SATELLITE-BASED SOLUTIONS FOR BEYOND-LEO SPACE SURVEILLANCE

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ABSTRACT

This paper will show the capabilities that a space based component of a space situational awareness system can offer with respect to the object population in beyond-LEO orbits. The main focus will be on space surveillance. Based on performance parameters, different space based solutions will be analyzed. Performance parameters are for example: achievable number of catalogued objects, selectivity of the observations, and mean revisit time. The performance is driven mainly by the selection of the orbits for the satellite constellation, the number of satellites and sensors used, by the observation strategies, and the instrument parameters. Most of the space based solutions for space surveillance presented in the last years have focused on objects in GEO, allowing some simplifications, i.e. with respect to the observation strategies. The necessary observation strategies to cover the object population in Molniya-type orbits, navigation satellite orbits, GTO, and GEO will be presented in this paper. The PROOF-2005 software will be used as a basis to simulate object detections. Post processing tools will be used to derive the needed performance figures. Based on the above results, the feasibility to build up and maintain an object catalogue for beyond-LEO objects solely relying on space based sensors will be discussed.

1. PERFORMANCE PARAMETERS

In order to satisfy the numerous user needs for a Space Situational Awareness System, the following sets of services have to be provided

- Survey and Tracking
- Imaging/Object Characterization
- Space Weather
- Near-Earth Objects survey and tracking

While space-based solutions would be beneficial for all four of those services, in this paper only the first part, survey and tracking will be analyzed. The analysis will focus on orbits above low Earth orbit. Of particular interest will be the orbital regions around the 12h navigation satellite orbits, the geostationary ring, the GEO transfer orbits, and Molniya-type orbits.

The survey and tracking service to be provided by a Space Situational Awareness system consists of a number of elements [1], including

- Detection, tracking, correlation and characterization of man-made objects
- Maintenance of an object catalogue
- Orbit manoeuvre detection and estimation
- Explosion and collision detection and characterization
- Conjunction warning, recommendation of suitable avoidance manoeuvres
- Re-entry risk assessment and initiation of alert procedures
- Identify non-compliance with international treaties and recommendations

The fidelity of a number of those services, including conjunction analysis, manoeuvre detection, explosion or collision detection is depending basically on the quality of orbit information that can be derived from the observations, on the temporal resolution of the orbit information available, and on the size thresholds. These parameters also drive the capability to build up and maintain a catalogue of objects.

The main questions to be asked in order to judge the performance of a survey and tracking element of a space situational awareness system targeted at the above mentioned orbit region are:

- How rapidly can a catalogue be built up?
- What is the average time between re-acquisitions (revisit time)?

2. SIMULATION ENVIRONMENT

Based on a catalogue of 5,589 objects in beyond-LEO orbits (apogee altitude above 1,000 km), the performance of the space-based space surveillance component will be evaluated.

As a first step, for a reference period of 60 days, the space-based sensors are simulated using the PROOF-2005 software of ESA [2]. The detection lists provided by that software are then used for further analysis. For that detailed analysis, a specific software named P3

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(Proof Post Processor) developed by the authors is used. That software is capable to simulate the build-up and maintenance of a catalogue of objects based on detection lists provided by PROOF and internal rules which provide the probabilities for a successful initial and re-acquisition of an object, depending on its orbit type and the times between subsequent observations.

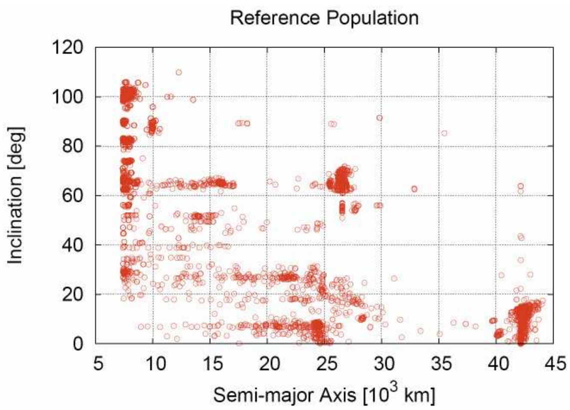

Figure 1. Semi-major axis vs. inclination of all reference objects in the simulation

