# SPACE-BASED SPACE SURVEILLANCE AS COMPLEMENTARY ELEMENT IN AN SSA ARCHITECTURE

J. Utzmann, A. Wagner
Astrium GmbH, 88090 Friedrichshafen, Germany

**Abstract**
Space-based telescopes can be an important complementing element to a ground-based SSA architecture by contributing to both the surveillance and the imaging aspect. This paper gives an overview of the unique benefits of space-based sensors and discusses possible and promising observation strategies.

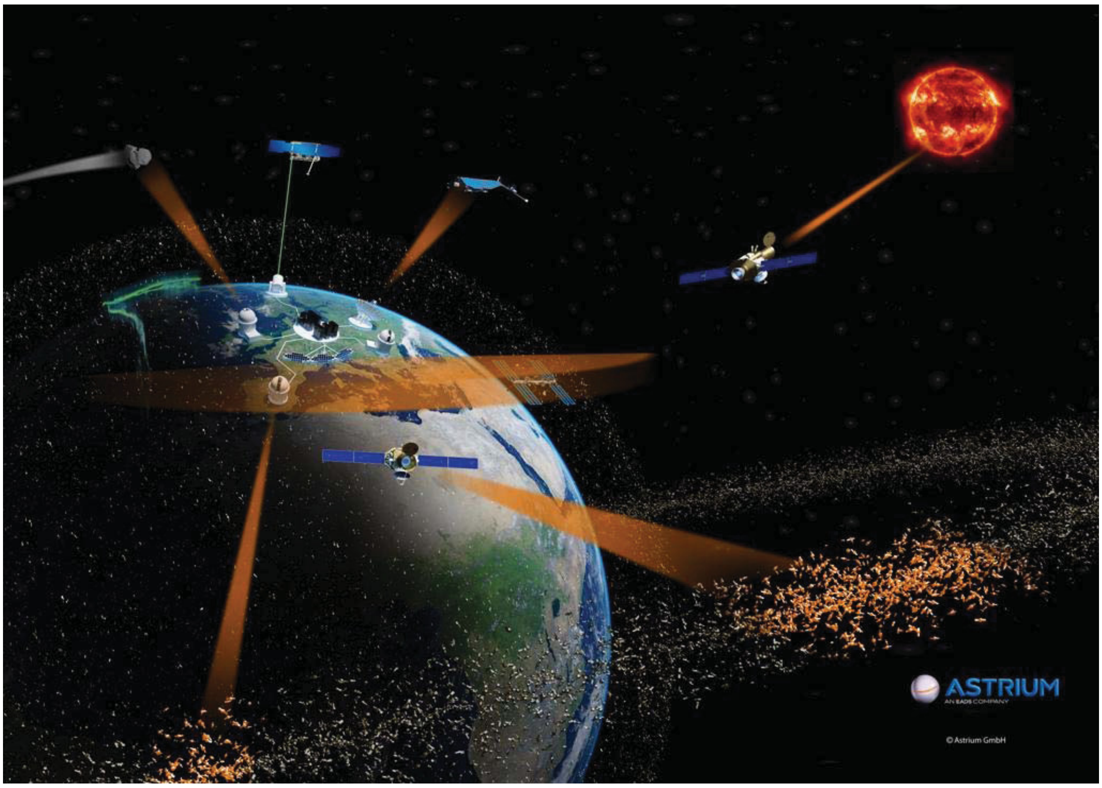

FIG 1. Sketch of an SSA architecture, consisting of ground- and space-based sensors, data centres and their networking.

## 1. INTRODUCTION

Up to the present day, a variety of studies regarding the development of a European SSA system architecture and the role of space-based space surveillance have been performed under the supervision of ESA [1-5].

Two of the most recent ones, the GSP "Study on the Capability Gaps Concerning European Space Situational Awareness" [4] and the "Proof of Concept for Enabling Technologies for Space Surveillance" [5] were successfully performed by a team under the lead of Astrium. In the framework of these studies, the SSA user needs were translated into functional and performance requirements. An overall architecture to meet these requirements (see sketch in Fig. 1) was specified and a phased implementation approach with increasing capabilities was proposed.

