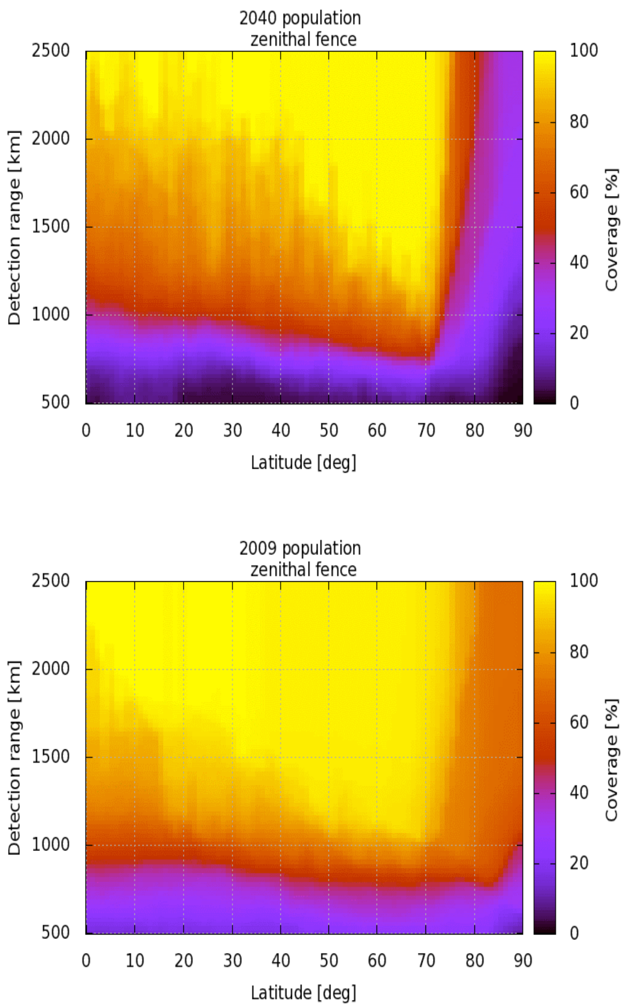


Fig. 11: Coverage performance of a zenithal fence as a function of radar latitude and detection range under 2009 condition (top) and 2040 conditions (bottom)

site which can be detected with moderate power levels. At low latitude sites passages are rare and tend to occur at more shallow elevation angles, where more power is required for their detection. The bottom of the diagram analyses whether high latitude sites are still a suitable choice in 2040, when the environment is even more significantly dominated by fragments, in particular in higher altitudes that are not that much affected by the self-cleaning effects of the atmosphere. According to what was discussed before, more power needs to be invested in order to cover the increased number of fragments in higher altitudes. Even if requirements are less ambitious, high latitudes still seem to be a good choice. While high latitude radars are meant to observe the majority of highly inclined orbits, the remaining low inclined orbits remain inaccessible. Fig. 12 analyses the influence of the latitude of a potential second surveillance radar, assuming that one is installed at 60^o latitude and that both radars work with a detection range of 1300km. Obviously, in 2009 and 2040, low latitude sites would be a good choice. It needs to be stressed that an accurate verification of the feasibility of a proper correlation of the observed tracks is pending.

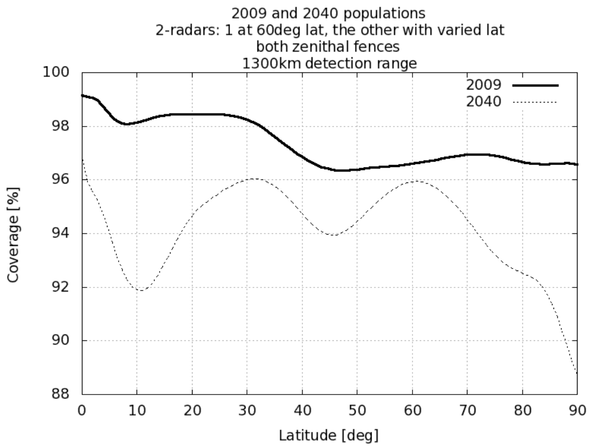


Fig. 12: Coverage performance of two zenithal fences with 1300km detection range where one is installed at 60º latitude