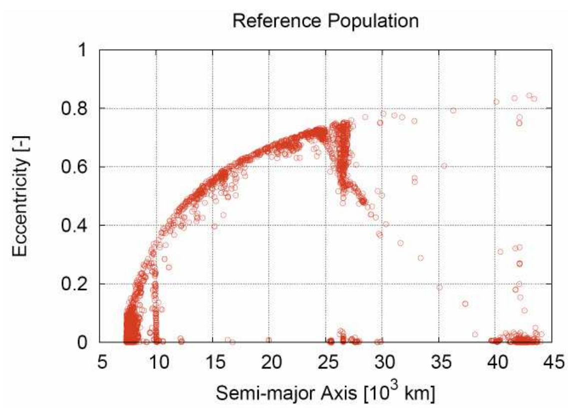

Figure 2. Semi-major axis vs. eccentricity of all reference objects in the simulation

Tracking strategies for beyond-LEO objects are not within the scope of this paper. The instruments simulated use pre-defined pointing strategies, performing a blind search strategy. Follow-up observations needed to catalogue newly detected objects are performed as a part of the blind search strategy.

3. SIMULATIONS

A number of different constellations of satellites have been analysed with respect to their suitability for serving as an element for the provision of survey and tracking data for the beyond-LEO object population.

As a reference, all constellations consisted of 6 spacecraft. Each spacecraft is equipped with an instrument or instrument array covering 6 degrees field of view.

The constellation design can be optimized in two ways: the first possibility is the maximization of the number of unique objects that can be detected, the second possibility is the maximization of the number of objects which can be observed and for which necessary follow-up observations can be performed by the satellites in the constellation in order to build up and maintain a catalogue of objects.

These different optimization parameters represent two different uses of the satellite constellation. The first variant (maximization of the number of unique objects detected - not tracked!) represents a constellation that only provides the survey part of space surveillance. In order to have the capability to build up and maintain a catalogue, additional resources (ground-, or space-based) are needed to perform the necessary follow-up observations - at least for those objects which have been newly discovered or which are not detected within the regular observations at a frequency high enough to permit a successful reacquisition.

The second variant (maximization of the number of unique objects which can be tracked - not just detected) represents a constellation where both the survey part and the follow-up observations needed in order to build up and maintain a catalogue of objects are performed by the elements of the constellation within a pre-determined pointing strategy.

3.1. SSO Dawn-Dusk

The classical orbit proposed for space-based space surveillance of the GEO ring is a sun-synchronous dawn-dusk orbit with a sensor pointing in anti-sun direction, parallel to the equatorial plane – meaning that the phase angle is never higher than 23.45 degrees in the centre of the field of view. Such a configuration has been the baseline for the first part of the simulations that have been performed for this paper.

Depending on the objective of the space-based component of a space surveillance system targeted at beyond-LEO objects, different in-plane positions of the six satellites are more or less favourable.

In case the space-based component has the only objective to fulfil the survey task of space surveillance, the main goal of the optimization is the maximization of the number of unique objects that can be detected (not catalogued) by the constellation. In this case, both follow-up observations and a part of the tracking activities are performed by an additional component of the space surveillance system which may be ground-, or space-based.

The best solution to place the six satellites in the dawn-dusk orbital plane is with equal spacing – with 60 degrees phasing. This configuration optimizes the geometrical coverage of section around Earth which is regularly passed by objects in a number of orbit regimes, especially those in GEO-, GPS-, and GTO-type orbits.

