

CAPABILITY OF A SPACE-BASED SPACE SURVEILLANCE SYSTEM TO DETECT AND TRACK  
OBJECTS IN GEO, MEO AND LEO ORBITS

**Jiri Silha<sup>1,2</sup>, Thomas Schildknecht<sup>1</sup>, Andreas Hinze<sup>1</sup>**

<sup>1</sup>Astronomical Institute, University of Bern, CH-3012 Bern, Switzerland,

[Jiri.Silha@aiub.unibe.ch](mailto:Jiri.Silha@aiub.unibe.ch),

<sup>2</sup>Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynská dolina, 84248 Bratislava, Slovakia

**Jens Utzmann, Axel Wagner**

Airbus Defence and Space, Germany, [Jens.Utzmann@astrium.eads.net](mailto:Jens.Utzmann@astrium.eads.net)

**Philip Willemsen, Frédéric Teston**

ESA ESTEC, The Netherlands, [Frederic.Teston@esa.int](mailto:Frederic.Teston@esa.int)

**Tim Flohrer**

ESA ESOC, Germany, [Tim.Flohrer@esa.int](mailto:Tim.Flohrer@esa.int)

In this paper we present the results from the coverage and the orbit determination accuracy simulations performed within the recently completed ESA study “Assessment Study for Space Based Space Surveillance (SBSS) Demonstration System” (Airbus Defence and Space consortium). This study consisted in investigating the capability of a space based optical sensor (SBSS) orbiting in low Earth orbit (LEO) to detect and track objects in GEO (geosynchronous orbit), MEO (medium Earth orbit) and LEO and to determinate and improve initial orbits from such observations. Space based systems may achieve better observation conditions than ground based sensors in terms of astrometric accuracy, detection coverage, and timeliness. The primary observation mode of the proposed SBSS demonstrator is GEO surveillance, i.e. the systematic search and detection of unknown and known objects. GEO orbits are specific and unique orbits from dynamical point of view. A space-based sensor may scan the whole GEO ring within one sidereal day if the orbit and pointing directions are chosen properly. For an efficient survey, our goal was to develop a leak-proof GEO fence strategy. Collaterally, we show that also MEO, LEO and other (GTO, Molniya, etc.) objects would be possible to observe by the system and for a considerable number of LEO objects to down to size of 1 cm we can obtain meaningful statistical data for improvement and validation of space debris environment models.

## I. INTRODUCTION

The space-based surveillance system, like the one which capabilities were investigated within the frame of this paper, has several advantages comparing to the ground-based systems. One of the major ones is the possibility of observing almost consecutively during 24 hours of survey, not to be interrupted by the daylight, which allows construct a leak proof fence for the GEO population. Another advantage is the absence of the atmospheric turbulence, which means higher measurements accuracy. In our work we were focusing on four major tasks. To investigate the coverage for GEO population by applying by us developed surveillance fence, to investigate how accurately the orbits can be determined for GEO, to see how many LEO objects can be tracked during the normal GEO surveillance and to investigate how accurately we can determine the initial orbit for LEO population. All these tasks are discussed in four separated sections.

Within this paper the GEO objects were defined by using a following filter for orbital elements. The semi-major axis had to be  $41,000 \text{ km} < a < 43,000 \text{ km}$ , the

inclination  $i < 15^\circ$  and the eccentricity  $e < 0.2$ . For the LEO objects their orbits were always with a semi-major axis below 8,378.15 km (mean altitude below  $< \sim 2,000 \text{ km}$ ).

Simulations were performed to assess the performance of the proposed GEO strategies with a respect to the detection coverage for GEO and MEO populations, as well the accuracy of the determined orbits for GEO. By using different observation scenarios in sense of assuming one, two, or two fences scanned twice, a different declination coverage and a scan speed, hence the number of measurements per object, the accuracies of determined orbits were from 10 km to less than 2.5 km in the geocentric position for the majority of the synthetic population of 300 GEO objects.

Furthermore, an interesting result of the assessments has been that the optical sensor can be used to collect the in-situ unique statistical information about the small LEO debris (including the mm size, where a knowledge gap currently exists). A considerable amount of such debris can be detected and characterized during a nominal GEO survey. LEO objects can reach high

apparent angular rates due to their high relative velocities and short ranges according to the SBSS. The initial orbit determination for such objects can be very demanding, as there is usually only one observation tracklet with a length of few seconds available. The tracklet is defined as the series of consecutive observations of the same object. To investigate the accuracy of the orbits determined from short tracklets, we simulated one sensor revolution of a LEO-LEO survey observation.

