IAC-17.A6.1.5x39614

THE DIFFERENCE METHOD: A SIMPLE AND EFFECTIVE ON-BOARD ALGORITHM FOR SPACE DEBRIS DETECTION

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Abstract

The Difference Method algorithm is developed within the European Space Agency (ESA) ”Optical In-Situ Monitor” project by the Astronomical Institute of the University of Bern together with Airbus Defence and Space. Main objectives are the autonomous on-board data reduction, consisting of image segmentation and object detection. These steps are critical in order to achieve an effective on-board processing pipeline optimizing the downlink bandwidth usage. Then, complementary analysis regarding astrometry, photometry and debris characterizations can be performed through the related on-ground processing chain. The baseline of the Difference Method is to process two successive exposures and detect moving objects (space debris) by performing a refined frames subtraction. This method is composed of five main parts which are: star detection, frame alignment, frame subtraction, data selection and data compression. This algorithm shows very convincing results. It can process two frames and detect faint debris streaks, down to peak SNR 2 in less than 1 second of execution time, fulfilling rigorous requirements concerning on-board computation power, available data bandwidth and streaks detection limits.

Keywords: Satellite, Telescope, Debris, Streaks, Detection, Image processing

Acronyms/Abbreviations

AIUB:	Astronomical Institute University of Bern
CCSDS:	Consultative Committee for Space Data System
DM:	Difference Method
DT:	Debris Tracking
ESA:	European Space Agency
GSTP:	General Support Technology Programme
H/W:	Hardware
I/O:	Input/Output
IT:	Inertial Tracking
MW:	Milky Way
OBPP:	On-Board Processing Pipeline
OGPP:	On-ground Processing Pipeline
SFG:	Synthetic Frame Generator
SNR:	Signal to Noise Ratio
SST:	Space Surveillance and Tracking
ST:	Sidereal Tracking
S/W:	Software
ROI:	Region Of Interest

1. Introduction

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. On ground tracking, with moderate apertures, of orbiting debris can detect and study debris with a size down to a few centimeters. However, small debris, down to millimeters, can not be detected. Nevertheless, these small sized debris objects can cause dramatic damages to operational satellites. Therefore, the population between 1 mm and 10 cm needs to be better understood. Proximity to LEO small debris enables "in-situ" measurements via optical observations.

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 detection of small sized (down to 1 mm) space debris in LEO as well as larger objects in GEO (see Utzmann et al. [1] and Flohrer et al. [2]). This paper focuses essentially on the on-board and on-ground image processing pipelines developed by AIUB. The On-Board Processing Pipeline (OBPP) is designed to extract Regions of Interest from raw images acquired by the space-based telescope and compress them to achieve an efficient downlink. Then, the On-Ground Processing Pipeline will perform image decompression, segmentation, and refine streaks and debris detection as well as photometry and astrometry measurements.

Section 2 will show a simplified view of possible observing scenarios. Then, Section 3 provides details on the OBPP and mainly on the DM: a step by step explanation of the DM algorithm as well as performance tests are exposed. The subsequent section presents a brief overview of the OGPP and, finally, current conclusions on this S/W development are summarized.

2. Observing Scenarios

Complex observing scenarios can be detailed for a space-based telescope. For the purpose of simple test definition they can be summarized in three main scenarios which will be used for tests of the OBPP and OGPP (see Table 1).

2.1 Sidereal Tracking

This scenario will results in an image containing point stars and debris streaks.

Within this scenario, a "slow object mode" can be defined. It will correspond to slow moving debris with respect to the star background and the line of sight. Debris streaks can thus be very short, close to a point.

A particular processing mode is needed to detect these kinds of slow moving objects. It consists in an additional loop in the OBPP performed on two exposures separated by a few tenth of seconds. This way, the slow moving debris object will have moved sufficiently to be properly detected.

2.2 Debris Tracking

In this scenario, images will contain a moving stellar background formed by identically sized and oriented star streaks as well as a point corresponding to the tracked debris.

