SURVEILLANCE RADAR DESIGN OPTIONS AS A FUNCTION OF CATALOGUING PERFORMANCE REQUIREMENTS

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1. ABSTRACT

Europe is preparing for the development of an autonomous space surveillance and situational awareness system. First concept and capability analysis studies have led to a draft proposal for the surveillance and tracking part of the system. This foresees, in a first deployment step, ground-based surveillance and tracking radar systems, a network of optical telescopes and a data centre. In a second step the system is planned to be extended by adding space-based assets and the associated ground-segment. The terrestrial part of the system will be responsible for the build-up and maintenance of a catalogue of space objects. Studies showed that one large phased array radar alone could act as the single means for the generation of a catalogue of LEO objects (apogee altitudes < 2000km). Catalogue initialisation requires the presence of objects in the radar search window for a minimum time span to enable orbit determination of sufficient accuracy. Catalogue maintenance requires objects to be re-observable after limited time spans so that they can be clearly correlated.

Today, the user requirements on the performance of the system are under definition. Different options to specify the desired system performance in terms of the resulting object catalogue have been proposed. One of them is to specify a certain coverage level of the existing NORAD catalogue. A second one is to request full coverage of all objects above a certain diameter threshold. Both approaches have certain advantages (e.g. the first one being verifiable by tests and the second one leading to an unbiased/independent catalogue). However, these requirements might impose different system designs in terms of the sensor location, and the dimensions and the orientation of the search field.

This paper outlines the consequences of the cataloguing performance requirements on the high-level system design. Simulation tools are used to investigate key parameters such as the optimum radar wavelength, the viewing direction and search field dimensions as a function of these specifications. First attempts to identify the most practicable approach to define the system and the corresponding sensor design are made with a focus on future expansion capabilities of the system (towards lower limiting diameters). Orbit determination accuracy and orbit information update cycles are addressed. Potential performance issues of a transition from a monostatic to a bistatic configuration are also analysed.

2. INTRODUCTION

2.1. Space Surveillance Activities in Europe

Space Surveillance denotes the task of systematically surveying and tracking all objects above a certain size and maintaining a catalogue with updated orbital and physical characteristics for these objects. Space Surveillance is gaining increased importance for the safety of operational spacecraft, e.g. for the avoidance of collisions with debris objects. Space Surveillance also provides the basic information for the characterization of the space debris population, for establishing space debris models, and for performing associated risk assessments. A particular issue is the re-entry of objects with large masses, where a significant portion may survive re-entry heating. Space surveillance provides an independent capability of determining the trajectory of a re-entering object and of supporting the assessment of risk on ground. While some European radar and optical facilities exist for tracking space objects on an ad hoc basis, Europe has no systematic, operational capability for space surveillance, and is hence strongly dependant on external information from the USA and Russia. France has developed the prototype space surveillance system GRAVES (Grand Reseau Adapté à la Veille Spatiale) for LEO, with limited capability concerning the detectable object size [1].

The envisaged European System for Space Situational Awareness (SSA) will cover the domains surveillance and tracking, space weather, Near Earth Objects (NEO) and Imaging. While the user requirements for the SSA system are still under definition, first design and performance analysis studies for the surveillance and tracking subsystem have been carried out in order to define the system architecture and to assess the costs of this core part of the system. These studies anticipated requirements for the cold-start and maintenance of a catalogue of space objects with full coverage of objects >10cm in LEO and >1m in GEO and MEO in

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autonomous operation (i.e. similar to NORAD catalogue). The proposed Surveillance and Tracking system was based on two elements, one for LEO and one for GEO and MEO surveillance. GEO and MEO surveillance was ensured by a mixed strategy combining survey and tasking. The survey was ensured by a number of dedicated telescopes (with apertures in the order of 0.5m to 1m), located at four different low-latitude sites. Additional telescopes (with similar apertures) located at the same survey sites performed the necessary tasked observations. The proposed LEO surveillance element was a single radar characterized by a large field of view (20° in elevation and 180° in azimuth), with a maximum range of 1500km for a 10cm sphere. The LEO definition used in this analysis corresponds to orbits whose apogee altitude is lower than 2000km. Such orbital objects represent almost 70% of the NORAD catalogue. The proposed strategy for LEO space catalogue maintenance is based on pure survey observations. The GRAVES system experience shows that if each object is observed every day, for at least 10s, the orbit estimation accuracy will be sufficient for object re-identification at next crossing as long as it occurs within 24hours [1]. This survey only approach requires a tracking procedure to identify the measurements belonging to the same object. The catalogue correlation procedure then either recognises that the object is already catalogued and updates its orbital parameters, or adds new objects (resulting from launches or explosions), or deletes objects (resulting from re-entry or original exploding object). This procedure allows the "cold start" to establish the catalogue and therefore, the system is autonomous.

