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IAC-18,A6,1,7,x46137

Optical In-Situ Monitor
A Breadboard System to Enable Space-Based Optical Observation of Space Debris

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Abstract

The goals of the ESA project "Optical In-Situ Monitor" are to design and integrate 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 activity`s breadboard system is comprised of the following three main elements:

Breadboard Instrument: Acquires images of space debris scenes generated by the Test Set-Up with the characteristics of the future flight model instrument.

Image processing pipeline: On-board debris detection and data reduction, on-ground astrometry and photometry.

Test Set-Up: Scene generator for space debris observation scenarios.

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 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. High accuracy is required for the scene generation part regarding motion and photometric accuracy because it serves as ground-truth for the system. As prime contractor, Airbus Defence and Space is responsible for project management, system and performance engineering, the breadboard instrument, and on-board data processing hardware issues. The required image processing software is being developed at the Astronomical Institute of the University of Bern (AIUB). Micos provides the space debris scene generator, emulating both debris and star background. The paper will provide an overview of requirements and the design of the three main elements as well as on the results of the end-to-end performance tests.
Keywords: SSA, SST, SBSS, Space Situational Awareness, Space Surveillance and Tracking, Space-Based Space Surveillance, Space Debris, Small Debris, In-Situ, Space-Based Telescopes

Acronyms and Abbreviations

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

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

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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

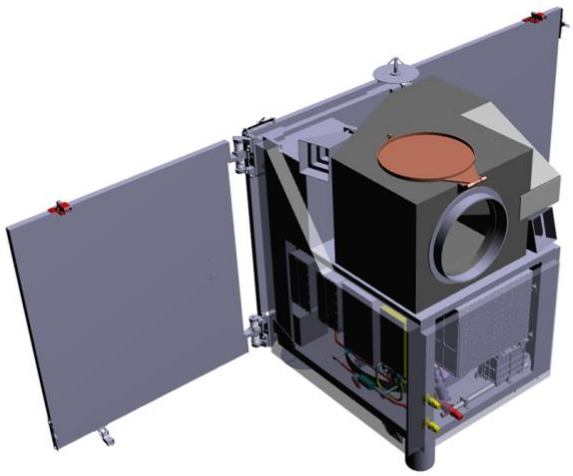

Fig. 1 SBSS demonstrator instrument on FLP-2 platform [2]

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, 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 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 (S/W): On-board debris detection & data reduction, on-ground astrometry & photometry

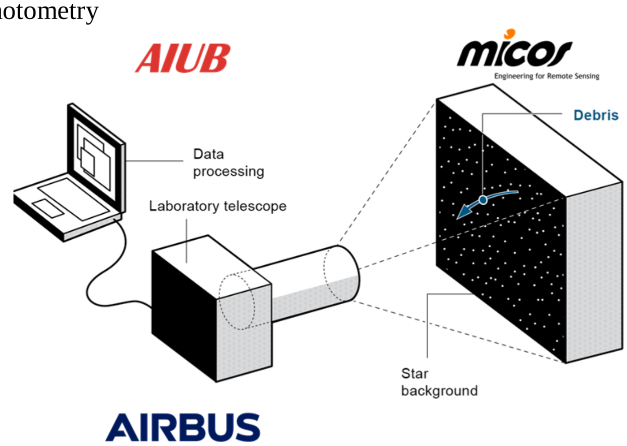

Fig. 2 Sketch of Breadboard System Elements

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

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baseline for the FM hardware is given by SBSS Demonstrator Phase A [2], see also section 6 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)

5. 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 interfaces to operate the TSU.

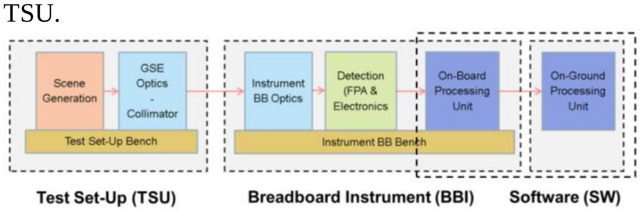

Fig. 3 Functional units conceptually representing the OBS architecture.

