Optical In-Situ Monitor – A Step towards European Space-Based Debris Observations

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ABSTRACT

The aim of the ESA GSTP activity „Optical In-Situ Monitor“ is to design and test a breadboard of a space-based space debris camera and to develop and test its end-to-end processing chain. The corresponding future flight model shall be used for the detection of small-sized (down to 1 mm) space debris in LEO as well as larger objects in GEO. It is intended to be flown on a platform in sun-synchronous orbit near the terminator plane. The breadboard system will constitute a unique facility to perform realistic tests of the end-to-end chain for debris observations within a controlled environment. This E2E chain starts from signal generation via the scene generator, is followed by the acquisition of images via the breadboard instrument and finally performs the data processing until the astrometric and photometric reduction step. The paper provides details on requirements and design of the breadboard system.

1. INTRODUCTION: SPACE-BASED OPTICAL DEBRIS MONITORING

The strengths of Space-Based Space Surveillance (SBSS) for SSA and space debris observations are

- Full longitudinal GEO belt coverage with one sensor enabling catalogue generation and maintenance [1]
- Tracking in all orbital regions (LEO, MEO, GTO, Molniya, NEOs) for orbit refinements
- 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

Once demonstrated for Europe, a space-based capability would be an ideal contributing asset for an overall Space Surveillance & Tracking (SST) system as well as to contribute to space debris research in a unique fashion. Generated measurements are based on passive optical detection in the visible spectrum; extracted first-level data are observation angles and apparent brightness.

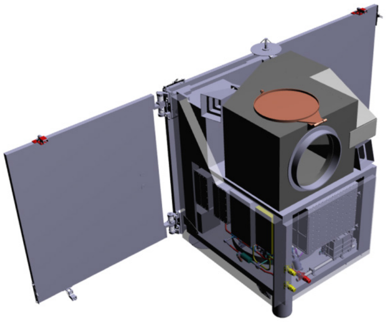

Fig. 1. SBSS demonstrator instrument on FLP-2 platform [2]

2. ESA „SBSS DEMONSTRATOR PHASE A“: PREDECESSOR ACTIVITY

In the 2012-2014 timeframe, two parallel ESA studies were conducted, one [2] by an Airbus-, the other by a GMV-consortium. These activities evaluated the feasibility of an SBSS demonstration mission based on a micro-satellite platform (~ 150 kg total) or as hosted payload on a dawn-dusk sunsynchronous orbit (SSO) and included the design of dedicated mission incl. instrument. Two types of missions were detailed:

Space Surveillance & Tracking (SST)

- GEO catalogue generation & maintenance
- Tracking in all orbits, incl. NEOs

Small LEO debris detections

- 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

The small LEO debris detection goal, introduced by the ESA CleanSpace initiative as additional study objective, turned out to be attractive: An “in-situ” sensor in the most congested LEO regime – polar SSO – performing continuous optical sampling of a relatively large observation volume (the system’s field of view) is unique compared to other methods like ground-based beam-park experiments with radar or impact detectors.

The Airbus study concluded furthermore, that both missions – SST & LEO small debris – can be operated simultaneously in an interleaved manner.

3. ESA “OPTICAL IN-SITU MONITOR”

The ESA “Optical In-Situ Monitor” has the following main objectives:

- Development & Test of an Optical In-Situ Monitor Breadboard
- Ability to perform tests of end-to-end observation & processing chain
- H/W in-the-loop in a controlled environment

Three main elements (shown in Fig. 2) constitute the breadboard system:

