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SPACE-BASED SPACE SURVEILLANCE AND TRACKING DEMONSTRATOR: MISSION AND SYSTEM DESIGN

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This paper presents the capabilities of a Space-Based Space Surveillance (SBSS) demonstration mission for Space Surveillance and Tracking (SST) based on a micro-satellite platform. The results have been produced in the frame of ESA's "Assessment Study for Space Based Space Surveillance Demonstration Mission" performed by the Airbus Defence and Space consortium.

The assessment of SBSS in an SST system architecture has shown that both an operational SBSS and also already a well-designed space-based demonstrator can provide substantial performance in terms of surveillance and tracking of beyond-LEO objects. Especially the early deployment of a demonstrator, possible by using standard equipment, could boost initial operating capability and create a self-maintained object catalogue. Furthermore, unique statistical information about small-size LEO debris (mm size) can be collected in-situ.

Unlike classical technology demonstration missions, the primary goal is the demonstration and optimisation of the functional elements in a complex end-to-end chain (mission planning, observation strategies, data acquisition, processing, etc.) until the final products can be offered to the users and with low technological effort and risk.

The SBSS system concept takes the ESA SST System Requirements into account and aims at fulfilling SST core requirements in a stand-alone manner. Additionally, requirements for detection and characterisation of small-sized LEO debris are considered.

The paper presents details of the system concept, candidate micro-satellite platforms, the instrument design and the operational modes.

Note that the detailed results of performance simulations for space debris coverage and cataloguing accuracy are presented in a separate paper “Capability of a Space-based Space Surveillance System to Detect and Track Objects in GEO, MEO and LEO Orbits” by J. Silha (AIUB) et al., IAC-14,A6,1.1x25640.

I. INTRODUCTION

The objective of the ESA study "Assessment Study for Space Based Space Surveillance Demonstration Mission (Phase A)" was to analyse the feasibility of an optical space-based space surveillance (SBSS) demonstration mission and to consolidate the design approach. Once demonstrated, such a space-based capability would be an ideal contributing asset for an overall Space Surveillance and Tracking (SST) system.

SST is part of SSA (Space Situational Awareness) and covers the detection, tracking and cataloguing of space debris and satellites. Additionally, SSA comprises the segments Space Weather (SWE) and Near Earth Objects (NEO). Figure 1 shows an exemplary SSA sensor architecture.

The activity aimed at providing an end-to-end system demonstration concept definition.

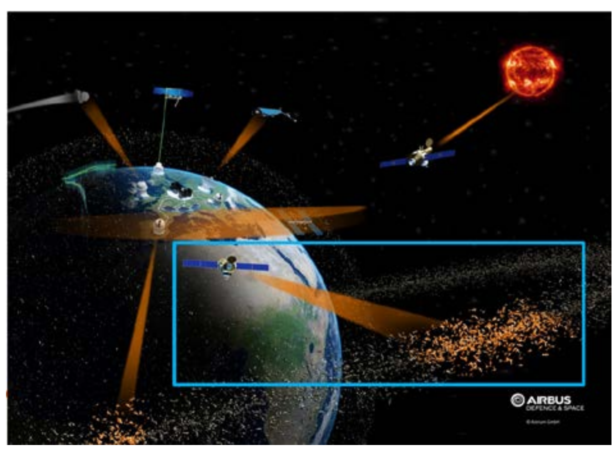

Fig. 1: Exemplary sketch of an SSA sensor architecture, including elements for SST, SWE and NEO.

II. SBSS USER REQUIREMENTS

The ESA SST System Requirement Documents (SRDs) [1] have been used to define user requirements for an operational SBSS and to derive a demonstration mission. The SRDs are applicable to the entire SST segment of ground- and space-based sensors, respective data centres, data processing and networking. However they do not indicate a design solution how to fulfil the SST requirements and thus how to provide the envisaged SST segment services. Many of the SST segment services (catalogue of these man-made objects, collision warning, detection and characterisation of in-orbit fragmentations, etc.) rely on the object catalogue, which again is a service by itself.