## II. SOFTWARE TOOLS

For coverage simulations, when we were investigating how many objects and with what kind of properties during the survey would be tracked from given population, we used ESA's Program for Radar and Optical Observation Forecasting (PROOF)<sup>1</sup>, the publically available TLE catalogue US Strategic Command (USSTRATCOM) and the MASTER-2009 population (reference epoch 20090501)<sup>1</sup>. With the PROOF program we simulated the survey strategy taking into account different types of populations such as GEO TLE (two lines elements), or MASTER-2009 LEO. As an output we always got so-called "crossings", objects which crossed our field of view (FoV) during the simulation. These can be considered as tracklets. For these we were able to extract information like the angular velocity, the phase angle, the apparent magnitude, the sensor-object distance, etc.

For the initial orbit determination and orbit improvement we used AIUB's program package called CelMech<sup>2</sup>, which contains ORBDet and SATORB programs. ORBDet is used for the initial orbit determination, while SATORB is designed for the orbit improvement. The major forces assumed during the initial orbit determination process are oblateness term  $C_{20}$  and the third-body perturbations due to the Sun and Moon<sup>3</sup>. For the orbit improvement the model is more complex including also the Earth's potential coefficients and order 12, the perturbations caused by the Earth tides, a simple radiation pressure model and corrections due to the general relativity.

In addition to the orbit improvement, SATORB allows the user to predict the orbital elements forward and backward in time. This capability was used to generate objects ephemerides. These were used for the orbit accuracy investigation for GEO objects after the measurement noise was added to them.

Thanks to a plugin feature of PROOF, which allows to use the PROOF's output directly as an input to the program ORBDet we could use the generated ephemerides of LEO crossings for the initial orbit determination. In the end we evaluated these orbits quality by comparing them to the "true" orbits of crossed objects. Obtained results will be presented in the end of this paper.

## III. SBSS MISSION

In our case, the SBSS system was assumed to be placed at the sun-synchronous orbit (SSO) with an altitude of  $\sim 700$  km above the Earth surface, and an inclination equal to  $\sim 98.0^\circ$ . The right ascension of ascending node (RAAN) was set the way that the orbit was always facing the anti-sun direction (see Fig. 1).

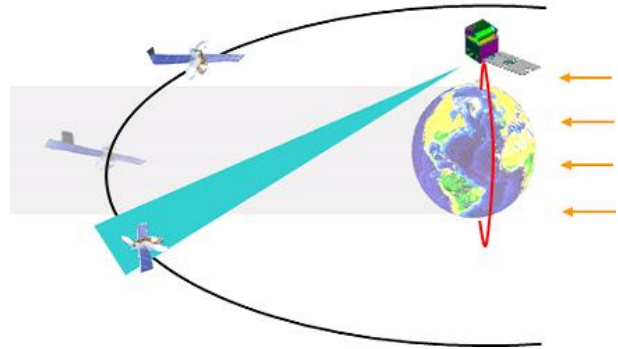


Fig. 1: SBSS observation concept. The SBSS system is always pointing close to the shadow to maximize the illumination of the targets by the Sun (orange arrows representing the solar radiation).

The basic strategy during all simulations was to point the sensor to the anti-Sun direction, close to the shadow to reach the maximum illumination of the target by the Sun (see Fig. 1). Assumed were two types of instruments, one with the  $5^\circ \times 5^\circ$  and one with the  $3^\circ \times 3^\circ$  of field of view (FoV). The first one was used for the operational SBSS system, which is the full performance system. The smaller value was tested for the demonstrator mission, which is the mission to test the capabilities and technologies which are scalable to the operational SBSS. For all simulations assumed was the sidereal tracking during the snapshots.

Further details about the SBSS mission and the system design can be found in a parallel paper<sup>4</sup>.

## IV. GEO COVERAGE SIMULATION

For the GEO coverage simulation, where we investigated the leak proof strategy, we simulated six fields with FoV  $5^\circ \times 5^\circ$ . The observations always started in the lowest declination equal to  $\delta_1 = -12.5^\circ$  (field center) and continued up to the highest declination equal to  $\delta_6 = 12.5^\circ$  (field center), where the fields were never overlapped. The right ascension was set up behind the Earth shadow, meaning that the object which crossed our stripe (fence) entered the shadow shortly afterwards. Such fences can be visible in the Fig. 2, where red arrows imply the motion direction of GEO objects. Because the position of the Earth shadow changes during the year according to the GEO population distribution, we investigated the coverage for two

different dates, the spring date (marked in Fig. 2 as the red fence) and the winter date (marked as the blue fence). Each field was observed for two minutes, where every three seconds one observation was performed. This leads to 40 observations per field in total. One minute was assumed as the time necessary to switch the field to a new position. With three minutes per field in total, there were 18 minutes necessary to perform one fence plus 2 additional minutes to move the field back to the initial position (from  $\delta_6$  to  $\delta_1$ ). In the end, the leak-proof fence which consisted from stripes with length of 20 minutes was simulated with PROOF.