The basic SSA system building blocks and technology options for space surveillance, tracking and imaging can be grouped into three segments: Ground-based optical sensors, space-based telescopes and ground-based radars. One solution proposed to relax requirements on the radar systems (e.g. power, number of sites) by introducing novel ground-based optical solutions for additional LEO and beyond surveillance. However in both studies, space-based surveillance sensors were identified as an important complementing element to the ground-based architecture. Space-based telescopes can provide a valuable contribution to both the surveillance and the imaging component of an SSA system.

This capability was already demonstrated in the past, when SBV (Space-Based Visible, 1996-2008) instrument improved greatly the build-up and maintenance of the US SSN object catalogue [6,7].

Space-based surveillance and imaging feature very different mission and observation profiles (see also Fig. 2 and 3). The surveillance component is driven by survey and tracking of objects. Here, space-based optics can offer enhanced performance w.r.t. the generation and maintenance of an object catalogue and maneuver detection. Imaging enables the analysis of an object regarding its capabilities, identification of its type, components, etc. and is based on sufficiently resolved object images. For GEO, this is feasible in a reasonable manner only from space due to the distance. In the following, only the surveillance aspect will be discussed.

Observation strategies focus largely on "deep-space" objects beyond LEO on GEO, MEO, GTO, HEO and Molniya orbits. Space-based LEO observation is also feasible to some extent, but encounters some serious challenges if the goal is total coverage of the population (see „Observation Strategies“).

For the detection of objects, one can either exploit the reflected sunlight for which the energy content is highest in the visible spectrum (Vis) and which depends on the phase angle towards the sun and the reflection properties of the surface material (albedo). A second possibility is the infrared (IR) detection of the object's thermal radiation. According to the observation strategy, a trade-off has thus to be made between being dependent from the phase angle but showing great sensitivity (Vis) or being phase angle independent with lower sensitivity (IR). However, the observation in the visible spectrum is deemed less problematic, as e.g. IR cooling issues are avoided and ranges are usually large while debris equilibrium temperatures are low.

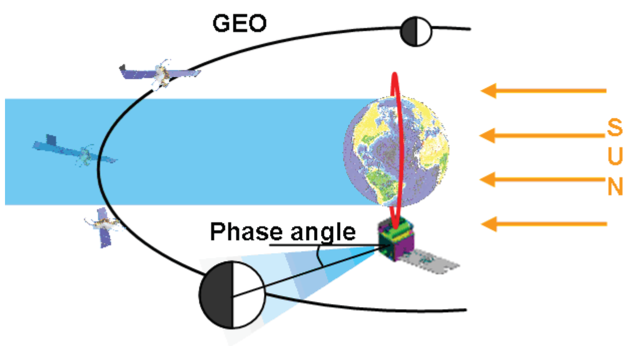


FIG 2. Surveillance of objects using reflected sunlight for detection.

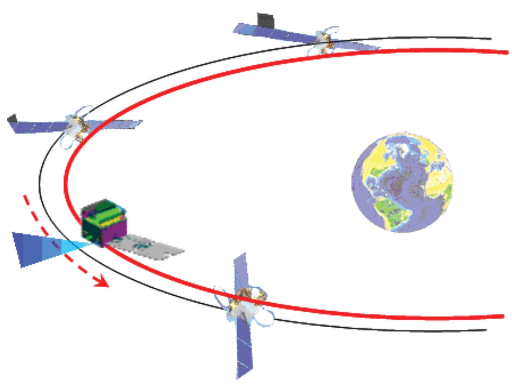

FIG 3. Imaging of objects via a sub-GEO s/c.

## 2. BENEFITS OF SPACE-BASED SPACE SURVEILLANCE

Whenever the unique features of space-based telescopes are discussed, one will usually hear the same few arguments (no weather/night time dependency, flexibility). However, there is much more to it. Beginning with those two most popular items, the properties that set space-based optics apart from ground-based systems (also radars) are elaborated in the following.