III. BENEFITS OF SPACE-BASED TELESCOPES

The strengths of space-based telescopes for SST are:

- **Full longitudinal GEO belt coverage with one sensor** enabling catalogue generation and maintenance (see Flohrer et al. [6]).
- **Tracking in all orbital regions** (LEO, MEO, GTO, Molniya, NEOs) for orbit refinements as a large volume of space can be accessed
- **Vicinity to LEO small debris** enables in-situ measurements
- **No restrictions by weather**, atmosphere and day/night cycle, hence operational robustness
- **High astrometric accuracy** (no atmospheric seeing, diffraction limited design possible)
- **No geographical and -political restrictions**

In order to achieve full compliance to all ESA SST requirements, a ground-based optical system can be jointly operated. In particular more than one sensor is needed to close coverage gaps in non-GEO orbit regimes like MEO, GTO and Molniya.

IV. OPERATIONAL SBSS MISSION GOALS

From above considerations, the main SBSS mission goals can be derived:

- **Build-up a GEO object catalogue from scratch via one spacecraft** and maintain it
- **Achieve GEO coverage** for objects ≥ 0.4 m and partial coverage of other regions
- **Achieve the accuracy and timeliness as required** by the SST SRDs (e.g., 2.5 km overall position accuracy after 3 days of measurements plus 2 days prediction)
- **Perform tasked tracking** of objects of interest in beyond-LEO regions
- **Detection of small LEO debris ≥ 1 mm**
- **Size estimation** via photometry and **light curve** analysis

For these goals, an operational system concept has been derived trading a multitude of design options against system performance, complexity and costs. Performed trades were e.g. number of s/c, telescope orbits, detection principle, accuracy requirements, exposure time, operational modes, observation strategies, instrument and detector design options, platform design, etc.

The mission has been designed such that the need for multiple satellites is avoided. Nevertheless, a possibility for enhanced performance is given by a constellation, e.g. consisting of the SBSS demonstrator and a later deployed fully operational SBSS.

Note that details about the operational mission design are not provided in this paper, but are reflected in the scaled-down demonstrator instead, which in turn is presented in the following.

V. SBSS DEMONSTRATOR: GOALS, CONSTRAINTS AND SYSTEM CONCEPT

The main idea for the SBSS demonstrator is to map the operational mission onto a concept that is compatible with

- **Low** technological risk
- **Re-use** as much as possible
- **Short development** timeframe
- **Low costs.**

The demonstration goals are no classical technology demonstration ones but

- **Demonstration of the end-to-end chain** from object detection to catalogue generation and sharing of representative data products with other SSA stakeholders. End-to-end functions can be tested and improved early; validation of product quality can be performed.
- **De-risking** of the operational concept and **to avoid overdesign and higher costs**
- **Achieve already significant, i.e. sufficiently high, performance**, enabling **early capability for the SST segment** without requiring a worldwide network of ground sites.

The main differences between the SBSS demonstrator and the operational mission are

- **Micro-satellite platform around 150 kg total launch mass** (existing bus such as Myriade, FLP, SSTL-150, TET-X, Proba)
- **Smaller optical instrument** sized to available P/L volume
- **Piggy-back launch** (constraints on SSO selection)

Apart from these differences, the observation strategies and metric accuracy from the operational mission are kept the same.

Table 1 summarises the main mission parameters for the SBSS demonstrator.

Parameter	Mission Baseline
# Telescope s/c	1 demonstrator satellite
Telescope orbit	LEO, 700 km reference altitude, sun-synchronous (SSO); dawn-dusk
Operational modes	Surveillance (primary) + small debris observations in LEO Tasked tracking (secondary)
Orbital regions for surveillance (anti-sun fence)	Emphasis on GSO objects; Plus: beyond-LEO (GTO, MEO, HEO, Molniya) via collateral detections
Orbital regions for tasked tracking	Emphasis on MEO objects, GSO, GTO, HEO, Molniya, LEO, NEOs
Pointing modes	Active pointing via platform

Table 1: Summary of mission parameters for the SBSS demonstrator.