2.3 Inertial Tracking

This is the most general scenario. It will produce images containing stellar streaks and also debris streaks with possibly completely different streak length and orientation.

This scenario allows a "slow object mode" too. It will correspond to slow moving debris with respect to the line of sight and result in debris streaks with almost the same length and orientation than stars streaks.

To extract debris streaks from all star streaks in the image, an additional loop in the OBPP is performed on images separated by a few seconds as in the slow object mode for sidereal tracking.

ID	Name	Stars	Debris
ST	Sidereal Tracking	Points	Streaks
ST-slow	Sidereal Tracking and slow object mode	Points	~Points
DT	Debris Tracking	Streaks	Points
IT	Inertial Tracking	Streaks	Streaks
IT-slow	Inertial Tracking and slow object mode	Streaks	Streaks

Table 1 Table of simplified scenarios.

3. On-Board Processing Pipeline and the Difference Method

The goal of the OBPP is to extract Regions of Interest (ROIs) from acquired images, containing a few reference stars and debris objects. The relatively low on-board computation power and memory availabilities require a simple and effective detection algorithm. A trade-off between 4 different algorithms has been performed. The Difference Method algorithm has been chosen as other methods were either too complex for the flying H/W (StreakDet, see Virtanen et al. [3]) or too weak with respect to the Signal to Noise Ratio detection limit such as a simple threshold detection or the boundary tensor method (see Kothe [4]).

The developed OBPP is based on the Difference Method (DM) to detect 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 (see Fig. 1)

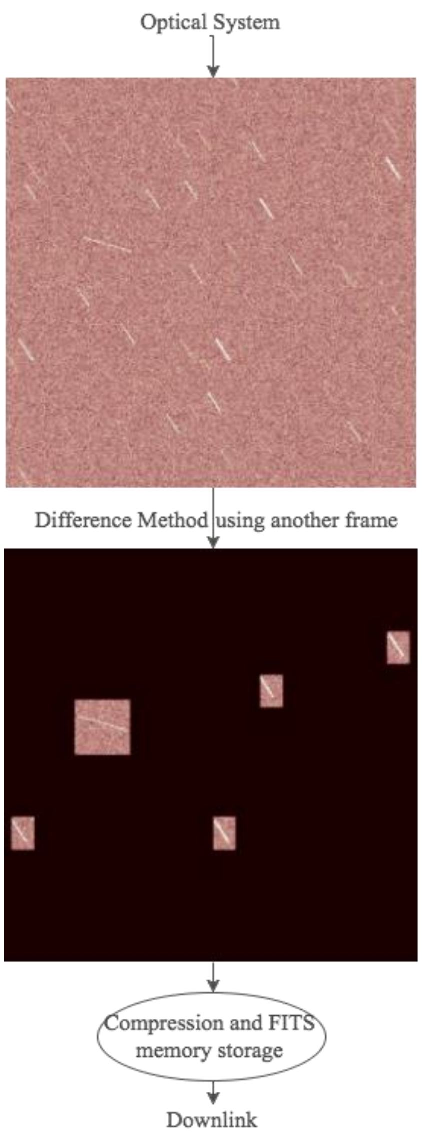

Fig. 1 I/O example of the DM. The last frame contains one ROI with the debris streak and other boxes containing reference star streaks.

Fig. 2 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.

Next sections give details of each of these steps.

