A SYSTEM DESIGN FOR SPACE-BASED SPACE SURVEILLANCE

Jens Utzmann [(1)], Axel Wagner [(1)], Jiri Silha [(2)], Thomas Schildknecht [(2)], Philip Willemsen [(3)], Frédéric Teston [(3)], Tim Flohrer [(4)]

[(1)]Airbus DS, Claude-Dornier-Str., 88090 Immenstaad, Jens.Utzmann@astrium.eads.net
[(2)]AIUB, Sidlerstrasse 5, 3012 Bern, Switzerland, Jiri.Silha@aiub.unibe.ch
[(3)]ESA ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, Philip.Willemsen@esa.int
[(4)]ESA ESOC, Robert-Bosch-Strasse 5, 64293 Darmstadt, Germany, Tim.Flohrer@esa.int

ABSTRACT

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 (Phase A)" performed by the Airbus DS consortium.
Space Surveillance and Tracking is part of Space Situational Awareness (SSA) and covers the detection, tracking and cataloguing of space debris and satellites. Derived SST services comprise a catalogue of these man-made objects, collision warning, detection and characterisation of in-orbit fragmentations, sub-catalogue debris characterisation, etc.
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. 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 and fusion, etc.) until the final products can be offered to the users.
The presented SBSS system concept takes the ESA SST System Requirements (derived within the ESA SSA Preparatory Program) into account and aims at fulfilling some of the SST core requirements in a stand-alone manner. The evaluation of the concept has shown that an according solution can be implemented with low technological effort and risk.
The paper presents details of the system concept, candidate micro-satellite platforms, the observation strategy and the results of performance simulations for GEO coverage and cataloguing accuracy.

1 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 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).

The activity aimed at providing an end-to-end system demonstration concept definition, focussing on the performance evaluation and the definition of all elements of the architecture, i.e. space segment including payload, launcher, ground segment and operational concept.