When the space-based component is responsible for performing both the initial and the follow-up observations needed to put an object into the catalogue, an in-plane configuration slightly different to the one described above has to be chosen. The simulations showed that – starting from the configuration described above – a reduction of the spacing between the satellites would lead to higher number of objects that can actually be catalogued, as the probability of follow-up observations increases. Two groups consisting of three satellites each – with a phasing between the satellites of each group of 15 degrees, and a phasing between the groups of 180 degrees are placed in the orbit plane. The satellite triplets increase the probability of successful follow-up observations, the splitting into two groups can help retaining some of the capabilities of the survey-optimized configuration described above, helping to detect a large number of unique objects.

Table 1. Performance of the SSO Dawn-Dusk- constellation optimized for maximum cataloguing performance

Orbit	Total	Undetected	Detected, not catalogued	Catalogued
OTH	3234	188	100	2946
GPS	212	42	63	107
GEO	963	1	231	731
GTO	182	4	111	67
MOL	114	18	82	14
HEO	884	84	458	342
SUM	**5589**	**337**	**1045**	**4207**

Tab. 1 gives an overview of the capabilities of the configuration. It performs exceptionally well in the GEO regime, where only one object remains completely undetected. About 75 percent of the GEO objects in the simulation can be put into the catalogue taking into account the timing of the follow-up observations and their associated probabilities for a successful re-acquisition. The remainder of the GEO objects require follow-up observations to be performed by other resources of the space surveillance system. Most of the objects that appear under 'OTH' (other objects) reside in the altitude regime between 1,000 and 2,000 km.

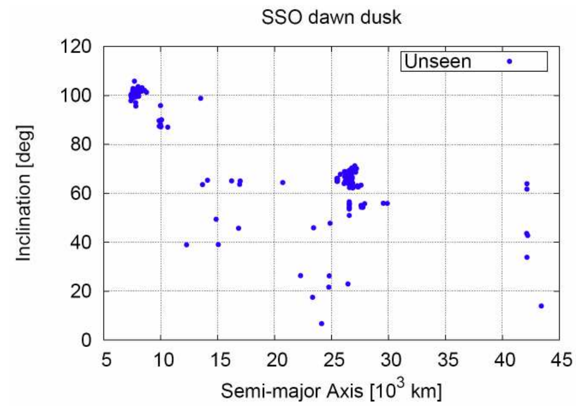

Figure 3. SSO Dawn-Dusk-Constellation: Semi-major axis vs. inclination of all objects in the simulation which cannot be detected at all

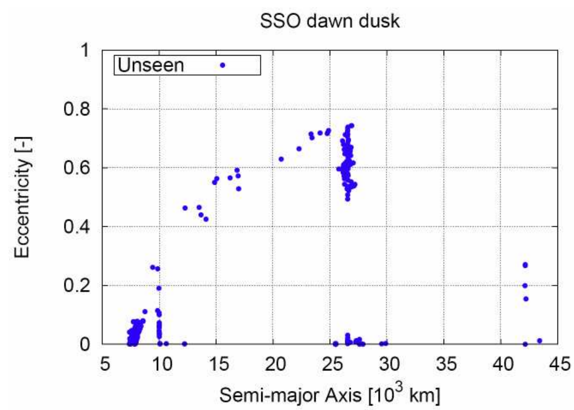

Figure 4. SSO Dawn-Dusk-Constellation - Semi-major axis vs. eccentricity of all objects in the simulation which cannot be detected at all

The proposed constellation which is at a mean altitude of 730 km can also cover the majority of that object population with over 90 percent of the objects being catalogued. The major share of that population which cannot be detected is dominated by SSO objects (see Fig. 3 and 4). Due to the relatively small right ascension coverage of the constellation, it exhibits a selective performance with respect to the right ascension of the ascending node of the target objects. Objects with a line of nodes nearly perpendicular to the line of sight of the sensors remain completely undetectable (see Fig. 5).