2.2. Next steps

In order to support the consolidation of the SSA user requirements and in view of a more refined definition of the radar system, several design options need to be analysed and require additional analysis. Among these are in particular the sensor site, the necessary survey volume that gives the minimum daily detection and tracking interval, the operating frequency, the operating power and the minimum detection and tracking interval.

Many other important design decisions will have to follow these first steps (not treated in this paper), among them the configuration of the system (bi-static or mono-static), antenna design, high-power amplification, receive/transmit modules, beam forming and steering principles and control and the processing (intermediate frequency, detection, product generation). The data products will be analysed and processed in a dedicated data centre where the catalogue maintenance is performed. This data centre is also responsible to perform catalogue correlation and object identification. It will also form part of the interface to the SSA users for the reception of dedicated requests and the delivery of data products. Services that satisfy dedicated user requests could comprise exact orbit determination for conjunction risk assessment or re-entry forecasts. Sensor tasking for such services would have to be handled by the data centre, while further analysis still needs to clarify which of these services could possibly be performed with the radar system (although its prime mission is catalogue maintenance) and which are to handled by specialised collateral sensors.

The design options identified before are currently the major drivers for the system architecture and performance. The latitude of the sensor together with the survey volume will define the degree of object population coverage, while the size of the survey volume also determines the system's capabilities in terms of scanning performance and thus catalogue correlation. Operating transmit power and frequency are two independent parameters that are both influencing the sensitivity of the system and thus the lower size limit of the space object population. However, the population of objects passing through the search volume needs to be scanned with sufficiently high frequency. This is in particular demanding for high gain antennas which come along with very narrow beam widths. Since all of these parameters influence several key performance figures of the radar at the same time and often in opposite sense, suitable design trade-off can only be found in a simulation in which all possible permutations of these parameters are studies.

2.3. Analysis tool

The analysis of the performance of the radar system with respect to these design options requires an analysis tool that is able to compute the key figures for all possible scenarios. This requires a fast and therefore simple simulation strategy that can be employed in batch processes in which hundreds of parameter combinations are analysed.

In response to these requirements, LIS^{4}A (LIght Space Surveillance radar System Simulation Approach) was developed [2]. It is intended to evaluate the performance of radar systems in terms of the share of detected objects that can be successfully correlated with respect to the total number of objects under study. Besides this major scope, the tool will also characterise the passage of objects through the search volume of the radar by computing the range-dependent average dwell time, number of objects and angular velocity. These passage parameters will help to support the optimisation of the search field as well as to analyse constraints on processing, beamwidth of the search beam, and scanning patterns. In the version used for this study, three groups of objects can be analysed:

- Catalogue objects: a file containing all objects of the public NORAD catalogue as of January 29th, 2007 amended with information on object diameters as per ESOC's DISCOS database [3]. This catalogue contains 11795 entries and constitutes the reference for the validation of the performance requirements for the full scale system

- Objects > 1cm: a file containing modelled objects as per ESA's MASTER-2005 (Meteoroid and Space Debris Environment Reference) [4] model for the epoch May 1st, 2005 (606,917 objects). This data file can be used to perform studies in response to the requirements for the extended system

- Uniform population > 1cm: a modeled population in which all orbital parameters are equally distributed. This equally weighted appearance of orbital parameters (see Figure 1) will generate an artificial scenario to test the capability of a system for leak-proof surveillance, i.e. provide surveillance capability for all kinds of physically possible orbits.

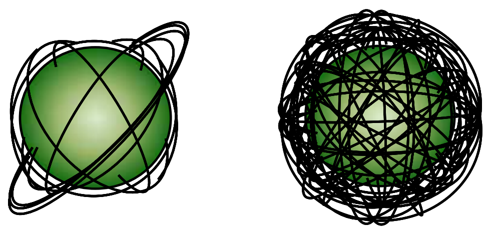

Figure 1: The real population (left) and the artificial population of uniformly distributed orbital parameters (right)

During the simulation, LIS^{4}A will extract and consider from these population files either (see Figure 2):
- LEO objects (apogee altitude lower than 2000km)
- Super LEO objects (apogee altitude lower than 10,000km and perigee altitude lower than 2000km)
- LEO-Transit objects (perigee altitude lower than 2000km and apogee altitude higher than 10,000km)