VI. EFFICIENT OBSERVATION STRATEGIES

The same observation strategies as for the operational system are proposed for the SBSS demonstrator. Two basic operational modes exist: Surveillance (primary) and tasked tracking (secondary).

VI.I Surveillance

The primary observation strategy for GEO surveillance exploits the shape of the GEO belt and hence the geometrical distribution of these objects in space (see Figure 2). It is possible to detect and re-visit the entire GEO population via observing a limited search window in right ascension and declination, see Figure 2. Leak-proof fences can be implemented by systematic pointing of the telescope's FOV in a step-and-stare manner. GEO objects cannot slip through such a pattern undetected if the scanning frequency is chosen accordingly. This leak-proof property ensures the reliable and timely generation of a complete catalogue. If the surveillance strategy would not be performed in such a way, coverage gaps would remain and accuracy would be negatively impacted through considerably longer re-visit times. Furthermore, detections of fragmentations, manoeuvres and other time critical events could not be ensured if the survey was not leak-proof. Such concepts have been proposed (and successfully demonstrated) for ground-based systems [7].

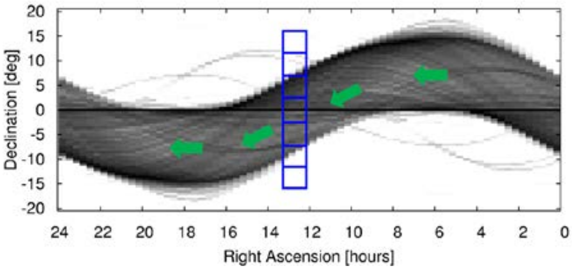

Fig. 2: Density plot of the GEO population and step-and-stare pointing pattern for the telescope FOV.

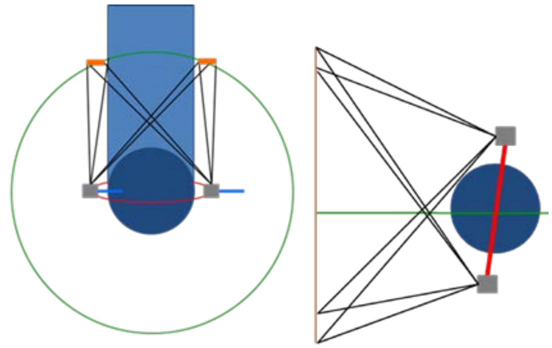

Fig. 3: Demonstrator orbit & observation geometry.

Two fence locations (see Figure 3) are required in order to obtain automatic follow-up observations. These are essential in order to achieve the accuracy and timeliness needed to catalogue formerly unknown objects. The angular separation between the fences is a compromise between obtaining measurement samples at different locations of an object's orbit and being able to access the fences from each position of the SBSS' orbit. Outages due to the Earth in the FOV should be minimized, resulting in a limited continuously observable region where the fences should be located. Higher SBSS orbits provide better access but need to be traded against orbital maintenance and post-mission disposal needs.

The most favourable telescope orbit is sun-synchronous (SSO) and near dawn-dusk in order to optimise pointing directions and access to targets. Frequent launch opportunities for an assumed piggy-back launch are given for such orbits. The best illumination conditions are given for anti-sun pointing, resulting in low phase angles for observed objects. The telescope itself is fixed and all pointing is performed by the platform.

Due to the rectangular field-of-view, the implementation of the leak-proof step-and-stare pattern is facilitated if the satellite's attitude is inertial. During the download of the payload data, the satellite's X-band antenna is nadir-oriented.

VI.II Tasked Tracking

As a secondary operational mode, the SBSS demonstrator will perform tasked tracking in all orbital regions, i.e. from LEO to beyond-GEO. Tasked tracking is similar to the telescope pointing for surveillance, however, the line of sight (LOS) is aimed to a volume of space where known object will pass through, potentially adapted to the expected angular rate. Orbits can be then systematically refined on request via respective observations. Tasked tracking is possible in a wider observation envelope (see Figure 4) outside the GEO survey region, provided the objects are sufficiently illuminated by the Sun. The duration and number of observations outside the nominal pointing envelope depends on the satellite's design (power, thermal) and the telescope's straylight rejection.