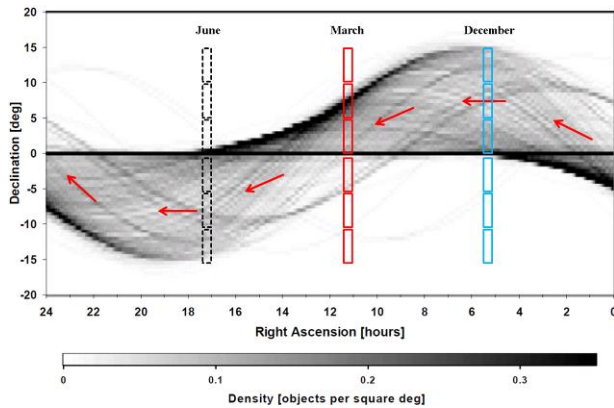


Fig. 2: Apparent object density as a function of geocentric right ascension and declination constructed from all catalogued GEO objects in DISCOS database (status Jan 2001). The logarithmic gray scale is a measure for density. Bin size:  $1^\circ$  in right ascension and  $0.5^\circ$  in declination. Fields observed during simulated PROOF simulations are marked by red and blue squares.

Simulations for two different dates were performed with the tool PROOF. Simulated was an observation strategy described in the beginning of this section (a fence with 20 minutes long stripes). For the spring simulation the chosen date was 15<sup>th</sup> of March 2012 and for the winter simulation the date was 10<sup>th</sup> of December 2012. Investigated were always 25 hours of survey. The TLE population from the publically available catalogue USSTRATCOM which fulfilled the condition for the detector-object range interval 20,000 km to 50,000 km was used. There were in total 2314 TLE objects for the spring and 2422 TLE objects for the winter simulation which passed our condition. From these TLE objects, 935 (spring) and 973 (winter) were GEO objects.

After 25 hours of simulated survey, we detected 1132 (49.0%) objects for the spring and 1150 (47.5%) objects for the winter simulation. From these, 797 (85.2%) and 814 (83.7%) were GEO objects. These numbers indicate that the tested observation strategy is not in fact a leak proof. Assuming that the integration time per fence equal to 20 minutes (1,200 s) and width

(and height) of the field equal to  $5^\circ$  (18,000 arc-sec), only objects faster than 15 arc-sec/s could cross the fence without being detected. However, as we will show later in next section, the time which was chosen to scan one field (2 minutes) is very conservative. Here one can expect that the GEO tracklet length will be up to 120 s. It is expected that by decreasing this value we will not affect the orbit determination accuracy dramatically, and on the other side we will achieve much better coverage (more stripes per same time). Another explanation for missing GEO objects can be the fact, that we didn't assume any fields overlaps. Some of the field to field crossings could not be recognized. These options will be further investigated.

In Fig. 3 is plotted a histogram with tracklet lengths obtained during the spring simulation. We got similar results also for the winter simulation. It is obvious from Fig. 3 that for the majority of the tracked objects ( $\sim 600$ ) we got 40 positions per tracklet, which is the highest number we could get concerning chosen observation strategy.

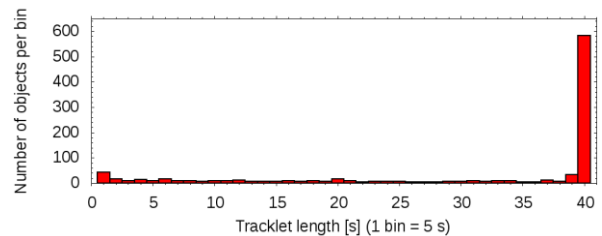


Fig. 3: Tracklet length [s] distribution of 797 GEO objects (tracklets) tracked during the GEO coverage simulation for the spring. Simulation covers a 25 hours long SBSS survey.

During the GEO coverage simulation we also tracked some objects on MEO orbits, namely on GTO (geosynchronous transfer orbit, mean motion  $n < 3$  rev/day,  $i < 30^\circ$ ,  $e > 0.6$ ), GNSS (global navigation satellite system orbit,  $1.5$  rev/day  $< n < 2.5$  rev/day,  $e < 0.2$ ), and Molniya orbit ( $60^\circ < i < 67^\circ$ ,  $0.5 < e < 0.8$ ,  $20,000 < a < 30,000$  km). These we analysed only for the spring simulation during which the fence was crossed by 48 GTO ( $\sim 7.9\%$  from the whole GTO population), 15 GNSS (6.1% from the whole GNSS population) and 19 Molniya objects (10.4 % from the whole Molniya population).