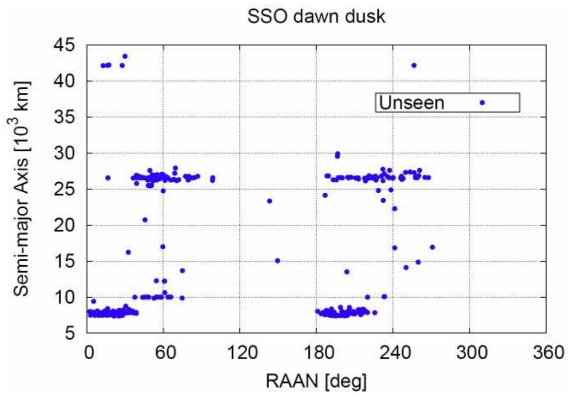

Figure 5. Distribution of RAAN vs. semi-major axis for all objects which cannot be detected during the selected simulation period

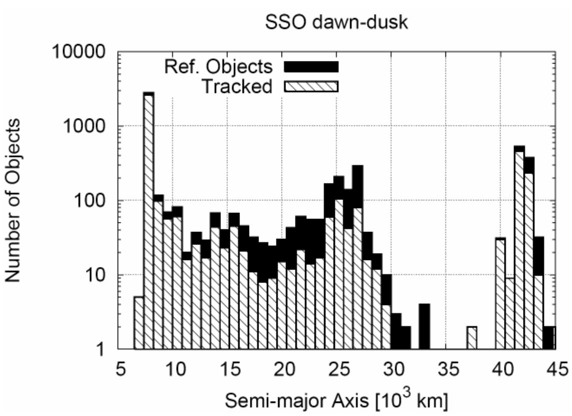

Figure 6. SSO Dawn-Dusk-Constellation: Tracked objects vs. reference objects

Objects in GPS and Molniya-type orbits can be detected and – at a lower share – be catalogued by the proposed configuration. However, the same selective effects with respect to the right ascension of the ascending node of the target objects as described for the objects on lower orbits above can be observed (refer to Fig 5). Therefore, the proposed constellation is not entirely suitable for cataloguing objects in the GPS and Molniya regimes. Other configurations, which cover a larger right ascension range, would enable a better performance with respect to these orbit regimes. Such configurations will be examined in the following.

3.2. SSO 3-Planes

The next configuration consists – again of six satellites which are placed in three sun-synchronous orbit planes at an in-plane phasing of 180 degrees. The three orbit planes comprise a dawn-dusk orbit (6h/18h), one 10h/22h orbit, and one 14h/2h orbit. In order to cover a larger right ascension regime compared to the preceding configuration enabling less selective observations in a number of the relevant orbit regimes (especially GPS, and Molniya-type orbits), the sensor lines of sights are as follows: The sensors in the dawn-dusk orbit are pointing in anti-sun direction, parallel to the equatorial plane. The other 2 sensors are also pointing parallel to the equatorial plane. However, their lines of sights are offset by 60 degrees from the sun direction. This means a less favourable object illumination and thus a lower probability that an object passing the field of view of a sensor can actually be detected. However, these lines of sights are needed to draw a non-selected picture of the orbit population.

Table 2. Performance of the three-plane SSO constellation optimized for maximum survey performance

Orbit	**Total**	**Undetected**	**Detected, not catalogued**	**Catalogued**
OTH	3234	1	493	2740
GPS	212	0	211	1
GEO	963	0	935	28
GTO	182	1	131	50
MOL	114	0	110	4
HEO	884	11	658	215
SUM	**5589**	**13**	**2538**	**3038**

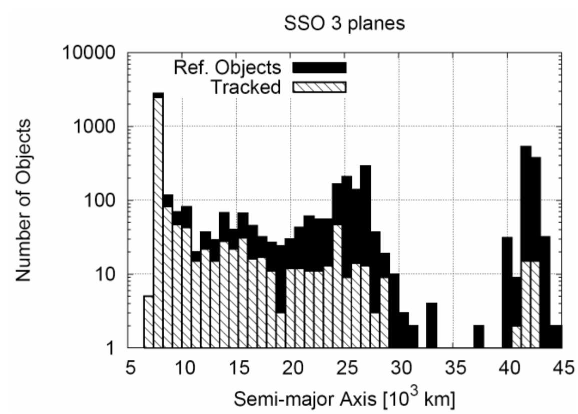

Figure 7. Three-plane SSO-Constellation: Tracked objects vs. reference objects – without additional resources allocated for follow-up observations and tracking, that configuration is not useful

