Space-Based Optical Component (SBOC) for the ESA VISDOMS mission

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ABSTRACT

As part of the ESA Space Safety Programme (S2P) the ESA Space Debris Office performs research and technology developments to ensure Europe's capability of monitoring the space-related traffic and in particular space debris that may endanger the space infrastructure. This encompasses the understanding and assessment of the amount, size distribution and density of debris in various Earth orbits with a particular emphasis on Low Earth Orbits (LEO), the region where the highest density of manmade debris objects is found.
In order to extend the capabilities of ground-based observations made using radar and optical technologies it is planned to place an optical telescope in a Sun synchronous Low Earth Orbit, which allows a permanent anti-sun viewing direction in order to maximise illumination of observed objects.
The feasibility of space-based optical observations using a telescope with around 20 cm aperture in such orbit has been demonstrated in previous ESA studies. From these activities a mission concept has been derived with the goal to significantly expand the knowledge of the sub-catalogue small-size space debris population in LEO.
The Space-Based Optical Component (SBOC) instrument is currently in its Phase B and the envisaged launch date for the corresponding VISDOMS (Verification of In-Situ Debris Optical Monitoring from Space) small satellite mission is 2027.
Main objectives of the ESA S2P S1-SC-11 SBOC Phase B activity can be summarised in the following three pillars:

- Instrument preliminary definition including requirements consolidation and design maturation to achieve system SRR and PDR
- Further development and de-risking of the on-board and on-ground image processing software
- Development of a detection and processing chain demonstrator using simulated and real-world images and performing end-to-end tests of the image processing software

The paper will provide an overview of the objectives of the mission, system requirements, design of the instrument and image processing developments.

1. SPACE BASED SPACE SURVEILLANCE

1.1 Advantages of Space Based Sensors

Space-based optical sensors are ideal assets for contributing to space situational awareness tasks. Their benefits are amongst others:

- Unique observation strategies from space incl. vicinity to targets
- Enable capabilities which are not possible from ground, e.g. in-situ monitoring of small-sized debris
- High availability, independence from weather, day/night
- Enhanced performance in timeliness and revisit
- Higher SST coverage and catalogue maintenance performance
- Independent of geographical location

1.2 ESA VISDOMS

Objective of the planned ESA VISDOMS mission (Verification of In-Situ Debris Optical Monitoring from Space) is to demonstrate the monitoring of sub-catalogue debris in Low Earth Orbit (LEO). This will allow significant improvement on the knowledge of this population, as these objects (down to sub-millimetre sizes) cannot be detected from ground and can only be measured in-situ. Small debris observations are not to be confused with the

cataloguing goal of Space Surveillance and Tracking (SST). 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 like MASTER and the reduction of satellite vulnerability. Nevertheless, classic surveillance and tracking of debris and satellites from space will also be demonstrated within the mission.
While such capabilities have been shown by various US and Canadian missions (such as SBV, US SBSS Block 10, Sapphire, NeosSat), several ESA activities have paved the way for European space-based optical observation of space debris, see Table 1.

Table 1: ESA activities related to space-based optical observations of space debris (non-exhaustive)

End Date	Activity
2022	**"Space-Based Optical Component: Further Development of a Hosted Optical Payload, Ground Segment Preparation, and Streak Detection Algorithm Finalisation" ESA S2P S1-SC-11** Instrument preliminary definition until PDR, further development of the on-board and on-ground image processing software and development of a detection and processing chain demonstrator
2020	**"System Requirements Definition for a Space-based Optical Component" ESA P3-SST-XI** Refined system requirements for a Space-Based Optical Component with the primary goal of observing LEO as well as the goal of observing objects in GEO, MEO, GTO and HEO orbits.
2018	**„Optical In-Situ Monitor", ESA GSTP** Breadboard system to test the E2E acquisition and processing chain with HW in-the-loop for space-based optical sensors
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"**

Within these activities, a mission concept has been developed that places an optical telescope with 20-30 cm aperture and wide field-of-view on a sun-synchronous dawn/dusk orbit between 600 and 900 km altitude [1]. This allows for a mostly anti-sun – pointing direction, hence well-illuminated targets. Such mission enables surveillance and tracking of objects in altitudes higher than LEO, but also detection of small LEO debris. The instrument itself can be flown either as a dedicated mission using a small satellite platform or as hosted payload. A dedicated mission allows more flexibility and mission performance since the pointing of the telescope can be tasked, while a hosted payload approach would result in a fixed pointing with less flexibility.