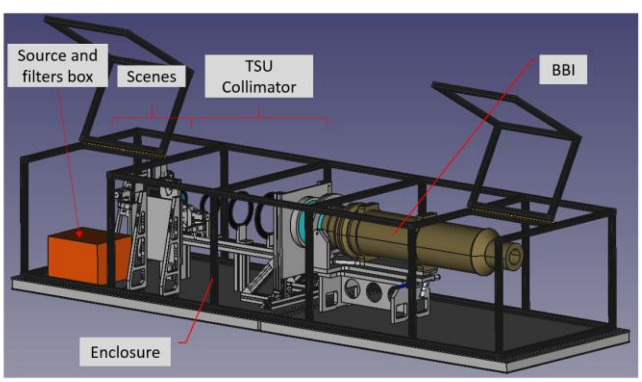

Fig. 4 CAD of the breadboard system design.

The finalised breadboard system hardware architecture is shown in Fig. 5

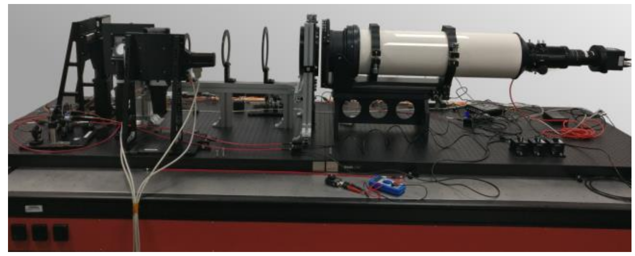

Fig. 5 Vreadboard system H/W without enclosure.

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).

6. Breadboard Instrument

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

- BBI Telescope
  - o APM Telescope: APM - LZOS Teleskop Apo Refraktor 180/1260
  - o including an iris diaphragm for BBI aperture adjustment
- BBI Camera
  - o FLI Camera MicroLine ML 11002
  - o 4008x2672 pixels, 9 µm pixels, 16 bit
- Control and Data Acquisition Unit
  - o Standard PC
  - o system command & control
  - o simulates on-board processing unit & stores acquired images
  - o performs also on-ground processing

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

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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

With respect to radiometric behaviour, the BBI will be able to resolve faint signals and it will be approximately representative of the SBSS FM.

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.

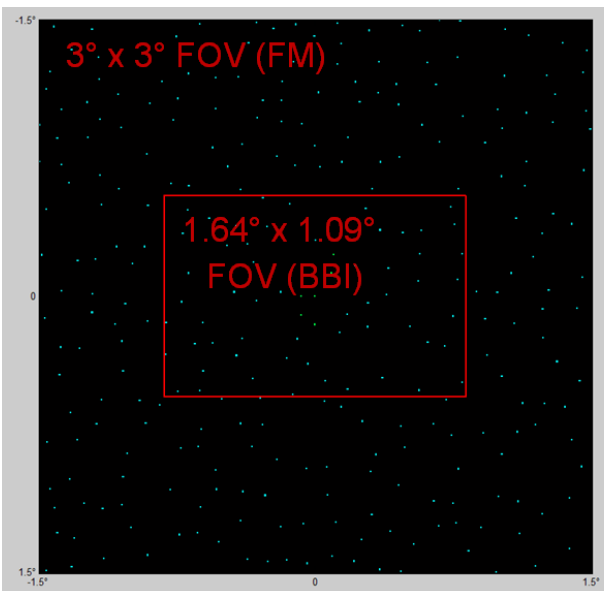

Fig. 6 FOV comparison between BBI and SBSS demonstrator FM.

7. 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.

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.

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.

