

First light of SWAP on-board PROBA2

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ABSTRACT

The SWAP telescope (Sun Watcher using Active Pixel System detector and Image Processing) is an instrument launched on 2nd November 2009 on-board the ESA PROBA2 technological mission.

SWAP is a space weather sentinel from a low Earth orbit, providing images at 174nm of the solar corona. The instrument concept has been adapted to the PROBA2 mini-satellite requirements (compactness, low power electronics and a-thermal opto-mechanical system). It also takes advantage of the platform pointing agility, on-board processor, Packetwire interface and autonomous operations.

The key component of SWAP is a radiation resistant CMOS-APS detector combined with onboard compression and data prioritization. SWAP has been developed and qualified at the Centre Spatial de Liège (CSL) and calibrated at the PTB-Bessy facility. After launch, SWAP has provided its first images on 14th November 2009 and started its nominal, scientific phase in February 2010, after 3 months of platform and payload commissioning.

This paper summarizes the latest SWAP developments and qualifications, and presents the first light results.

Keywords: SWAP, CMOS-APS, PROBA2

1. SWAP ON PROBA2

The PROBA2¹ mission has been launched on 2nd November 2009 with a Rockot launcher in a sun-synchronous orbit at an altitude of 725 km. Its nominal operation duration is 2 years with possible extension of 2 years. PROBA2 is a small satellite developed under an ESA General Support Technology Program (GSTP) contract to perform an in-flight demonstration of new space technologies and support a scientific mission for a set of selected instruments^{2,4}. The mission is tracked and data downloaded to the ESA Redu Mission Operation Center.

The Sun Watcher using Active Pixel System detector and Image Processing⁵ (SWAP) is a compact instrument which is part of the PROBA2 payload (Fig 1) that observes the Sun in extreme ultraviolet (EUV) and demonstrates the performance of the CMOS-APS technology in space environment. SWAP provides continuous images of the Sun in a narrow bandpass with peak at 17.4nm.

The SWAP instrument was built upon the heritage of the Extreme ultraviolet Imaging Telescope⁷ (EIT) which monitors the solar corona since 1996 on-board the SOHO mission. The SWAP field of view is larger than EIT, which allows following in an autonomous mode the coronal mass ejections (CME) by taking advantage of the PROBA2 spacecraft off-pointing agility combined with its active pixel sensor (APS) sensor performances and an on-board image processing. SWAP also offers the advantage of high image cadence (maximal 3 per minute, 1 per minute in nominal operations) to monitor transitory phenomena. In contrast to EIT, SWAP is an off-axis Ritchey-Chrétien telescope within a restricted volume, simpler baffling and smaller aperture. Due to the strict allocated mass and power budget (10 kg and average power of 5W), a deep optimization of the instrument electronics and a lightweight mechanical structure were necessary.

SWAP has been entirely developed and tested by the Centre Spatial de Liège (CSL) of the University of Liège, and calibrated in collaboration with the Royal Observatory of Belgium (ROB), within the framework of a European collaboration and with the support of the Belgian industry including Thales Alenia Space ETCA, AMOS, Deltatec, Fill

Factory/Cypress Semiconductor and OIP Sensor Systems. Since launch, the Royal Observatory of Belgium ensures the follow-up of SWAP to withdraw the scientific results.

