OPTICAL IN-SITU MONITOR BREADBOARD SYSTEM

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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 (see Flohrer et al. [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.

2 ESA „SBSS DEMONSTRATOR PHASE A“: PREDECESSOR ACTIVITY

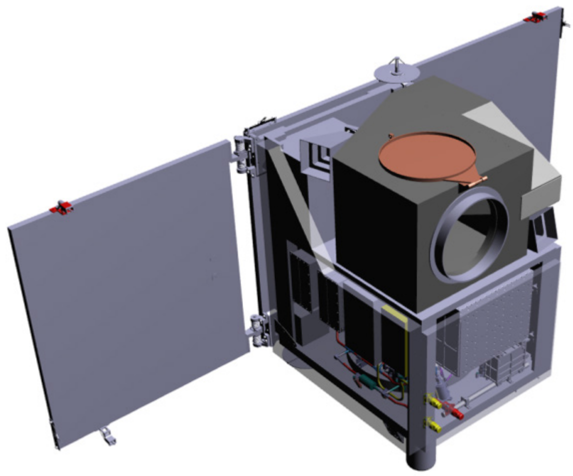

Figure 1. SBSS demonstrator instrument on FLP-2 platform [2]

In the 2012-2014 timeframe, two parallel studies were conducted within ESA GSP, 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,

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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 "Optical In-Situ Monitor", an ESA GSTP activity of 24 months, kicked-off in February 2016 and 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 Figure 2) constitute the breadboard system:

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

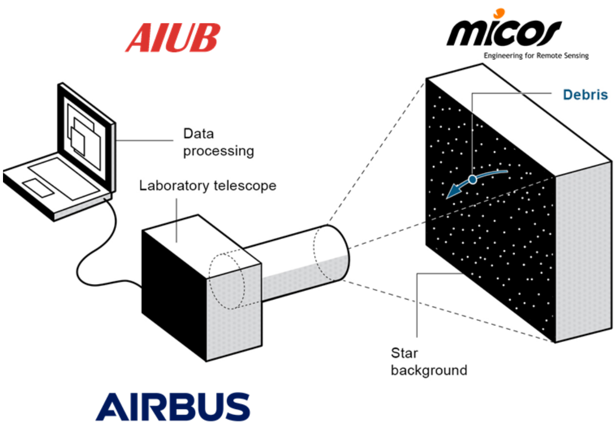

Figure 2. Breadboard System Elements

The project consortium consists of the following partners and responsibilities:

- Airbus (D): Prime, System Engineering, Breadboard Instrument, On-board Processing H/W
- AIUB (CH): Image Processing S/W, Observation Scenarios
- Micos (CH): Test Set-Up

4 SYSTEM REQUIREMENTS

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], see also section 7 for details.

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)

Based on ESA's User, Technical and Observation Requirements (see also section 5), a detailed set of System Requirements for the three main elements BBI, TSU and S/W have been derived. An exemplary overview is provided in the following tables.

Table 1. Exemplary Breadboard System Requirements

BBI	System Requirements
Aperture	Goal: 200 mm, Threshold: 100 mm
FOV	Goal: 3° x 3°, Threshold: 1° x 1°
PSF	EE shall be variable (30% - 80%).
Readout noise	Goal: 10 e-/pixel, Threshold: 20 e-/pixel
[…]	[…]

TSU	System Requirements
Debris & star brightnesses	8-18 mag (22 x 10^6 ph/s/m^2 to 22 x 10^2 ph/s/m^2)
Debris velocities	0-1 deg°/s
Position and timing accuracy	Ground-truth knowledge ≤ 1 arcsec
[…]	[…]

S/W	System Requirements
On-board sensitivity	SNR=4 (threshold) – 1 (goal)
On-board data reduction	1:100 (threshold) – 1:1000 (goal)
On-ground astrometry	Total astrometric accuracy goal: 1/10 pixel iFOV for SNR ≥ 10
[…]	[…]

5 OBSERVATION SCENARIOS

The reference observation scenarios to be simulated by the breadboard system were derived for a telescope platform in LEO detecting small LEO debris (LEO-LEO) for statistical purposes and for the surveillance of GEO objects from LEO (LEO-GEO).