## V. ORBIT DETERMINATION FOR GEO

Once the GEO object is tracked by the fence and its tracklet is obtained, it is necessary to perform the tracklet correlation (linking) and then the initial orbit determination or the orbit improvement. The first step, the tracklet correlation is a rather complex problem that we will be not addressed here. We assumed that the tracklet correlation during the observations is ideal.

For the simplicity, we created a synthetic GEO population of 300 objects, which should well represent the real GEO population (see Fig. 4). In Fig. 4 every red dot represents one population consisting from 100 objects which orbits were defined as follows. For the semi-major axis we have chosen the mean value of 42,165 km. For the eccentricity two values have been chosen, 0.00025 and 0.0025. For the inclination values  $1^\circ$  and  $14^\circ$  were set. For the RAAN the value was set to  $60^\circ$ , for the argument of perigee to value was set to  $0^\circ$  and for the mean anomaly we randomly generated a value between  $10.7^\circ - 39.5^\circ$  to make objects observable from the observation site.

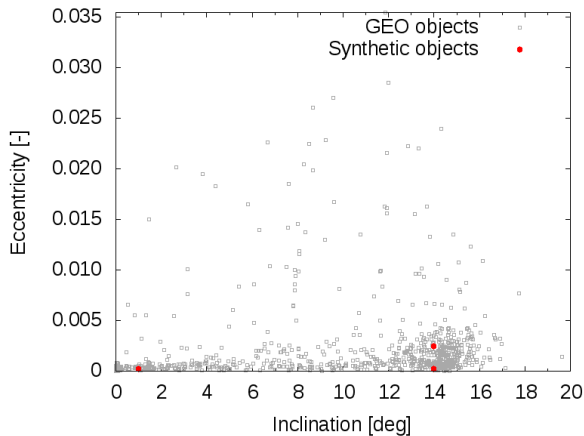


Fig. 4: Inclination versus eccentricity. Elements are plotted for the synthetic GEO population (red circles) and TLE GEO population (to June 2013) (gray circles).

As an observation site due to the technical constraints of the software we didn't choose the SSO orbit, but the ESA's Optical Ground Station (OGS) at the Teide Observatory at Tenerife, Spain. From the geometrical point of view, in general, it can be assumed that the OGS as the ground-based site would have closer ranges to the GEO objects than the space-based sensor, and consequently would reach better observation accuracy. On the other side, for the space-based system a much stronger effect of parallax is introduced, due to the very fast change of the position of sensor, which is believed that also contributes to the improvement of the determined orbit accuracy. For that reason we do not expect large differences between results we would get for the ground- and space-based sensor for GEO objects rising from the geometry.

Several observation scenarios were taking into account during the GEO accuracy simulations. Three basic configurations for the fence were simulated, the one fence per revolution with the best coverage but smallest number of tracklets, two fences per revolution with the optimised coverage (Fig. 5) and four fences per revolution with the lowest coverage. The declination

coverage, which affected the length of the tracklet and also the number of observations per tracklet was chosen between values  $6^\circ - 30^\circ$ . Tracklet lengths were within an interval 21 s - 150 s and tracklets had a number of positions from 100 to 14 depending on the scenario configuration.

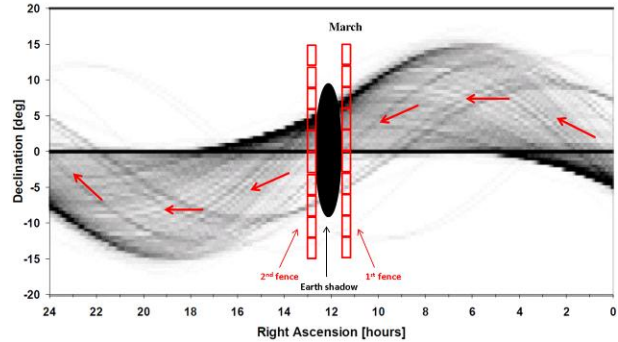


Fig. 5: An observation scenario example. Plotted is the two fences scenario configuration with the  $30^\circ$  coverage in declination. The Earth shadow is plotted in the middle. This is one of three basic configurations used during the GEO accuracy simulations.

During the simulations we used the program SATORB to generate ephemerides for synthetic 300 GEO objects and to add noise into the measurements which was set to be 0.64 and 1.23 arc-sec. These accuracies rise from the assumed sensor and telescope properties<sup>4</sup>. In every case first two tracklets were used for the initial orbit determination with the program ORBDDET, after the initial orbit was obtained all tracklets were used for the orbit improvement performed with SATORB.

For all scenarios three days of follow up (FUP) observations were simulated. For some cases we also simulated 6, 8, and 9 days of FUP. After the improved orbit was determined from all available measurements, we generated ephemerides three days into the future from these orbits and we compared them with ephemerides generated by the true elements. In the end, we calculated the root RMS values of determined errors and we chose highest RMS values after three days of prediction. These were then used to evaluate given observation strategy.