### 24/7 availability

No limitations are imposed by weather (clouds, rain, aerosols, absorption), the day/night cycle and scattered light in the atmosphere (Moonlight). Hence, observation and tasking is continuously possible, provided the technical means e.g., up-and downlink are available.

### Operational flexibility at any time

Being able to apply and switch between the most suitable observation strategies, the surveillance of different orbits can be implemented very efficiently. Furthermore, dedicated tracking of single objects is feasible over a longer period of time and a larger portion of the sky than with ground-based telescopes.

### No geographical and geopolitical restrictions

Finding the right location is an issue for ground-based telescopes. For GEO surveillance, an equatorial distribution as homogeneous as possible is needed. This requires most likely the operation of systems on non-national respectively non-European territory. Planning reliability w.r.t. the administration of such assets on foreign territory must be considered, as well as security issues and costs for operations and staff.

### Great timeliness and access to specific objects

In order to respond to time-critical events such as maneuvers, imminent or occurred collisions and other threat scenarios, space-based telescopes offer the means to quickly access objects and regions in space. This is more difficult from ground, if the required timeliness should be reliably better than the orbital period of the objects. A large number of sensors (also radars) must be available and distributed all over the world. The timeliness and access requirement has been one of the essential design drivers for SBSS Pathfinder [8].

### Enables total coverage

Without a large number of ground based radars and telescopes, there will always be gaps w.r.t. the coverage of the population of some orbital regions. Space-based telescopes can close these gaps by employing search strategies that have been adapted to the problem.

### Quasi-tracking

The fast detection of objects and high revisit-rates (objects are re-observed soon) combined with good metric accuracy allows „quasi-tracking“: The orbit determination for the objects can be based on the observations while performing the survey. No dedicated tracking is needed. This improves correlation and cataloguing of objects and enables faster detection of maneuvers, threats and events (collisions ...).

**Increase in detections and metric accuracy**

Because no atmospheric disturbances (turbulences, absorption, etc.) affect the performance of the telescope, enhanced sensitivity and thus the detection of smaller objects is possible. Background noise is as low as it can be. Diffraction limited optics become feasible: Without the atmosphere degrading spatial resolution, metric accuracy is optimized. No complex adaptive optics is needed. Since (depending on the mission profile) the distance to the target will be smaller from space, sensitivity and resolution increase and thus position knowledge, which is also interesting for imaging. Last but not least, the fusion of sensor data is possible e.g., with radar data in order to improve accuracy.

**Synergies**

Commonalities with other space missions can be exploited e.g., the support of missile tracking and early warning tasks (target discrimination, midcourse-tracking). Space-based sensors have the potential to provide timely and flexible access to objects for re-entry analyses. Observations and tracking of Near Earth Objects (asteroids, comets) are possible. Moreover, space surveillance payloads could be integrated piggy-back as secondary payloads or themselves offer accommodation opportunities for other SSA related instruments (e.g. Space Weather sensors).

**Performance in comparison with ground-based sensors**

One space-based telescope only has the potential to match and exceed the performance of many ground-based optical elements combined (SBV: "most productive deep-space optical sensor" [6]).

**Scalability of constellations**

Performance gains can be achieved by the expansion of one satellite to a constellation of several spacecraft. An adapted observation profile provided, this allows a greater coverage of orbit populations, even faster follow-up observations and further improvement of cataloguing capabilities.

**Flexible observation strategies from space**

The trade-space for observation concepts is very large: Choosing different telescope orbits and pointing strategies, strategies can be optimized and adapted for underlying requirements like revisit-rates and timeliness (see "Observation Strategies"). Ground-based telescopes are more limited here. Both active (sidereal, rate-track) and passive pointing (fixed telescope) modes can be employed. Some strategies, e.g. employing sun synchronous orbits allow continuous pointing in the right-ascension - declination inertial system.