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

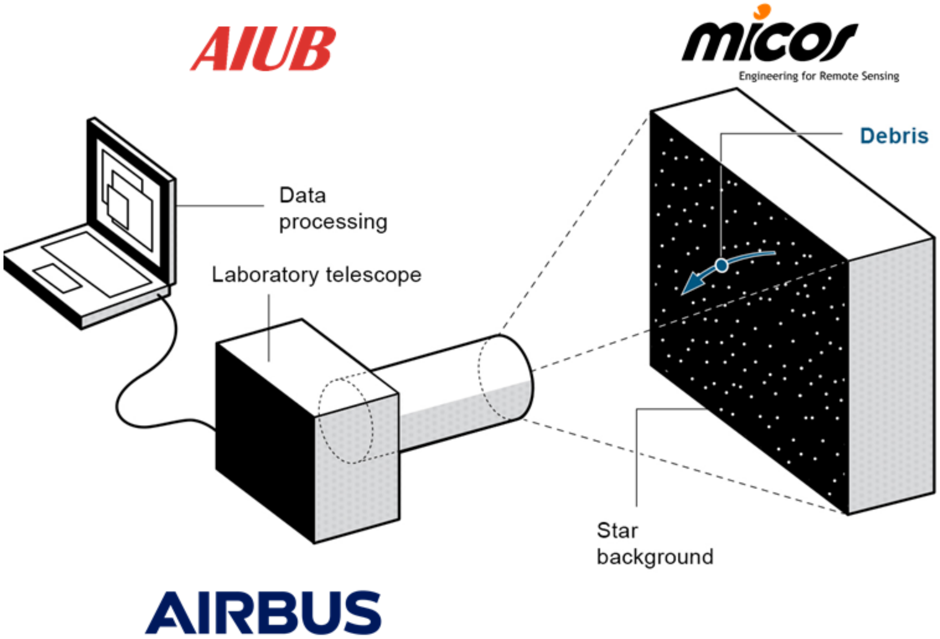

Fig. 2. Breadboard system elements and responsibilities

The breadboard system shall be able to host instruments for space debris observations of various scales up to the future flight model (FM) baseline (aperture factor 0.5 – 2, FOV factor 0.3 - 3). The baseline for the FM hardware is given by SBSS Demonstrator Phase A [2]. The breadboard system shall simulate

- bright and faint streaks
- of constant and varying brightness, and
- of various angular velocities,
- in front of a realistic star background and background signal
- representative for GEO surveillance & small LEO debris detection

Emulating realistic space debris observations in the lab is challenging, as above high level requirements translate into ambitious sensitivity and accuracy goals:

- LEO debris ≥ 1 mm, GEO objects > 0.7 m
- Brightness down to 17-18 mag
- Angular rates up to several deg/s
- Accuracies better than 1 arcsec (astrometry) and 0.1 mag (photometry)

4. OVERALL BREADBOARD SYSTEM DESIGN

The Overall Breadboard System (OBS) encompasses the Test Set-Up part (TSU a.k.a. the scene generator), the Breadboard Instrument (BBI) and the Control and Data Acquisition Unit which stores and processes the images and provides also the I/F to operate the TSU.

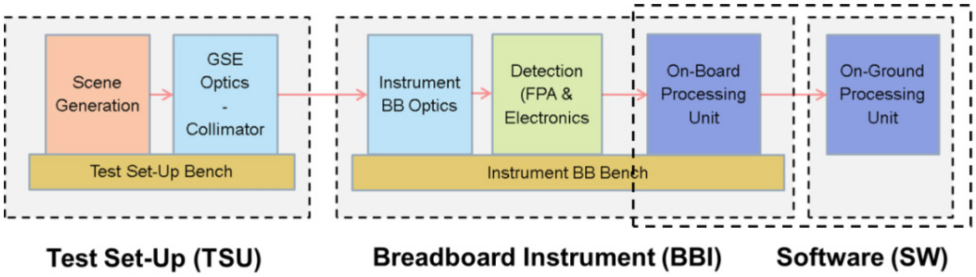

Fig. 3. Functional units conceptually representing the OBS architecture.

In order to allow a selection of a preferred concept leading to a design baseline, following design drivers were considered:

- Minimize and avoid the need for customized H/W, i.e., usage of COTS components whenever possible also in view of minimizing lead times.
- Goal to represent the end-to-end chain from signal generation, imaging and data processing to study the most influential parameters for mission performance.
- Generation and processing of representative signals is considered more important than actually aiming for a similar instrument design.
- Aim for a flexible and configurable optical set-up to represent the optical properties of the target instrument but also to adjust the main parameters (EE, iFOV, SNR, sky background noise, camera noise) to characterise their impact on the final products, which are: Astrometry (angles) & photometry (brightness).

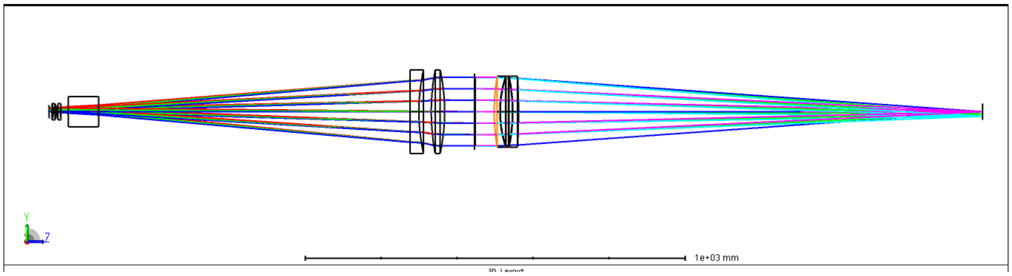

Fig. 4. OBS optical model.

