TOWARDS EUROPEAN SPACE-BASED OPTICAL OBSERVATIONS OF DEBRIS AND NEOS

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ABSTRACT

Several ESA activities have paved the way for European space-based optical observation of both space debris and NEOs.

"ESA SSA CO-II SSA Architectural Design" identified a space-based capability as an ideal contributing asset for an overall Space Surveillance & Tracking (SST) system.

"ESA GSP SBSS Phase A" evaluated the feasibility of an SBSS demonstration mission based on a micro-satellite platform (~ 150 kg total) on a dawn-dusk sunsynchronous orbit and included the design of dedicated mission incl. instrument. Two types of missions were detailed: SST and Small LEO debris detections.

"ESA P2-SWE-X" identified a NEO monitoring mission as optional payload for an L1 or L5 Space Weather satellite.

The "ESA GSTP Optical In-Situ Monitor" breadboard system provides an optical facility to realistically test the end-to-end signal acquisition and processing chain with H/W in-the-loop for space-based space surveillance sensors.

The paper will provide an overview of these activities and show that technological readiness is achieved to enable initialisation of an Engineering and Flight Model of such a system.

1 AN (INCOMPLETE) HISTORY OF ACTIVITIES

The following table provides a non-complete list of ESA activities studying space-based optical sensors with SST, Small Debris (sub-catalogue) and NEOs missions.

Overall benefits of space-based sensors for these purposes – either stand-alone, as secondary payload or as part of a larger system architecture – are:

- Unique observation strategies from space
- High availability, independent of weather, day/night
- No geographical and geopolitical restrictions

In the following chapters, **bold** activities are briefly summarized.

End Date	Activity
2018	**„Optical In-Situ Monitor“, ESA GSTP** breadboard system to test the E2E acquisition and processing chain with H/W in-the-loop for space-based optical sensors
2015	**“SWE-X Enhanced Space Weather Monitoring System”** identified a NEO monitoring mission as optional payload for an L1 or L5 Space Weather satellite
2014	**„Assessment Study for Space-Based Space Surveillance Demonstration Mission, Phase A“, ESA GSP** evaluated the feasibility of an SBSS demonstration mission based on a small platform: 2 missions: SST and Small LEO debris detections.
2014	**„CO-II: SSA Architectural Design“, ESA SSA PP** identified a space-based capability as an ideal contributing asset for an overall Space Surveillance & Tracking (SST) system
2010	„Proof of Concept for Enabling Technologies for Space Surveillance“, ESA GSTP
2007	„Study on the Capability Gaps Concerning European Space Situational Awareness“ ESA GSP
2006	“Space-Based Optical Observation of Space Debris”

Table 1. ESA activities related to space-based optical observations of space debris and NEOs

Proc. 1st NEO and Debris Detection Conference, Darmstadt, Germany, 22-24 January 2019, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Jehn, F. Schmitz (http://neo-sst-conference.sdo.esoc.esa.int, January 2019)

2 ESA CO-II SSA ARCHITECTURAL DESIGN

This activity, performed within the ESA SSA Preparatory Programme during 2012-2014 aimed at the top-down design for 3 SSA Segments (SST, SWE, NEO)

- System Requirements Consolidation
- Architecture options trade-off
- Baseline selection, detailing & costs

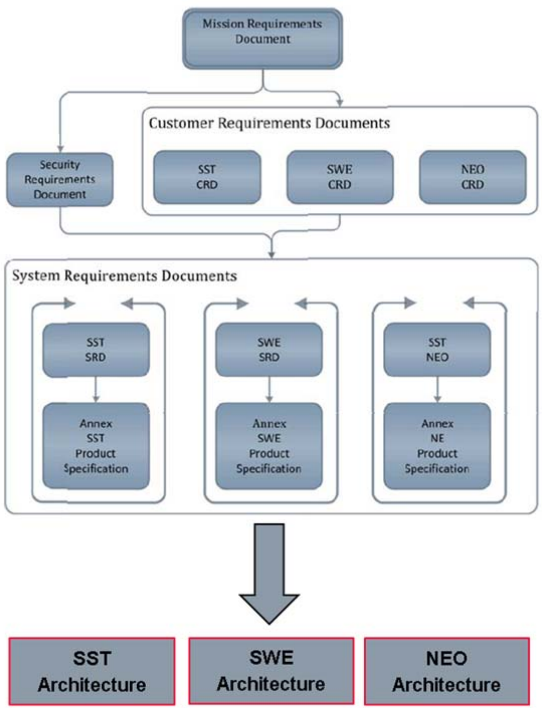


Figure 2. Top-down architectural design process in CO-II

For the SST segment, following services had to be covered:

Service
Service #1: Catalogue of Man-made Objects (CAT)
Service #2: Collision Warning (COL)
Service #3: Detection and Characterisation of In-Orbit Fragmentations (FRG)
Service #4: Re-entry Predictions for Risk Objects (RER)
Service #5: Object and Manoeuvre/Mission Characterisation (OMC)
Service #6: Special Mission Support (SMS)
Service #7: Characterisation of sub-catalogue debris (DEB)

Table 3. Envisaged ESA SST services in CO-II

The selected SST system architecture baseline had been designed to be compliant with the ESA SST system requirements and comprised the following sensors:

- 1 Surveillance radar → full coverage of LEO population
- **SBSS system (1 demonstrator + 1 operational s/c) to cover beyond-LEO orbits**
    - o **High performance towards ESA SST System Req.**
    - o **High availability, independent of weather, day/night**
    - o **Robustness and operational flexibility**
- Optical surveillance system (4 sites, ≥ 4 telescopes/site)
- operated jointly and complementarily
- Tracking system (radars and telescopes) to complete coverage, for contingency support, re-entry, …

In addition, the necessary data centre and processing infrastructure baseline had been derived.

A space-based optical space surveillance (SBSS) system had been an important element of the overall SST system architecture.

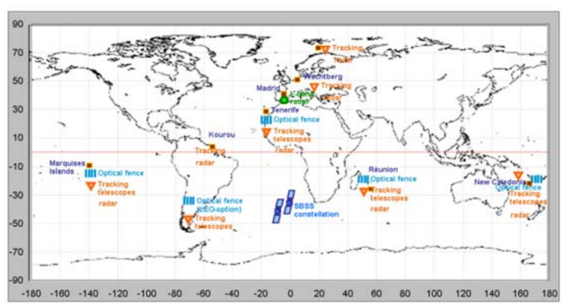


Figure 4. Sensor network proposed for CO-II

3 ESA „Assessment Study for Space Based Space Surveillance Demonstration Mission (Phase A)“

In a similar timeframe as CO-II, a Phase A study has been conducted from 2012-2014 with the following goals:

- Definition of an operational SBSS mission
- Design of an SBSS demonstration mission
    - o Micro-satellite platform (~ 150 kg total) or as hosted payload

- Design of dedicated mission incl. instrument
- Passive optical detection, visible spectrum
- Dawn-dusk SSO ≥ 700 km

3.1 SST and Small Debris missions

Two missions were studied in particular:

- **Space Surveillance & Tracking (SST)**
  - GEO catalogue generation & maintenance
  - Tracking in all orbits, incl. NEOs
- **Small LEO debris detections (ESA CleanSpace)**
  - Statistical sampling ≠ SST (no cataloguing, only coarse OD)
  - Objects as small as 1 mm (“in-situ” detection due to vicinity)
  - Improvement of debris models: Significant knowledge gaps for LEO debris between 1 mm – 10 cm size