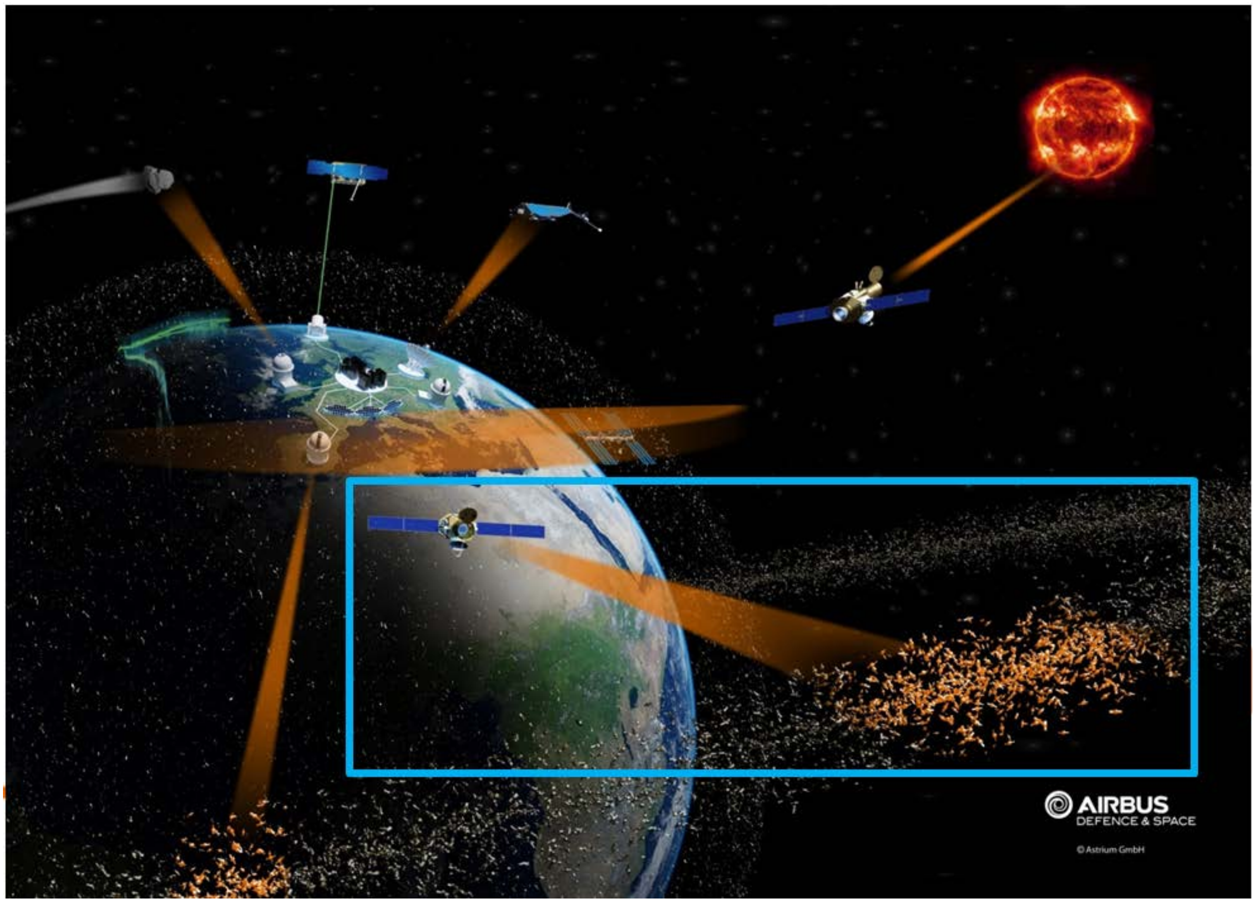

Figure 1. Exemplary sketch of an SSA sensor architecture, including elements for SST, SWE and NEO segments. SBSS is part of such a fully-fledged SSA system.

2 SBSS USER REQUIREMENTS

The ESA SST System Requirement Documents (SRDs) in their latest revision [1] have been used as a basis to derive SBSS user requirements. 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 is a service itself.

The role of an SBSS in an overall SST system should reflect the strengths of space-based telescopes for SST, which are:

- **Full longitudinal GEO belt coverage with one sensor** enabling catalogue generation and maintenance.
- **Access to large volume of space for tasked tracking** of objects (MEO, GTO, Molniya, LEO, NEOs) for orbit refinements
- **Robustness** for optical SST system: Insensitive to weather, atmospheric conditions, day/night cycle, less sky background.

- **High astrometric accuracy** possible as the telescope system can be built to be diffraction limited (no atmospheric seeing)
- **No geographical and -political restrictions** as for ground-based sites

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.

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

- **Perform and sustain GEO surveillance** and tracking operations
- **Build-up an object catalogue** from scratch and maintain it
- **Achieve GEO population coverage** and partial coverage of other regions (MEO, etc.)
- **Achieve the accuracy and timeliness as required** by the SST segment
- **Perform tasked tracking** of objects of interest in beyond-LEO regions

Functional and performance requirements were defined as a subset of the ESA SST SRDs, e.g.

- Cataloguing **GEO objects > 0.4 / 1.0 m**
- Cataloguing with **2.5 km accuracy** after 3 days of measurements plus 2 days prediction
- **Size estimation** via photometry
- **Light curve** analysis

Compliance regarding these requirements has been confirmed for the SBSS concept.

3 SYSTEM CONCEPT

The SBSS 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, targeted debris population, instrument and detector design options, platform design, etc. Some results of the performed trades are presented in the following.

3.1 Operational SBSS Concept

The primary objective of the operational SBSS is the generation and maintenance of a GEO catalogue via one SBSS spacecraft. The mission is explicitly designed such that the need for multiple satellites to achieve this goal is avoided. Still, the accuracy, timeliness and coverage as required by the SST segment shall be achieved by the operational SBSS.
Although only one SBSS is required to achieve the cataloguing goal, a possibility for enhanced performance is given by a constellation consisting of the SBSS demonstrator and the later deployed operational SBSS.

As a secondary operational mode, SBSS 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. Their orbits can be then systematically refined on request via respective observations.

The most favourable telescope orbit for the observation of objects is sun-synchronous (SSO) and near dawn-dusk in order to optimise pointing directions and access to targets. 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. Table 1 summarizes the main properties of the operational SBSS instrument.

It is sufficient to employ a small satellite bus for the operational spacecraft, as the payload – a wide field-of-view (FOV) telescope, see Table 1 – is relatively compact. Depending on the desired final configuration and fuel needs, a total launch mass well below 1000 kg is estimated and could be as low as 300 kg. Ground-stations at high latitudes and an X-band system for payload data are favourable in order to manage data volume. An overall operational lifetime ≥ 10 years is targeted.