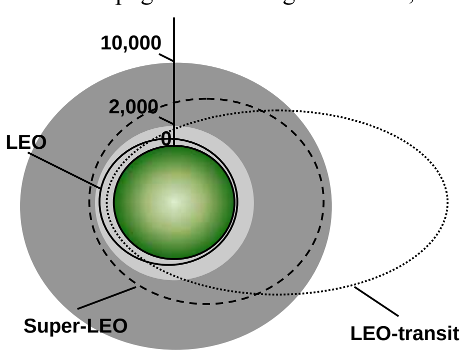

Figure 2: Definition of orbital regions used in this study

LIS^{4}A considers a radar search field cone that is centred on the Earth's surface for a given sensor latitude *lat* (i.e. mono-static configuration). The search field is defined through upper and lower azimuth (A_{low}, A_{up}), elevation boundaries (h_{low}, h_{up}) and through an upper and lower range limit (R_{low}, R_{up}). These six parameters define a volume in space that is moving with the Earth rotation. The tool will only consider passages of LEO objects through this volume. For any given range inside this volume, the sensitivity of the system is considered to be constant with azimuth and elevation and only range dependent. The range dependency is implemented with the help of a user defined reference value, the maximum range at which a spherical object with a radar cross section of -20dBm^2 (0.01m^2) can still be detected (R_d). For that purpose, LIS4A implements a formulation for the radar cross section that assumes all objects to be perfectly conducting spheres. The wavelength λ needs to be defined to enable the description the characteristics of which are displayed in Fig. 1 for a wavelength of 0.5m. The threshold of -20dBm^2 has been selected because this would correspond to a geometric cross section of an object with 11.28cm diameter (assumed to be close to the limit of the US SSN catalogue).

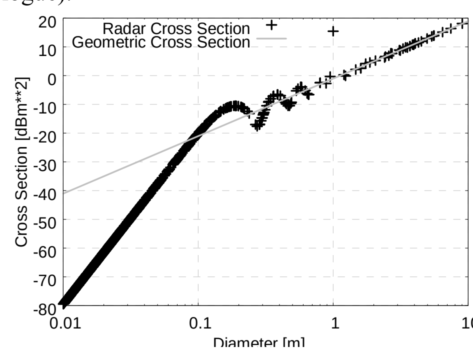

Fig. 1: Formulation used for the relationship between RCS and diameter (λ =0.5m)

The radar equation is used to extrapolate from the reference value to other ranges (R_x) inside the range window, to determine the minimum detectable radar cross section (σ_x) in [m^2] at that range (1) [2]:

$$\sigma_x = \left(\frac{R_x}{R_d}\right)^4 (0.01)^2 \qquad (1)$$

The definition of the major geometric configuration parameters of the tool is summarised in Figure 3. LIS4A performs a simplified simulation of object passages through the search volume for a user defined simulation period. The simulation process is optimised with respect to the fast detection of object passages and their characterisation using simple geometric principles and a simplified orbit propagation that assumes the orbits to be circular for short arcs and that considers gravitational perturbation due to J2 (Earth flattening) as the only perturbation force acting on the orbit [1]

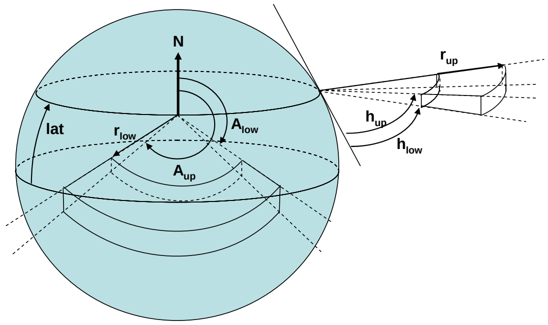

Figure 3: Geometric configuration parameters for LIS^{4}A

The prime output of the tool is the percentage of the analysed population that has gone through valid detection and correlation with the given system, i.e. re-observation within 24hours and detection for at least 10 consecutive seconds. Besides that the tool will provide statistics on passage parameters that can help to derive requirements on the scanning frequency, scanning beamwidth and processing [1].

LIS^{4}A is available in executable form compiled for Windows XP and Linux. It can be executed from the command line of a DOS/bash shell.

3. SURVEILLANCE OF LEO OBJECTS

In this first step, the observability of the LEO objects as contained in the population of catalogue objects will be analysed as a function of the radar parameters. The observation volume can be optimised independently from the selected operating frequency. In the following the influence of the geometric parameters (sensor location, orientation and size of the observation volume) on the catalogue maintenance performance is analysed.

3.1. Site and viewing direction

For the location of the sensor, since none of the LEO objects follows any degree of synchronism with Earth rotation, only the latitude is relevant. Within the LEO object environment we can not expect any objects with constant argument of perigees, so that we can assume an environment which is symmetric w.r.t the equator. Accordingly, only the influence of the latitude on one hemisphere needs to be analysed. In the following, the latitude has been varied from 0° to 90° and the centre elevation of the sensor has been varied from 10° to 90°, while the search volume has been left constantly South staring with boundaries from 90° to 270° azimuth and a width of 20° in elevation. A wavelength of 0.5m (UHF band) has been considered. Figure 4 shows the percentage of the population passing through the search volume. It can be seen that at latitudes around 65°, large numbers of objects are observable at all elevations, which is due to the large number of highly inclined objects in the catalogue. Figure 5 shows the percentage of the population which can be detected. In particular, objects at very low elevations can not be detected due to the long ranges. Figure 6 shows the percentage of the population which can be correlated. At high elevation and low latitudes in particular only a small fraction of the detected objects fulfill the criterion of being detected for at least 10s within 24h (and thus be correlated).