Different orientations for the satellite platform and the telescope's line-of-sight (LOS) have been taken into account to analytically describe the motion of debris objects and stars on the SBSS focal plane as function of

- Sensor parameters (orbital period, inclination, LOS angle)
- Target parameters (range, angular rate, direction, mean anomaly).

This serves as input for commanding the scene generator and for synthetically generated test images. Some non-exhaustive examples are given below. Note that the description of LEO-LEO debris observations follows object characteristics obtained from PROOF-2009 runs using the MASTER-2009 statistical population.

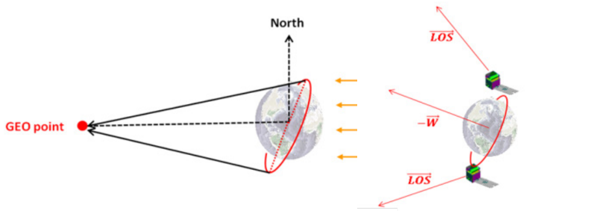

Figure 3. Left: LOS pointing to GEO range point. Right: LOS non-inertial pointing.

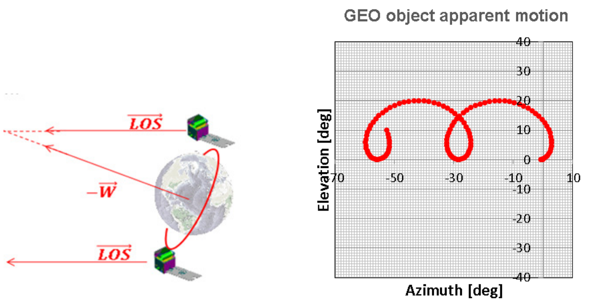

Figure 4. Left: LOS inertial pointing. Right: Motion of a GEO object in instrument coordinates Az-El for this scenario.

6 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.

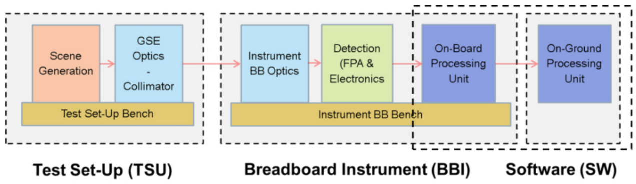

Figure 5. Functional units conceptually representing the OBS architecture.

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).

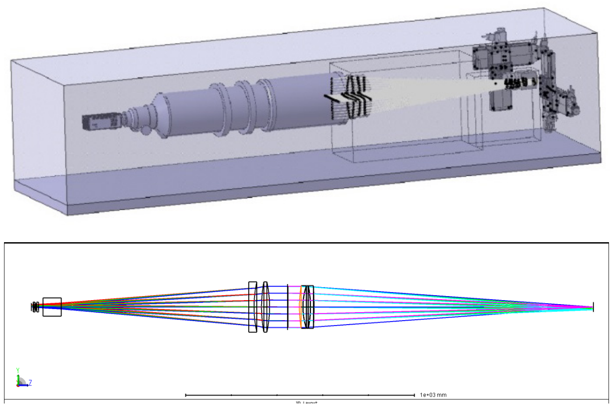

Figure 6. Above: OBS CAD model. Below: OBS optical model.

7 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
  - 14 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

Figure 7. Pictures of the selected BBI telescope (left) and BBI Camera (right).

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

Table 2. 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. A CAD model schematic illustrating the baselined BBI with custom mount and iris diaphragm is presented below, as well as a model of the Three-Mirror Anastigmat (TMA) design of the SBSS demonstrator FM instrument.