5. BREADBOARD INSTRUMENT

The BBI is composed of three separate elements with following selected components

- BBI Telescope
  - including an iris diaphragm for BBI aperture adjustment
  - APM Telescope: APM - LZOS Teleskop Apo Refraktor 180/1260
- BBI Camera
  - i.e., the detector plus detector readout
  - FLI Camera MicroLine ML 11002
  - 4008 x 2672 pixels
  - 9 µm pixel size, 16 bit
- Control and Data Acquisition Unit
  - Standard PC simulates on-board processing unit & stores acquired images
  - performs also on-ground processing
  - used as well for overall breadboard system command & control

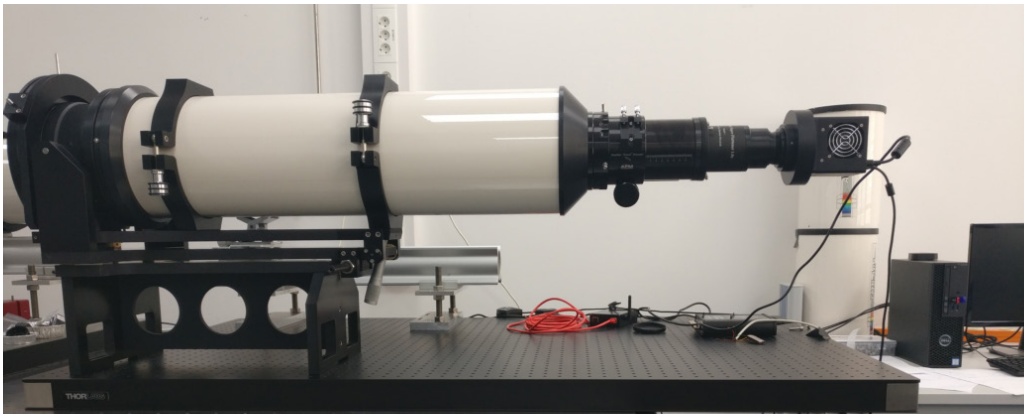

Fig. 5. BBI as-built.

The combination of telescope and camera yields the following parameters for the BBI in comparison with the envisaged SBSS flight model instrument:

Table 1. Comparison between BBI and SBSS demonstrator instrument parameters.

Parameter	**IN-SITU BBI**	**SBSS FM**	**Unit**
Aperture	180 (20-180)	200	mm
FoV	1.64 x 1.09	3 x 3	deg
F/#	7	2.55	
Optical design	Apochromatic Refractor	TMA Reflector	
Transmission	> 0.9	0.9	
Pixel IFOV	28.5	23.5	µrad
	5.88 (4x4 binning)	4.85	arcsec
Sensitivity	16	16.5	MV
Exposure time	0.5	0.5	s
Frame period	1	1.5	s/frame

The BBI will have the means to finely align its entrance pupil to the exit pupil of the TSU, as well as to finely align the detector plane to the telescope focal plane. With regard to radiometric behaviour, the BBI will be able to resolve faint signals and it will be approximately representative of the SBSS FM. Below, one can see the comparison for two types of objects: a) slow objects featuring a speed of 18 arcsec/s –blue/green points; b) fast objects featuring a speed of 1 °/s – debris objects – red/violet points. Furthermore, the size of the BBI field-of-view compared to the envisaged flight model is depicted. Although smaller, it will allow performance characterisation of all relevant parameters, in particular for long and faint object streaks.

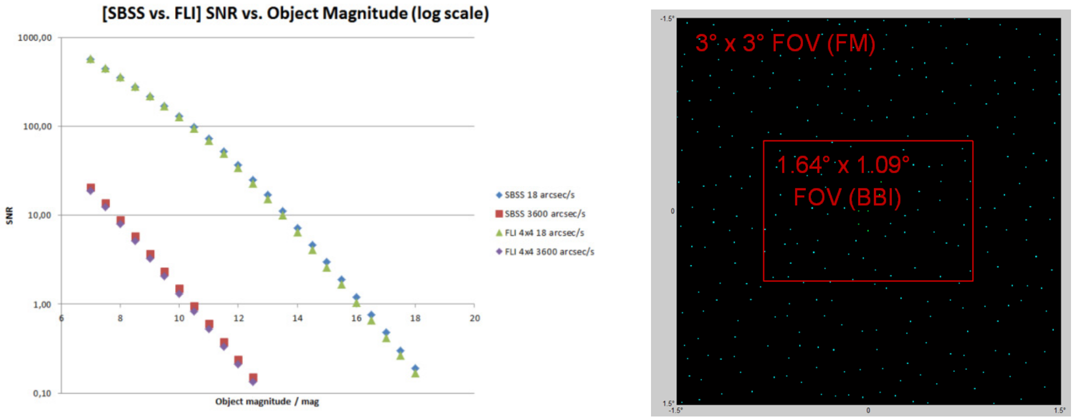

Fig. 6. Left: SNR performance comparison between BBI and SBSS demonstrator FM for slow and fast moving objects. Right: FOV comparison between BBI and SBSS demonstrator FM.

6. TEST SET-UP

In order to test the image processing in realistic conditions, a proper scene to be observed must be generated: This is the role of the test set-up (TSU) developed by Micos Engineering GmbH.

The main goal of the test set-up is to provide the scene to be observed by the breadboard instrument (BBI) while remaining modular enough to act as an OGSE for a future flight instrument. Among the scene features, the TSU shall generate a continuous background, a star background and a debris object. Each of these features shall be independently tuneable in intensity. In addition, the star background and the debris object shall be moveable in order to emulate their relative motion that would be observed from an actual in-situ debris monitor satellite.