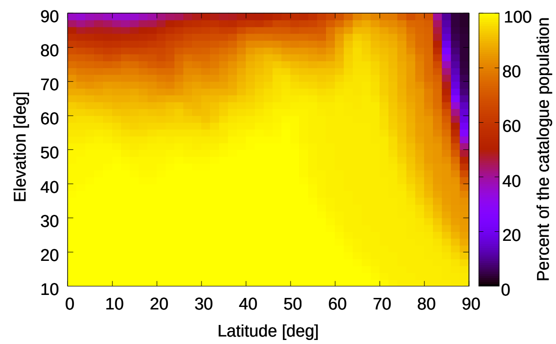

Figure 4: Objects passing through the search volume

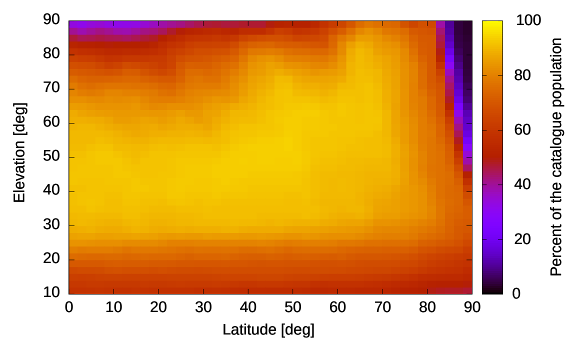

Figure 5: Detected objects

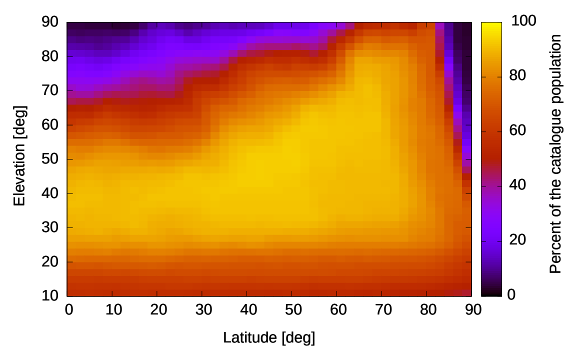

Figure 6: Correlated objects

3.2. Influence of lower size limit

The catalogue population is assumed to have an altitude dependent lower size threshold. The modeled population of objects > 1cm contains those catalogue objects but also modeling results for objects below the catalogue threshold. Figure 7 shows the correlation performance of the system when the modeled population is filtered for objects > 5cm regardless of the altitude.

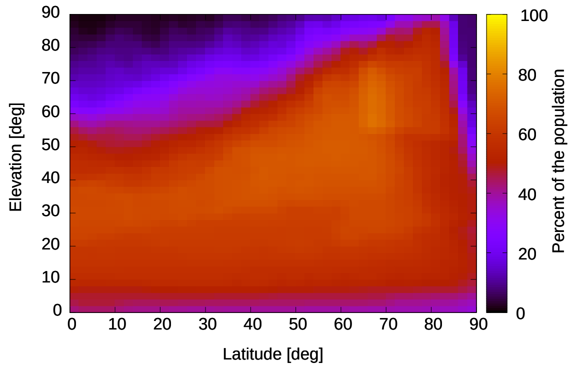

Figure 7: Correlated objects (modeled population >5cm)

The decrease in correlation performance is related to the large number of small objects in high ranges (altitudes) that cannot be observed with the performance of the USSTRATCOM system, which, on the other hand will be able to see objects <5cm in very close ranges. This analysis shows that an altitude dependent lower size threshold will be the most natural result of a surveillance radar.

3.3. Leak-proof survey

Apart from the lower size threshold, another important parameter of a surveillance system is the capability to cover all physically possible orbits (also those that might not be used currently) in the region of concern with the same performance. Such a “leak-proof” capability is achieved when a 100% coverage level for the uniform population is achieved. Figure 8 shows the catalogue correlation performance for such a population of objects >10cm.