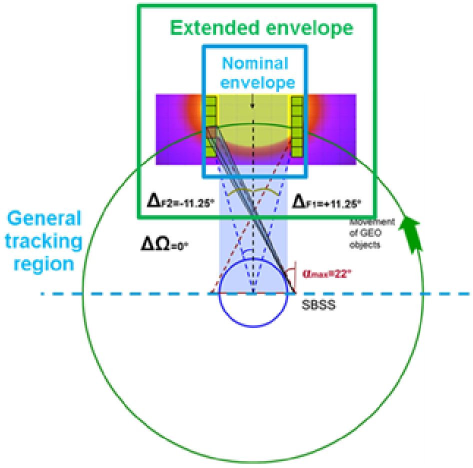

Fig. 4: Envelope for tasked tracking.

VII. DEMONSTRATOR INSTRUMENT WITH LARGE FOV AND APERTURE

The SBSS demonstrator instrument (shown in Figure 5) can be considered a smaller version of the operational one, with its size, mass and power being compatible with existing micro-satellite platforms:

- Mass: 34.1 kg total
- Power: 41.9 W total

Table 2 summarises the instrument's main properties.

Instrument	Value
Aperture diameter	**200 mm** (operational: 280 mm)
Field of View	**3°x3°** (custom CMOS) **2.74°x2.74°** (existing CCD) (operational: 5°)
Optical design	**TMA**
Detector	**2240 x 2240** (custom CMOS) **2048 x 2048** (existing CCD)
Pixel size	**12x12 µm²**
iFOV	23.5 µrad
Nominal frame period	**1.5 s/frame**
PEM	Proximity Electronics Module features existing **14-bit ADC**
ICPU	Instrument Control & Processing Unit provides on-board payload data reduction function and **64 Gbits of mass memory**

Table 2. Properties of the demonstrator instrument.

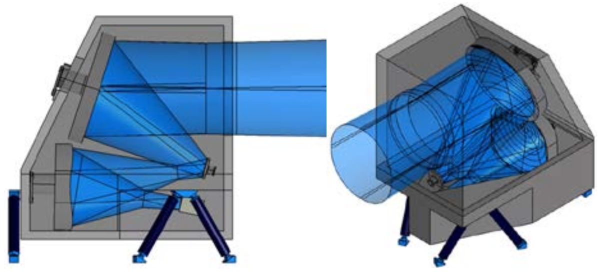

Fig. 5: SBSS demonstrator instrument.

Two different detector options are proposed: An existing CCD design (baseline option), which actually needs no new technology development, and a custom CMOS detector that still needs to be designed.

VIII. SUITABILITY OF MICRO-SATELLITES

Extensive trades and comparisons of different available micro-sat platforms (i.e. SSTL-150, TET-X, Myriade, Proba) were performed. In particular, the adaptations needed for implementing the SBSS mission were analysed along with TRL, pointing stability, agility, data handling and transmission, payload embarkation (volume, power, mass), launcher compatibility, propulsion, post-mission-disposal, etc., to name a few of the assessments.

As general conclusion, all examined platforms can be made compatible with an SBSS demonstration mission (see Figure 6). The different buses show individual advantages and drawbacks, but under the bottom-line it is possible to implement the concept with limited adaptations.

One common weakness of the micro-satellite platforms is that their orbit altitude is limited by the offered propulsion capabilities. To recall the previous observation strategies section, higher orbits are favourable for GEO observation geometry. While it is expected that there is no need for extensive orbit maintenance to reach the mission goal, and that the frequency of collision avoidance manoeuvres will be low for the selected orbit, the driving parameter is post-mission disposal (PMD) for compliance with space debris mitigation guidelines. The limited or sometimes in baseline configuration non-existing amount of Δv of the micro-sats requires slightly lower orbits for the demonstrator in order to ensure a re-entry into the atmosphere within 25 years. To give an example, 700 km are the limit for Myriade instead of the operational SBSS' desired reference altitude of 750 km. A de-orbiting device e.g. based on drag-augmentation principle could be used to further support proper PMD at higher orbital altitudes.