The Test Set-Up shall be as representative as possible of the actual orbital situation, meaning that the implementation of its features and their motions must also be registered with a high accuracy (less than 1 arcseconds in angular space) in order to mitigate the errors coming from the TSU while evaluating the image processing performance, i.e. it shall be able to provide a ground-truth.

Scene features

As previously mentioned, the TSU generates three distinct features: a continuous background, a star background and a debris object. These elements are merged into one scene in the angular space by an optical system that we will call the TSU collimator from now on.

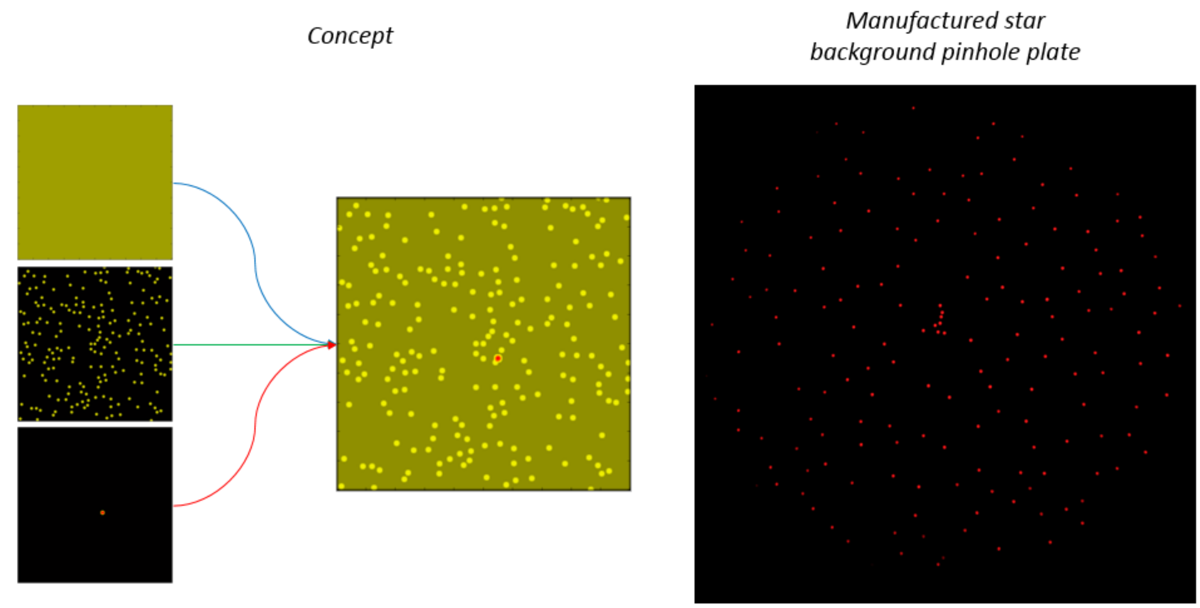

Fig. 7: TSU scene features. Left side: Continuous background (top), star background (middle) and debris object (bottom) Right side: All features merged into one scene by the optical system, an arrow showing a possible debris object motion.

In order to comply with the requirements in terms of angular spread of the stars/debris object elements and the FOV, a normal LCD screen could have neither the required resolution, nor the required contrast, leading to a pinhole plate solution, where the pinholes are created by photolithographic methods. More than the small pinhole size achievable (in our case 10 µm diameter pinholes other a 10 cm by 10 cm plate for the star background), this also allows to effectively characterize the relative position of the stars to values that after the TSU collimator translate to 0.2 arcsecs, allowing more budget to be allocated to uncertainty on the features motion.

Fig. 7 represents the different scene elements, each one has its own illuminating channel comprising optical density filters from 0 (no attenuation) to 4 (104 ph/secs attenuation). Such attenuation would correspond to an intensity difference between stars of magnitude 8 to 18.

Following the adaptability goal of the system to an eventual flight instrument, the scenes -and their motion presented later- are already sized to provide a 3° by 3° FOV.

Features motion

The envisioned observation scenarios contain cases where the satellite is tracking the debris and others where the stars are fixed with regard to the satellite FOV. These situations lead to enable independent motion on both scenes: star background and debris object. The motion is implemented by precision mechanical stages geared with linear optical encoders. These encoders, placed on each motion direction, allow to properly monitor the actual motion of the scenes. In order to mitigate uncontrolled delays between all channels during motion recordings, the encoders are linked to the work station through a synchronous acquisition card.

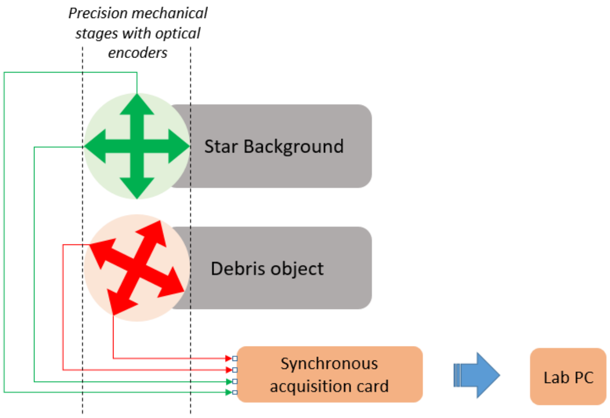

Fig. 8: Schematic view of the stars and debris objects motion control.