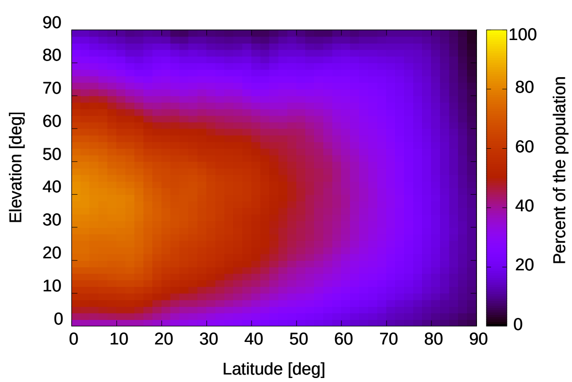

Figure 8: Correlated objects (uniform population of objects > 10cm)

Although not all objects of that size might be detectable in higher ranges, it can already be depicted that a leak-proof survey of objects in LEO, when complying with the applicable size regime, is possible from sensor sites in low latitudes and with moderate elevation angles. In combination with Figure 6 one can observe that the conditions for the surveillance of the USSTRATCOM catalogue population are also optimum for the same conditions.

3.4. Wavelength and correlation performance

A LIS^{4}A simulation has been performed for a range of wavelengths and an exemplary observation geometry of a South staring instrument with 30° centre elevation located at 35° latitude, with the dimensions of the search volume being 20° in elevation and 180°in azimuth. Figure 9 gives the results for the catalogue population and Figure 10 gives the results for the modelled population (in absolute numbers).

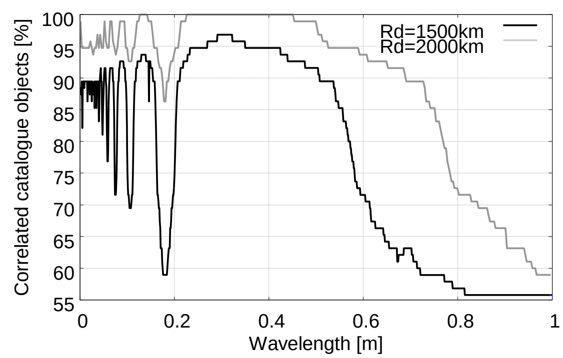

Figure 9: Correlation of the catalogued population

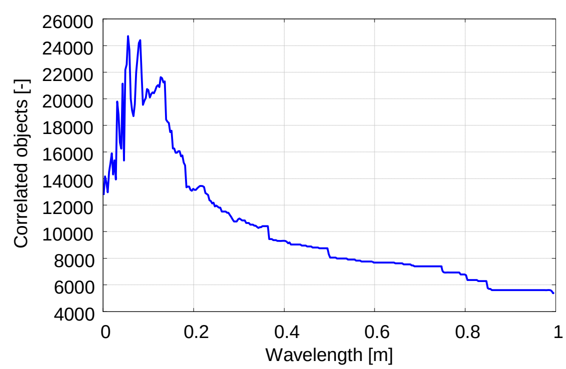

Figure 10: Correlation of the (modeled) overall population

One can see that catalogue saturation can be achieved around wavelengths of 0.3m which is in line with the analysis above which revealed the maximum sensitivity of the radar to be at a wavelength slightly above the minimum object diameter. Correspondingly, Figure 10 confirms that the catalogue size will grow when the wavelength is further reduced, however with the situation getting sub-optimal for the larger objects.

This effect shall be analysed in a repetition of the simulation involving modeled small-size objects as done for Figure 7. While Figure 7 has been generated for a wavelength of 0.5m, the results in Figure 11 stand for a wavelength of 0.1m.

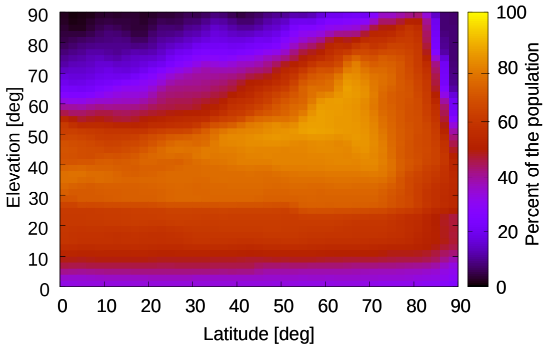

Figure 11: Correlated objects (modeled population >5cm, wavelength 0.1m)

The comparison reveals that the high detection probability of smaller objects with the shorter wavelength by far over-compensates the loss in the detection of larger objects. The results also show that the largest number of fragments is obviously on orbits close to 65° inclination which is best observed from corresponding latitudes and higher elevations to achieve a shorter range.