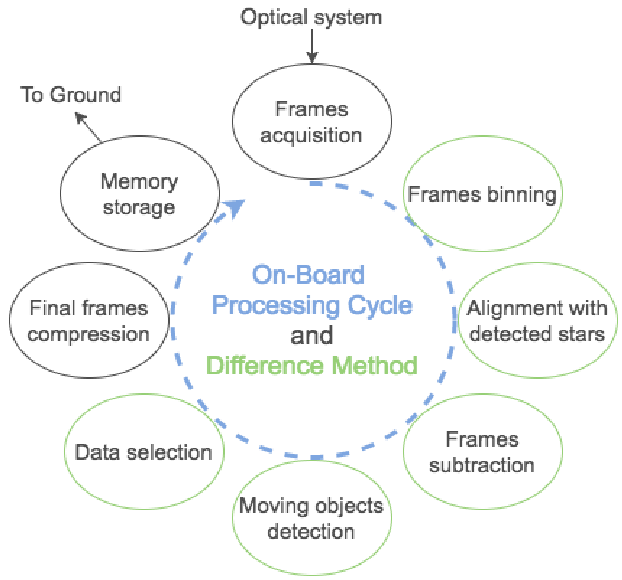

Fig. 2 Simple view of the On-Board Processing Pipeline.

3.1 Frames Binning

The binning consists in a simple summation of 4x4 pixels.

<u>Goals:</u>

- Decrease frame size => decrease computation time.
- Increase SNR levels => useful for frame subdivision afterward, for detection of ROIs.
- Quicker centroid and displacement vector determination.

3.2 Detection of stars

This step will detect bright objects in frames (mainly stars if not too many cosmics) and extract their positions (see Fig. 3). It scans the whole image and detects pixels above a given threshold. Then it will compute the centroid within a box, given by the known pointing drift of the telescope, around the first detected pixel. Objects containing at least one saturated pixel are discarded.

Goals:

- Have reference stars. All detected objects at this point will be added to the final selected frame.
- Positions of stars are used to compute the displacement vector needed to align frames A and B, assuming no rotations of the field of view.

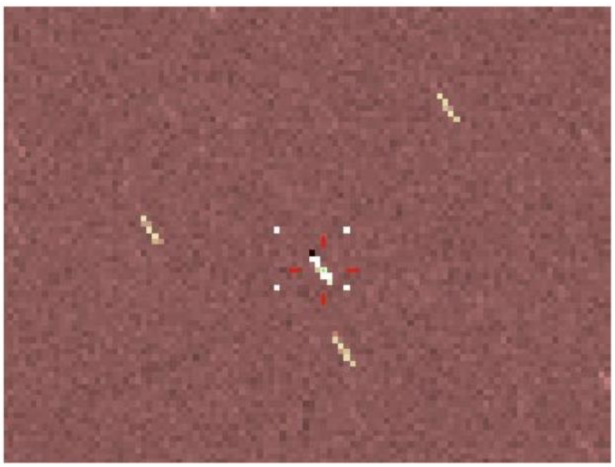

Fig. 3 Detection of bright stars. The black pixel is the first detected pixel and the 4 white pixels represent the box in which the centroid is done. The center of the red cross gives the measured position of the star.

3.3 Alignment and Frame Subdivision

Knowing the displacement vector from detected stars, overlapping parts of frame A and B can be subdivided in small parts of size "h x h" binned pixels (usually 3 x 3). Then, the value assigned to one of these subdivided parts (see Fig. 4) is given by the sum of all pixels with intensity greater than a given threshold based on the background noise level. It will remove all pixels close to the background noise level in this subdivided part. The difference in the next step will be performed on these assigned values.

Goals:

- Extract overlapping parts in frames A and B.
- Subdivision is necessary to minimize effects of small misalignments due to integer displacement vector.
- Sum pixels inside subdivided parts neglecting background level pixels will increase the difference and thus, the probability of detection.

3.4 Frames Subtraction

The difference is performed between subdivided parts of frames FA and FB. To extract information from FA, the subtraction FA-FB needs to be done. To extract information from FB, the subtraction FB-FA needs to be done as explained in Fig. 5. Only positive values are taken into account to generate both subtracted images. Ideally the difference should give 0 everywhere and ≠ 0 on a moving object. In reality, it's not exactly the case due to misalignment and "cut" stars lying on 2 neighbouring subdivided parts as well as shot noise of bright sources. To try to minimize this effect we can sum with given weights nearest subdivided parts with the central one and after, do the difference.