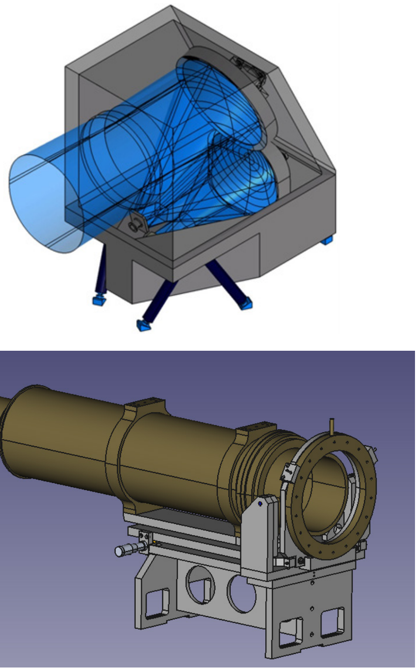

Figure 8. Top: SBSS FM instrument design; bottom: BBI CAD Model.

One particularity of this setup is the inclusion of an iris diaphragm in front of the BBI telescope enabling one to vary in a controlled way the PSF of the optical system. In Figure 9 one can see how the PSF is changing across the detector for an aperture of 180 mm (top) and an aperture of 100 mm (below). This is an important feature to study the impact of PSF in algorithm performance.

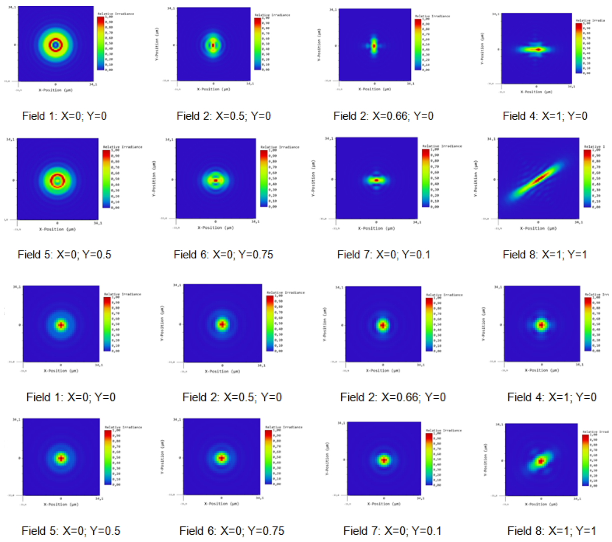

Figure 9. Different PSFs across the detector for different BBI apertures. Top: 180 mm; Bottom: 100 mm.

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.

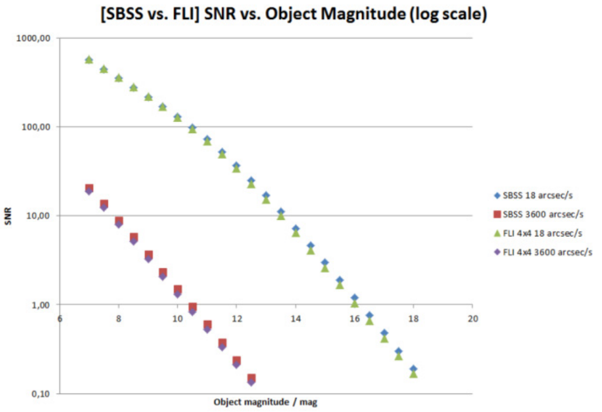

Figure 10. SNR performance comparison between BBI and SBSS demonstrator FM for slow and fast moving objects.

Last but not least, the following figure depicts the size of the BBI field-of-view compared to the envisaged flight model. Although considerably smaller, it will allow performance characterisation all relevant parameters, in particular for long and faint object streaks.