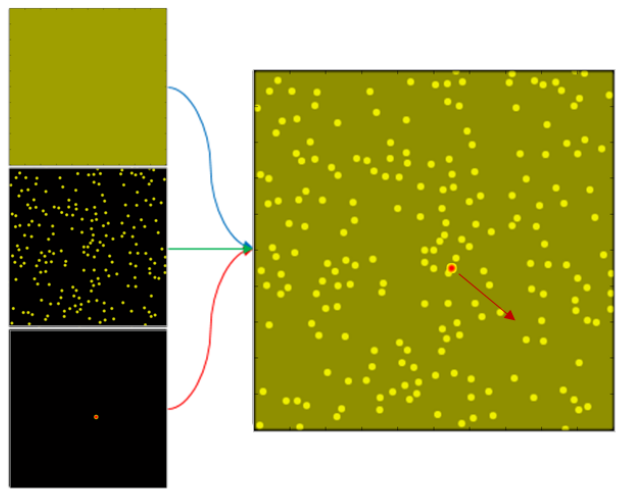

Fig. 7 TSU scene features. Left side: Continuous background (top), star background (middle) and debris object (bottom) Right side: All features merged into one scene by the optical system, an arrow showing a possible debris object motion.

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.

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.

Fig. 8 below shows an actual capture of a TSU feature through the BBI.

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Fig. 8: Example of TSU features, as observed from the BBI. Extracted from an actual measurement and scaled for better visibility

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.

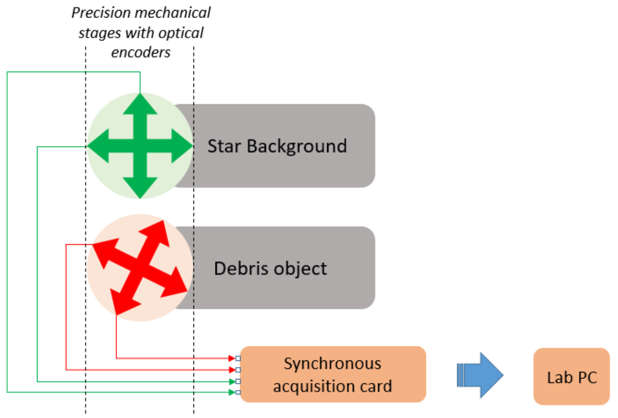

Fig. 9 Schematic view of the stars and debris objects motion control.

8. 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 Fig. 10).

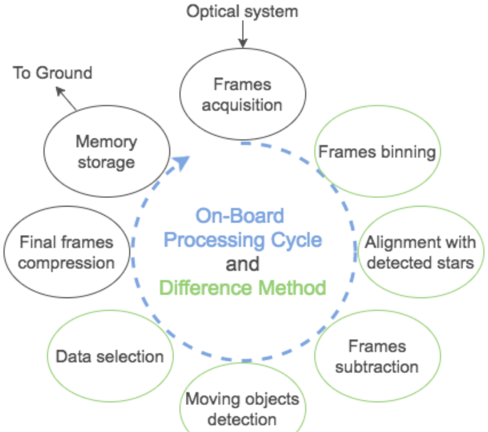

Fig. 10 On-Board Processing Pipeline

Fig. 11 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]. Fig. 12 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.

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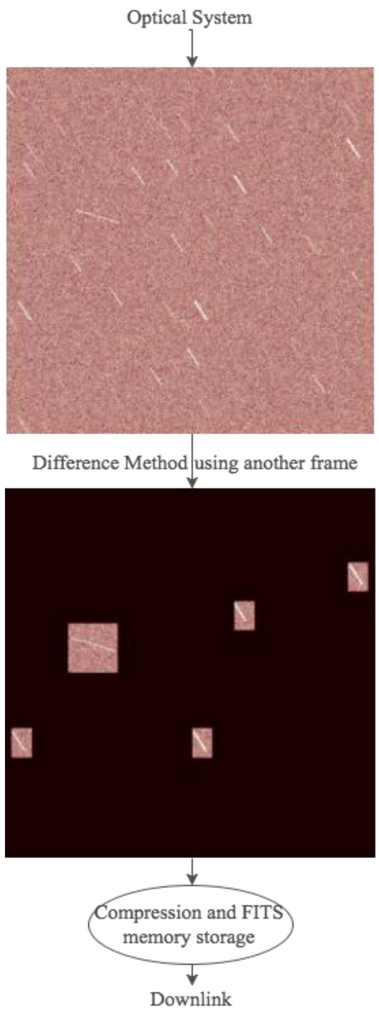

Fig. 11 I/O Difference Method

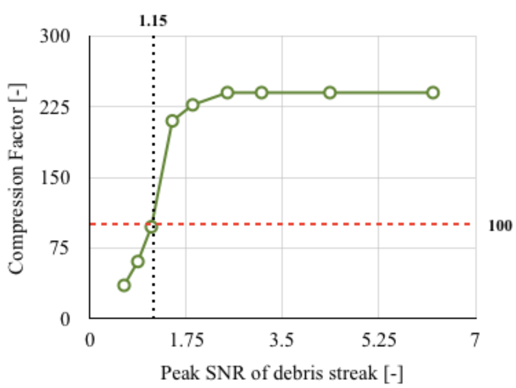

Fig. 12 Compression achieved for test frames containing 1 debris streaks and 20 detected stars.