Goals:

- Perform the subtraction between subdivided frames to extract 2 new frames FA-FB and FB-FA containing all information needed to finally extract moving objects.

3.5 Detection and Data Selection

The detection step will scan the 2 subtracted frames to find subdivided parts with intensity higher than a given threshold, meaning the presence of a moving object. Then it will extract the corresponding region from the original frame.

At this point, images contain only ROIs where a possible moving object can be. Stars are missing and need to be added to these selected frames. Since we know positions of reference stars from previous step, boxes containing these references stars can be added to selected frames.

It will results in 2 selected frames with pixel's intensities equal 0 everywhere but in selected regions.

Goals:

- Extract moving objects.
- Build final selected frames with same resolution than original images.
- Send images with reference stars to ground to perform astrometry and photometry measurements.

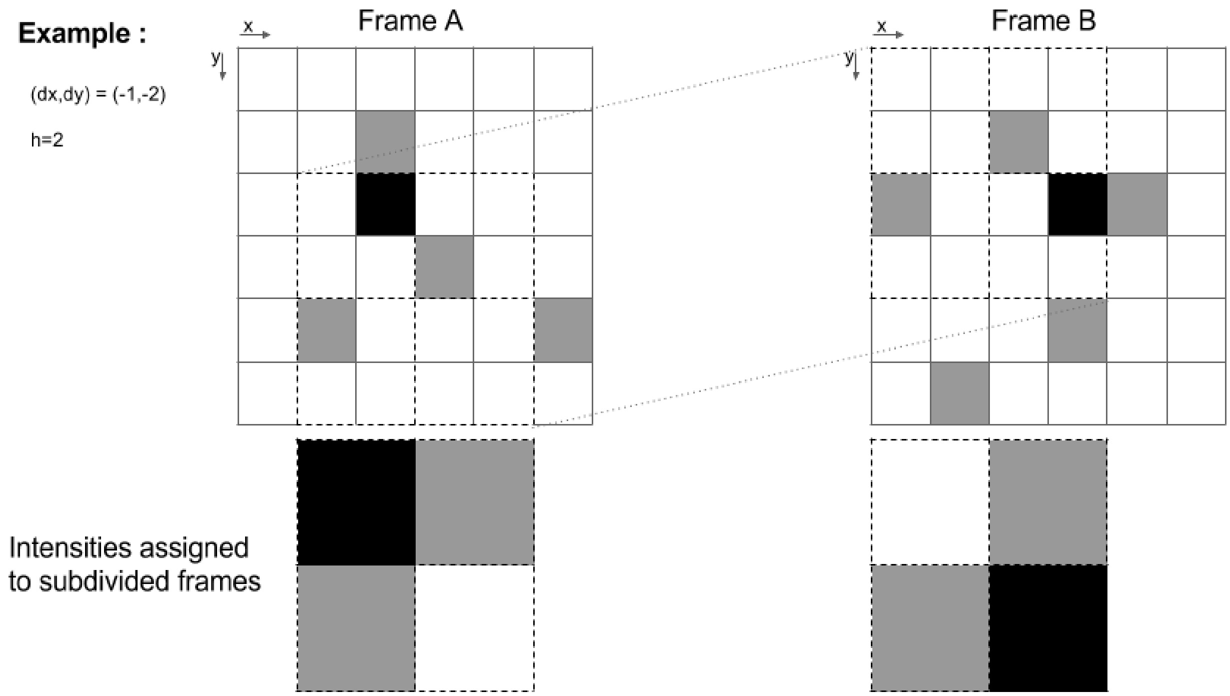

Fig. 4 Explanation of the subdivision step with two 6x6 frames and a subdivided frames dimension 2x2. Knowing the displacement vector (dx, dy) it's easy to extract overlapping frames (big dashed box) and subdivide it into four 2x2 parts (small dashed boxes). Then, corresponding subdivided parts intensities are computed with pixel above a given threshold.