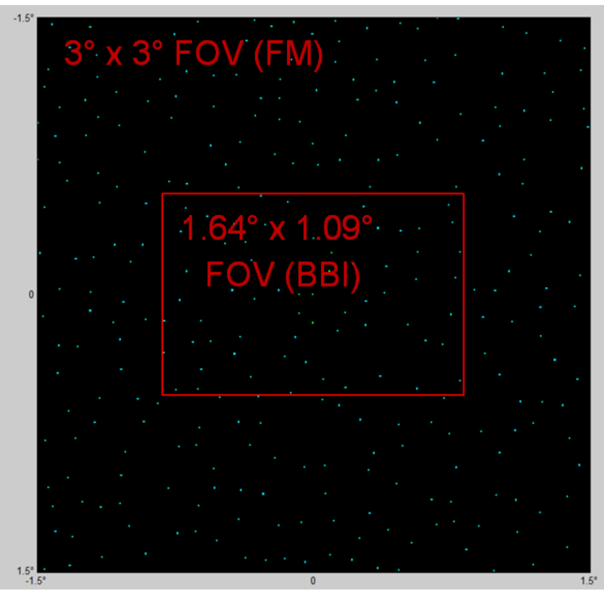

Figure 11. FOV comparison between BBI and SBSS demonstrator FM.

8 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.

8.1 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.

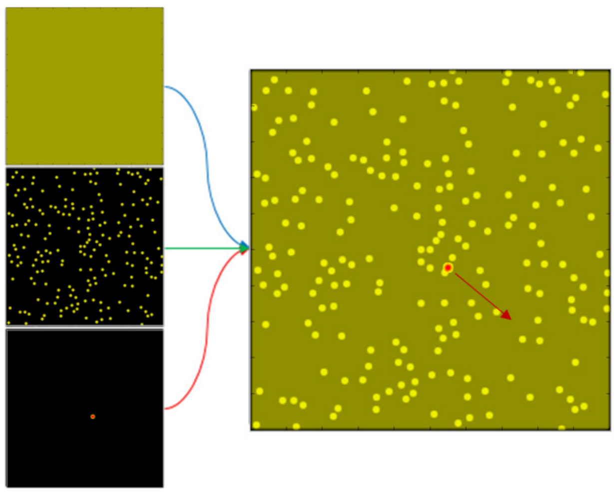

Figure 12: TSU scene features. Left side: Continuous background (top), star background (middle) and debris object (bottom) Right side: All features merged into one scene by the optical system, an arrow showing a possible debris object motion.

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.

Figure 12 represents the different scene elements, each one has its own illuminating channel comprising optical density filters from 0 (no attenuation) to 4 (10^4 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.

8.2 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 working station through a synchronous acquisition card.

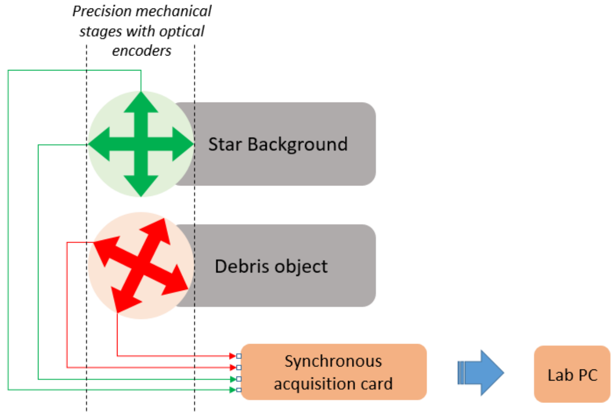

Figure 13: Schematic view of the stars and debris objects motion control.

In Figure 13, 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.

8.3 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.

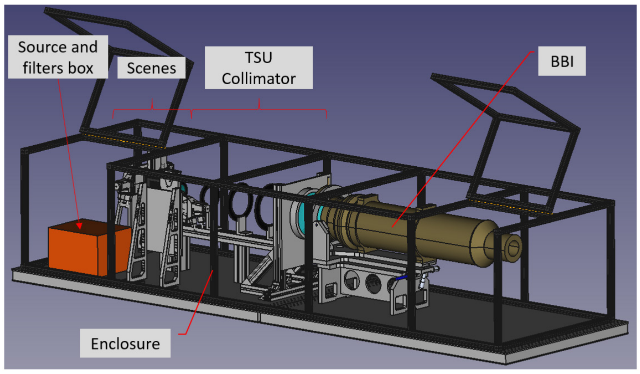

Figure 14: CAD of the entire breadboard system, from the TSU to the BBI. Motion controllers, wires and optical fibres, as well as the BBI camera are not represented. The panels of the enclosure were hidden to see through.