3.5. Improving the orbit determination performance

So far, the constraints applied in the simulation only concentrated on catalogue correlation, i.e. the necessary steps to take in order to maintain all detectable objects in a catalogue, regardless of the accuracy of the orbit information. The quality of the orbit information, however, depends on the arc length (i.e. the time over which the object is observed) and the revisiting period. While the 10s arc length and the 24h revisiting period are the minimum required for correlation, Figure 12 analyses the characteristics of the catalogue population in terms of revisit times and arc length. For this simulation a radar located at a latitude of 35° and observing a range in azimuth from 90° to 270° and in elevation from 20° to 40°. It shows that, optimally, almost all the population can be observed for at least 30s every 12h. This means that the expected orbit determination accuracy for this radar configuration will in fact be factors higher than what is required for the pure object correlation. Figure 13 shows the distribution of dwell times of correlated catalogue objects for the exemplary observation geometry (for an optimized wavelength of 0.3m) and a maximum revisiting period of 24h. In confirmation of Figure 12 one can see that the lowest dwell time of the correlated objects is indeed on the order of 30s. It can also be depicted that the majority of the dwell times is even much longer with the corresponding positive impacts on the orbit accuracy.

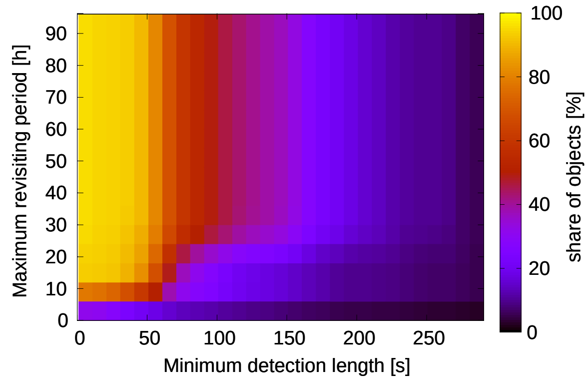

Figure 12: Characteristics of the catalogue population in terms of revisiting period and arc length (*lat.* 35°, *h* 30°)

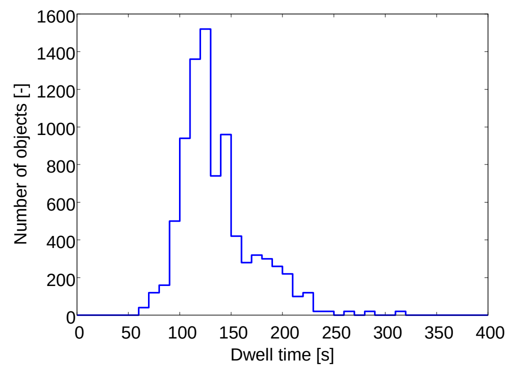

Figure 13: Dwell time of objects in the search volume

4. LEO-TRANSIT

4.1. Modelled population

In the following, we will concentrate on the population of objects intersecting the LEO region. Depending on the apogee height of these objects, the surveillance of this group of objects might be supported by optical telescopes. However, for the analysis of design options it is of interest how far the surveillance radar is able to contribute to the surveillance of this group of objects and whether the optimum observation geometry is in line with that for the LEO objects. The modeled population filtered for objects > 10cm is used together with a search field of 90° to 270° in azimuth and 20° to 40° in elevation and a wavelength of 0.5m. Figure 14 compares the share of the population that is geometrically intersecting the search field with the share of the population that can actually be detected and successfully correlated. It appears that only combinations of moderate latitudes and elevation angles lead to satisfactory results. These geometries achieve a significant span in right ascension in the optimum altitude for the LEO transient objects which are dominated by fragments on GTO and Molniya orbits. The correlation performance is at 60% in the best case for the given performance parameters (detection range (R_x) = 2000km) which is attributed to the long revisiting periods and the, on average, long ranges. It is interesting to note that the optimum region in the latitude/elevation parameter space does not overlap with the optimum parameter space for the LEO catalogue, which means that a radar design which is optimised for both populations is difficult to achieve.

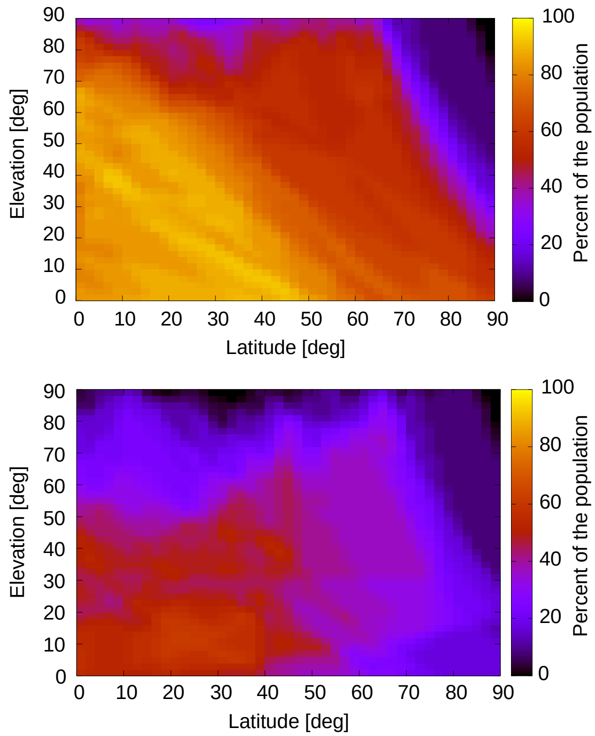

Figure 14: Share of FOV passing (top) and correlated (bottom) LEO-transient objects > 10cm (modelled population)

4.2. Leak-proof survey

While the performance of ground-based surveillance radars for LEO-transient objects is clearly limited, the simulation using a modeled population with uniformly distributed parameters additionally underlines that, as expected, a leak-proof survey of these objects is impossible. Nevertheless, as Figure 15 shows, in contrast to the LEO case the optimum regions in the latitude/elevation parameter space of the uniform population are nearly identical to that of the modeled population.