We simulated in total 9 different observation scenarios, with different number of fences or tracklet lengths. For the relatively good coverage, when we could have  $>99\%$  of GEO objects tracked per day, the most promising results were obtained for the case when two fences (two tracklets per day) were assumed and when the tracklet length equal to 21 s (14 observations per tracklet). A similar configuration is plotted in Fig 5, but instead of the  $30^\circ$  declination coverage we assumed  $21^\circ$ . We got the largest RMS in the position error for all



300 synthetic GEO objects equal to only 12.3 km after three days of prediction. As expected even better results we got for six and nine days of FUP, 5.9 km and 3.7 km, respectively. The evolution of the position error's RMS during three days of prediction for the mentioned case can be seen in Fig. 6.

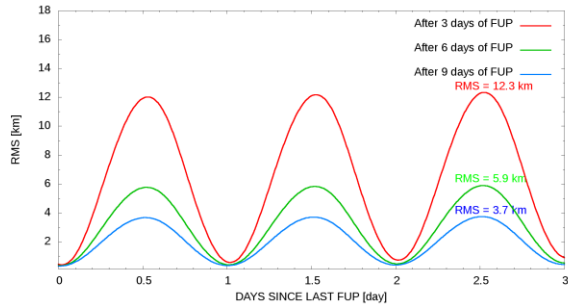


Fig. 6: RMS values for the error in position determined for 300 synthetic GEO objects and the case two fences and tracklet length equal to 21 s. Plotted are RMS values calculated after the last FUP measurement till three days of prediction. Three (red), six (green) and nine (blue) days of FUP were investigated during given scenario.

By changing the configuration, the RMS values mentioned in previous sections can be further improved, but one should be expecting that this will be done at the expense of other parameters such as the coverage, the number of tracklets per object, or the tracklet length (number of measurements per tracklet). This is valid also other way around. By decreasing tracklet lengths, or number of tracklets per object, the coverage can be improved, but the accuracy decreased.

We assumed two fences scanned twice per revolution, where the tracklet length was 40.5 s. Four tracklets per day were obtained. After 3 days of FUP we were able to reach a worst accuracy for the RMS for the error in position along an entire orbit within three days of prediction equal to 1.9 km for all 300 synthetic GEO objects.

It is important to point out that the proposed demonstrator allows to flexibly implement observation strategies<sup>4</sup>.

In previous two cases we assumed the demonstrator FoV equal to  $3^\circ \times 3^\circ$ . However, for the operational SBSS system, a FoV of  $5^\circ \times 5^\circ$  is planned. For that reason we also ran simulation assuming the operational SBSS FoV. In this case, one should be expecting a higher coverage, as well larger tracklet lengths. We investigated a scenario with four fences and with 100% coverage ( $30^\circ$  in declination). The tracklets would have in this case lengths equal to  $\sim 27$  s. This simulation showed that by using given parameters we can get the worst RMS for the position error within three days of prediction less than 1.9 km. With the 100% of coverage

this is definitely the best result we got during our GEO accuracy simulations.

## VI. LEO COVERAGE SIMULATION

Even considering that the primary task of the proposed SBSS system is GEO surveillance, as we already showed with MEO objects one can expect some sort of side products during these types of observations. Another population which will be crossing the FoV of a sensor placed at SSO orbit are for sure LEO objects. The LEO population behaves much different than the high altitude objects. LEO particles distances between the object and sensor are very low, several dozen to hundreds of kilometres. This originates to high angular velocities and tracked objects leave only few seconds long tracklets after they are detected on the sensor.

For the LEO coverage simulation we used the same simulation inputs as we used for the GEO coverage simulation. A space-based sensor was assumed, where one fence with 6 fields and the time duration of 20 minutes was used. The FoV had the size equal to  $5^\circ \times 5^\circ$ . As a tested population this time we used LEO statistical population inside the model MASTER-2009<sup>1</sup>. Objects larger than 1 cm and smaller than 100 m in diameter were investigated within the sensor-object range 12,000 km. Because the LEO population is rather equally distributed over the nodal band, we did not expect any large variations in coverage arising from the different pointing direction during the year. For that reason we only ran simulation for the spring scenario with expectation that we will get very similar results (the number of tracked objects and objects physical and dynamical properties) for the winter simulation, as well.

There were in total around 110,000 tracklets of LEO objects crossed the FoV during the LEO coverage simulation. In Fig. 7 are plotted the sensor-object ranges as a function of the inclination. The survey covered all inclination regimes, where plotted are from  $0^\circ$  to  $120^\circ$ , in which the majority of the LEO population is placed. In some cases tracked objects reached very close vicinities to the sensor. The ranges varied from few tens of kilometers to 9,000 km.