Tab. 2 and Fig. 7 show that, as far as cataloguing performance is concerned, the three-plane SSO configuration is clearly inferior to the configurations proposed above. Due to the lower probability for successful follow-up observations in all orbit regimes, the number of objects which can be catalogued just based on the observation data gathered by the constellation and its predetermined pointing is very low. For the GPS and Molniya orbit regimes the constellation can in hardly any case provide the necessary follow-up observation opportunities.

However, under a different setting that constellation may prove to be very useful. It is an excellent performer in the pure survey task. There are virtually no orbit regions where the constellation does not fulfil its survey requirements well. More than 99% of all objects in all relevant orbit regimes examined can be observed. In combination with additional resources allocated for the follow-up observations and tracking, such a configuration may prove to be very useful.

3.3. Low Inclination LEO

As a consequence of the results for the SSO Dawn-Dusk-Constellation examined above, another configuration was examined, addressing the selectivity problem of that configuration by scanning a larger right ascension range.

This configuration, again consisting of six satellites does not use an SSO but a near-equatorial (i.e. 7 degrees inclination) orbit at about 720 km altitude. The satellites are equally spaced in their common orbit plane. The sensors are assumed to be zenith-staring, basically forming an optical fence (but with large holes) around the equator, covering a wide range of right ascension. Here, precautions have to be made to avoid conditions where the sensor would point directly into the sun. Instruments capable of observing at high phase angles would be an asset for this kind of configuration.

Table 3. Performance of the near-equatorial constellation optimized for maximum survey performance in the GPS, GTO, and Molniya orbit regimes

Orbit	Total	Undetected	Detected, not catalogued	Catalogued
OTH	3234	606	2549	79
GPS	212	0	211	1
GEO	963	562	399	2
GTO	182	13	87	82
MOL	114	9	105	0
HEO	884	57	590	237
SUM	**5589**	**1247**	**3941**	**401**

The instrument parameters were optimized in order to maximize the share of objects in GPS-type orbits which can be detected. The sensitivity with respect to GEO objects is not high, due to the low pixel dwell times caused by horizon fixed, zenith-staring observation strategy causing larger angular velocities of the objects in the sensor frame. However, the configuration fulfils its goal to detect all 212 GPS-type objects in the simulation setting. The capability of cataloguing without the aid of additional sensors tasked for follow-up observations and tracking is very low. Fig. 8 shows the cataloguing performance without the aid of additional sensors.

This configuration may be beneficial in combination with additional resources targeted at follow-up observations and tracking.

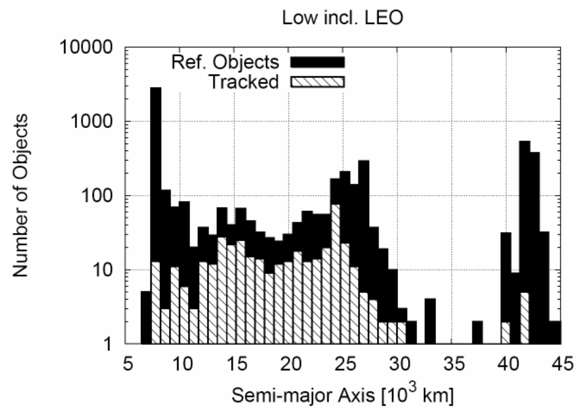

Figure 8. Near-equatorial constellation: Tracked objects vs. reference objects – without additional resources allocated for follow-up observations and tracking, that configuration is not useful

3.4. Overview

The three configurations examined in the preceding chapters showed very different results. However, they showed for which uses the different configurations may be usable.