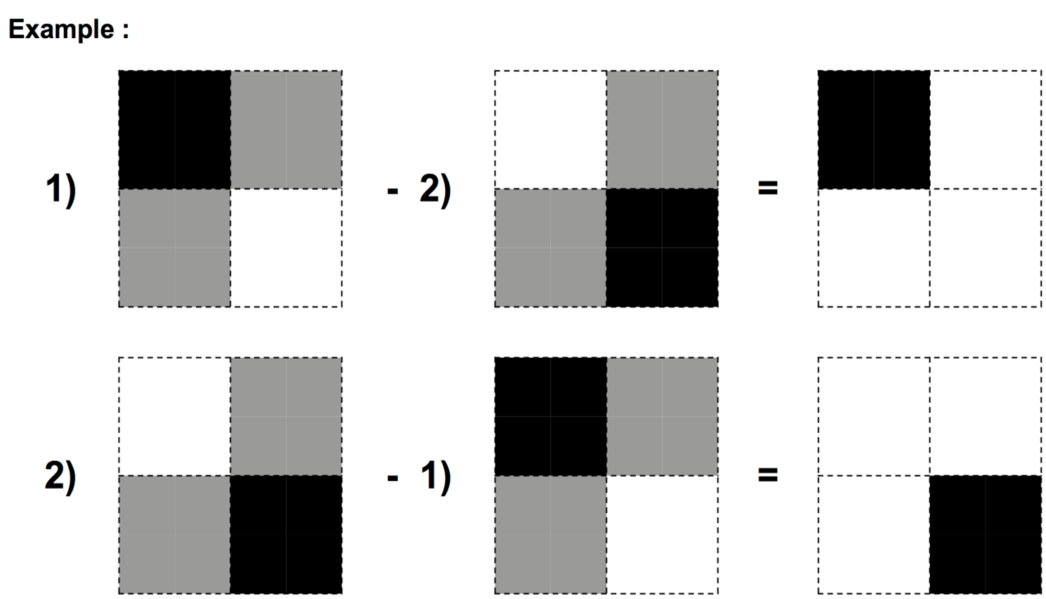

Fig. 5 Example of subtraction between overlapping subdivided frames A and B. Only positive intensities after the subtraction are kept to form the two subtracted images. In this simple example, no weights are applied to compute intensities of subdivided parts.

3.6 Compression

Since final selected images have very special characteristics (mainly 0 pixels), an effective and lossless compression can be implemented by scanning final selected frames and removing all 0 pixels (column-wise or row-wise).

This will first transform the image in a 1-D vector stored in a FITS file.

In addition to this lossless compression, a CCSDS Rice lossless compression [5] can be applied on the 1-D vector to further gain in compression.

Goals:

- Remove all 0 pixels from selected frames, keeping all information we want (lossless compression).
- Send efficiently to ground compressed images within the data bandwidth availability.

4. Performances of the OBPP

To test the OBPP, real or simulated images are needed. In the context of this project, AIUB has developed a Synthetic Frame Generator which can simulate acquired images containing a (non-)moving star background with (non-)moving debris. The resolution of images, the stellar density and its apparent velocity, the number of debris, their orientations, velocities or SNR can be chosen. The PSF's size of generated streaks can also vary as well as the cosmic ray content using simulated cosmic rays environments based on an orbit crossing the South Atlantic Anomaly.

To test the OBPP, a few hundreds pairs of synthetic images with various characteristics, containing one moving debris, have been created. All of them needed to be processed to preform statistical analyses of the OBPP. For each test, the compression factor achieved for the OBPP output file, the false negatives ratios as well as the average detection rate have been analysed. The false positive ratio is implicitly taken into account by the compression ratio.

The targeted minimum compression ratio for each processed frame is 1/100 and the maximum false negative ratio is 10%. More importantly, the average detection rate shall be more than 90%.