In Fig. 8, one can see that the axes of the two scenes are not necessarily aligned. Such related shifts are corrected during the calibration phase via optical metrology.

In order to improve setup flexibility, the motion implementation is based on fitting timed positions left at the operator discretion. The commissioning phase of the stages responsible for the star background and debris object included motion tests that provided excellent results. Measured optical encoder output for a motion commanded by a 50 points serial is presented in *Fig. 9* below:

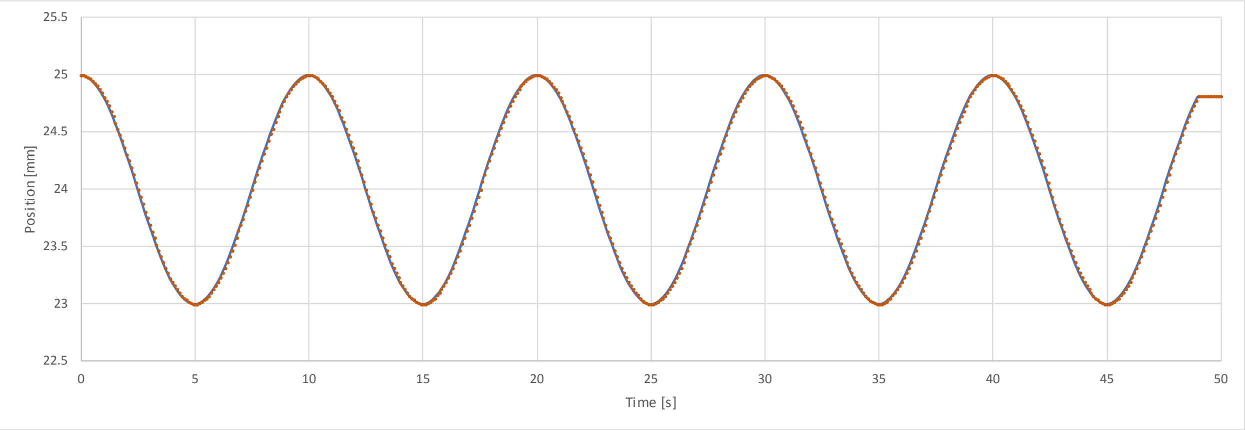

Fig. 9: Mechanical stage motion measured every 100ms, result of a path fit made from 50 points.

As the stages shall reach micrometric levels knowledge to ensure expected star background and debris motions, their accuracy was also tested with success, following paths having low amplitude like shown in *Fig. 10*:

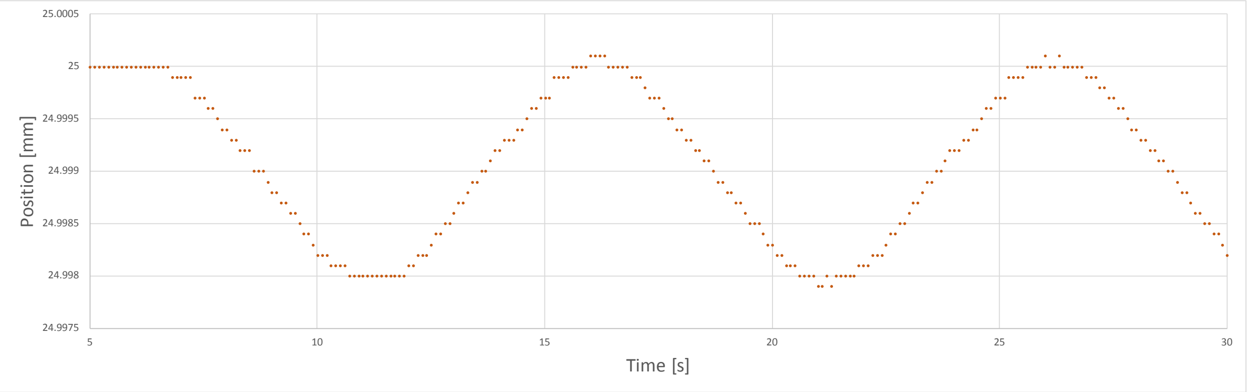

Fig. 10: 2µm Peak-Peak motion, acquired every 100ms, demonstrating mechanical stage accuracy.

Test Set-Up Collimator

The optical system, merging the scenes together and bringing them to the angular domain, works close to the diffraction limit over an angular diameter of 2.1° and provides an output pupil of 200 mm diameter. The design being dioptric, it is intended for narrow spectral bandwidth use to provide its full performance.

The TSU collimator also includes defocused ghosts, anti-reflection coatings on the optics and internal baffling in an attempt to maximize the potential contrast of the scene.