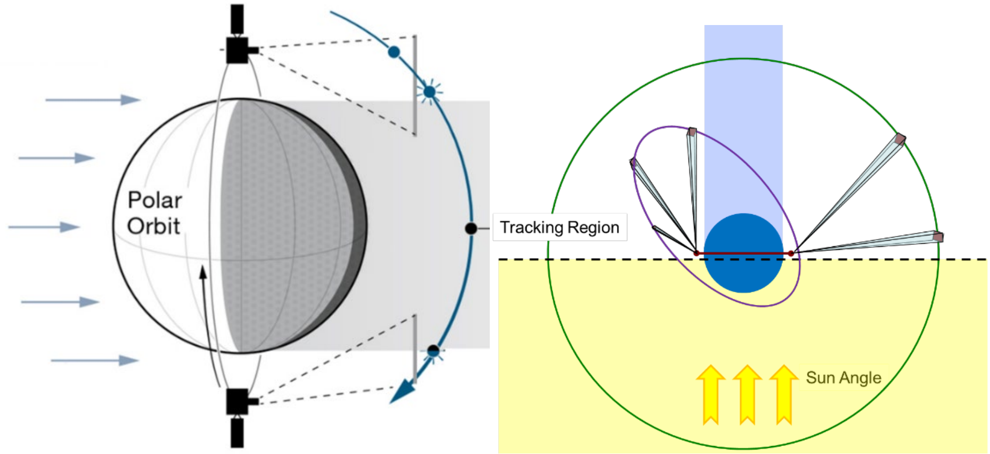

Fig. 1: Left: Debris detection configuration of a satellite in a sun-synchronous orbit (SSO). Right: Potential surveillance and tracking operations geometry from SSO as a secondary mission goal.

In order to assess the feasibility of the basic mission concept and to test the end-to-end processing pipeline a breadboard system has been developed and successfully demonstrated in a previous activity. [2, 3]
Within the current Phase B study the primary instrument of this mission as well as the data processing pipeline is being developed.

2. SBOC INSTRUMENT

2.1 Mission Requirements and Assumptions

SBOC is the instrument for the ESA VISDOMS mission. Main mission requirements and assumptions include:

- Enhancement of the statistical knowledge about LEO objects by detecting and characterising objects with a diameter of 1 mm or larger.
- Space Surveillance and Tracking of objects in orbits beyond LEO.
    - Detection and characterisation of objects in geo-stationary orbit with diameter of 70 cm or larger.
    - Observation of objects in Medium Earth Orbits with a diameter of 40 cm
- Operation in a LEO sun synchronous orbit between 600 km and 900 km altitude near the terminator.
- Hosted payload or dedicated mission based on a micro-satellite platform.

2.2 Baseline Mission Scenario

During the primary small debris detection mission, the instrument monitors regions opposite to the Sun direction and will perform continuous observations with high frame rate and a nominal exposure time of 0.5 s. Observations are performed sidereal, i.e. stars will appear point-like while space objects will appear as a streaks when passing the field-of-view (FOV). Streak lengths are dependent on the angular speed of the objects and the exposure time. The observed star background will change over time. Since the orbit is sun-synchronous, the orbital plane will rotate with roughly 0.041 arcsec/s. An additional rotation of the instrument in case of a nadir-pointing host-spacecraft must also be taken into account. During surveillance and tracking mission operations a longer exposure time may be used to increase signal to noise ratio (SNR) for slow objects.

2.3 Instrument design drivers

The instrument design is driven by the mission requirements and considers several additional constraints (cost, etc.). Main drivers are instrument mass and size as well as sensitivity and achievable astrometric accuracy (Fig. 2).