The detection efficiency of a streak can be defined as the percentage of detected pixels in the streak or, in other words, the fraction of the debris streak that is selected by the DM in the output image. Thus, the average detection rate for one test is defined as the average of all percentage of detected streaks for each tested frame.

The false negative ratio can be defined according to the fraction of detected pixels per streak. For this test, a false negative (i.e. a non-detected streak) will be defined as a debris streak with less than 75% of detected pixels.

For this paper, results of the peak SNR detection limit test, with a sidereal tracking scenario, are given. Peak SNR is defined as the maximum debris streak's pixel value over the overall noise that affects the debris streak.

4.1 Peak SNR Detection Limit Test with ST Scenario

To perform this test, an optimized set of parameters driving the OBPP is found by targeting the minimum compression ratio allowed. Using the same set of parameters, twenty pairs of simulated images (per peak SNR 1, 1.5, 2 and 3) containing one debris object are processed by the OBPP. It means 160 frames in total in which, one debris streak needs to be detected.

All characteristics concerning the images and the debris for this test are listed in Table 2.

Image size [pix x pix]	**2048 x 2048**
Scale [arcsec/s]	4.85
Exposure time [s]	0.5
Interval time b/w two exposures [s]	1
Elevation angle from MW plane [deg]	60
Sigma of PSF [pix]	0.665
Enclosed Energy per pixel [-]	30%
Cosmic rays density	No Cosmics
Pointing Err. [arcsec/s]	0
Binning before DM [pix x pix]	4 x 4
Number of streaks per frame [-]	1
Peak SNR [-]	1, 1.5, 2, 3
Streak orientation angle [deg]	45
Debris apparent velocity [arcsec/s]	511
Debris length [pix]	52.7
Stars orientation angle [deg]	33
Stars apparent velocity [arcsec/s]	0
Stars streaks length [pix]	0

Table 2 list of frame, stars, and debris characteristics.