On the other hand, the challenges involved with space missions should not go unmentioned. Spacecraft life is usually limited. The aperture diameter of the telescopes is more restricted than for ground-based ones due to size, weight and hence cost reasons. Space-based sensors are ambitious from a technical point of view. For SSA purposes, precise and cost efficient telescope attitude knowledge plus low line-of-sight jitter is required as well as near real-time downlink in order to initiate reactions or follow-up observations in time. Also onboard processing in order to reduce the volume of data is a sophisticated topic.

However, it shall be emphasized that the required basic technologies do exist and are already tested [4,5]. In fact, many of the given benefits have been already demonstrated successfully. A brief, non-comprehensive overview is given in the following.

## 3. HERITAGE AND DEVELOPMENTS

As a matter of fact, a variety of SSA and surveillance related missions have already been performed or are being planned. Table 1 provides an overview.

TAB 1. Space-based surveillance missions.

| | |
|---|---|
| **USA** | |
| ***SBV*** on MSX | 1996-2008, The Space Based Visible Sensor, US SSN |
| STSS ATRR | 2009, Space Tracking and Surveillance System Advanced Technology Risk Reduction satellite, primary mission missile defence, also SSA |
| ***SBSS*** Block 10 „Pathfinder“ | 2010-today, SBV follow-on, US SSN |
| SBSS Block 20 constellation | Air Force & DoD: Studying options for SBSS follow-on |
| ANGELS | Planned to launch as a hosted payload in 2012-2013, Autonomous Nanosatellite Guardian for Evaluating Local Space; Vis and IR in-situ imagery; “understanding space-based GEO SSA”, AFRL |
| SODDAT | NASA RFI, Small Orbital Debris Detection, Acquisition, and Tracking; Small LEO debris (1-10cm @ 1000km) from LEO |
| **Canada** | |
| MOST | 2003-today; also SSA demonstrations |
| ***Sapphire*** | Planned to launch in 2011; SSA mission |
| ***NEOSSat*** | Planned to launch in 2011; NEO & SSA mission |
| **Germany** | |
| AsteroidFinder | Planned to launch in 2013; DLR; NEO & space debris mission |

**SBV**

Being the most prominent example for space-based surveillance so far, SBV (The Space-Based Visible) was launched in 1996 on MSX (Midcourse Space Experiment; Ballistic Missile Defense). After the nominal end-of-life of MSX's primary instrument „Spirit III“ after only 10 months (IR, cryogenic cooling), space surveillance via SBV became the primary goal of operations. After successful technology demonstration, SBV was transitioned in 1998 to being the first and only operational space-based space surveillance sensor of the US SSN and was in operation until 2008 before it was decommissioned due to the age of the platform. SBV provided both angle measurements for the orbit determination of objects and photometric data (brightness, phase angle) for object characterization.

Being a rather small secondary payload with a fixed 15 cm optics with no real-time access to it (observation planning 6-8 weeks in advance) some limitations w.r.t. its operations had to be accepted. Further constraints include an observation time of only eight hours (2 x 4h, 30% actual CCD integration time) per day and data downlink only two times per day. Despite those rather severe limitations, SBV provided valuable contributions to the US SSN catalogue. More than 400 tracked objects per day and high revisit-rates had a direct impact on the quality and accuracy of the object catalogue. The average age of the Two-Line-Element (TLE) sets was reduced by 20% from 5 to 4 days, while the metric accuracy proved to be better by a factor of 2.5 better than measurements with the ground-based GEODSS. This enabled better initial orbit determination and a slower increase of position errors with time, resulting in improved cataloguing capabilities. Regarding its performance towards the total number of catalogued GEO objects, SBV was actually deemed the "most productive deep-space sensor" in comparison with all other ground-based telescopes and could reduce the number of US satellites in GEO "lost" from the catalogue by 80%. Further achievements include the tracking of dedicated high-priority targets (adversary s/c, manoeuvring satellites, re-entry objects); characterization of objects via light curve analysis; tracking of LEO objects and support to early warning tasks. Last but not least, one of the most important side-effects of SBV's operation was the development of efficient search and tasking strategies (see also "Observation Strategies"). Many more details can be found in the SBV papers of MIT's Lincoln Laboratory [6,7].