Table 1. Properties of the operational SBSS instrument.

Instrument	Value
Aperture diameter	**280 mm** (driven by sensitivity requirements).
Field of View	**5°x5°** (driven by coverage requirements)
Optical design	**TMA** (large FOV and large aperture)
Detector	**4k x 4k CMOS** (metric accuracy, high framerate, low noise)

3.2 SBSS Demonstrator: Goals and Constraints

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**
- **Already achieve significant SST performance** w.r.t. GEO surveillance and w.r.t. tracking in all orbital regions

In particular the latter point enables an **initial operating capablity 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 2 summarizes the main mission parameters for the SBSS demonstrator.

Table 2. Summary of 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** **Tracking (secondary)**
Orbital regions for surveillance	Emphasis on **GSO objects**; Plus: beyond-LEO (GTO, MEO, HEO, Molniya) via collateral detections
Orbital regions for tracking	Emphasis on MEO objects, GSO, GTO, HEO, Molniya, LEO, NEOs
Pointing modes	**Active pointing** via platform
Observation strategies	**GEO/GSO belt: Anti-sun GEO Fence;** **Non-GEO: Tasked tracking**

3.3 Observation Strategies

The same observation strategies as for the operational system are proposed for the SBSS demonstrator for both surveillance and tracking.

The primary observation strategy for GEO surveillance exploits the shape of the GEO belt and hence the geometrical distribution of these objects in space. 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.

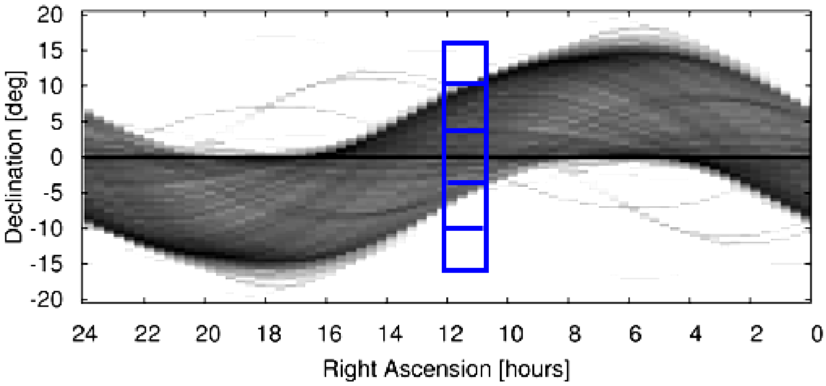

Figure 2. Density plot of the GEO population. The blue step-and-stare pattern indicates the limits of a fence through which all GEO objects will pass within 24 hours.