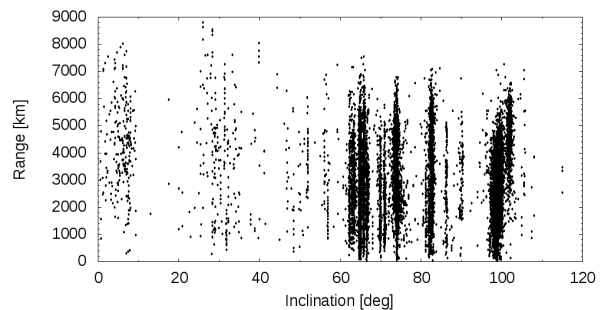


Fig. 7: Inclination vs. minimum sensor-object range of 110,000 LEO tracklets tracked during the LEO

coverage simulation for objects from 1cm to 100 m. Simulated was 25 hours long SBSS survey.

Due to close ranges and very high relative velocities, the tracked objects reached large angular velocities. The histogram distribution for 110,000 tracklets is plotted in Fig. 8. A large fraction of tracklets (~ 25%) had angular velocities between 1000 - 1585 arc-sec/s (0.3 to 0.4 deg/s). Due to the fact that the detectability of the objects is function of its brightness, the angular velocity (time spend on one pixel) and the sensor properties (sensitivity, quantum efficiency, etc.), we also plotted magnitude versus angular velocity in Fig. 9. For the majority of the tracklets we got magnitudes brighter than 20. By assuming the telescope and sensor parameters during the demonstrator mission <sup>4</sup>, it can be expected that there will be more than 5,000 objects with SNR higher than 2.

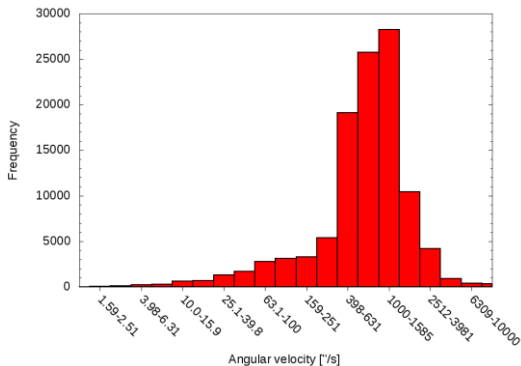


Fig. 8: Relative angular velocity [arc-sec/s] distribution of 110,000 LEO tracklets tracked during the LEO coverage simulation for objects from 1 cm to 100 m. Simulated was a 25 hours long SBSS survey.

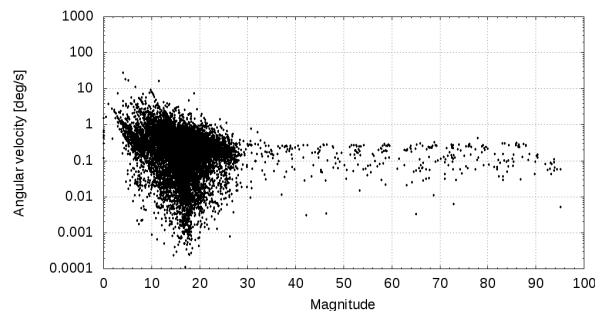


Fig. 9: Apparent magnitude versus relative angular velocity [deg/s] distribution of 110,000 LEO tracklets tracked during the LEO coverage simulation for objects from 1cm to 100 m. Simulated was a 25 hours long SBSS survey.

During the LEO coverage simulation we took into account only objects larger than 1 cm in diameter. Therefore, we also performed a simulation with objects from 1 mm to 1 cm size within the sensor-object range equal to 500 km by using the same simulation settings

as in previous case. According to that additional simulation we would obtain about 53,000 tracklets for 1 mm to 1 cm population during simulated 25 h of observation. For the angular velocity distribution we got different results as we got for the previous population. The majority of the objects reached angular velocities between 1.75°/s - 2.8°/s (6,000 arc-sec/s to 10,000 arc-sec/s). Due to the high angular velocities, most of these objects would not be detectable with their very low signal to noise ratios (SNR). Despite this fact, one should be expecting at least few to dozens of particles smaller than 1 cm in diameter to be detected (SNR > 2) during one day of the proposed SBSS survey by taking into account the demonstrator’s sensor and telescope properties <sup>4</sup>.