The 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.

9. On-Ground Image Processing S/W

The On-Ground Processing Pipeline (OGPP) uses 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 mean noise (Fig. 13).

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.

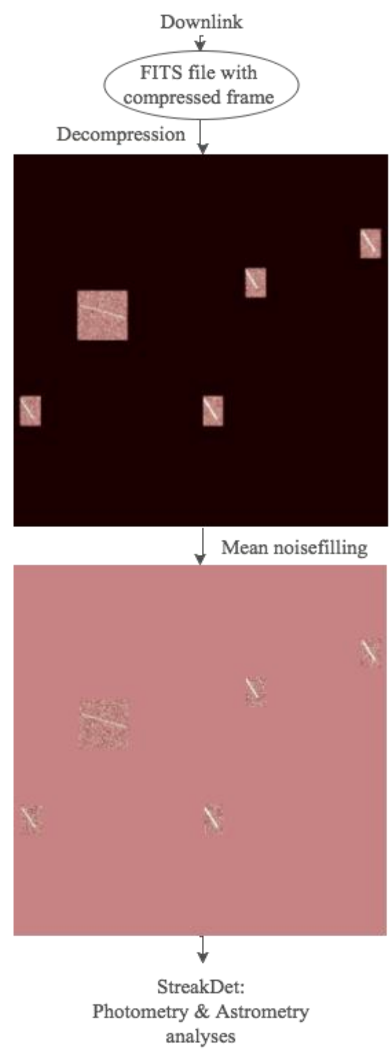

Fig. 13 On-Ground Processing Pipeline

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10. On-Board Image Processing Hardware Platform

Based on the on-board image processing pipeline developed by AIUB, Airbus has performed an assessment regarding suitable on-board H/W platforms. The goals were 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. 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.

Table 2. 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

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.

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. 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.

11. End-to-End Tests

After assembly, integration and test of the breadboard system components as described above, the system has been tested end-to-end (E2E) in order to test its performance. E2E means that different observation scenarios have been run using the Test Set-Up, images have been acquired by the Breadboard Instrument, the complete astrometric and photometric reduction has been performed (OBPP & OGPP) and the result has been compared to the known ground-truth.

Fig. 14 The breadboard system assembled & integrated.

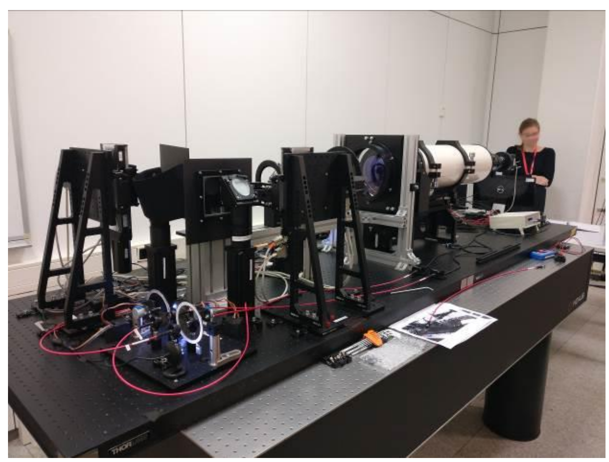

Fig. 15 The breadboard system without enclosure.

The following figure shows the superposition of three consecutive images where the path of the debris object is marked in green (object moved from left to right) for a scenario with sidereal pointing (stars = points, objects = streaks). 14 streaks were acquired; streaks 1, 7 and 14 are shown.