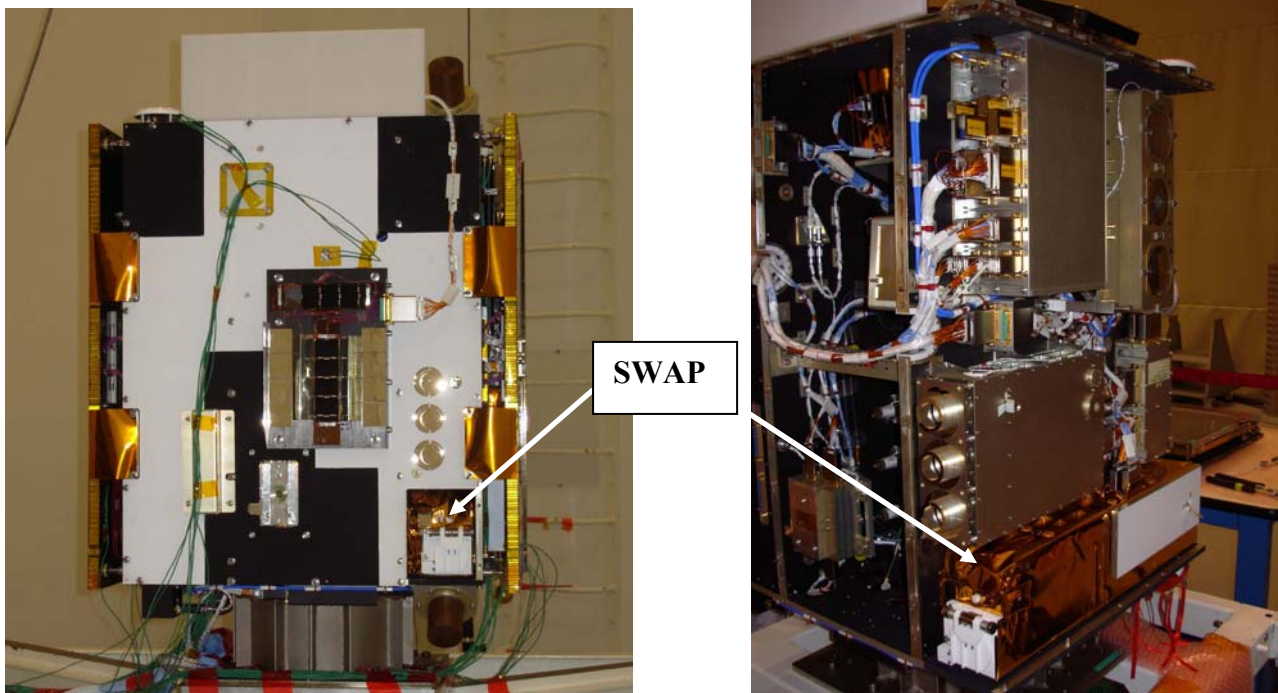


Fig 1. SWAP mounted on the PROBA-2 platform. Left: During acoustic tests of PROBA2 in Intespace, Sun-facing panel. Right: during AIV at Verhaert.

Compared with similar instrument launch previously (Table 1), SWAP provides a higher temporal resolution but at only one wavelength with off-pointing capabilities. It also demonstrates the ability of CMOS detector to be used for science application.

Table 1. SWAP main parameters vs. EUVI and EIT

	SWAP	EUVI	EIT
Wavelength(s)	17.4nm	17.1, 19.5, 28.4, 30.4 nm	17.1, 19.5, 28.4, 30.4 nm
Detector	Shutterless 1k x 1k CMOS detector	CCD 2k x 2k detector with shutter	CCD 1k x 1k detector with shutter
Location	Inside magnetosphere, Earth view	stereo view: ahead & behind Earth	L1 view
Field of view	54 arcmin (3.4 solar radius)	54 arcmin (3.4 solar radius)	45 arcmin (2.8 solar radius)
Pixel size	18 μ m (3.16 arcsec)	13.5 μ m (1.6 arcsec)	21 μ m (2.6 arcsec)
Entrance pupil	33 mm	98 mm	120 mm
Pointing	sun-centered FOV with flexible off-pointing	sun-centered FOV	sun-centered FOV
Cadence	1 min (up to 18s)	10 min	10 min to 2h
Launch	November 2010 (PROBA2)	October 2007 (STEREO)	December 1995 (SOHO)

2. LATEST DEVELOPMENTS AND QUALIFICATIONS

The SWAP instrument design, environmental tests and calibration have been described in previous papers^{5,6,14,15}.

After integration on PROBA2, SWAP has also been submitted to spacecraft environmental validation, including vibration, thermal vacuum and acoustic tests. This last one revealed the need of reinforced front EUV filter to survive launch acoustic constraints.

A mechanical characterization of commercial standard LUXEL filters has been conducted and led to the selection of 20 lines per inch reinforced mesh Nickel grid, with 500A polyimide film, to support the 1500A Aluminum filter (Fig 2).



Fig 2. 20lpi Nickel mesh grid filter

Following this new front filter selection, a depressurization test of the SWAP instrument has been performed to validate the two instrument filters resistance to the pressure variation they have to survive during launch. The air evacuation from the SWAP is indeed guaranteed by dedicated venting holes (with labyrinths for straylight protection) designed to ensure a minimum delta-pressure around the SWAP filters, but had never been tested before.

Fig 3 shows the 0.25m vacuum chamber of CSL used for this test. Fig 4 shows the theoretical Rockot launch curves vs. measured test pressure variation. Pumping has been optimized to reproduce as much as possible the launch depressurization and chamber repressurization had been performed using clean Nitrogen for cleanliness reasons.

Following these final tests, the SWAP instrument has been mounted on PROBA2 and connected to its DC/DC sub-unit (IIU) and to the PROBA2 on-board computer (ADPMS). The SWAP instrument has been co-aligned with PROBA2 star trackers and with the LYRA instrument, with better than 20 arcsec accuracy. Functional tests were then performed at spacecraft level to validate the flight operational scenarios.

The instrument has always been maintained under clean Nitrogen purge until launch to limit molecular contamination during the two years of storage and to provide dry environment for the detector and the two coated mirrors avoiding early ageing due to the ambient humidity.