As can be seen in Figure 14, 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.

9 ON-BOARD IMAGE PROCESSING S/W

The whole 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 and lead to 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 baseline of the DM is to process two successive exposures and detect objects (space debris) moving relative to the star background performing a refined frames subtraction. This method is composed of five main parts which are: Frames binning, frames alignment with detected stars, frames subtraction, moving objects detection and data selection (see Figure 15).

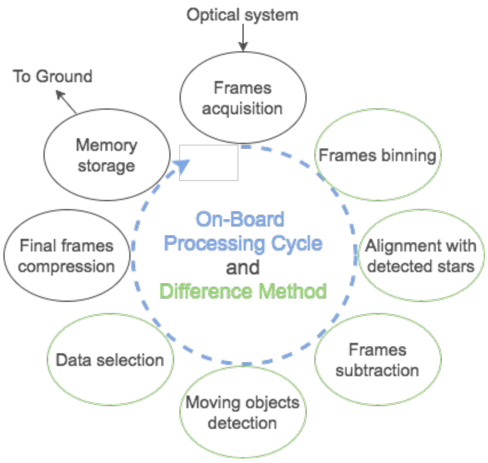

Figure 15. On-Board Processing Pipeline

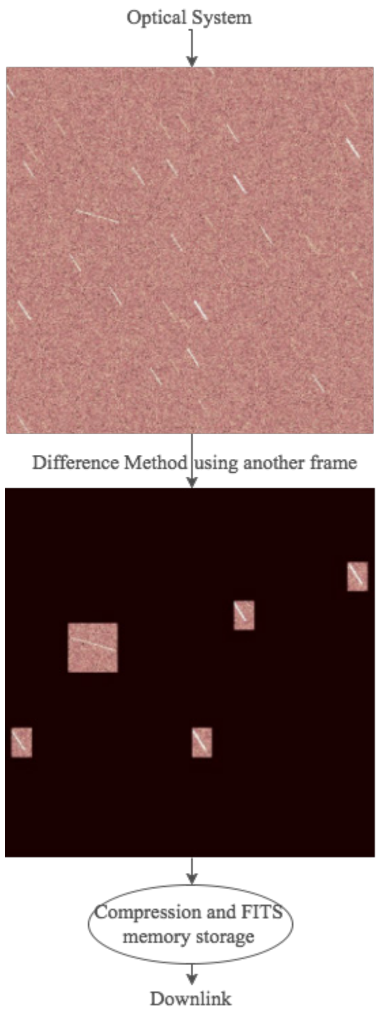

Figure 16. I/O Difference Method

Figure 16 shows the kind of reduced images obtained after the DM algorithm. These output frames are composed of small selected regions corresponding to detected 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]. Figure 17 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.

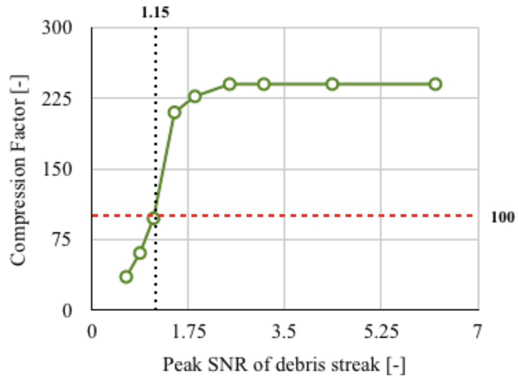

Figure 17. Compression achieved for test frames containing only 1 debris streaks and 20 detected stars using both developed compression algorithm and CCSDS Rice data compression algorithm on the final FITS file.