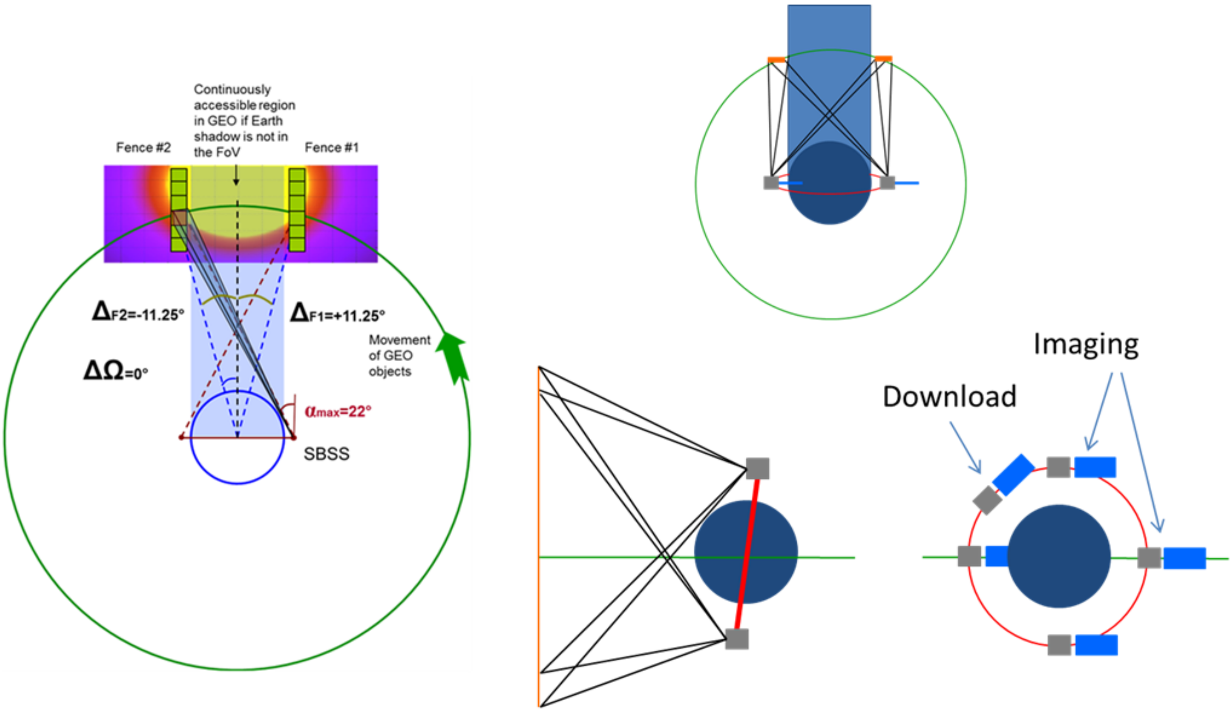

Figure 3. SBSS demonstrator orbit and observation geometry.

Two fence locations 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.

Assuming a piggy-back launch for the SBSS demonstrator spacecraft, a dawn-dusk sun synchronous orbit is an option that features both good observation geometry as well as rather frequent launch opportunities.

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.

The secondary observation strategy tasked tracking of known objects for refinement of their orbits is possible in a wider observation envelope 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.

3.4 Demonstrator Instrument

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

- Three-Mirror Anastigmat (TMA) with 20 cm aperture
- Mass: 34.1 kg total
- Power: 41.9 W total
- Proximity Electronics Module (PEM) features existing 14-bit ADC
- Instrument Control & Processing Unit (ICPU) provides on-board payload data reduction function and 64 Gbits of mass memory

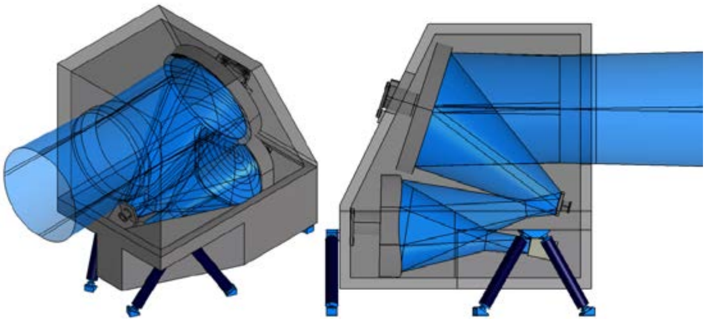

Figure 4. SBSS demonstrator TMA instrument.

Two different detector options are proposed: An existing CCD design (baseline option) which needs no technology development and a custom CMOS detector enabling a slightly larger FOV.

Table 3. Properties of the SBSS demonstrator instrument.

Instrument	Value
Aperture diameter	**200 mm**
Field of View	**3°x3°** (custom CMOS) **2.74°x2.74°** (existing CCD)
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**

4 SUITABLITITY OF MICRO-SATELLITE PLATFORMS FOR SBSS MISSION

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. 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 Observation Strategies section, higher orbits are

favourable for GEO observation geometry). While orbit maintenance and collision avoidance manoeuvres are considered useful but optional assets, 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.