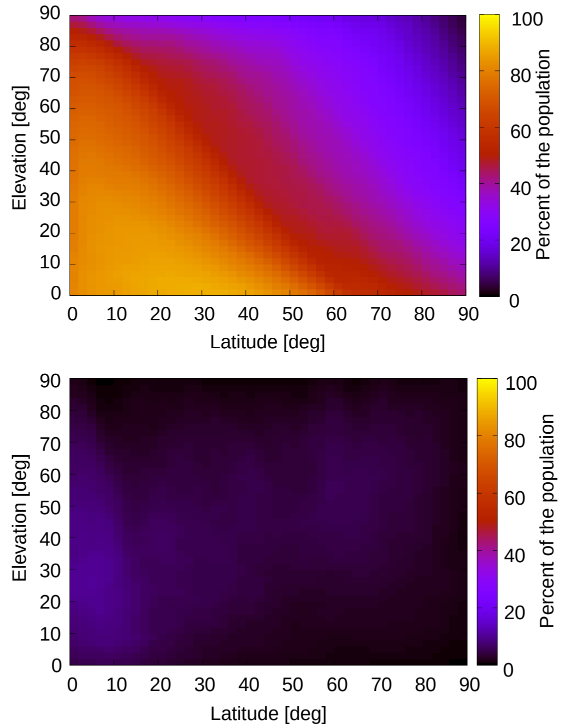

Figure 15: Share of FOV passing (top) and correlated (bottom) LEO-transient objects >10cm (uniform population)

5. SUPER-LEO

5.1. Modelled population

Objects in super-LEO orbits (i.e. between 2000km and 10000km) remain the last population to be analysed. This group of objects is potentially the most difficult to observe (altitudes too high for radars and too low for optical telescopes). Therefore it is interesting to understand the possible contribution of a ground-based radar surveillance system to the screening of this region. Figure 16 shows the result for the modeled population >10cm. The discrete structure of the plots reveals that the modeled population (and even more the catalogue population) consists only of a few samples in this orbital region. A combination of sensor site latitudes of around 20° and elevation around 40° seem to allow a satisfactory survey. Interestingly, this is compatible with the optimum parameters for LEO surveillance. However, one may not neglect that modelling depends very much on existing surveillance data (i.e. for the detection of fragmentations) which is limited. A large part of the modeled super-LEO population will thus correspond to the content of the catalogue, which, most likely, is generated under the same conditions as the simulation results shown here (ground-based radar surveillance).

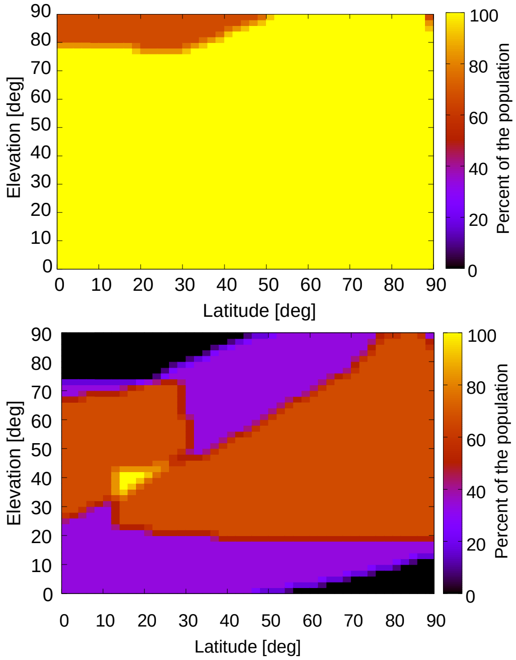

Figure 16: Share of FOV passing (top) and correlated (bottom) super-LEO objects > 10cm (modelled population)

5.2. Leak-proof survey

Figure 17 shows the simulation results for the uniform population of objects >10cm.