This OBPP shows very convincing 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.

10 ON-GROUND IMAGE PROCESSING S/W

On-Ground Processing Pipeline (OGPP) is currently still 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 on-board software and fill all empty regions with the mean noise (Figure 18).

The next step aims to extract crucial information on debris 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 (~ 5 arcsec pixel iFOV) 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.

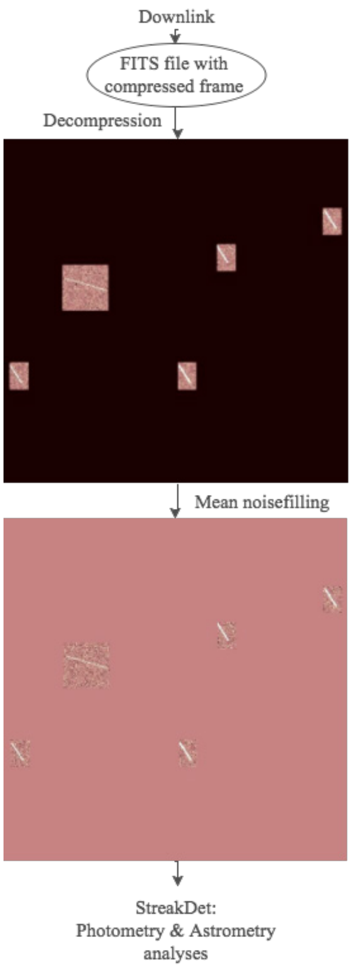

Figure 18. On-Ground Processing Pipeline

11 ON-BOARD IMAGE PROCESSING HARDWARE PLATFORM

Based on the on-board image processing pipeline developed by AIUB and described in section 9, Airbus has performed an assessment regarding suitable on-board H/W platforms. The goals are to trade-off (soon) existing options for on-board processing H/W and to perform a feasibility study via prototype porting of the on-board S/W.

The image processing requirements are challenging in terms of on-board execution performance.

Suitable technologies for the processing units can be summarised into three different categories: General Purpose Processors/DSPs, FPGAs/ASICs and Specialised Processing Units. GPPs, and also in part Digital Signal Processors (DSP), provide the easiest development environment and highest developer productivity but the throughput rate is rather low compared to FPGA or Specialised Processing Units and the power consumption relatively high. FPGAs are mass produced devices containing numerous look-up tables and other elements interlinked by configurable interconnects. This approach is less efficient than ASICs since there will inevitably be unused elements of the FPGA, however it offers greatly enhanced flexibility. It combines multiple cores with different characteristics to allow efficient mapping of algorithms with high processing demand. Most of these SPUs are essentially an array of processing elements with efficient access to memory. The increased specialization makes them more efficient but more difficult to program.

For the Optical In-Situ Monitor activity and a potential future mission, three different processors were initially considered: A commercial ARM Cortex R5 general purpose processor, a rad-hard MicroSemi RTG4 FPGA and an Airbus-designed High-Performance Data Processor (HPDP), which falls into the SPU category.

11.1 ARM Cortex RX5

Texas Instruments' ARM Cortex RX5 is a general purpose microprocessor designed to be used in diverse applications such as automotive, handheld and mobile devices or signal processing. It has a 32-bit RISC CPU with up to 300 MHz clock speed, dual core lockstep CPUs (2 redundant cores) with error signalling and an error correction function for its flash and RAM with built-in self-tests.