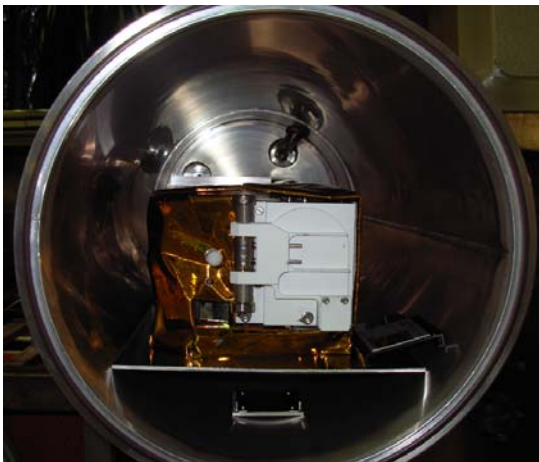


Fig 3. Depressurization test chamber

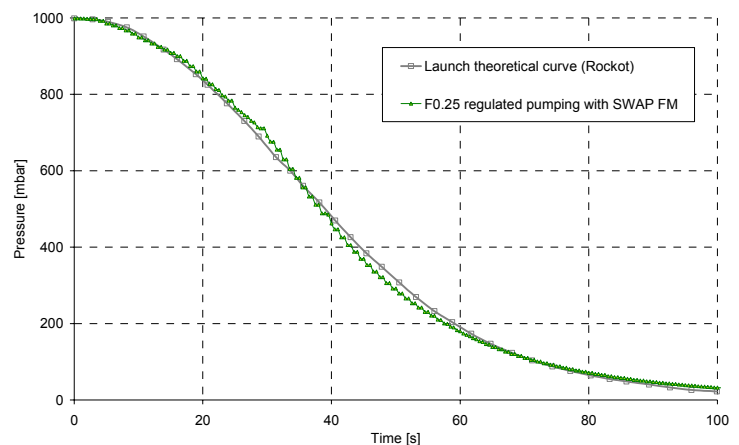


Fig 4. Depressurization slope

The reflectivity of mirrors witnesses, that have followed the flight mirrors during the AIV campaign, will be measured and used to correlate the theoretical instrument performance with in-flight instrument response, and quantify the possible reflectivity degradation during the on-ground storage before launch.

3. SWAP FIRST LIGHT

3.1 Instrument health check and first light

Two weeks after launch, on Nov 17, 2009, the SWAP electronic was switch on and first commands were sent to perform health checks and get first housekeeping values.

On November 20, the very first (dark) SWAP image was brought to the ground. On December 14, 880 images have been collected (600 dark and 280 LED images) to derive preliminary in-flight instrument performances.

On 14th December 2009 at 07:43, following a 24 hours detector annealing sequence, the SWAP door (which can open only once and never reclose) has been opened

First light was obtained 12 hours later (Fig 5). The Sun pointing and the spacecraft stability were not yet adjusted, but the image proved that the instrument was working nominally (EUV filters, mirrors, detector, and electronic).

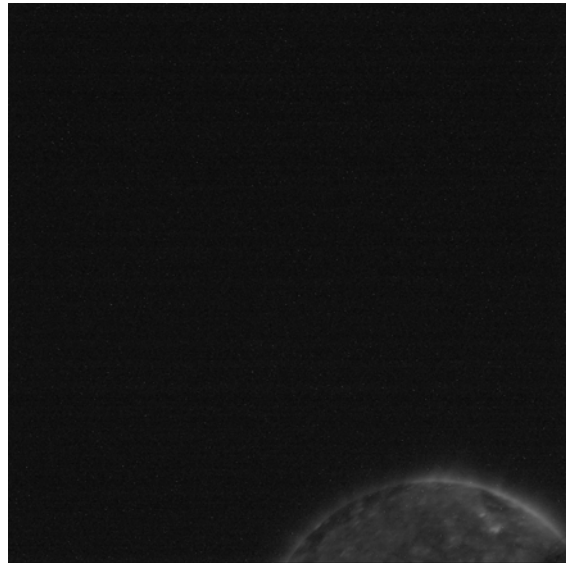


Fig 5. SWAP first light

3.2 Door opening sequence

To obtain first lights of EUV instrument, cautions are required to avoid very fast degradation of the optical surfaces (filters, mirrors and detector) with EUV light that could polymerize contaminants on them. The most critical element is the detector, the coldest optical surface, on which contaminants could be trapped.

SWAP detector is however surrounded by a cold cup always 5 to 10 degrees cooler. The cold cup is thus the coldest surface in the instrument cavity, providing a first barrier to detector contamination.

A decontamination heater is also used to outgas the condensed material (annealing), taking advantage of venting holes located on each side of the focal plane EUV filter in front of the detector cavity, allowing contaminant evacuation during detector and cold cup annealing.

Fig 6 gives a schematic view of the SWAP detector cavity with major components.

In the detector cavity, two redundant LEDs (A and B) are also arranged on each side of the detector to perform in-flight calibration images used to monitor the detector degradation.

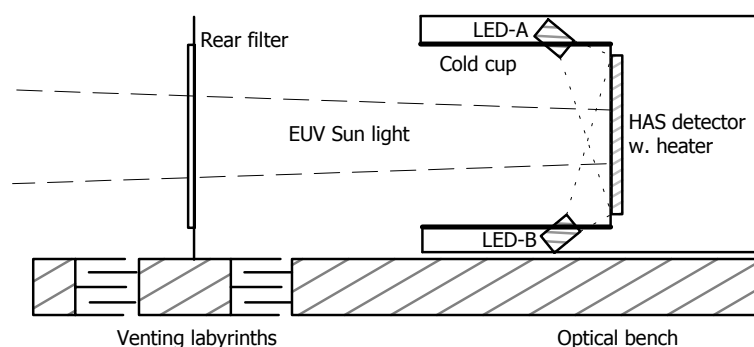


Fig 6. SWAP focal plane assembly and detector cavity

SWAP door opening sequence is shown on the Fig 7 and has been run six weeks after launch, ensuring no air remains in the instrument cavity.

Following a first set of reference images (dark and LEDs), the detector has been annealed for 24 hours at +50°C. The spacecraft has then been off-pointed (3-arcdeg) to avoid Sun EUV light directly hit the detector surface at the time the door was opened.

The door opening sequence has been run, followed by a second annealing sequence of 12 hours to ensure residual contaminants on the optical surfaces would leave the instrument cavity.

First light Sun images were then obtained, with dark reference images that were taken before and after, in off-point, to quantify a possible direct degradation by Sun illumination.

During the whole sequence, housekeeping (HK) data (in particular detector temperature) was monitored to allow a correct interpretation of the reference dark and LEDs images.