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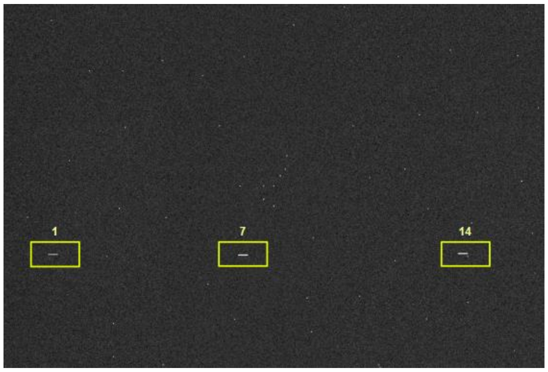

Fig. 16 Sidereal example. Object moves with 100”/s.

The image series shows the same scenario but with an additional tracking motion (both stars and objects = streaks). Single images shown (no superposition).

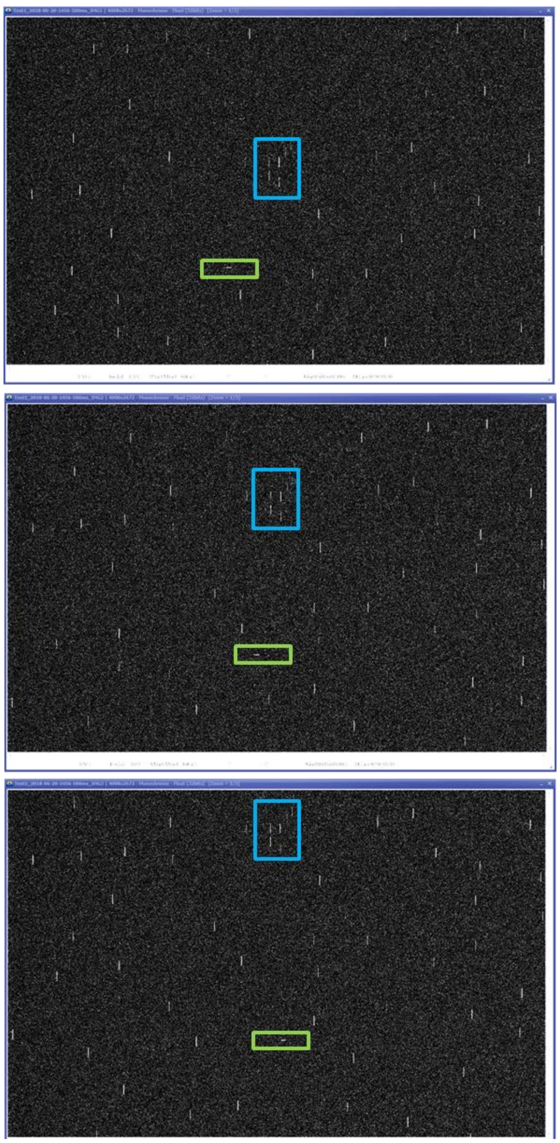
Fig. 17 Non-sidereal example. Stars move with 200”/s.

The next figure shows again a sidereal test case, this time with an object moving diagonally through the entire field-of-view with an angular rate of 100 arcsec/s.

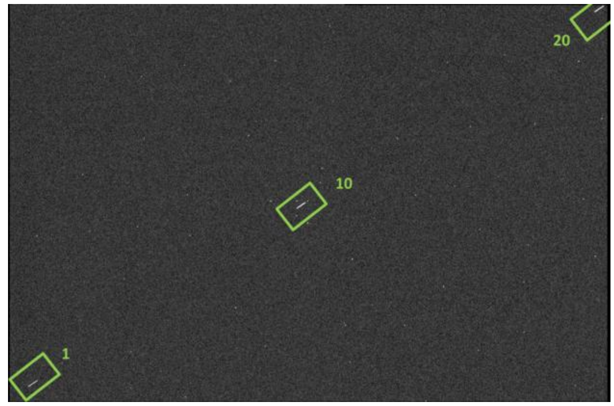

Fig. 18 Visualization of diagonal debris motion in. 20 streaks were acquired per test run. Streak 1, 10 and 20 are shown for illustration.