The SSO Dawn-Dusk Constellation is well-suited for cataloguing the GEO population and objects in a part of the other orbit regimes. Its major drawback is the selectivity with respect to the right ascensions of the ascending node.

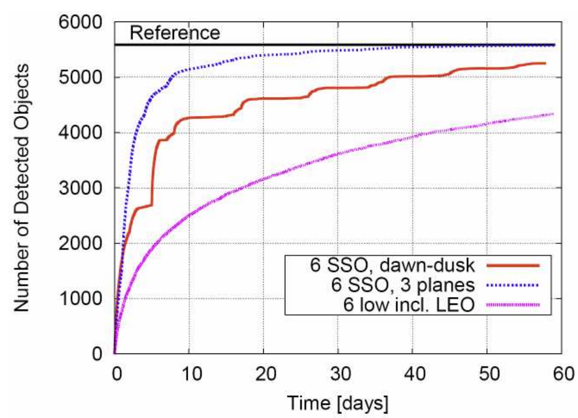

Figure 9. Comparison of the survey performance of the three configurations examined

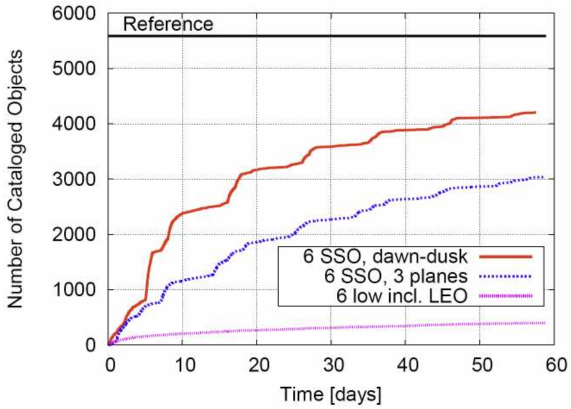

Figure 10. Comparison of the cataloguing performance of the three configurations examined

The second configuration, with three sun-synchronous orbit planes at 120 degrees plane offset shows the best survey performance – depicted by the number of unique objects detected in Fig. 9. As a standalone component – without external tracking resources – it would not serve its purpose very well as it is not optimal for providing follow-up observation data (see Fig. 10). However, as a pure survey-oriented constellation, it would be the best choice of all the configurations presented here, as it is also not selective with respect to the right ascension of the ascending node.

The last configuration examined has similar capabilities, but it is more focused on certain orbit regimes. Its cataloguing performance is very poor, as successful follow-ups are very rare. The biggest advantage of the near-equatorial, zenith-staring constellation is its survey capabilities with respect to the GPS, GTO, and Molniya orbit regimes.

3.5. Optimization of Space-Based Survey and Tracking

The above mentioned drawback of the SSO Dawn-Dusk-Constellation (selective coverage of GPS and Molniya orbit regimes) can be dealt with by combining that constellation with a near-equatorial component. The latter component consists of 2 satellites equipped with three optical sensors each, improving the total field of view for one satellite in the direction tangential to the orbit. The centre instrument is targeted at zenith direction. The lines of sights of the other two instruments are offset by 5 degrees.

The two near equatorial satellites have an in-orbit phasing of 180 degrees, and their mean altitude is 870 km. he six satellites in the SSO dawn dusk orbit are placed in the orbit plane in two groups consisting of three satellites each – with a phasing between the satellites of each group of 15 degrees, and a phasing between the groups of 180 degrees.

Table 4. Performance of the 8-satellite constellation optimized for maximum cataloguing performance in all beyond-LEO orbit regimes

Orbit	Total	Unde-tected	Detected, not cata-logued	Catalogued
OTH	3234	22	229	2983
GPS	212	7	41	164
GEO	963	1	158	804
GTO	182	0	58	124
MOL	114	2	54	58
HEO	884	15	289	580
SUM	**5589**	**47**	**829**	**4713**

Tab. 4 shows that the system can perform very well in all relevant beyond-LEO orbit regimes. With few exceptions, the system is capable of detecting almost all of the objects in the simulation setup. For about 20 percent of the objects, follow-up observations have to be provided by other resources in order to include them into the catalogue. The remaining 80 percent of objects can be put into the catalogue without requiring any additional sensor resources (see Fig. 11 and 12).