Following this sequence, regular sets of reference dark and LEDs images were taken to quantify possible early detector degradation, but up to now no contamination effect was observed.

However the impact of the detector temperature variation was clearly visible on dark images as well as the LED temperature variation, as presented in the next chapter.

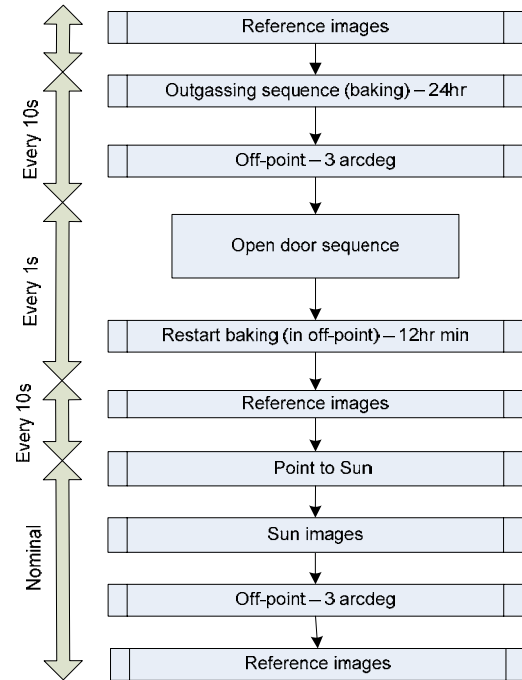


Fig 7. SWAP door opening sequence

4. IN-FLIGHT CHARACTERIZATIONS

Before entering in operational mode, the SWAP instrument has been submitted to a series of functional, performance and validation tests, during the 3 months of commissioning. Preliminary in-flight characterizations are here summarized.

4.1 Observation tuning

One of the first commissioning activities was to improve the spacecraft Sun pointing to center the Sun in the SWAP images, including large angle rotation (4 per 90 minutes orbit) effect, and improving the spacecraft stability.

In parallel, the SWAP imaging parameters (integration time, detector offsets, compression mode and parameters, etc) were optimized. Automated image acquisition sequences were also validated.

The integration time has so been fixed to 10s and maximum cadence to 18s. During the nominal operations, images are compressed using JPEG progressive compression (theoretical compression factor of 4, which is actually 2.5 to 3).

4.2 Dark current

Dark subtraction is a tricky problem for SWAP images as the detector is not at constant temperature so dark current is not constant.

Furthermore, the SWAP detector temperature which was expected to be below -10°C is varying around 0°C, due to spacecraft temperature which is 15 to 20°C higher than expected, resulting in a relatively high thermal noise.

Fig 8, obtained on 1st and 2nd Dec 2009, shows the dark current dependence with temperature. In the operational range, around 0°C, it shows that approximately 1DN has to be counted per additional °C.

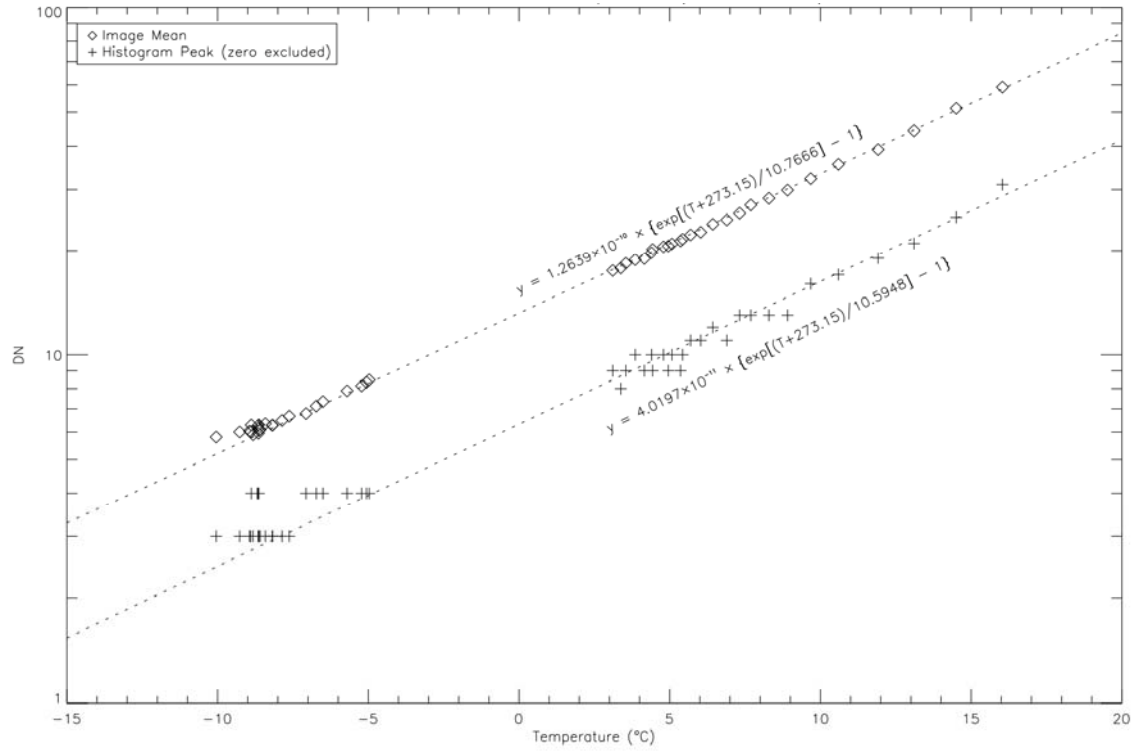


Fig 8. SWAP dark current vs. temperature (image mean and histogram peak).