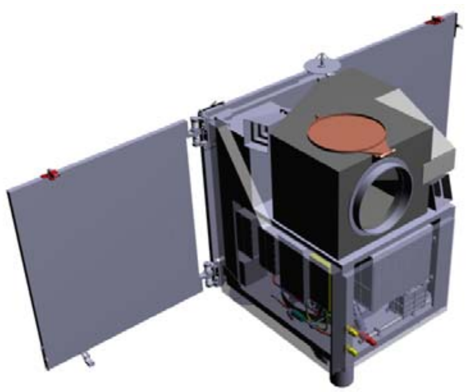


Figure 5. SBSS demonstrator instrument on FLP-2 platform

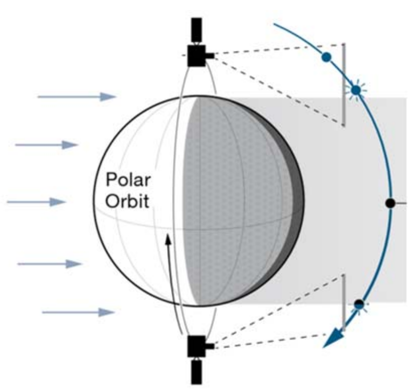
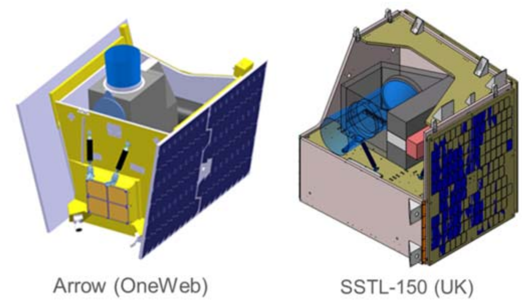


Figure 6. Dawn-dusk orbit and pointing direction of SBSS

3.2 Suitability of Micro-Satellite Platforms

Overall approach of the study was to define an operational mission and then downscale the mission to fit existing micro-sat platforms mission for demonstration.



It could be shown that high performance can be already achieved for the SBSS demonstrator:

- GEO catalogue, partially other orbit regimes
- Tracking in all orbits, incl. NEOs
- LEO Small Debris

Since the concept is scalable, enhanced performance can be achieved in constellation.

ESA SST SRDs i1r4	SBSS Demonstrator	Operational SBSS	Constellation: Demonstrator & Operational SBSS
All GEO objects ≥ 0.4/1.0m	Compliant	Compliant	Compliant & enhanced performance
Cataloguing with a spherical accuracy 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 7. Performance vs. ESA SST System Requirements.

3.3 Demonstrator Instrument

Following points summarize the features of the demonstrator instrument:

- Smaller version of the operational instrument
  - 20 cm (demo) vs. 28 cm (operational)
  - 3°x3° FOV (demo) vs. 5°x5° (operational)
- Size, mass and power compatible with existing micro-sat platforms
- TMA design for large FOV & large aperture
- On-Board Image Processing (debris detection, data volume reduction)

Instrument	Value
Aperture diameter	200 mm
Field of View	3°x3° (CMOS)
Optical design	TMA
Detector	2240 x 2240 (CMOS)
Pixel size	12x12 µm²
iFOV	23.5 µrad
Nominal frame period	1.5 s/frame

Table 8. SBSS demonstrator instrument parameters.

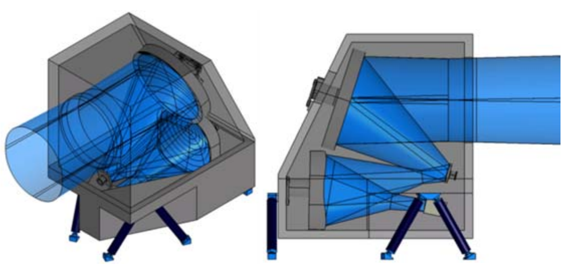


Figure 9. SBSS demonstrator instrument design.

3.4 Observation Mode: Survey

Main observation mode is the discovery and cataloguing of formerly unknown GEO objects (survey mode).

- Anti-sun pointing optimises illumination of observed objects
- Suitable for GEO surveillance & LEO small debris
- GEO belt coverage with one sensor for SST