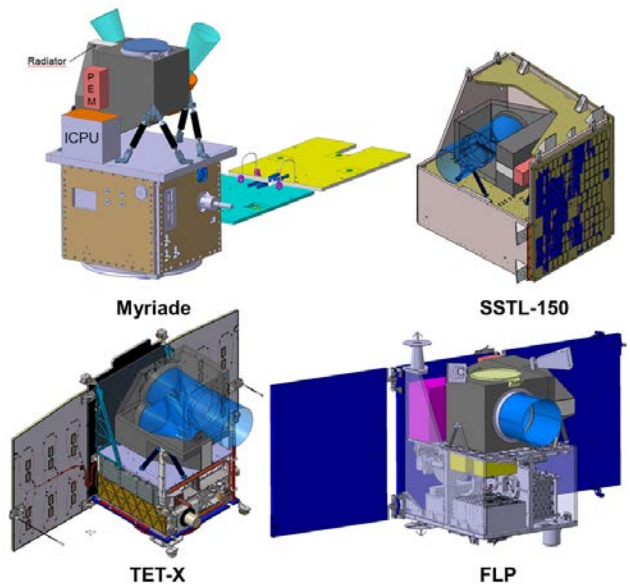

Fig. 6: Accommodation of the SBSS demonstrator instrument on different micro-sat platforms.

Table 3 summarizes the characteristics of the SBSS demonstrator platform.

Platform	Value
Platform type	**Micro-satellite platform** (FLP, Myriade, SSTL-150, TET-X, Proba)
Launch mass	**≤ 150 kg**
Stabilization	3-axis stabilisation
P/L data link	**X-Band** (Baseline: 60 Mbps)
PMD	**25 years orbit until re-entry**
Lifetime	**≥ 5 years**
Ground-stations	**High latitude**; Svalbard, alternatively Kiruna + Inuvik or Tromso + Prudhoe Bay
Launcher	**Piggy-back** launch (e.g. Ariane 5, PSLV, Soyuz, Vega, Falcon 9)

Table 3: Properties of the SBSS demonstrator platform, ground-segment and launcher.

IX. SBSS DEMONSTRATOR ON FUTURE LOW-COST PLATFORM (FLP)

A new promising platform option emerged with the Future Low-Cost Platform (FLP, see Figure 7). Preliminary assessments show the full compatibility of this bus with the SBSS demonstrator mission requirements, its distinct feature being the modern, top state-of-the art platform concept. Moreover, FLP includes a de-orbiting device. FLP has been developed under Astrium coaching at the University of Stuttgart‘s Institut für Raumfahrtsysteme (IRS). Through consequent professional design, this platform is suitable for LEO missions (default) but extensible also to GEO, Lagrange Point or Lunar missions. FLP's first application will be an Earth Observation mission called „The Flying Laptop“; the piggy-back launch is foreseen for late 2014 from Baikonur.

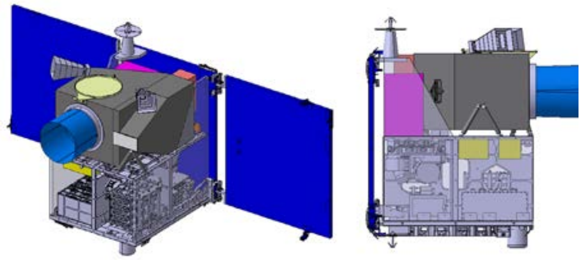

Fig. 7: The SBSS demonstrator instrument on FLP.

X. SURVEILLANCE AND TRACKING PERFORMANCE

A variety of simulations were performed for representative GEO objects and different observation strategies, showing that already the SBSS demonstrator is able to generate and maintain a catalogue. Note that the detailed results of performance simulations for space debris coverage and cataloguing accuracy are presented in a separate paper [5].

Remarkably, the achieved performances are close or often even compliant to the operational goals and SST system requirements (see Table 4).