4.3 Detector response evolution

To monitor the detector response evolution with time, the two focal plane LEDs are used, in an off-point mode to avoid Sun illumination (as there is no shutter in SWAP). The LED pattern on the detector is unfortunately not uniform, as shown on Fig 9, and some rows are not illuminated with LEDB. This is due to the very compact focal plane assembly, where the LEDs are nested within the cold cup as shown in Fig 6. Nevertheless, these patterns are sufficient to monitor the detector evolution and quantify its response.

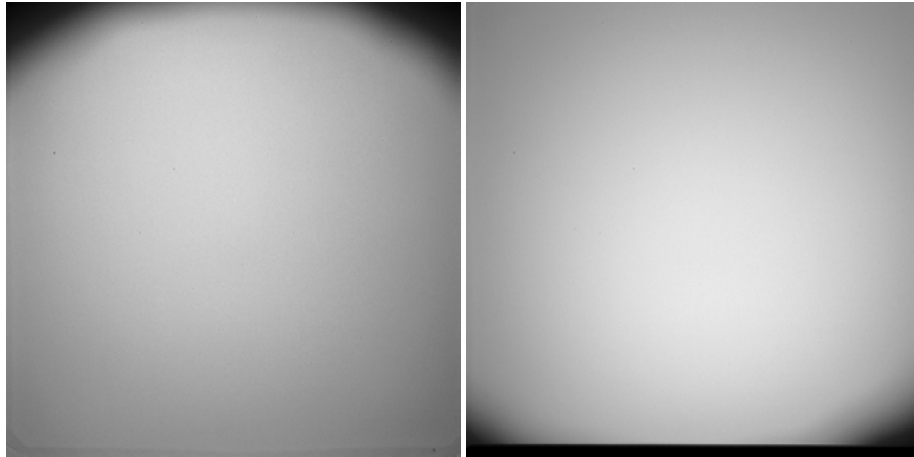


Fig 9. SWAP LEDA and LEB image pattern

Since the instrument has been switch on in November 2009, series of 3 seconds correlated double sampling (CDS¹) dark and LEDs images have been taken at regular interval, and also before/after annealing sequences. The mean over the LED and dark image has been computed and plot versus time, together with the detector temperature (Fig 10).

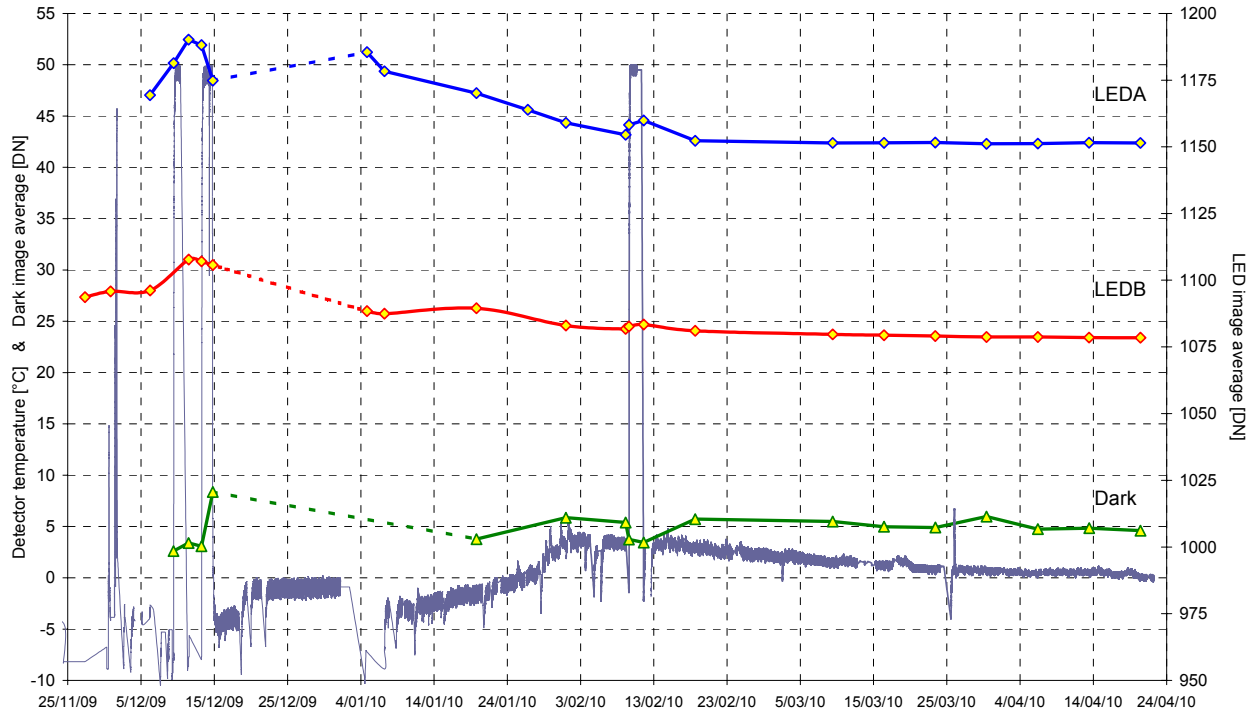


Fig 10. Detector response to LEDs over time

As shown on Fig 11, not only the dark images but also the LEDs image mean is related to the detector temperature. Indeed the LEDs temperature is following the detector temperature, close to each other and thermally linked by the cold cup, and LED emissivity is inversely proportional to its temperature. On view of these plots, we can conclude that, up to now, the detector response is very stable and that no degradation can be observed.