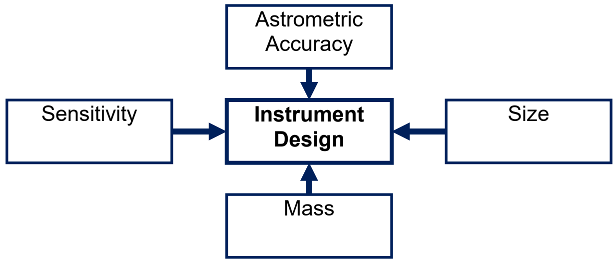

Fig. 2: Main drivers of the instrument design

Instrument size and dimensions should allow its accommodation on a small satellite platform. During the Phase A study an exemplary accommodation using different European platforms has been conducted (Fig. 3).

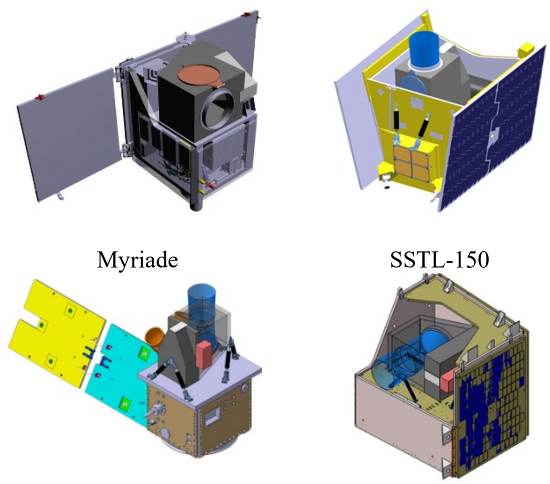

Fig. 3: Accommodation of SBOC instrument on small satellite platforms

The sensitivity requirement is described by a function which depends on the apparent brightness and angular velocity of an object. If an object is slower and/or brighter, each detector-pixel can collect more energy, which will therefore increases SNR and therefore detectability. Using a detector with larger pixels could theoretically increase sensitivity by allowing more energy to be detected by each pixel. Beyond a certain threshold for ensquared energy, this would however reduce astrometric accuracy as no sufficient centroiding would be possible, which makes a trade-off necessary. Further effects, like the spot size and pointing stability sensitivity have to be taken into account additionally.

3. INSTRUMENT DESIGN

The SBOC instrument consists of four main elements: An Opto-Mechanical Assembly which includes the telescope as well as the structure, the detection chain which includes the Focal Plane Assembly (FPA), the Front End Electronics (FEE) as well as additional hardware to handle the generated data and the Instrument Control and Processing Unit (ICPU). An overview on the components is shown in Fig. 4 and the main system parameters are listed in Table 2.

Table 2: System parameters of SBOC

System parameter	Value Phase B
Volume / Mass / Power	Suitable for a micro-satellite
Aperture diameter	200 mm
Optical design	TMA

image size	2680 x 3546
Field of view	3.4° x 4.5°
IFOV	4.54 arcsec
Nominal frame period	1.5 s per frame
Nominal exposure time	0.5 s

3.1 Telescope

SBOC uses a fixed optical telescope of TMA design with a large FOV. Based on the analysis conducted in previous activities this design has been chosen as it achieves the best trade-off between sensitivity, astrometric accuracy, size and mass constraints. A large field of view increases the volume of the surveyed region and therefore improves the mission return. In addition, due to the larger field of view it is much more likely to detect the same object in two consecutive images (up to a threshold angular rate), which would enable a coarse orbit determination.

3.2 Detection Chain

The detection chain for SBOC possesses the following features:

- A large format detector, which enables a large field-of-view.
- Low noise characteristics to provide high sensitivity.
- High framerates to allow the detection of fast objects.

3.3 ICPU

The Instrument Control and Processing Unit is used for:

- On-board processing of the generated images
- Overall instrument control
- Management of house-keeping parameters
- Time management and system synchronisation
- Power management
- Interface to the spacecraft

As SBOC will be primarily operated in a continuous imaging mode the ICPU must be capable of processing the generated raw images inside the same time frame as they are generated. Due to the high frame rate and the large number of detector pixels the size of the raw data would exceed the available bandwidth and storage capacity by orders of magnitude, which makes an extensive on-board processing for data-reduction necessary (see section 4). Additionally, the ICPU must be able to handle the above listed tasks in parallel.