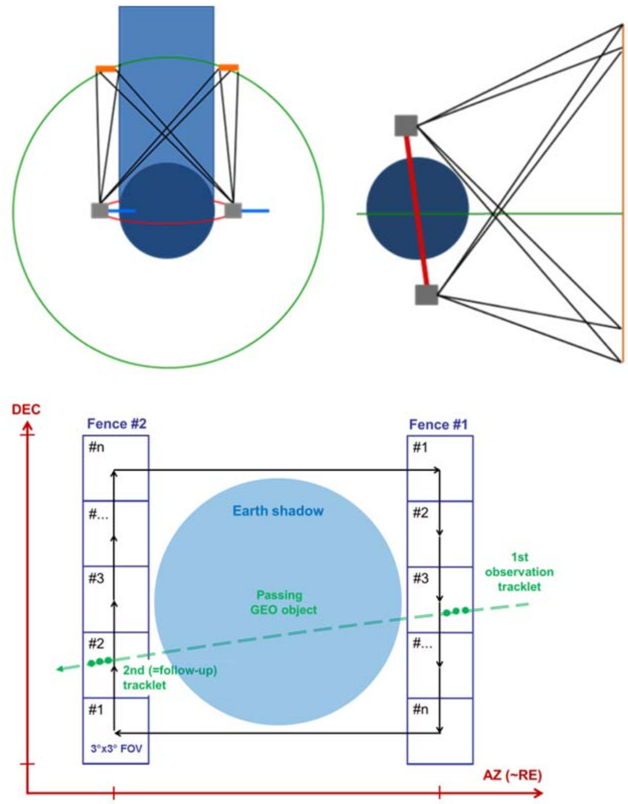


Figure 10. Observation strategy for survey

3.5 Observation Mode: Tracking

Secondary observation mode is orbit refinement for known objects (tracking mode) and can be performed in all orbital regions from LEO to beyond-GEO, including NEOs:

- Planning and scheduling of access times
- Large volume of space accessible
- Fidelity depends on satellite design

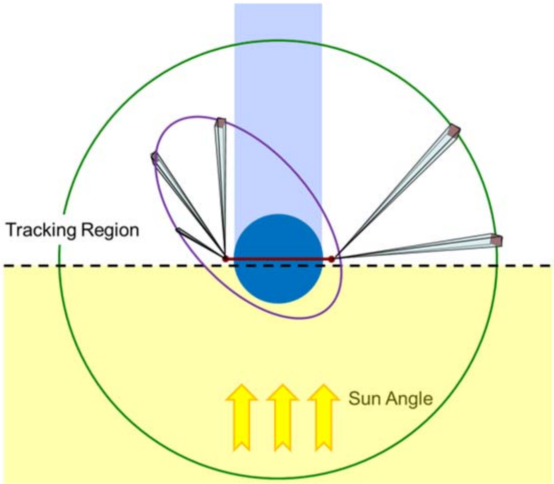


Figure 11. SBSS tracking mode

3.6 Observation Mode: Small LEO Debris ≥ 1 mm

Small debris observations entered the study as additional objective upon ESA request (ESA CleanSpace).

Conclusions were:

- Small Debris mission possible during SST mission
  - Framerate ~ 1/s
  - Large numbers of LEO small debris detections
- Small Debris observations ≠ SST
  - Objects as small as 1 mm
  - Too small and fast for conventional SST
  - No cataloguing, only coarse OD
  - Statistical sampling for improvement of debris models, reduction of S/C vulnerability

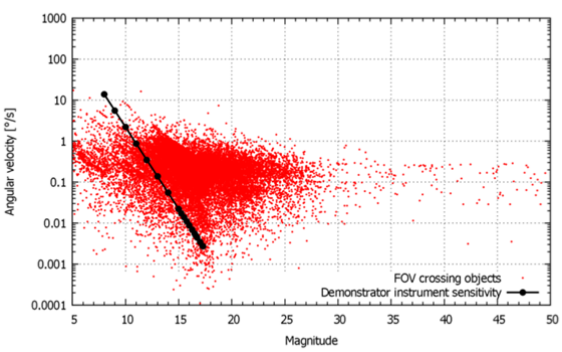


Figure 12. Detection thresholds for small debris population

4 SWE-X Enhanced Space Weather Monitoring System - NEO Monitoring Element

During the ESA Space Weather study "SWE-X", the analysis of operational SWE missions at two different locations has been performed:

- Sun-Earth line mission ("L1")
- Away-Sun-Earth line mission ("L5")

One element of the activity has been the investigation of a NEO secondary P/L for L1 and L5:

- Goal: Warn about close approaches or potential impact threats of near-Earth asteroids or comets objects
- Small objects from the direction of the Sun not detectable from ground → space-based sensors as only possibility
- L1 orbit offers unique possibility to look back towards Earth
- L5 orbit offers unique possibility to look between Sun and Earth

4.1 Detection Performance

A suitable NEO instrument should bring the following properties:

- High sensitivity to detect also smaller NEOs
- Large observation volume to maximise detections
- High astrometric accuracy for NEO orbit determination

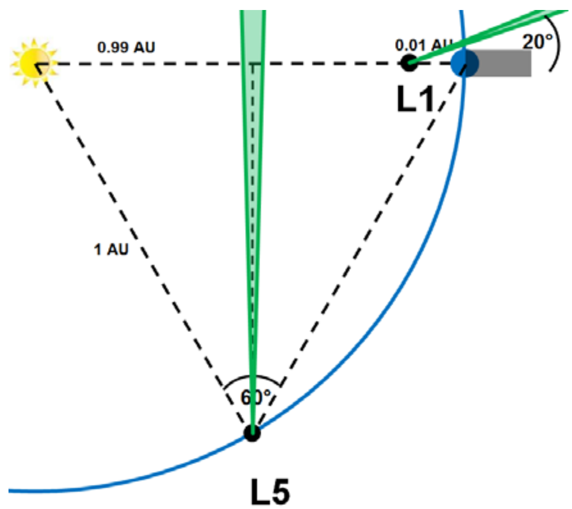


Figure 13. NEO observations at L1 and L5 points.

In order to provide a preliminary quantification of possible detection performances, 3 different instruments have been examined:

- **SPOSH**: Small aperture (6.5 mm), huge angle (120°x120°), prototypes exists
- **ASTRO APS**: Larger aperture (36 mm), very wide angle (20°x20°), existing STR
- **SBSS Demonstrator instrument**: Large Aperture (200 mm), wide angle (3°x3°); existing design from Phase A study

Figure 14: The three exemplary instruments used for the performance estimates

Simulations have been conducted for various observation strategies using the following configuration:

- AS4NEO by Deimos
- NEO population: Morbidelli (2000) synthetic, 4486 objects
- 10 years simulated time

Different pointing directions have been implemented and simulated.

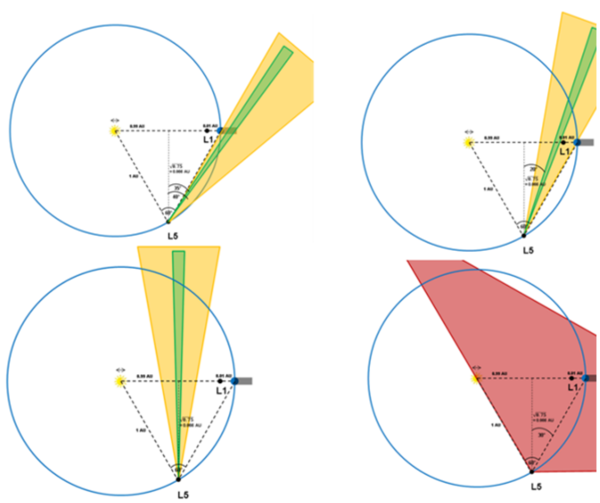


Figure 15: Pointing strategies for NEO observation from L5.

Best performance has been achieved for the SBSS demonstrator instrument with scanning pattern: A sufficiently large aperture is needed for sensitivity, while the scanning pattern provides the necessary coverage of a large volume of space.

SBSS Demonstrator Case	Number of observed objects	Number of re-observed objects	Discoveries	Visibility (d), ave. & 1-σ
L5 scenario +35°	137	41	43 (31.3%)	2.56; 4.56
L5 scenario +20°	179	54	55 (30.7%)	2.78; 3.31
L5 scenario 0°	271	107	98 (36.2%)	2.63; 3.98
L5 scenario 0° (scanning)	1197	1193	523 (43.7%)	-

Table 16: Results for the SBSS demonstrator instrument.