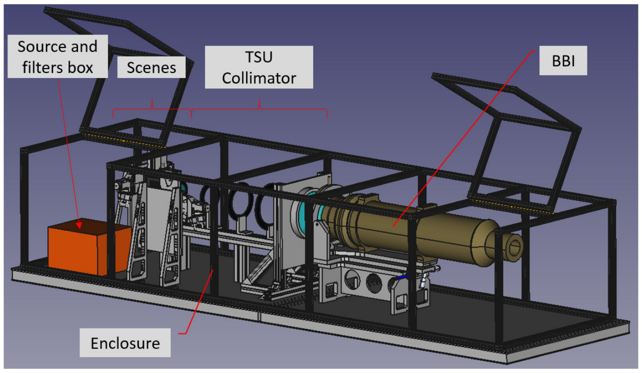

Fig. 11: CAD of the entire breadboard system, from the TSU to the BBI. Motion controllers, wires and optical fibres, as well as the BBI camera are not represented. The panels of the enclosure were hidden to see through.

As can be seen in Fig. 11, the whole assembly is covered by an enclosure, effectively mitigating stray light that could jeopardize the contrast of the scenes if left unchecked. The enclosure itself is provided with doors, allowing access to the TSU scenes and BBI focal plane, may adjustments be needed, but also for general demonstration purpose.

7. ON-BOARD IMAGE PROCESSING S/W

The On-Board Processing Pipeline (OBPP) has been developed within this project by the Astronomical Institute of the University of Bern (AIUB).

Main objectives of the OBPP are the autonomous on-board data reduction, preliminary image segmentation and object detection. These steps are critical in order to achieve an effective on-board processing pipeline optimizing the downlink bandwidth usage. The main part of the OBPP, called the Difference Method (DM), has been specially developed with the aim of being simple, fast and efficient.

The developed OBPP is based on the Difference Method (DM) to detect Regions of Interest (ROIs) in frames. Its operation consists in making the difference (subtraction of 2 images) between successive frames to extract region containing an object moving relative to the star background. In a perfect situation (same noise pattern and perfect alignment of the two images) the difference between 2 images gives 0 in each background pixels and something different from 0 in each moving object's pixel.

Fig. 12 shows the simplest way to represent the OBPP. First, single exposures are binned to increase the SNR of debris streaks. Then, bright non-saturated stars are detected and their positions are extracted. They will be used to align 2 images in order to perform a refined frames subtraction. Finally, ROIs containing possible moving objects are extracted and reference stars are added to the final selected frame, followed by its compression.

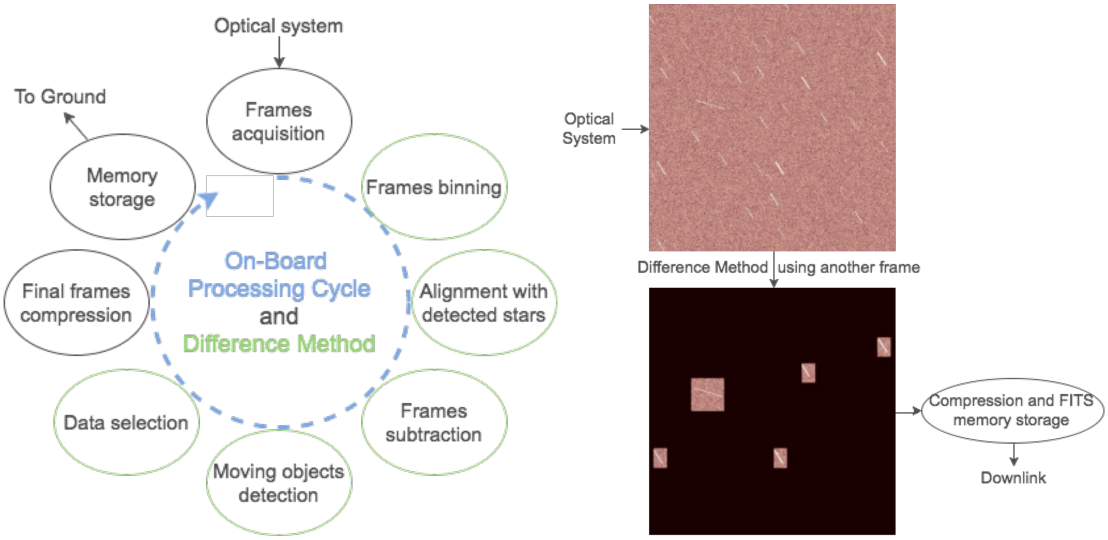

Fig. 12. Left: Simple view of the On-Board Processing Pipeline. Right: I/O example of the DM. The last frame contains one ROI with the debris streak and other boxes containing reference star streaks.