11.2 Microsemi's RTG4 FPGA

Microsemi's RTG4 device is the fourth generation of flash based RadHard FPGAs(~150k LEs, up to 300MHz at MilGrade Conditions), designed for applications in space. The number of logic gates, registers and specialised multiplier blocks is significantly higher as in the current generation of FPGAs. Therefore the device is announced to be suitable for signal processing tasks in satellite applications. It has high-speed memory interfaces (up to 667Mbps) and it is shown as very performant for the boundary tensor algorithm. Airbus DS in Ottobrunn evaluated this device using an evaluation board from Microsemi by porting one of the Airbus GNSS applications onto the technology. The GNSS application contains the signal processing functions suitable to assess the technology for this kind of purposes.

11.3 HPDP

The HPDP, based on the XPP-III Core by PACT XPP Technologies is a radiation hardened, reprogrammable array processor, a 16 bit architecture designed in 65 nm STM C65SPACE technology. The main component of the XPP-III Core represents a dataflow array, consisting of two-dimensionally arranged Processing Array Elements (PAEs), connected by a communication infrastructure that can be reconfigured at runtime, as well as the operations performed by each PAE.

The XPP core architecture is modular in nature and consists of a number of reconfigurable Processing Array Elements (PAEs) connected by a reconfigurable data and event network. Two types of PAEs exist: a RAM-PAE and an ALU-PAE. The vertical data and event routing channels are always contained within a PAE, in the form of Forward Registers (FREGs) that route vertically from top to bottom, and Backward Registers (BREGs) that route vertically from bottom to top.

The array network is enhanced by VLIW-type processors called Function-PAEs (FNCs), which are used for controlling and configuring the network and execution of control type processing.

11.4 Hardware selection

The following table shows a trade-off between the three proposed platforms:

Table 3. On-board Processing H/W Platform Trade-off

	MicroSemi RTG4	**ARM Cortex R5**	**HPDP**
Data Proc. Units	No Floating Point Unit Mapping to FixPoint possible	Floating Point Unit available	No Floating Point Unit Mapping to FixPoint possible
Imple-mentation	VHDL or IP Core (C)	C-code	Native Mapping Language (NML)
Usability for DM	Irregular control flow → port to VHDL challenging Possibility to accelerate parallel DM parts	C port performed Easy to port on Hardware	Not suitable for Sequential Processing Less performant than RTG4 Slow for irregular data flow

The ARM Cortex R5 has been chosen as baseline for further assessments within the perimeter of the activity. It is most promising w.r.t. execution performance, as the on-board processing algorithm (i.e. the Difference Method) favours a microprocessor architecture due to its flow control with nested loops and conditions. Space qualification is expected; the ARM features a double core processor and an error correction monitoring function. Moreover, the ARM is attractive from a cost point of view. As fall-back solution, the MicroSemi RTG4 fpga is considered.

12 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 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.

At the current point of time, the system design has been finalised as described in this paper and the H/W components have been procured. S/W development is ongoing regarding the ground-based processing chain.

In the next step, the integration and test of all elements will be conducted. After a successful Test Readiness Review, the end-to-end system tests and performance analysis will begin, which is foreseen for Q4/2017.

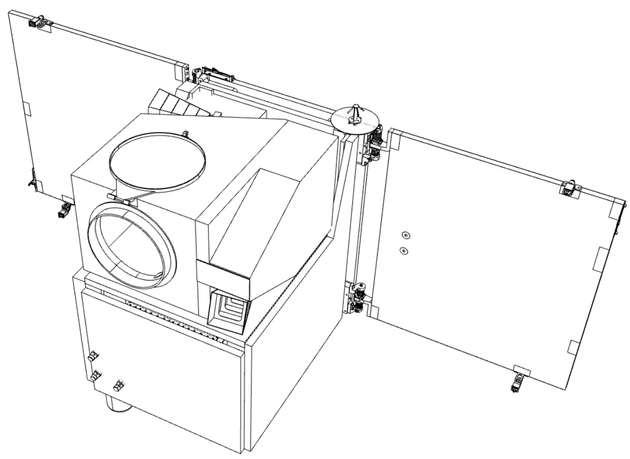

Figure 19. Sketch of SBSS instrument on FLP-2 platform.

13 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

14 REFERENCES

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