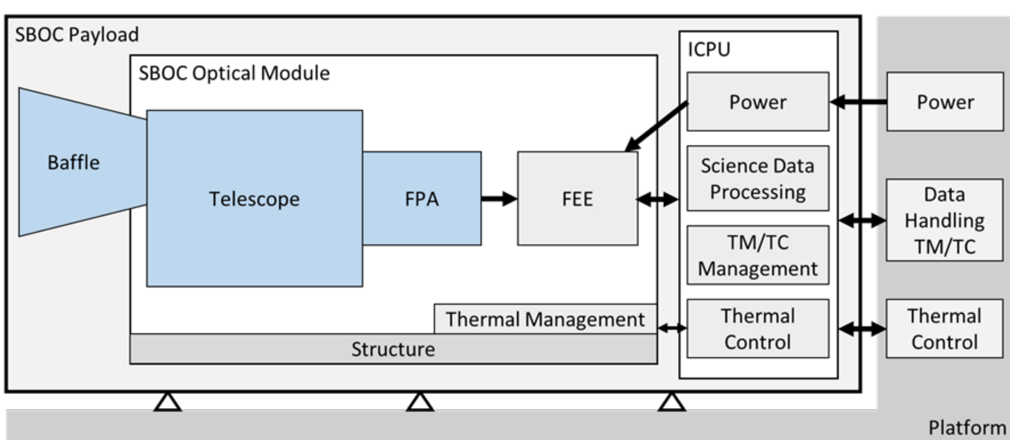

Fig. 4: Block diagram of the SBOC instrument

4. IMAGE PROCESSING PIPELINE

The full image processing pipeline consists of an on-board part running on the ICPU and an on-ground part. As described in section 3.3 this design is necessary to minimize the data that needs to be sent to ground.

4.1 On-board data reduction

As part of the on-board data reduction algorithm all raw images are processed. Object streak candidates are identified and marked as regions of interest (ROIs). Moreover, a defined number of stars are identified and marked as ROIs for the purpose of astrometric reduction on-ground. Those areas are stored in a separate dataset, keeping the pixel and position information [4].
All other parts of the image are discarded to reduce data volume. Therefore, the size of the resulting dataset depends on the number of stored ROIs, which makes it necessary to tune the sensitivity of the algorithm to reach the required data reduction but not discard any potential streak. The size of the generated data is further reduced by using conventional compression algorithms.

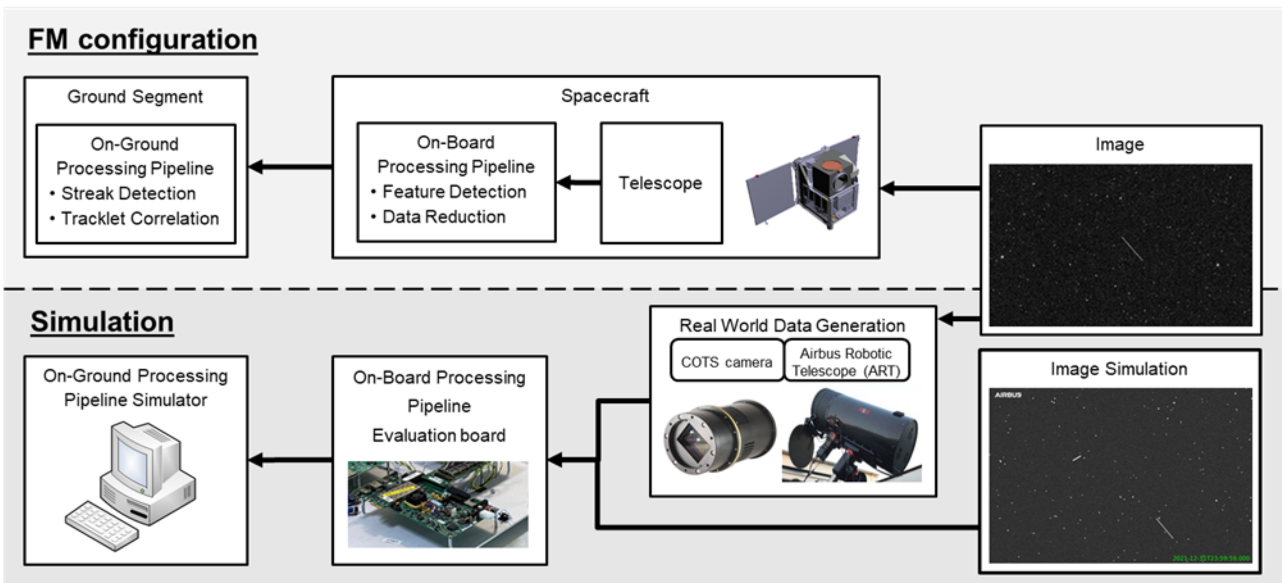

Fig. 5: Data processing pipeline in-flight and during development and testing on-ground