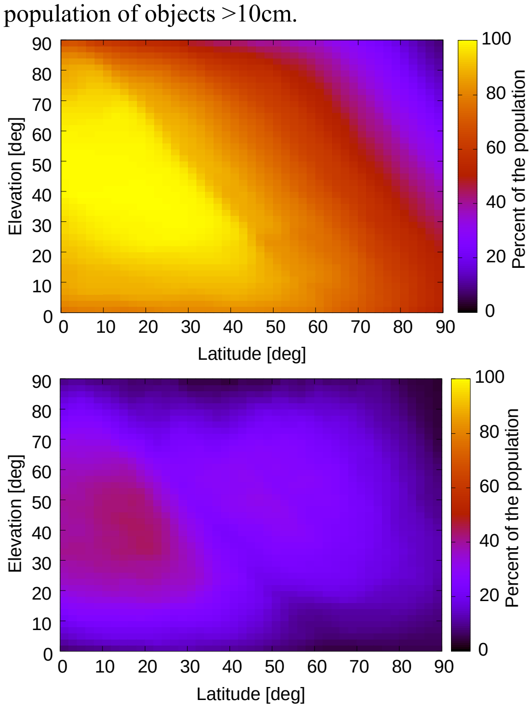

Figure 17: Share of FOV passing (top) and correlated (bottom) super-LEO objects >10cm (uniform pop.)

While a leak-proof survey is not possible (due to objects on high-altitude circular orbits), it can at least be optimized by selecting the same radar parameters as optimized for the surveillance of the modeled super-LEO population.

6. BISTATIC RADAR CONFIGURATION

Bistatic radar configurations become necessary when a Continuous Wave approach is selected instead of a Pulse-Doppler radar. Continuous Wave radars only require a small bandwidth and are therefore a promising solution. Since only monostatic systems have been studied so far, it is interesting to understand whether a bistatic configuration can keep up with the performance investigated before. For this purpose LIS^{4}A has been modified to allow the analysis of bistatic radars. For Figure 18 a transmitter at a latitude of 35° and a search field of 90° to 270° in azimuth and 20° to 40° in elevation and a wavelength of 0.5m has been simulated.

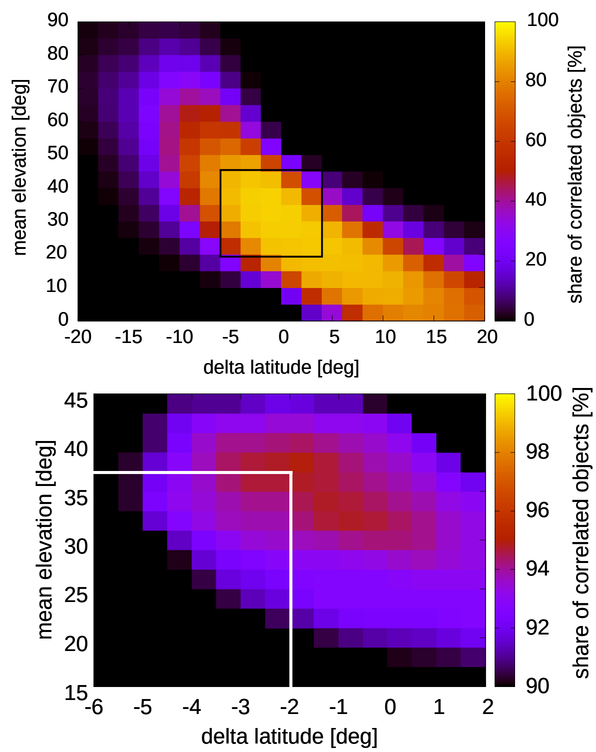

Figure 18: Correlation performance as a function of the relative position and elevation angle of the receiver in a bi-static configuration (bottom: close-up view)

The difference in latitude of the receiver position and the elevation of the receiver search volume has been varied. The azimuth range of transmitter and receiver are identical. Optimum correlation performance is achieved when the receiver is placed 2° further to the South. This reduced the range to the objects. The receiver has to stare at slightly higher elevations to compensate for the parallax. The achieved performance is comparable to that of the mono-static system analysed before.

7. CONCLUSIONS

An engineering tool (LIS^{4}A) to optimise the search volume of a ground-based phased-array radar for space surveillance has been developed. It provides key parameters to radar designers for the development of a system for the cold-start and maintenance of a catalogue of space objects. Preliminary design analysis with the help of LIS^{4}A show that a a single, powerful surveillance radar in low latitudes observing a large range of azimuths performs best in terms of LEO catalogue coverage and will even be able to perform a leak-proof survey. It was also found that an S-Band radar performs worth in terms of NORAD catalogue correlation but offers better expandability options when the catalogue is to be extended to smaller object sizes. When taking the corresponding observational constraints into account, the same system can also substantially contribute to the surveillance of super-LEO objects and (with difficulties) LEO-transient objects. A bistatic solution can provide similar performance when transmitter and receiver have a North-South separation of up about 2° in latitude (i.e. ca. 220km).

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