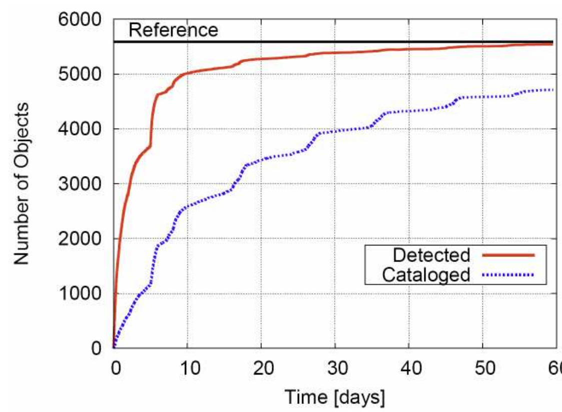

Figure 11. 8-Satellites dual plane constellation: Comparison of survey performance (Detected) with cataloguing performance (Cataloged)

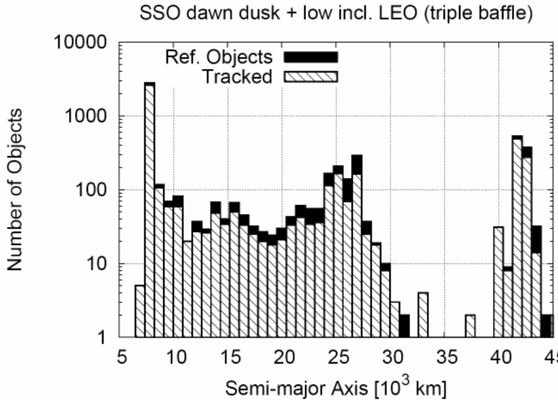

Figure 12. Performance of the 8-satellite constellation: Tracked objects vs. reference objects

Fig. 13 shows the average time between re-acquisitions of all objects in the simulated catalogue. A short revisit time is mandatory for a successful object correlation in the catalogue maintenance. According to [3], a 14 day re-observation period is needed to e.g. maintain a catalogue of GEO objects. This constraint is fulfilled by the simulated observation scenario. The mean revisit time is well below one week for all orbit regimes. The majority of re-acquisitions take place within 2 days for all catalogued objects. This relatively short time frame might in addition allow for a monitoring of object manoeuvres and still provide a successful correlation process.

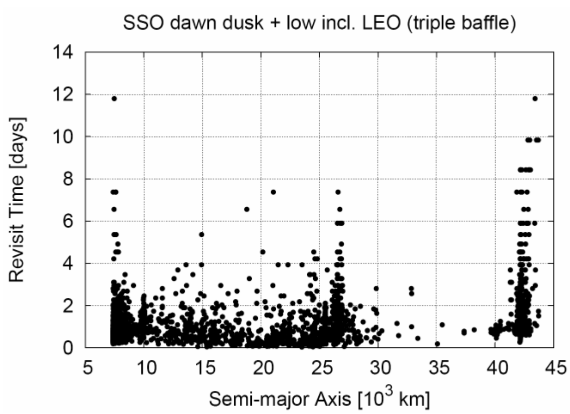

Figure 13. Simulated average time between re-acquisitions of catalogued objects

4. SUMMARY

Space-based sensors can provide a valuable contribution to the space surveillance component of a space situational awareness system. They are especially useful for orbits beyond LEO, both in combination with additional sensor resources on the ground, or self-standing. By using a proper combination of sensors it is possible to catalogue a large share of the object population, just using space-based assets.

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[3] Vanwijck X., Flohrer T., Possible contribution of space-based assets for space situational awareness, paper IAC-08-A6.5.5, 59th International Astronautical Congress, Glasgow, 2008