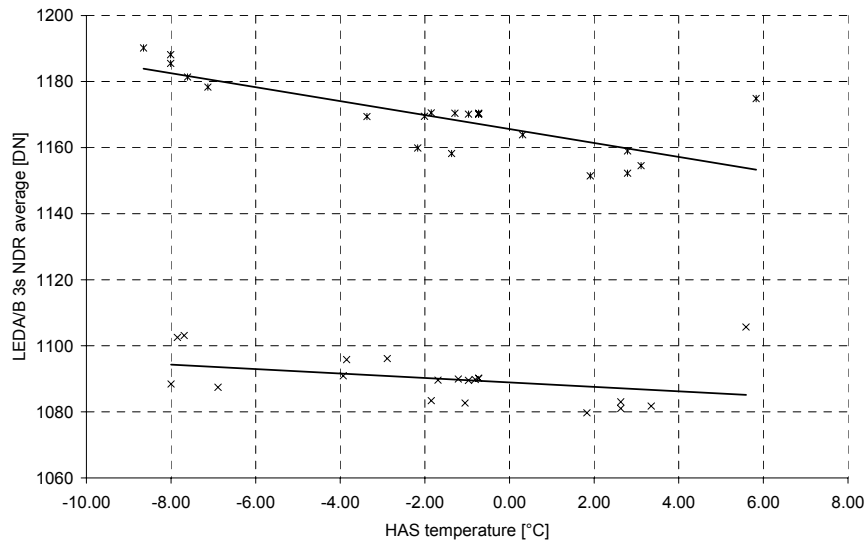


Fig 11. Detector response to LEDs vs. temperature

¹ Also named « NDR » for Non Destructive Readout

Since the SWAP door opening sequence, only one annealing of the detector has been performed (during 24 hours), as it had no significant effect on the detector response to LED light. This indicates that the contaminant level is probably very low. Annealing will however be performed on a regular basis to ensure possible new contaminants are released.

4.4 Instrument straylight

Taking advantage of the Earth eclipses that occurred at the beginning of the mission and of the spacecraft off-pointing capabilities, the straylight level has been quantified. Dark images have been taken over two orbits with a 3-arcdeg off-point (angle at which straylight should be negligible due to the instrument internal baffling design).

Fig 12 shows dark images mean (10 seconds CDS) over the two orbits, taken in off-point, together with the detector temperature variation. Apart from the thermal readout noise, which is of the order of 1DN per °C, the straylight level is less than $\frac{1}{2}$ DN. This ensures that the LED images used for detector response monitoring, performed at a 3-arcdeg off-point, have no parasitic solar straylight. Further similar sequences will be made with other off-point angles, to correlate with calibration measurements^{14,15}.

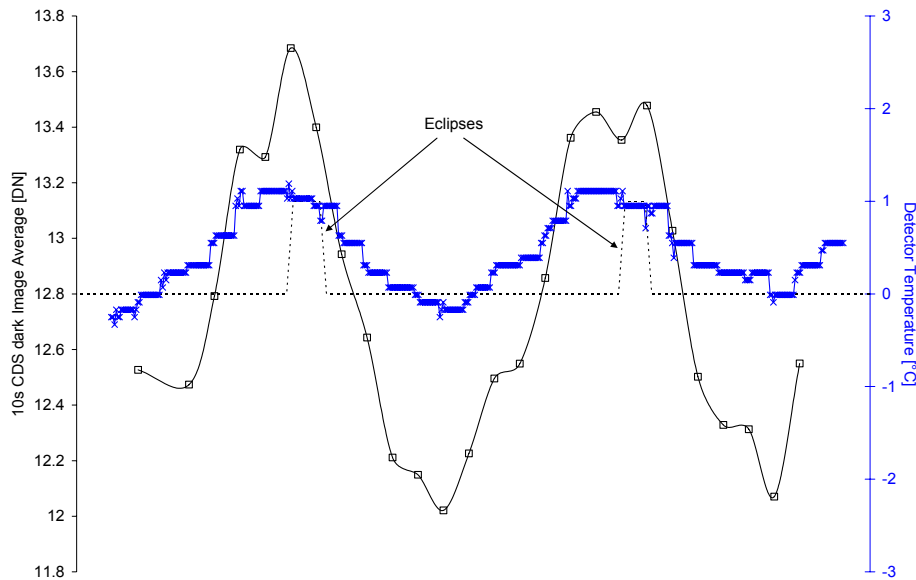


Fig 12. Dark images over two orbits with a 3 arcdeg off-point

Very long exposure images were also made. To our surprise, the off-limb corona does not get bigger with increasing exposure time. This means that we are not limited by stray-light. Instead the 'upper limit' of the corona is determined by the point where the solar signal is as strong as the dark current.

4.5 Bright pixels and Cosmic rays

The SWAP detector is an CMOS-APS and not a CCD. The essential difference is that for a CMOS-APS detector every pixel has its own read-out electronics and thus behaves slightly different from the neighboring pixels. Essentially we have 1 million individual pixels and a small fraction of it (<0.5% but still thousands of pixels) are not behaving. With onboard processing we can adequately process these images, even before they get to the ground.