**SBSS (Space-Based Space Surveillance), Sapphire and NEOSSat:**

SBV's success as a pathfinder for space-based space surveillance led to the development of the SBSS spacecraft and other satellites.

*SBSS* is a dedicated sensor in the US SSN and was launched in launched in 9/2010 into a 630 km sun synchronous orbit (SSO). It features a 30 cm wide angle optics, detection in the visible spectrum and a filter wheel for SOI (Space Object Identification). Because the telescope is attached to a light-weight beryllium gimbal, high agility for fast tracking and switching between different targets is ensured without the need of slewing the spacecraft. In comparison with SBV, sensitivity, timeliness, capacity and accuracy are considerably enhanced. SBSS now allows for 24 hours of observation time per day and near real-time availability of the data [8].

Besides a full-size solution like SBSS, smaller satellites will contribute to space surveillance. The DND's (Canadian Department of National Defence) *Sapphire* satellite is planned for launch in 2011 and is foreseen to be a contributing sensor of the US SSN, including shared tasking and coordination with JSpoC. The 150 kg micro-sat with an SBV-like instrument (15 cm, 1.4° FoV) will operate on a 750 km SSO. It will survey orbits in the 6000 to 40000 km altitude regime and is also envisaged for early warning applications [9].

*NEOSSat* by Defence Research and Development Canada (DRDC) and CSA (Canadian Space Agency) is slated to be launched into an SSO also in 2011. Its dual mission covers both space surveillance and the detection and tracking of asteroids. The surveillance part comprises the detection and precise position determination of objects in 15000 to 40000 km altitude and tracking them down to 6000 km. An important goal is the technical demonstration of the military use of micro-satellites. The 75 kg spacecraft features a 15 cm telescope with 0.85° FoV and detects objects in the visible spectrum. NEOSSat will cover many research topics such as optimization of survey strategies, object correlation, photometry, data fusion with ground-based sensors and image processing [10].

## 4. OBSERVATION STRATEGIES FOR SURVEILLANCE

**Restrictions and parameters**

The parameter space for space based surveillance is very large. The detection of objects depends on the brightness of an object, which is besides surface properties linked to the phase angle in the visible and to the temperature in IR. Furthermore, the brightness of the background (stars, galaxies, stray light ...) plays an important role as well as the design of the telescope and its orbit (angular rates, coverage, selectivity ...). Also the properties of the surveillance spacecraft properties w.r.t. AOCS for pointing, power and radiation influence the selection of observation strategies and vice versa.

Moreover, a decision has to be made regarding which requirements towards accuracy, timeliness and revisit-rates should be imposed. These depend on the original user needs: If only routine surveillance for catalogue maintenance is required, requirements can more relaxed than if an independent orbit determination (OD) and cold start capability shall be ensured or whether time accurate maneuver detections are asked for.

The size of the object catalogue depends on the sensitivity of telescope: The smaller the detectable debris sizes, the larger the number of catalogue objects will be. The build-up of the object catalogue is linked to the length of the observation period, because more accurate initial ODs can be performed from processing as many frames containing the object as possible over a long arc of its orbit. Furthermore, the generation of the catalogue will be faster, the shorter the time until the first observation of an object is (timeliness). A better maintenance of the catalogue is achieved, if the observation strategy ensures the frequent observation of an object (high revisit-rate), which supports a more accurate OD. Also, the more frames of an object are recorded, the more information on its orbit is available, resulting in more accurate position vectors.