## VII. INITIAL ORBIT DETERMINATION FOR LEO

Initial orbits are usually simplified and are used as an input for the subsequent orbit improvement step. However, parameters like semi-major axis or the orientation of the orbital plane can be calculated very precisely in some cases. For that reason, one can also use the initial orbits and the number of tracked objects to statistically describe the required population. For LEO-LEO detections, as we already showed, it is very difficult to get meaningful number of positions per only one acquired tracklet for the orbit determination purposes. Usually, tracklets obtained during LEO-LEO measurements are only few seconds long. However, we simulated once again the SBSS observation survey to see how accurately determined the LEO orbits can be from such short tracklets. The following results came from the simulation performed within an ESA project “Improvements of Space Object Observation Strategies and Processing Techniques Trough Using Silicon-Based Hybrid CMOS Detectors” dedicated to the investigation of CMOS type of cameras capabilities <sup>5</sup>.

Again, PROOF tool was used to run the simulation, the SBSS sensor was placed at the same SSO orbit that it was for GEO and LEO coverage simulations. The FoV was assumed to be 5°x5° and we slightly increased the frame-rate due to the high angular rates of tracked LEOs from 0.5 to 2 frames/s. As an astrometric error the value of 0.9 arc-sec was chosen. During this simulation we also introduced a new parameter called the epoch registration accuracy, which plays a very strong role when very fast objects are tracked. In our case we have chosen for this parameter value equal to 0.5 ms. During the simulation, we used MASTER population within the size interval from 1 cm to 100 m with the sensor-object range below 3,500 km. To reduce the large number of tracklets, we investigated only one orbital revolution of SBSS, therefore 100 minutes (1.7 h). The LOS was stable and pointing all the time in the anti-Sun direction close to the shadow. This is slightly different strategy we used

for the GEO and LEO coverage simulations, but for tracked LEO objects we are not expecting different dynamical properties considering effects on the initial orbit determination procedure.

There were in total 9507 LEO and MEO objects tracked during the simulation, from which 9023 were LEO objects. Tracked LEO objects showed similar properties (angular velocity, magnitude, ranges, etc.) as the ones detected during the LEO coverage simulation mentioned in earlier. Majority of the tracklets had lengths from 5 s to 10 s. Assuming that the frame-rate was 2 frames/s, this means 10 to 20 measured positions per object. The tracklet length distribution is plotted in Fig. 10.

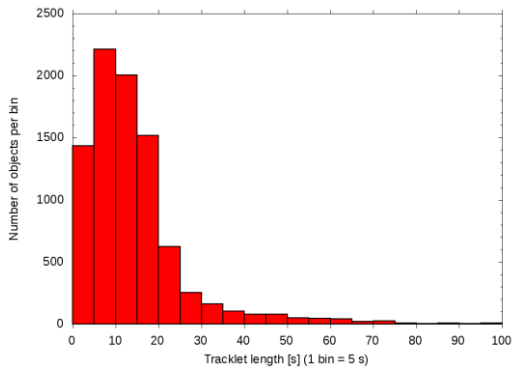


Fig. 10: Tracklet length [s] distribution of ~ 9,000 LEO objects (tracklets) tracked during the LEO initial orbit determination simulation for objects from 1cm to 100 m within the sensor-object range of 3,500 km. Simulated was a 100 minutes long SBSS survey (one sensor revolution).

The tracklets obtained from the simulation were used as an input for the program ORBDDET for the initial orbit determination procedure. The circular orbit ( $e = 0$ , the argument of apogee not defined) was assumed during this step. For some cases we were also able to perform the orbit improvement and acquire an eccentric orbit for them. By assuming only basic forces for perturbations like the luni-solar gravitational force and the Earth oblateness, we determined the initial circular orbits for more than 5,000 LEO objects (~57%). We compared these orbits with the true elements/parameters like the semi-major axis, inclination, RAAN, geocentric position and velocity. We were interested to assess how accurately these parameters could be determined during a SBSS survey for LEO objects. Some of the obtained results are plotted in Fig. 11 and Fig. 12, namely for the semi-major axis and the inclination accuracy.

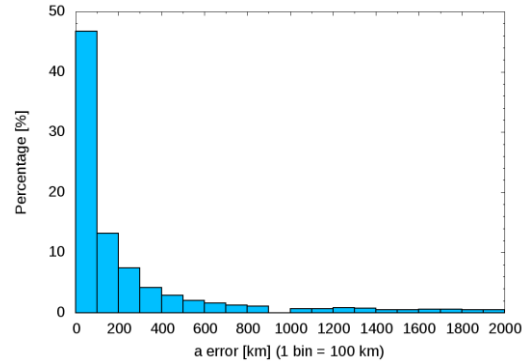


Fig. 11: Error in the determined semi-major axis [km] as a function of percentage of objects per given bin. There were in total 5140 LEO objects (100 % in figure) with a determined orbit.