As PROBA2 flies on low Earth orbit, it passes 3 times per day (on consecutive orbits) through the South Atlantic Anomaly (SAA). As a consequence bright spots and stripes are present in the images taken while passing the SAA (example on Fig 13). The spacecraft flies at a speed of $(2 \pi \text{ Earth radius}) / 99 \text{ min} = 25\,000 \text{ km/h}$, so, crossing the SAA is a matter of only a few minutes.

One particular event has been observed on 13 January 2010 (Fig 14), a very high energy cosmic ray ("Oh my god" particle) producing a very bright spot on the detector. Fortunately, the APS detector device has by design a good tolerance to radiation and is not damaged by these cosmoics.

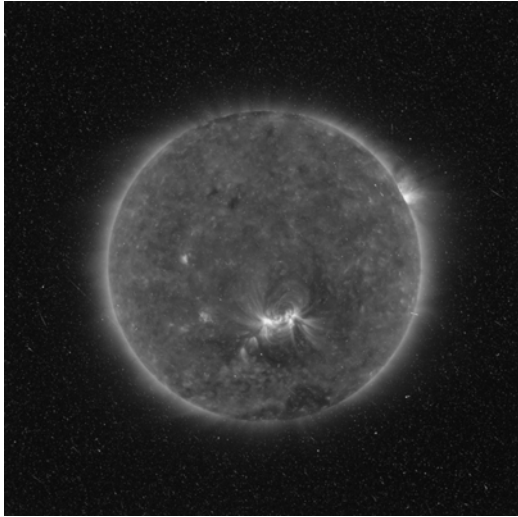


Fig 13. Cosmics during pass over the SAO

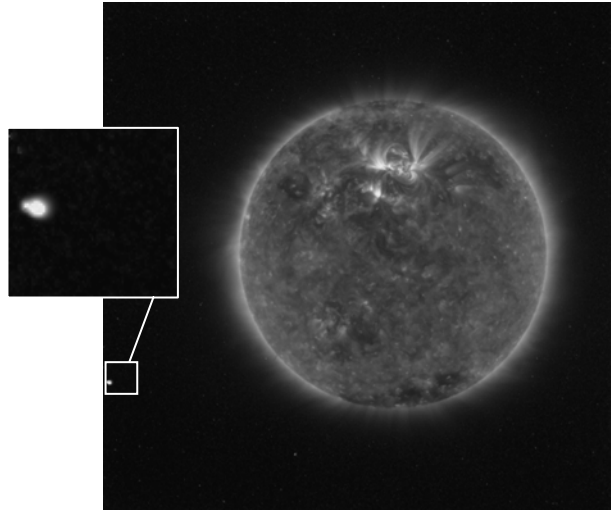


Fig 14. High energy cosmic ray

4.6 Flat fielding

Especially for constructing flat fields, off-pointing capabilities of the spacecraft is a great help to be able to carefully sweep the Sun through the field of view to get a homogenous exposure, as shown on Fig 15.

4.7 Annular eclipse

On January 15, an annular solar eclipse happened above Asia. The successful prediction of the times that the Sun, the Moon, the Earth and PROBA2 were co-aligned to catch the images shown in Fig 16.

The eclipse was the opportunity to cross-check the SWAP plate scale based on the moon diameter:

3247.37 [arcsec] along X axis, i.e. 54.123 arcmin

3238.16 [arcsec] along Y axis, i.e. 53.969 arcmin.

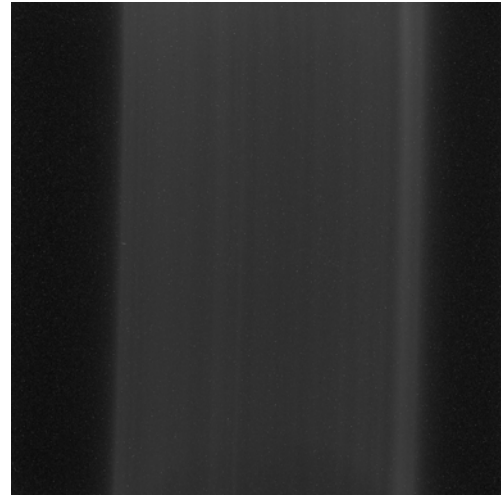
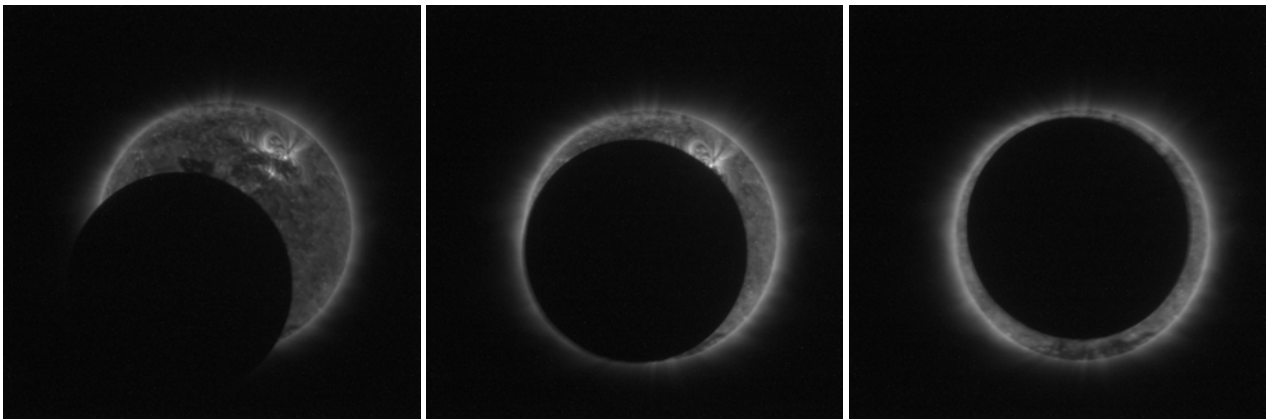