Above figure shows the kind of reduced images obtained after the DM algorithm. These output frames are composed of small selected regions corresponding to reference stars and moving objects. Consequently, removing all 0 (black) pixels allows a good compression ratio before memory storage. This lossless compression step has also been specially developed an optimized for this particular type of images. It results in a one dimensional image containing all information needed to reconstruct corresponding 2D image during on-ground decompression.

A high compression ratio, better than 1/100, can easily be achieved. Nevertheless, an additional compression is performed on these one-dimensional images using the CCSDS Rice data compression algorithm [3].

Fig. 13 shows that with a combination of these 2 compression steps, a compression ratio of 1/230 can be achieved for test frames containing only 1 debris streak with various SNR levels.

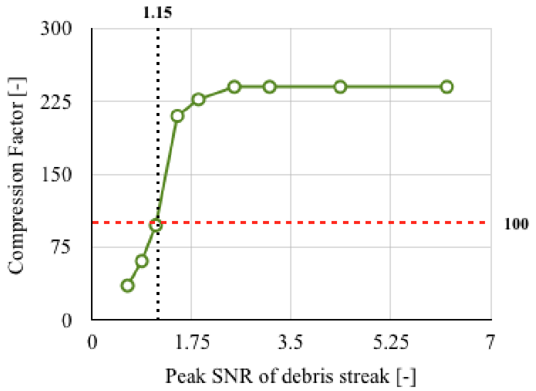

Fig. 13. Compression achieved for test frames containing only 1 debris streaks and 20 detected stars using both developed compression algorithm and CCSDS Rice data compression algorithm on the final FITS file.

The OBPP shows promising results. It can process 2 frames and detect faint debris streaks, down to a peak SNR = 1.2 in less than 1 second of execution time, fulfilling rigorous requirements concerning computation power, compression ratio, available data bandwidth and streaks detection limits.

8. ON-GROUND IMAGE PROCESSING S/W

The On-Ground Processing Pipeline (OGPP) is currently under development. It will be built by the Astronomical Institute of the University of Bern (AIUB) using mainly the StreakDet code [4] which has been developed within an ESA activity by a consortium led by the Finnish Geodetic Institute.

StreakDet requires specifically defined FITS files containing a full decompressed image. The first step of the OGPP is to decompress and rebuild the exact same image produced by the DM algorithm and secondly, fill all empty 0 pixels regions with random noise based on optical characteristics of the H/W (see Fig. 14). Filling empty regions with noise might be not ideal since these regions were already discarded by the OGPP and it should not be necessary to run StreakDet on them again. However, the current StreakDet implementation is designed to run on full images and not on fragmented frames. This could be an additional modification to be implemented in the StreakDet code.

After these 2 steps (decompression and noise-filling), the image can be processed by StreakDet. It will perform a refined streak detection using precise segmentation and classification steps. Then, crucial information on debris are extracted using photometry and astrometry measurements. StreakDet compares stars on the frame with UCAC4 stellar catalogue to extract positions and magnitudes of debris. Targeted performances are astrometric accuracy better than 1 arcsec and photometric accuracy better than 0.1 mag.

Together with debris streaks characteristics such as length and curvature, position and magnitudes can lead to coarse orbit determination and rough debris size estimation.

Below figure shows a simple view of the OGPP architecture with its eight main steps.

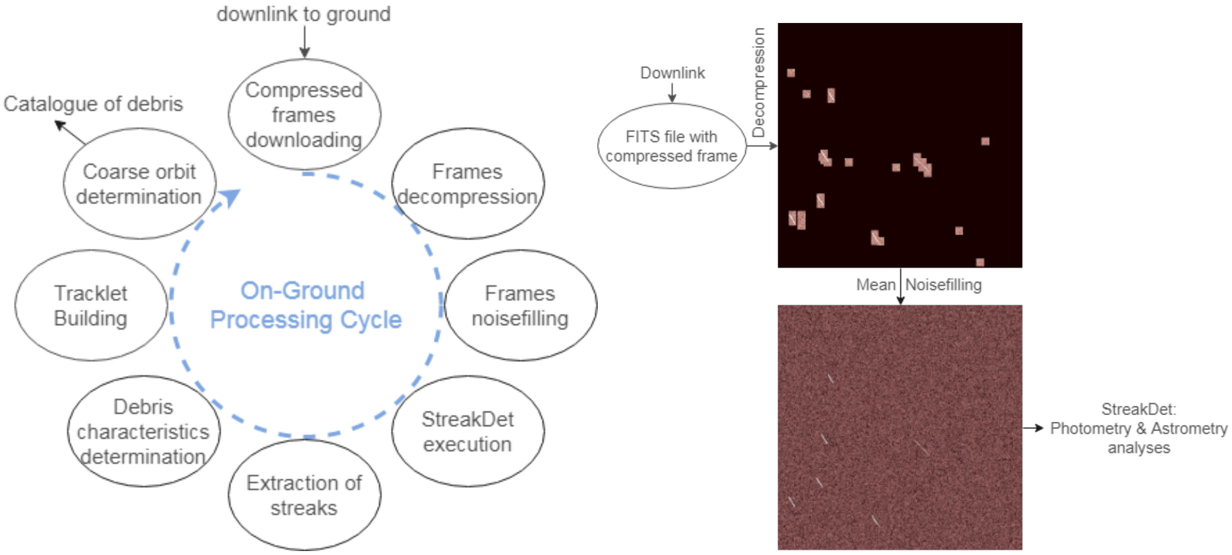

Fig. 14. Left: Simple view of the On-Ground Processing Pipeline. Right: Example of images after decompression and noise-filling steps, before executing StreakDet.