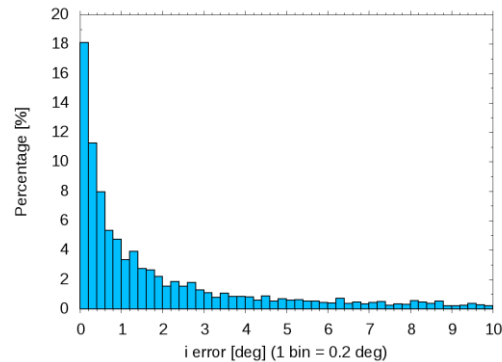


Fig. 12: Error in the determined inclination [deg] as a function of percentage of objects per given bin. There were in total 5140 LEO objects (100 % in figure) with a determined orbit.

We obtained very promising results in sense of the obtained accuracy for initial orbits. For the semi-major axis (Fig. 11) for 50 % of objects this parameter was determined with an error below 120 km. For the orbital plane we got 50% of objects with an error below  $1.2^\circ$  for the inclination (Fig. 12) and for 50% of objects we got an error below  $2.1^\circ$  for the RAAN (not plotted). By using better epoch registration accuracy (e.g. by using an electronic shutter) these values can be greatly improved. A higher frame-rate would also increase the accuracies slightly.

Presented results for initial orbits accuracies showed that the LEO-LEO configuration can be very beneficial for the statistical evaluation of the LEO population above 1 cm in diameter, i.e. for the improvement and validation of space debris environment models in an area where currently a knowledge gap exists. Better accuracies also provide good chances to succeed in correlating tracklets for old but also newly discovered LEO objects and particles, which is necessary for the orbit improvement and additionally for temporary cataloguing, if eventually desired.

## VIII. SUMMARY AND CONCLUSION

In our paper we investigated and analysed the coverage that can be achieved with a space-based space surveillance system (SBSS) placed at the Sun-synchronous orbit. During the simulations we used ESA's tool PROOF and a given TLE population to simulate one day of a SBSS survey. The proposed GEO leak proof fence observation concept showed a leakage of about 16% for GEO objects. A further investigation has to be performed in this direction. One of the causes could be –due to the assumption that the maximum angular velocity of GEO objects is 15 arc-sec/s. Because some GEO objects can reach faster angular velocities they could pass the fence without being tracked. However, there is still a room for an improvement. By decreasing the field tracking times, accordingly shortening the tracklets lengths, every each field can be covered more often and also this leakage can be removed widely. Alternative that during the simulations the fields were not overlapping has to be considered, as well, as an explanation for this leakage.

To establish a GEO catalogue with objects with meaningful accuracies of their orbits, we investigated several different survey scenarios to find the most suitable one to achieve a good accuracy, but also a good coverage. A population of 300 synthetic GEO objects was created. We simulated a different number of tracklets per day with different lengths, reflecting the selected observation strategy scenario. During these simulations we used AIUB's programs ORBDDET for the initial orbit determination and SATORB for the orbit improvement. SATORB considers all relevant perturbation forces, while ORBDDET takes only into account the luni-solar gravitational effects and the Earth oblateness. We obtained best results for the scenario where four fences per an object revolution were assumed with tracklet length equal to 27 s. There we got for the worst RMS value in the position accuracy along one full orbit less than 1.9 km after three days of follow-up measurements and after consecutive three days of prediction. Of course, we had to assume that a successful linking of the tracklets was achieved.

Except for GEO objects, the SBSS system would track also MEO and LEO populations. For LEO objects we investigated a coverage for 1 cm to 100 m size objects from the statistical MASTER-2009 population of ESA. A considerable number of LEO objects can cross the FoV during one day of survey. About 110,000 tracklets were obtained during simulated 25 h, but not implying sufficient illumination conditions..

For LEO one should expect only one short tracklet per object. For that reason we ran simulations, where we studied the initial orbit determination accuracy for LEOs from a single crossing of the FoV. By using ORBDDET we successfully determined circular orbits for about 57% of tracked objects, where two thirds of these orbits were circular and one third was eccentric. For more than half of them the semi-major axis was determined with accuracy below 120 km. For the inclination we achieved an accuracy below 1.2°. These values indicate that for a considerable amount of LEO objects, which would cross the SBSS's FOV during one orbital revolution can be used for further statistical evaluation of the population. This implies, that some objects can be observed repeatedly with sufficient revisit times for follow-ups.

In this paper we presented observation strategies developed for the space-based surveillance system proposed within an ESA project "Assessment Study for Space Based Space Surveillance (SBSS) Demonstration System". A leak-proof fence for GEO objects is possible with such a system, when the surveillance strategy is properly designed. By increasing the number of scans per fence, every of two fences scanned twice during one revolution, we are able to reach accuracy of the position for the majority of tracked GEO objects below 1.9 km after three days of prediction, using only the space-based observations. Such a system would be also able to track considerable amount of LEO objects, which can be further used for statistical purposes or cataloguing. We'll continue to investigate the leak-proof fence survey and study possible enhancements.

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