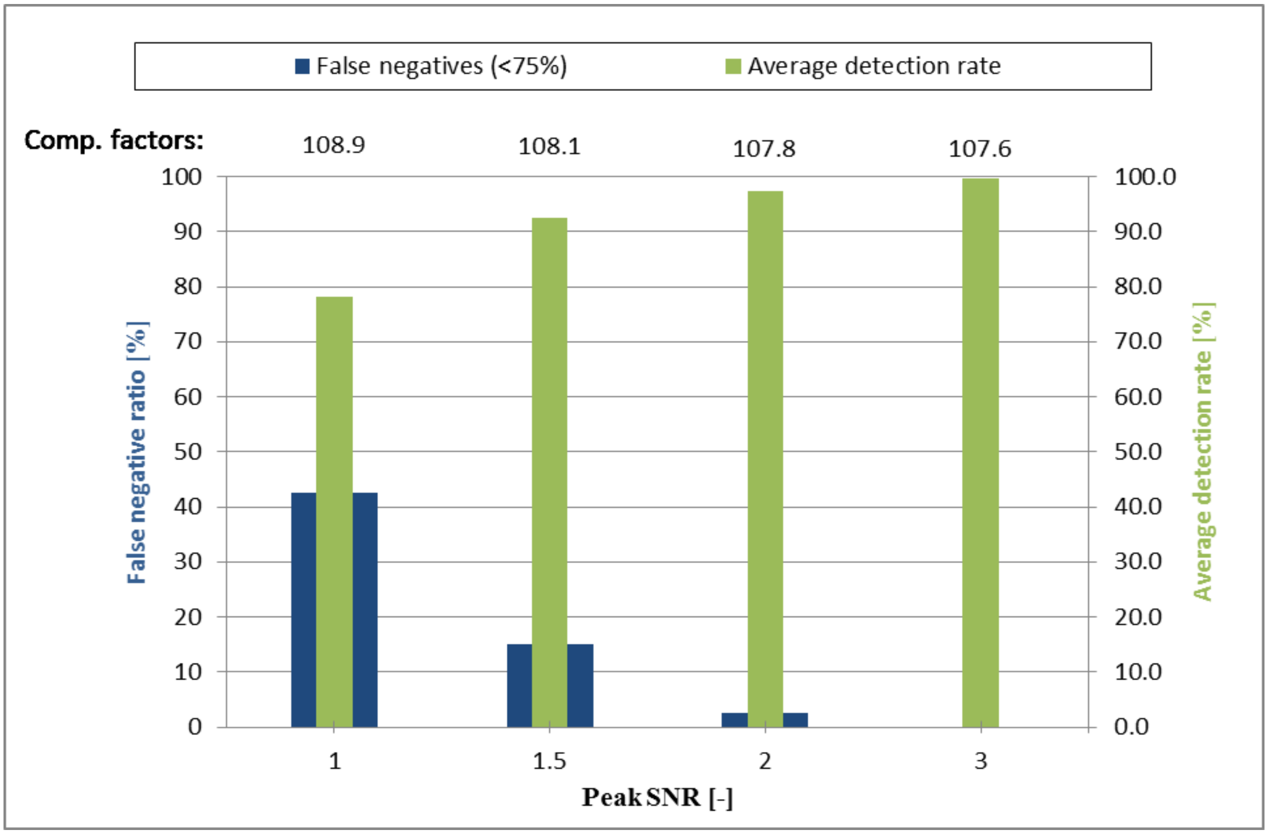

Fig. 6 Graph showing the false negative ratio (<75% detected streaks pixels) and the average detection ratio for 20 pairs of frames containing one debris streak and point stars (ST scenario) as a function of the debris peak SNR. The compression factor is always greater than 100 and the average detection rate is always greater than 90% but for peak SNR = 1.

Fig. 6 shows results of this test using 40 images for each peak SNR.

Knowing previously mentioned requirements, the case with peak SNR=2 is compliant with all of them:

Compression factor of 107.8	> 100
Average detection rate of 97%	> 90%
False negative ratio of 3 %	< 10%

Nevertheless the peak SNR 1.5 case is fulfilling 2 out of 3 requirements with an average detection rate of 93% which proves the efficiency of the OBPP and the DM. Moreover, one can also note that for peak SNR 1, the average detection rate is still very good with 78%.

4.2 Processing Time

On of the main requirements for the OBPP is to process two images in less than 1 second. This requirement can be verified only on a prototype of the final OBPP ported to C and implemented on H/W.

Airbus performed successfully this test after porting and optimization of AIUB's Matlab code in C on an ARM Cortex processor. Two frames were processed in 0.8 seconds.

5. On-Ground Processing Pipeline

A trade-off discarded the StreakDet (see Virtanen et al. [3]) software for the OBPP. However, it was decided to use it in the On-Ground Processing Pipeline as the main code to extract debris streaks information. The whole OGPP is currently still under development. It has been built by AIUB, using mainly StreakDet.