**Space-based surveillance of LEO objects**

The observation of LEO objects from LEO (here defined as < 2000 km altitude) faces some challenges, depending on the individual observation strategies:

High relative angular rates might shorten the pixel dwell time and therefore lead to small integration times, which lead to lower sensitivity for detection. Orbit determination is also a critical issue in this regards: Objects with large angular rates may have very long streaks. However, start and end points must lie within the frame and must be precisely definable (faint object signals for high relative velocities!). A minimum of two frames of an object is deemed necessary in order to be able to extract three independent pairs of angles (azimuth, elevations). If there are many objects in the field-of-view (FoV) simultaneously, saturation effects and difficulties w.r.t. their discrimination might arise.

Objects on similar orbits like the telescope are detected either never or with reduced revisit-rates ("selectivity"), which is unfavourable w.r.t. the total coverage of the LEO population. In order to circumvent this problem, a constellation of many satellites is required.

Depending on the orbits of observer and object, illumination conditions can be very different and variable. To give an example, a sun synchronous dawn-dusk telescope has a constant attitude towards the Sun, but the illumination of observable objects varies quickly.

On the other hand, LEO-LEO observations may be of interest for the statistical detection of small scale debris on selected orbits as sensitivity might be enhanced due to the proximity to the objects.

If good timeliness is required for the observation of distinct LEO objects (similar to early warning tasks), observations from LEO could also be interesting here. Nevertheless, one has to deal with the problem of orbit selectivity.

The observation of LEO objects from MEO, GTO and GEO could circumvent selectivity and angular rate issues, but results in lower sensitivity due to larger distances. Depending on the orbit altitude, radiation belt problems might impact operations. Also, Earth and Sun must not be in the FoV, hence only strategies involving „looking past, but as close as possible“ are feasible.

Last but not least, the competition is strong for LEO observation: Ground-based radars are very suitable for this task, as most of the LEO population can be covered by one single radar only, provided it can be placed at an appropriate location. Moreover, ground-based telescope concepts for higher LEO altitude regimes (> 1300km) have been proposed lately [5].

Because of the aforementioned reasons, space-based observation of LEO objects will not be considered a main driver for the development of surveillance concepts and strategies here.

**Observation strategies for beyond-LEO objects**

The paper will now put the focus on space-based surveillance concepts for beyond-LEO objects (see also Fig. 4-6). In particular, the most common observation modes concentrate on GEO, respectively geosynchronous objects, followed by GTO, MEO, HEO (highly elliptical orbit, e.g. XMM Newton with 18000 km x 103000 km x 61.8°) and Molniya orbits.

The *observation close to the Earth shadow* from a sun synchronous dawn-dusk orbit maximizes sensitivity by searching the region for which the phase angle towards the sun is as low as possible. This can be achieved by sidereal pointing in the inertial system of the telescope orbit, hence stars are fix and non-inclined GEO belt objects drift through the search region once per 24 hours. In order to capture inclined objects, coverage of +/- 15° declination is required. An object in GEO is shadowed for a maximum of ca. 70 minutes for about 100 days per year; a half-angle of 8.9° is shaded maximum. Besides that, phase angles down to 0° are possible. In contrast to e.g. pinch pointing (see below), the observations can be made uninterruptedly all over the year. Many variants are conceivable, such as the continuous observation of one inertial point, the change between two inertial points before and after the shadow for better re-visit rates or employing passive instead of sidereal active pointing by using a fixed anti-sun looking telescope.