Astrometric performance - i.e. theoretical ground truth position compared to measured position - is presented for this example. 20 consecutive streaks have been acquired for an overall number of 50 test runs. Table 3 shows bias (meanVals) and standard deviation (meanSigma) for the center points of all 20 consecutive streaks. Each line/data point is the result of evaluating the QQ plot for 50 samples.

There is a large portion of the FoV (i.e. in the center region) which yield very good results with sub-arcsec accuracy, however it can be observed that bias and standard deviations increase towards the edges of the FoV. This behaviour is attributed to the effects of higher distortion and lower PSF quality towards the edges of the field-of-view. Since the image processing software in its current version does not take into account a mapping model, it is expected that the application of a distortion map will considerably improve performance in the outer FoV regions. The team is currently assessing ways of implementation that compensation.

Radiometric accuracy was also tested. For the test, the debris magnitude was defined as 10.83 with the TSU H/W. 60 acquired images (20 images for 3 streaks) yielded a constant bias of 0.28 mag with a standard deviation of 0.06 mag, which is considered good photometric performance well within requirements.

Apart from the tests cases presented above, many other observation scenarios mimicking different spacecraft altitudes and attitudes were simulated.

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Table 3. Bias (meanVals) and standard deviation (meanSigma) for each streak.

	meanValsRA["]	meanValsDEC["]	meanSigmaRa["]	meanSigmaDEC["]
	34,69	19,33	24,74	7,79
	18,05	9,77	20,40	8,64
	16,72	8,25	26,43	8,04
	16,79	3,89	26,77	6,75
	6,32	5,95	4,12	2,84
	7,52	2,07	13,35	3,81
	2,94	2,58	2,59	1,06
	1,57	1,54	2,69	0,80
	0,79	1,53	0,90	0,78
	-0,06	0,50	0,58	0,40
	-0,05	0,48	0,59	0,38
	0,07	0,40	1,02	0,62
	0,07	0,42	1,00	0,62
	0,05	0,36	0,89	0,48
	0,10	0,40	0,91	0,55
	0,24	0,14	0,34	0,28
	0,21	0,28	0,33	0,64
at	0,63	0,39	0,44	0,40
	0,72	0,66	0,45	0,85
at	1,17	0,34	0,58	0,39
	1,25	0,40	0,44	0,30
at	0,84	0,17	1,67	1,01
	1,06	0,38	1,44	0,76
at	1,10	-0,02	2,01	1,11
	1,23	-0,12	1,88	1,33
at	1,00	0,00	1,52	1,09
	-0,27	-0,81	3,47	2,39
at	-0,25	-1,38	2,88	2,01
	0,13	-1,45	2,65	2,36
at	-1,55	-3,08	3,29	3,62
	-2,79	-3,69	4,51	4,31
at	-6,83	-5,42	6,62	3,90
	-7,12	-6,24	7,10	5,18
at	-10,85	-9,30	8,01	6,32
	-10,25	-8,93	6,91	6,04
at	-16,02	-12,34	9,35	5,53
	-16,97	-13,47	10,52	7,29
at	-20,06	-15,47	6,20	4,91

12. Conclusion

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.

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

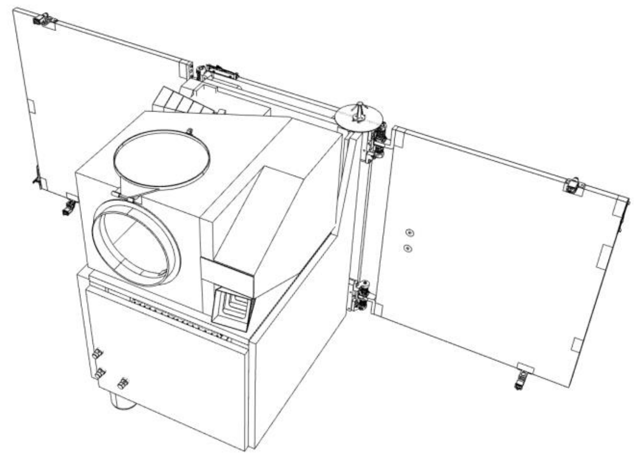

Fig. 19 Sketch of SBSS instrument on FLP-2 platform.

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