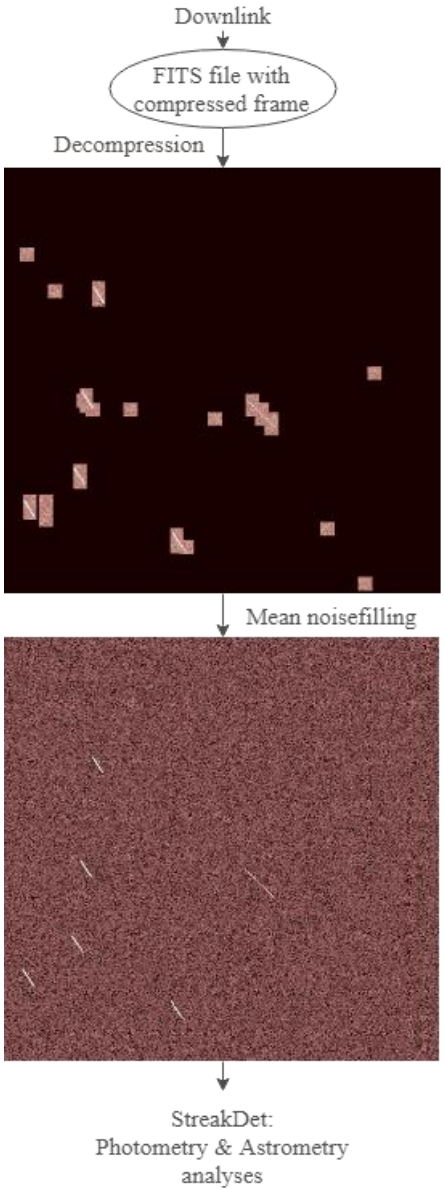

Fig. 7 Example of images after decompression and noise-filling steps, before executing StreakDet.

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. 7). Filling empty regions with noise is not an ideal case. Since these regions were discarded by the OGPP it should not be necessary to run StreakDet on them. StreakDet is designed to run on full images and not on fragmented frames. This could be an important modification to implement in 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.

Fig. 8 shows a simple view of the OGPP architecture with its eight main steps.

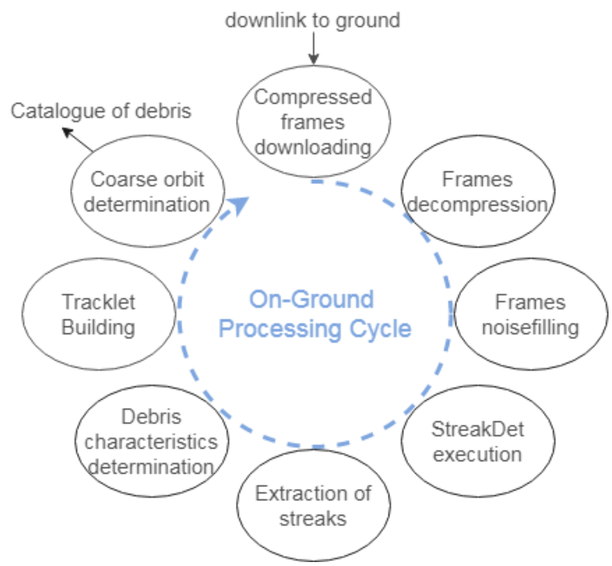

Fig. 8 Simple view of the On-Ground Processing Pipeline.

6. Conclusion

This paper shows a small but representative fraction of the work realized within the In-Situ Monitor project with respect to on-board and on-ground image processing pipelines.

The test related to the peak SNR detection limit proves that the Difference Method is compliant with the requirements of the project. It can successfully detect ROIs with moving debris streaks and select reference stars. Reaching debris peak SNR detection limit between 1.5 and 2 is remarkable. Achieving such low peak SNR detection with an autonomous on-board detection algorithm is essential to monitor very small debris objects. Other tests performed at AIUB showed that the OBPP successfully achieve targeted performances with respect to false negatives, compression ratio and peak SNR detection limit in a majority of cases with various scenarios, background and debris characteristics. Moreover, according to Airbus tests, the requirement on the processing time for 2 images is fulfilled. An ARM Cortex processor was able to process the OBPP on two frames in 0.8 seconds.

In conclusion, the OBPP can process two frames and detect faint debris streaks, down to peak SNR 2 in less than 1 second of execution time, fulfilling rigorous requirements concerning on-board computation power, available data bandwidth and minimum detected object brightness. The simplicity and the efficiency of the DM make the OBPP an optimized way to rapidly reduce raw exposures by selecting reference stars and ROIs.

The OGPP is still a work in progress. Nevertheless, using StreakDet (see Virtanen et al. [3]), make the OGPP inherit from an already complex and refined streak detection algorithm fully developed and optimized for ground-based telescopes. For sure, StreakDet will need to be updated to suit the characteristics of the In-Situ Monitor project images and is an excellent starting point. First execution of StreakDet already gives promising results using images corresponding to the Sidereal Tracking scenario with one moving debris object.

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