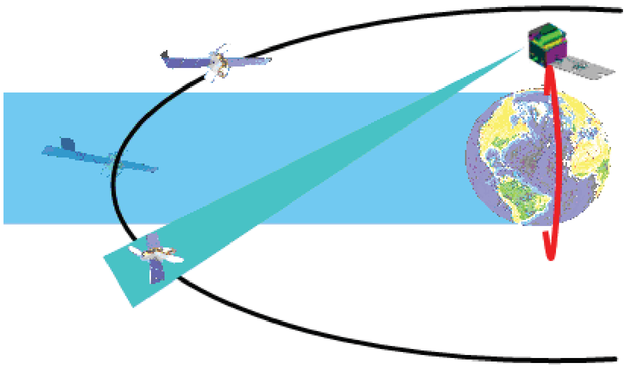

FIG 4. Observation close to the Earth shadow

The so-called *„pinch points“* strategy exploits the fact that GEO/GSO objects without AOCS (debris, fuel depleted) build-up inclination up to 15° and then reduce it again. This cycle with a period of 53 years occurs due to orbital perturbations caused by the Sun, the Moon and the oblateness of Earth, which couple inclination and right ascension of ascending and descending nodes. This results in the formation of two regions with high object density, so-called „pinch points“ in the inertial system. They are crossed daily by the majority of GSO objects and make compact search patterns possible, as only a small declination range needs to be examined in these regions. This becomes especially interesting for small FoVs and was successfully applied SBV [7]. However, as right ascension of these regions remains constant at about 65° and 245°, the phase angle w.r.t. Sun changes

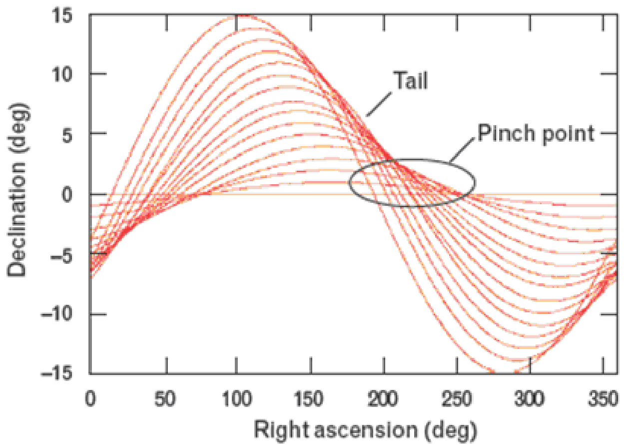


FIG 5. Pinch points [7]

continuously throughout the year. This requires a switch of searched pinch point twice a year and impacts negatively on sensitivity. Suitable telescope orbits are for example SSOs (but risk of Earth getting inside FoV) or an orbit with constant RAAN (i=90°) and fixed orientation towards the pinch points.

A telescope on a *LEO equatorial orbit* could employ a simple satellite design with a fixed optics in the satellite coordinate system e.g., looking radial towards GEO. Then, the complete GEO belt is scanned in only one LEO orbit, which results in high re-visit rates and timeliness, properties that are favourable for cataloguing. This makes the strategy also a good candidate for observing MEO, GTO and Molniya objects, which eventually will cross the equatorial plane. On the other hand, illumination conditions and thus sensitivity are changing continuously and rapidly. Furthermore, coverage gaps will exist for large phase angles and if the Sun is in the FoV. The „fast scan“ of GEO may also be problematic regarding orbit determination: The relative angular rate between telescope and objects is approx. $\Delta\omega$=200 arcsec/s, which results in a shorter visibility of objects than e.g. with inertial pointing using an SSO telescope ($\Delta\omega$=15 arcsec/s), which has a negative impact on initial orbit determination. Furthermore, the question arises if discrimination of some GEO objects will still possible, as they will appear like blurred „pearls on a string“. To give an example, for an integration time of one second, the minimum distance between GEO objects must be approximately 41 km in order to avoid overlaps. However, co-located station keeping of several satellites in distances of about 10 km per +/- 0.05° (=74 km) box is already standard nowadays. Moreover, stars appear also as streaks with their lengths differing only marginally of those of the objects ($\Delta\omega$=15 arcsec/s), making image processing and orbit determination more challenging. Last but not least, the question of how to achieve coverage of a larger declination range, e.g. by altering the elevation of the telescope's line-of-sight needs to be examined more closely.