4.2 On-Ground Processing

The received data on-ground includes all the necessary information (stars and potential object streaks) to continue with astrometric and photometric reduction and to characterise the detected object. Finally, tracklet linking is performed where possible.

4.3 Simulation Pipeline

During the SBOC Phase B activity the image processing pipeline has been implemented to evaluate the performance of the used algorithms and to test the achievable data reduction rate. An overview on the pipeline for the flight model and during the development phase is given in Fig. 5.
The on-board part of the processing pipeline is implemented on an evaluation board with processing hardware similar to the actual flight model. For the on-ground part the StreakDet [5] software is adapted to be used with the reduced images.

As an input, simulated images (Fig. 6) generated by Airbus' SST software suite "Special Perturbations Orbit determination and Orbit analysis toolkit" (SPOOK) [6] as well as real world images generated by the Airbus Robotic Telescope (ART) [7] are used.

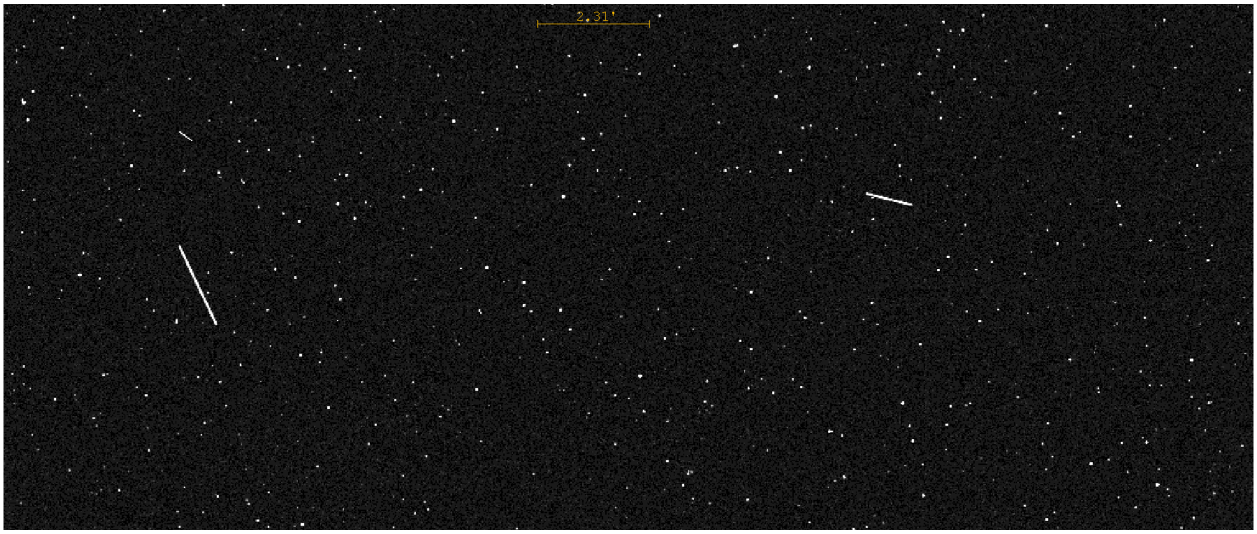

Fig. 6: Simulated sensor image including two streaks and one cosmic.

5. CONCLUSION AND OUTLOOK

In this paper, an overview of the objectives of the VISDOMS mission and the related SBOC instrument development has been provided.

PDR (Preliminary Design Review) for the instrument is targeted for October 2023. With the follow-on activity, it is planned to bring the instrument design to CDR status (Critical Design Review), to procure LLIs (Long-Lead Items) and to progress on the mission architecture and design including identification and assessment of suitable platforms.

6. REFERENCES

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