ESA SST SRDs i1r4	SBSS Demonstrator	Operational SBSS	Constellation: Demonstrator & Operational
All GEO objects ≥ 0.4/1.0m	**Compliant**	**Compliant**	**Compliant & enhanced performance**
Cataloguing with spherical envelope of ≤ 2.5 km	**Coverage, accuracy & timeliness can be traded.**	**Compliant**	
Cataloguing within 72 hours after the first observation		**Compliant**	
Pre-cataloguing within 72 h	**Compliant**	**Compliant**	

Table 4: Compliance of SBSS regarding the GEO surveillance performance.

The operational SBSS alone achieves full performance in GEO. In other orbital regions, SBSS achieves partial but not full coverage. In constellation, system performance can be further enhanced. Moreover, within a constellation of demonstrator and operational s/c, the SBSS demonstrator could be used to follow up non-GEO objects in order to catalogue them and improve coverage in these regions.

The main drivers for the difference between demonstrator and operational mission are the instrument field-of-view and platform agility. If these differences can be further reduced for the demonstrator, increased performance can be expected.

The demonstrator telescope's sensitivity threshold regarding minimum detectable object sizes has been determined with via radiometric calculations and the assumptions shown in Table 5. The given size and brightness ranges result from different assumed phase angles and limiting pixel-SNRs for detection (from conservative SNR=5 to SNR=3).

For the inertial GEO fence, for which the observation location remains fixed w.r.t. the Earth shadow, the angular rate of observed objects is assumed as ω_{rel}=18 arcsec/s (15 arcsec/s in GEO + margin). For the rate-track GEO fence, where the fence is simply moved with the expected GEO angular rate, a reduced remaining angular velocity of ω_{rel}=3 arcsec/s allows for longer signal dwell and exposure times. The same holds for MEO tracking.

The CCD's larger video chain noise leads to a slight decrease of sensitivity compared to the customised CMOS detector option. However, both options are compliant with the demonstration goals.

Scenario	**CCD option (existing)**	**CMOS option (customised)**
Inertial GEO fence	**0.9-1.5 m** 16.4-15.6 mag	**0.7-1,2 m** 16,9-16,1 mag
Rate-track GEO fence	**0.4-1.0 m** 18.1-16.2 mag	**0,3-0,8 m** 18,5-16,7 mag
MEO tracking	**0.3-0.6 m** 18.1- 16.2 mag	**0,2-0,5 m** 18,5-16,7 mag

Table 5: Sensitivity limits for the demonstrator telescope. Assumptions: Diffuse reflecting spheres, albedo = 0.1; phase angle 0°-50°, limiting SRN 3-5,, integration time 0.5-1.6 s, sky background brightness = 21.9 mag/arcsec^2

Since a few years publications [2,3] propose higher global albedo values of 0.17-0.18 instead of the standard value of 0.1. The assumption of such higher albedo figures would lead to smaller detectable object sizes.

XI. SMALL DEBRIS DETECTIONS IN LEO

The additional objective of detecting small-sized debris in LEO entered the study upon request by ESA. This topic, being part of ESA's CleanSpace initiative which assesses the environmental impact of ESA activities, was fully supported by Airbus DS and integrated into the SBSS demonstrator concept.

Small debris observations are not to be confused with the cataloguing goal of SSA's Space Surveillance and Tracking segment. On the contrary, the objects of interest are the ones being too small and too faint for conventional SST.

Better knowledge of this "sub-catalogue" population comprising vast numbers of particles way beyond the number of catalogued objects is valuable for the improvement of space debris environment models and, hence, serves the reduction of satellite vulnerability.

For the activity, preliminary small debris observation requirements were provided by ESA and used as a basis for deriving an according system concept.

The main small debris mission goals can be summarized as:

- Improvement of knowledge of small-size debris in LEO
- Detection via passive optical observation
- Debris population ≥ 1 mm
- Focus at LEO altitudes between 700 and 1500 km
- Statistical sampling (not cataloguing, but characterization incl. coarse orbit determination)

In order to answer the questions how a small debris mission should look like and whether it can be compatible with the SBSS concept for SST, the observable small debris objects were characterized via simulations. The properties of the SBSS demonstrator's instrument were kept, along with the nominal pointing strategy for GEO survey. This anti-sun pointing direction is favourable also for small debris observations and resembles strategies that have been analysed in previous studies with similar objectives [4]. Moreover, the SBSS demonstrator's reference orbit altitude of 700 km is fully compatible with observation of debris between 700-1500 km altitude. In total, an observation duration of 25 h was simulated with ESA PROOF using the ESA MASTER-2009 statistical LEO population ≥ 1 mm.