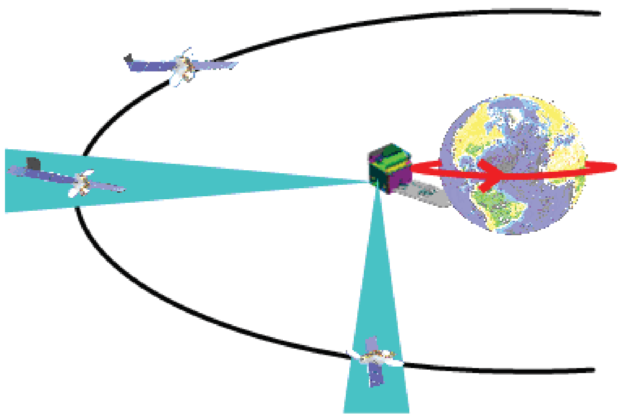

FIG 6. LEO equatorial

**Constellations for beyond-LEO surveillance**

One surveillance satellite only is able to achieve tremendous results. In order to achieve even better performance gains, single spacecraft concepts can be extended to constellations. An "over the top" configuration which optimizes detections, cataloguing and coverage of GEO, Molniya, MEO and GTO has been proposed [11] in order to demonstrate the versatility of constellations. It employs in total eight low-cost satellites with fixed telescopes (Fig. 7). From those, two groups of three satellites each are placed on a dawn-dusk SSO in 730 km altitude with fixed anti-sun pointing of the telescopes. A phasing of 15° between the s/c of one group and a phasing of 180° between the groups is applied. While the triplets ensure more follow-up observations, the two groups ensure the observation of a larger number of unique objects. Two additional zenith-looking satellites with 180° phasing on an almost equatorial 870 km orbit mitigate the selectivity w.r.t. MEO and Molniya objects. This constellation of simple telescopes is capable of cataloguing of 80% of all objects stand-alone (Fig. 8). The remaining 20% require follow-up observations by other resources.

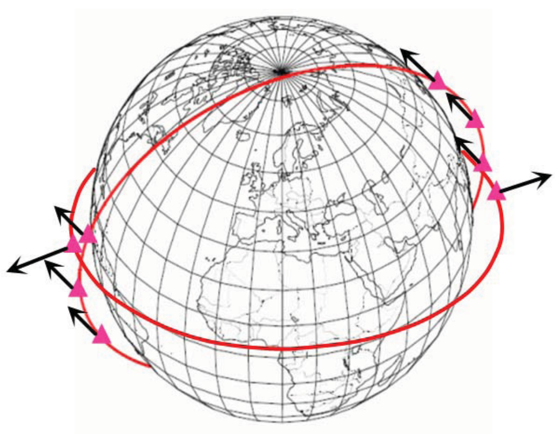

FIG 7. High-end constellation of eight satellites [11].

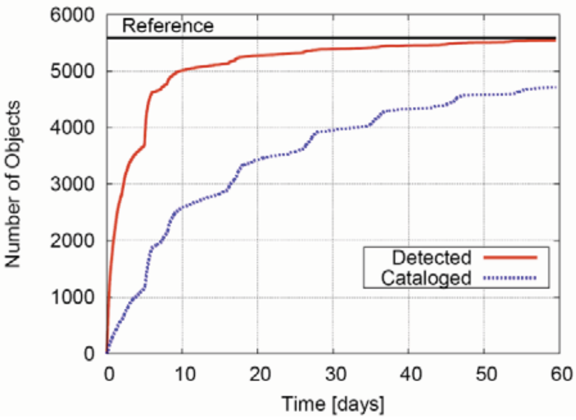


FIG 8. Cataloguing performance over time [11].

## 5. CONCLUSION

Space-based SSA sensors can play a major role in an SSA system architecture. They offer unique benefits and complements compared to ground-based systems and help increasing survey, tracking and object characterization performance. Many of these advantages and capabilities have already been demonstrated with great success and have led to follow-on missions like SBSS. Space-based surveillance solutions can range from full-scale SBSS to micro-satellites. Development risk is low, as the required basic technologies are already proven and tested.

Last but not least, a European or national space-based demonstrator mission is considered to be a desirable next step in order to gain experience regarding search strategies, mission planning, object correlation and -characterization, data fusion and image processing.

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