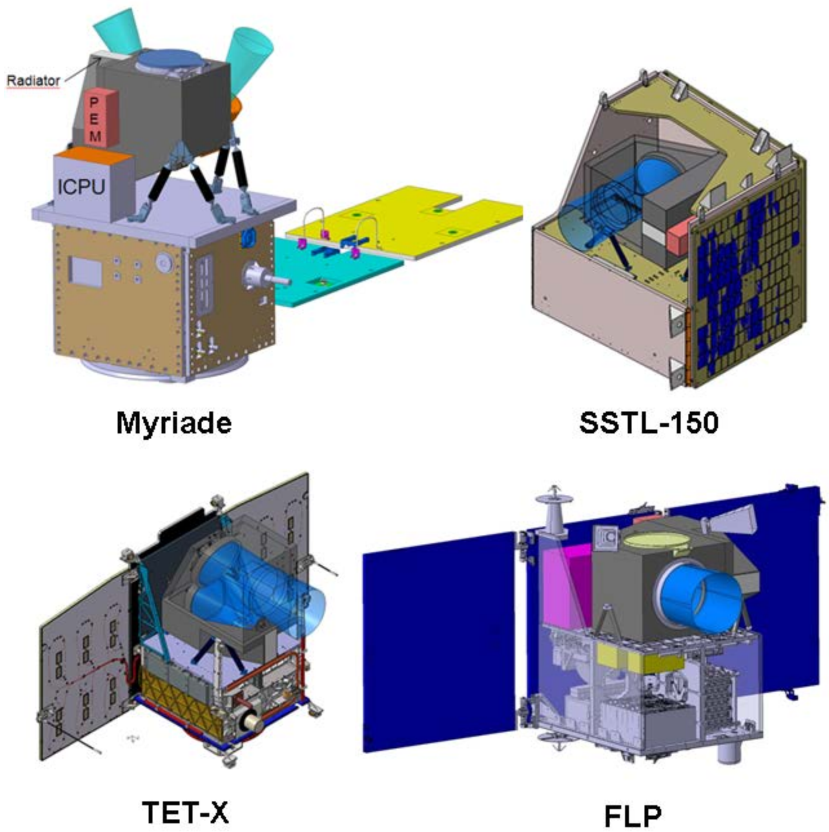

Figure 5. Accommodation of the SBSS demonstrator instrument on different micro-sat platforms.

A new promising platform option emerged with the Future Low-Cost Platform (FLP). 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.

For the detailing of the SBSS demonstrator mission, Myriade was exemplarily chosen. The AS100 platform requires limited adaptations: Primarily the addition of one star tracker (2 SST heads in total) and the use a reinforced structure (Taranis for CNES, qualified in 2012). Other minor adaptations like thermal and electrical architecture, solar array canting and flight S/W tuning were also considered. Based on the Myriade configuration, detailed system budgets and performance were derived. Furthermore, overall mission performance was evaluated based on this configuration. Table 4 summarizes the characteristics of the SBSS demonstrator platform.

Table 4. Properties of the SBSS demonstrator platform, ground-segment and launcher.

Platform	**Value**
Platform type	**Micro-satellite platform** (Myriade, SSTL-150, FLP, TET-X, Proba)
Total launch mass	**≤ 150 kg** (Myriade baseline: 133 kg)
Stabilization	3-axis stabilisation
Data up/downlink	**X-Band** (Myriade baseline: 60 Mbps)
Post-mission disposal	**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)

5 SURVEILLANCE AND TRACKING PERFORMANCE

A variety of simulations were performed for representative GEO objects and different observation strategies, showing that the SBSS demonstrator is able to generate and maintain a catalogue. Remarkably, the achieved performances are close or even compliant to the operational goals and SST system requirements. 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.

It is emphasized that the main drivers for the difference between demonstrator and operational mission are the instrument field-of-view and platform agility.

- FOV: 3°x3° (demonstration) vs. 5°x5° (operational)
- Agility: Micro-sat AOCS (Myriade baseline for the performance assessment) vs. Custom

If these differences can be further reduced for the demonstrator, another increase in performance is expected.

Table 5. Compliance of SBSS regarding the GEO surveillance performance.

<table>
<tr><th>ESA SST SRDs i1r4</th><th>SBSS Demonstrator</th><th>Operational SBSS</th><th>Constellation: Demonstrator & Operational SBSS</th></tr>
<tr><td>All GEO objects ≥ 0.4/1.0m (SST-SRD-6695 & SST-SRD-6696)</td><td>Compliant</td><td>Compliant</td><td rowspan="4">Compliant & enhanced performance
Either increased GEO performance or the demonstrator SBSS is free for other duties, e.g. tracking for orbital refinement in all orbital regions.</td></tr>
<tr><td>Cataloguing with a spherical accuracy envelope of 2.5 km (SST-SRD-6710)</td><td rowspan="2">Coverage, accuracy & timeliness can be traded.</td><td>Compliant</td></tr>
<tr><td>Cataloguing within 72 hours after the first observation (SST-SRD-8927)</td><td>Compliant</td></tr>
<tr><td>Pre-cataloguing within 72 h (SST-SRD-6729)</td><td>Compliant</td><td>Compliant</td></tr>
</table>

The demonstrator telescope's sensitivity threshold regarding minimum detectable object sizes has been determined with via radiometric calculation and the assumptions given in Table 6. 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 GEO velocity + 20% 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.