As shown by Figure 8, a large number of objects cross the instrument's FOV during the simulation time but many of them are too faint or too fast to be detected. However, a considerable number of particles can still be seen with sufficient SNR. With decreasing object diameter the number of detections also decreases as the particle needs then to be observed at closer range and at a moderate angular rate in order to generate sufficient signal. From a proper calibration of the instrument this result allows to provide sufficient feedback to the tasks of modelling the space debris environment.

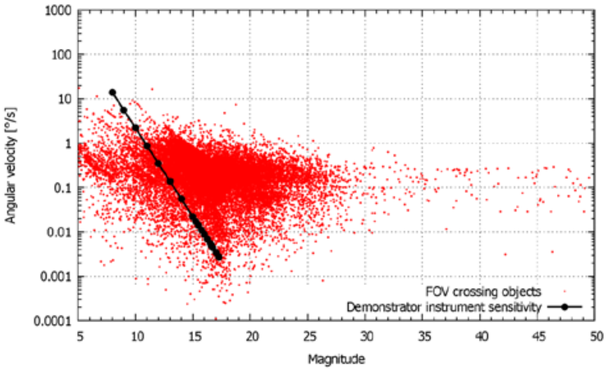

Fig. 8: Sensitivity limits of the SBSS demonstrator instrument. Objects below the curve can be detected.

From the properties of the detectable small debris population, respective observation requirements can be derived. In particular, exposure time and frame period must be chosen accordingly. A minimum of two frames per object is required for orbit determination purposes, but more are advantageous. Frame periods can be derived from the distribution of observable objects w.r.t. angular rate. A reasonable cut-off for the majority of objects can be made at 1500 arcsec/s.

Based on this, a small debris mode can be defined which is fully compatible with the SST mission, see Table 6. This means that the implementation of the small debris observation concept is possible while leaving the SST mission unchanged. Both missions can be performed at the same time and are compliant with the SBSS demonstrator design, including pointing direction, instrument characteristics and data rates.

In addition, a campaign mode with higher frame rate can be implemented and operated at distinct periods of time for the detection of very fast objects.

Mode	Application	Frame period (s/frame)	t_{int} (s)	Consecutive frames per object
Nominal (continuous)	Small debris detection & GEO survey	1.50	0.5	4.8 for ω=1500"/s
High frame rate (campaign)	Very fast objects	0.25	0.25	4.3 for ω=10000"/s

Table 6: Modes for small debris observations.

XII. CONCLUSION

A system design has been performed for both operational space-based space surveillance and an according demonstration mission.

The major findings of the "Assessment Study for SBSS Demonstration Mission (Phase A)" are in summary:

- **High performance** already for the SBSS Demonstrator:
  - **GEO catalogue**
  - **Tracking in all orbits**, incl. NEOs
  - **LEO small debris** during SST
- **Re-use & mature technologies**: Low risk, short schedule
- **Micro-sat platforms are suitable** for SBSS demo mission
- No classical technology demonstration but end-to-end chain until product generation

The SBSS demonstrator has been designed to optimise mission performance based on existing micro-satellite platforms and overall re-use of technology. The concept can however be up- and downscaled easily!

[1] *Space Situational Awareness - Space Surveillance and Tracking System Requirements Document*, SSA-SST-RS-RD-0001_i1r4, i1r4, 13.03.2013

[2] Kessler, D.J., Jarvis, K.S., *Obtaining the properly weighted average albedo of orbital debris from optical and radar data*. PEDAS1-B1.4-0023-02, COSPAR 2002

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[4] Valtonen, E., Peltonen, J., Riihonen, E., Eronen, T, Flohrer, T. et al. *Space-Based Optical Observation of Space Debris*, Final Report, TN-SBO-AIUB-010, 2006

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