Fig 15. Flat fielding using spacecraft off-point movement



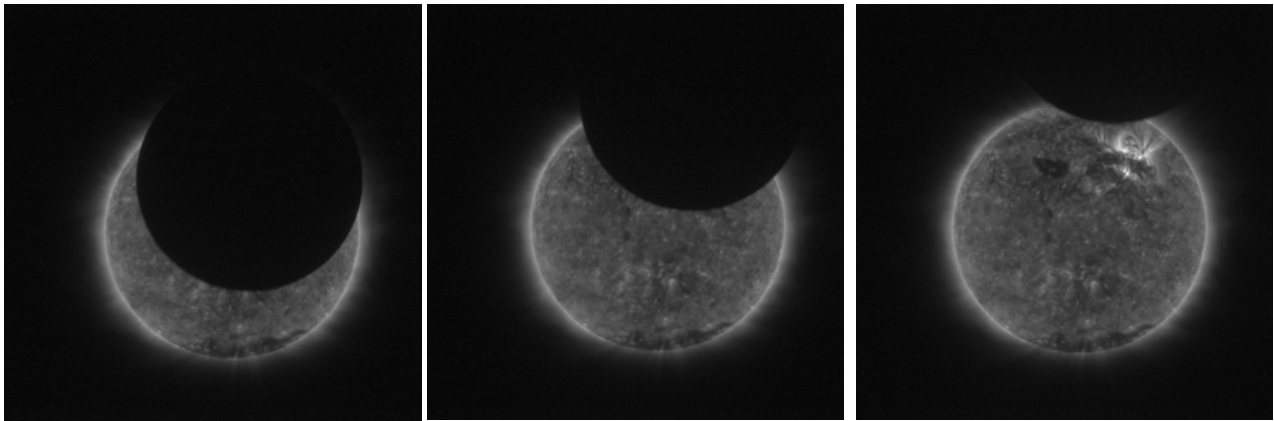


Fig 16. January 15, 2010 Earth annular eclipse

4.8 Image processing

The raw images are first reformatted, decompressed and saved into engineering (or level0) FITS files with a header containing all information on acquisition and processing times, s/c pointing, s/c position, instrument settings and parameter settings used to acquire the image.

In a next step, they are further processed and calibrated to produce base science (or level1) FITS files, following the procedures below:

- Correction of ‘bad’ pixels (hypersensitive or ‘dead’). These are replaced by the average of their neighbors. This calibration step can be performed onboard.
- Handling of saturated or missing pixels.
- Subtraction of the dark current, taking into account the detector temperature at the time of image acquisition.
- Flat fielding & Despiking
- Image rotation to get Solar North up. In a second step, the pixels are slightly scaled to perfectly squared pixels. Finally, the image is centred on the solar disk centre.
- Normalization to the exposure time.

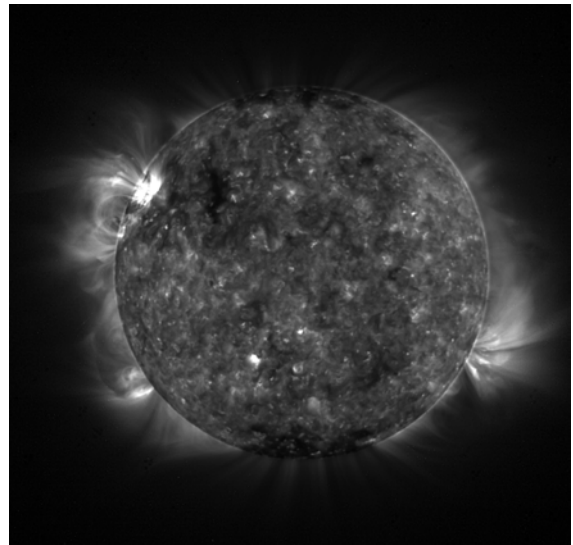


Fig 17. Processed image

Fig 17 gets, apart from the nominal procedures, some extra processing to enhance the off-limb region.

An average 750 daily images are taken with on-board compression and recoding, with a compression factor ~ 4 . Data are available to all users on <http://proba2.sidc.be>, ordered in year/month/day folders.

- Raw Engineering FITS: reformatted, decompressed, long header
- Base Science Data FITS: calibrated, science header
- PNG files: for quick look purposes

5. CONCLUSIONS

SWAP is an instrument to be used in the frame of the space weather and solar science. It provides high temporal cadence up to 18s (1min nominal) with limited blooming due to CMOS detector, and onboard data-processing and prioritization.

Data are available in near-real time (9 passes/24hrs with image priorities). Off-pointing capabilities (automatically) also provide the capabilities of CME tracking up to a few degrees, with a flexible commanding from the Science Center.

In-flight performances analyses have been started during commissioning, and are continued to improve knowledge of the instrument behavior and capabilities.

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