5 ESA "Optical In-Situ Monitor"

As successor to the SBSS Phase A activity, a breadboard system for the space-based optical observation of space objects has been developed in the 2016-2018 timeframe. The goals of this system and the activity are to achieve technological readiness to enable initialisation of an Engineering and Flight Model of the instrument as soon as a suitable target platform has been selected. The latter could be a larger host platform or an own dedicated microsatellite as studied in the SBSS Phase A studies.

Focus of the Optical In-Situ Monitor breadboard system is to provide and test a realistic end-to-end signal acquisition and processing chain with H/W in-the-loop.

Three main elements have been developed:

- Test Set-Up: Generator for characteristic space debris scenes
- Breadboard Instrument: Acquires representative images
- Image Processing Pipeline: On-board debris detection & data reduction, on-ground astrometry & photometry

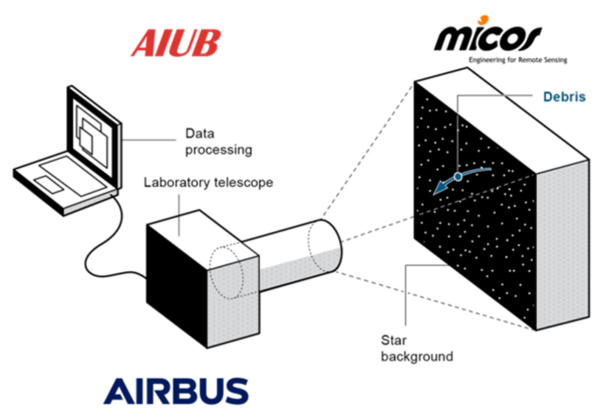


Figure 17: Sketch of Optical In-Situ Breadboard elements

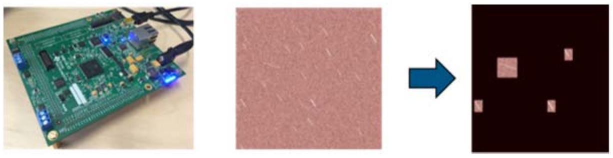


Figure 18: On-board object detection and image processing

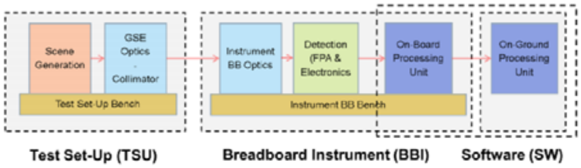


Figure 19: Overall System Concept

Figure 20: Breadboard Hardware

End-to-end testing has been successfully performed, demonstrating the system's capability to deliver high astrometric and photometric accuracy.

- Acquisition of images
- for representative observation scenarios
- Complete astrometric and photometric reduction (OBPP & OGPP)
- Comparison of results to known ground-truth.

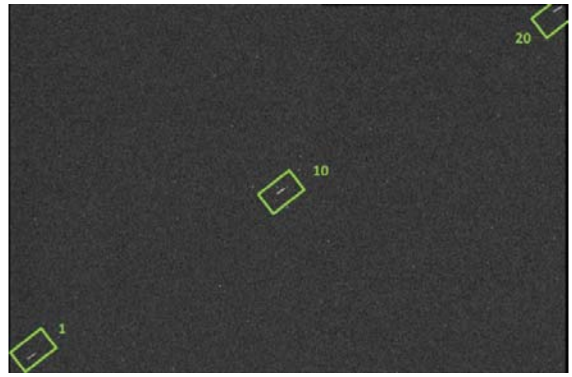


Figure 21: End-to-end test case

6 CONCLUSION: TOWARDS EUROPEAN SPACE-BASED OPTICAL DEBRIS OBSERVATION

Several ESA activities have paved the way for European space-based optical observation of both space debris and NEOs.

All necessary building blocks are now available:

- Use Cases & System Requirements
- Demonstrator & operational mission designs (S/C & G/S)
- Instrument designs
- Micro-satellite platforms for implementation
- Simulation tools for performance evaluation
- Image processing software prototype for on-board detection and on-ground processing
- Prototype implementations on on-board processing H/W
- H/W breadboard system for realistic E2E signal acquisition and processing chain

Technological readiness is therefore achieved, enabling the next step: Implementation of a Flight Model.