9. ON-BOARD IMAGE PROCESSING HARDWARE PLATFORM

The on-board image processing pipeline developed by AIUB was ported by Airbus from Matlab into C. The algorithm was run on two different platforms for evaluation: a PC and an ARM Cortex R5F, the latter being a candidate for the future flight H/W. The image processing requirements are challenging in terms of on-board execution performance, therefore optimizations to improve processing speed were successfully performed.

Results obtained with the PC

Tests showed that the resulting images from C and Matlab implementations are identical. The FITS library has been adapted to the needs of the project:

- reduced functionality (only small part is needed for the project)
- needed parts customized, e.g. to avoid Linux system calls
- adding an offset for the definition of unsigned integers
- Rice compression: used separately, not from FITS library.

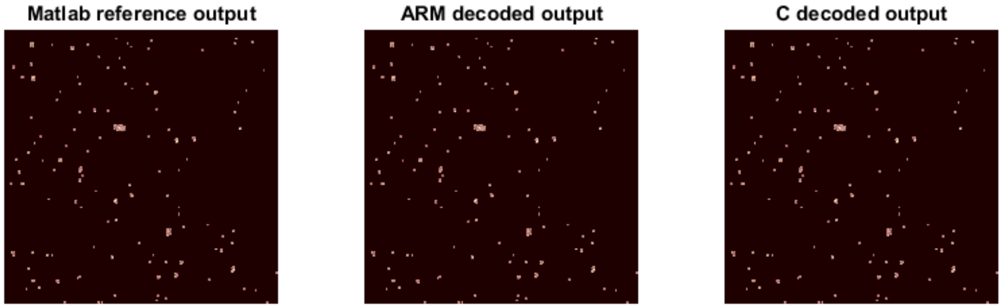

Fig. 15: Comparison between Matlab reference output, ARM decoded output and the C decoded output.

Design and Results obtained with the ARM Cortex R5F Processor

The hardware platform onto which the C-version of the Differences Method (DM) is ported is the Texas Instruments TMS570LC4357, based on the ARM Cortex R5F core, placed on a Hercules Development Kit (HDK) developed by Texas Instruments.

Note that this platform is an in-expensive COTS development board with limited resources (e.g. memory) and is not intended to serve as flight H/W. However, the ARM microprocessor architecture is identical. With the exception of slow I/O operations (from and to the SD-card), the execution times are expected to be comparable.

The HDK itself features different modules and extensions, of which the external synchronous dynamic random access memory (SDRAM) with 8MB, connected via the EMIF was crucial for the Difference Method. The provided JTAG interface and embedded emulator (XDS100v2) were used throughout the whole implementation for debugging and loading the appropriate firmware. Moreover the available microSD card slot is a necessary module, since the featured external SDRAM was too limited to store around 16MB of image data plus some overhead for the calculations. Thus, a 1GB microSD card was used and the appropriate SPI interface implemented.

Even though the ARM and the reference implementation are both written in C they differ very much in the actual implementation and data flow. This is mostly due to the fact that the ARM is a very low powered board with very limited resources (300MHz, 8.5MB RAM), opposed to the host computer running the reference implementation (3.7GHz, 8GB RAM). The initial and non-optimized implementation on the ARM took more than 60 seconds to perform the DM on the same input images that were processed on the host in less than 0.5 seconds. The implementation on the ARM could however be successfully optimized and now performs the DM on two images within 0.755 s. On top of this execution time, some overhead due to slow I/O operations from and to the SD-card is produced, which is however expected to be reduced to a negligible amount for a flight H/W board (no SD-card).

10. CONCLUSION AND NEXT STEPS

A breadboard system for the space-based optical observation of space objects has been developed. The goals of this system and the activity are to achieve technological readiness to enable initialization 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.

At the current point of time, integration and test of all H/W components is ongoing, the on-board S/W prototype is finalized and the on-ground S/W is under development.

The activity will conclude with an extensive E2E system performance analysis, expected for Q4/2017.

11. ABBREVIATIONS AND ACRONYMS

BBI: Breadboard Instrument
FM: Flight Model
OBPP: On-Board Processing Pipeline
OBS: Overall Breadboard System
OGPP: On-Ground Processing Pipeline
OGSE: On Ground Support Equipment
FOV: Field of View
SBSS: Space-Based Space Surveillance
SSO: Sunsynchronous Orbit
SST: Space Surveillance and Tracking
TSU: Test Set-Up

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