This hypothetical architecture shall be used for preliminary assessment of the achievable orbit accuracy at orbit determination epoch and after 48-72 hours in regard to the expected accuracy as discussed before. For this, tracking data is generated from numerically propagated orbits of a few sample objects in Tab. 4. Among the examples are the CZ-2 upper stage that caused the conjunction with Envisat, a fragment from the Feb. 10 Iridium-33 / Cosmos-2251 collision on a highly eccentric orbit, being one of the most frequent chasers for Envisat, and Globalstar and the ISS as representatives of objects in high and low altitudes. The measured quantities are subject to a statistical noise. For the RMS of these noise figures the following assumptions have been used (Tab. 3):

Tab. 3: 1-sigma RMS noise values used in the simulation

Quantity	**1-sigma RMS noise**
Range:	30m
Elevation:	0.2º
Azimuth:	0.2º
Range-rate:	5m/s

Tab. 4: Sample objects and their orbits

Cosmos-2251 debris	altitude: 757km, e: 0.022, i: 74.0º
Envisat	altitude: 790km, e: 0.001, i: 98.6º
CZ-2 Rocket Body	altitude: 737km, e: 0.009, i: 98.3º
Globalstar	altitude: 1520km, e: 0.001, i: 52.0º

Data of 8 days length is used for the subsequent orbit determination process, which is initialized with the help of a TLE orbit in order to emulate the fact that a certain limited a priori knowledge is available, once the catalogue is built up. The resulting orbit is then compared to the numerically-propagated reference at orbit determination epoch and in the time frame from 48h-72h. The latter value will size the accuracy envelope and the first value will have to be compared to the results in Fig. 9 and Fig. 10 (which are given for the orbit determination epoch). The results are shown in Tab. 5.

Tab. 5: Simulation results for achievable orbit determination 1-sigma accuracy for selected reference orbits

Sample	**± 12h around orbit determination epoch**			**48h-72h after orbit determination epoch**		
	Radial [m]	Along-track [m]	Cross-track [m]	Radial [m]	Along-track [m]	Cross-track [m]
Cosmos-2251 debris	2	70	62	24	751	58
Envisat	14	27	74	9	117	70
CZ-2 Rocket Body	11	23	75	6	90	71
Globalstar	2	83	53	5	207	48

It should be noted that this is not a covariance estimate resulting from the orbit determination process but a comparison to a truth reference. While the preliminary requirement of 20m x 100m x 20m is close to be fulfilled for four objects, obviously, there are considerable problems with low altitude orbits. The suspected reason for this is the low number of passages that are limited to the equatorial site. The preliminary criterion for the cross-track component is not fulfilled for all objects, but less critical for conjunction assessment. Further studies and trade-offs are required. The results for the most critical radial component, however, are encouraging.

CONCLUSION

The core expectations of the future users and stakeholders of the surveillance and tracking segment of the future SSA system have been analysed and translated into a set of consolidated requirements. The collision avoidance service as the most substantial product of the system has been used for this purpose. It has been shown that in the critical LEO regime, objects above 5cm diameter in 800km (with corresponding scaling to other altitudes) will have to be covered with an accuracy of a few tens of meters in order to allow for successful prediction of potential catastrophic collision events with operational, manoeuvrable payloads. A first analysis on the corresponding system design shows that surveillance radars can fulfil that task with affordable requirements on operating power. Care has to be taken for the dynamic changes in the environment throughout the lifetime of the system.

GLOSSARY

ARES	=	Assessment of Risk Event Statistics
DISCOS	=	Database and Information System Characterizing Objects in Space
DRAMA	=	Debris Risk Assessment and Mitigation Analysis
EMR	=	Energy-to-Mass Ratio
ESA	=	European Space Agency
GEO	=	Geostationary Earth Orbit

GTO	=	Geostationary Transfer Orbit
IADC	=	Inter-Agency Debris Coordination Committee
JSpOC	=	Joint Space Operations Centre
LEO	=	Low Earth Orbit
LEOP	=	Launch and Early Operation
MASTER	=	Meteroid And Space Debris Terrestrial Environment Reference
MEO	=	Medium Earth Orbit
MRO	=	Mission Related Object
OCRF	=	Object Centred Reference Frame
SSA	=	Space Situational Awareness
TLE	=	Two Line Element
USSTRATCOM	=	US Strategic Command

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