Table 6. Estimated sensitivity limits for the demonstrator telescope at GEO and MEO.

Scenario	CCD option (existing)	CMOS option (customised)	Assumptions:
Inertial GEO fence	**0,87-1,49 m objects** 16,36-15,57 mag	**0,68-1,18 m objects** 16,91-16,07 mag	- Diffuse reflecting spheres - Albedo = 0.1 - 0° < phase angle < 50° - 3 < SNR < 5 - 0.5 s < t_int < 1.6 s - Sky background 21.9 mag
Rate-track GEO fence	**0,42-0,96 m objects** 18,06-16,24 mag	**0,34-0,76 m objects** 18,52-16,74 mag	
MEO tracking	**0,27-0,62 m objects** 16,24-16,06 mag	**0,22-0,49 m objects** 18,52-16,74 mag	

Note that above estimates are quite conservative, as since a few years publications [2], [3] propose higher global albedo values of 0.17-0.18 instead of the standard 0.1. The assumption of such higher albedo figures would lead to smaller detectable object sizes.

6 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 models and 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. 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 using the ESA MASTER-2009 statistical LEO population ≥ 1 mm.

As shown by Figure 6, 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.

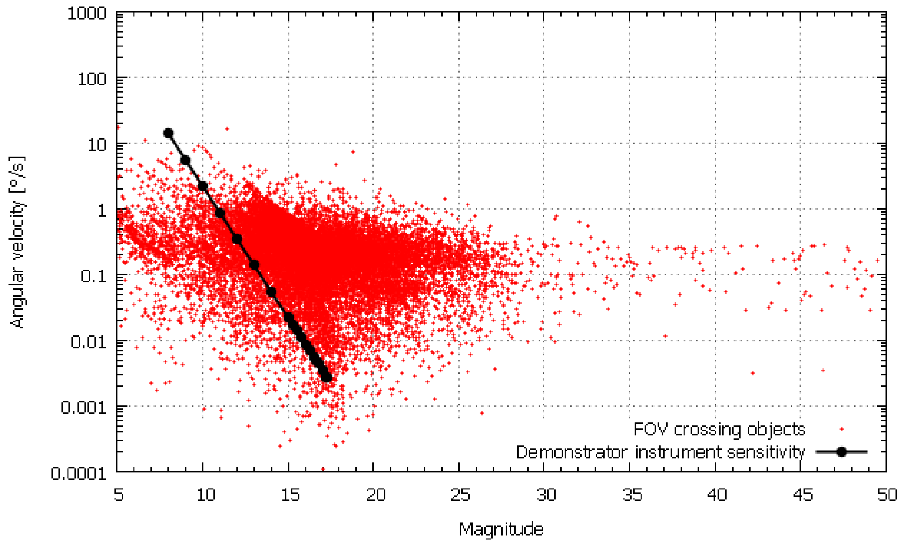

Figure 6. Sensitivity limits of the SBSS demonstrator instrument. Objects below the curve can be detected.

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 7. 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.

Table 7 . Operational modes for small debris observations

Mode	Application	Frame period (s/frame)	Exposure time (s)	ωrel (''/s)	Consecutive frames per object
Nominal framerate (GEO survey, continuous operations)	**Small debris detection & GEO surveillance**	**1,50**	**0,5**	**1500**	**4,8**
High framerate (campaign mode)	**Detection of very fast objects** with limited probability	**0,25**	**0,25**	**10000**	**4,3**

7 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:

- **Micro-sat platforms are suitable** for an SBSS demonstration mission
- **Re-use & mature technologies** for low risk and a short development schedule
- No classical technology demonstration but **end-to-end chain until product generation**
- **GEO catalogue generation and maintenance** already by the SBSS demonstrator; partially also in other orbit regimes (MEO, GTO, Molniya, etc.)
- **Tasked tracking can be performed in all orbit regimes**, incl. NEOs
- **LEO small debris ≥ 1 mm** can be observed in-situ without changing the SST mission
- **Mission performance close to operational SST goals** can be achieved by the demonstrator
- **Initial operating capability** for the SST segment can be obtained early without other optical sensors.

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!

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