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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 174 nm 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, APS- CMOS, PROBA2

1. SWAP ON PROBA2

The PROBA2[1],[2] mission has been launched on 2nd November2009 with a Rockot launcher to a Sun-synchronous orbit at an altitude of 725 km. Its nominal operation duration is two 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 [3]. The mission is tracked and data downloaded to the ESA Redu Mission Operation Center (near Redu in Belgium).

The Sun Watcher using Active Pixel System detector and Image Processing[4],[5],[6] (SWAP) is a compact instrument which is part of the PROBA2 payload (Figure 1) that observes the Sun in extreme ultraviolet (EUV) and demonstrates the performance of the CMOS-APS technology in space environment. It also proves for the first time a two-mirror off-axis optical system with multilayer coatings for the EUV imaging of the Sun. SWAP provides continuous images of the Sun in a narrow bandpass with peak at 17.4 nm.

The SWAP instrument was built upon the heritage of the Extreme ultraviolet Imaging Telescope [7],[8] (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) performances and an on-board image processing. SWAP also offers the advantage of high image cadence (maximal 3 images per minute, 1 per minute in nominal operations) to monitor transient 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 operational follow-up of SWAP and the scientific evaluation of the results.

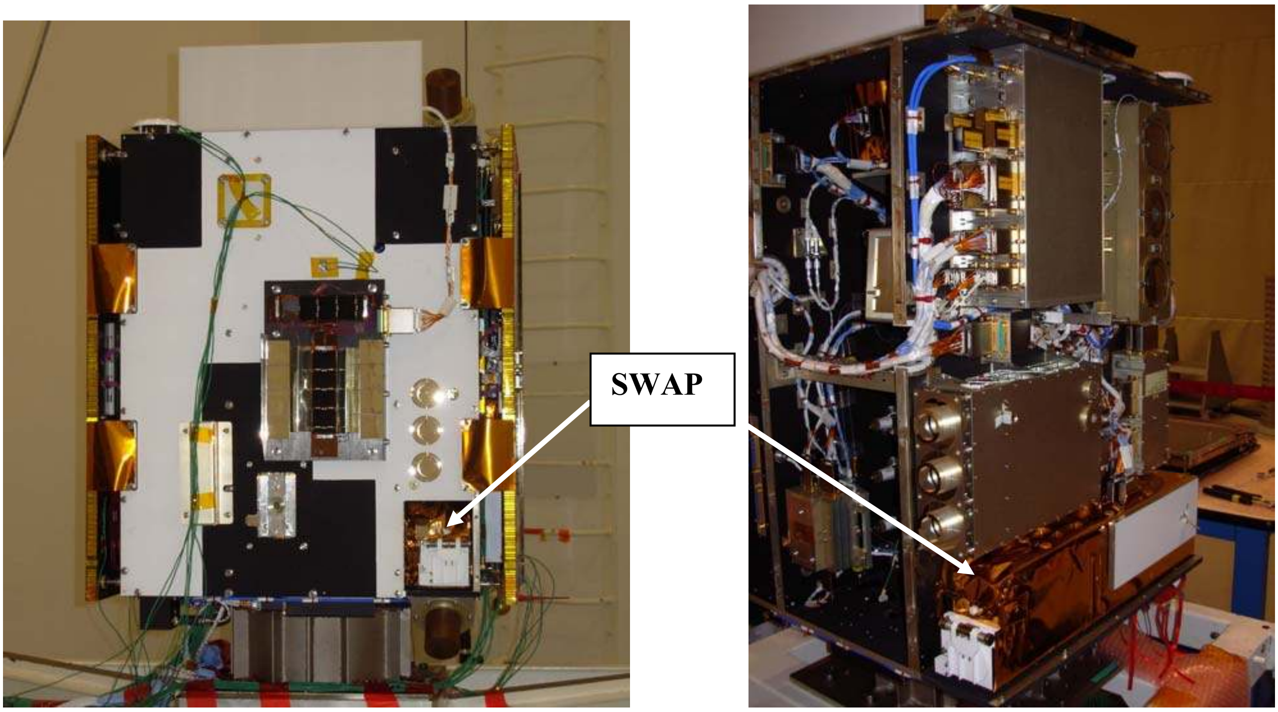


Figure 1. SWAP mounted on the PROBA-2 platform. Left: During acoustic tests of PROBA2 at Intespace, Sun-facing panel. Right: during AIV at Verhaert.

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

Table 1. SWAP main parameters vs. EUVI and EIT instruments

	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: in ecliptic plane	L1 view
Field of view	54 arcmin (3.4 solar radii)	54 arcmin (3.4 solar radii)	45 arcmin (2.8 solar radii)
Pixel size	18 µm (3.16 arcsec)	13.5 µm (1.6 arcsec)	21 µm (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 (Spacecraft)	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 [4],[5],[9],[10].

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 loads.

A mechanical characterization of commercial-standard LUXEL filters has been conducted and led to the selection of 20 lines per inch (lpi) reinforced mesh Nickel grid, with 50 0A polyimide film, to support the 1500 A aluminium filter (Figure 2).

Figure 2. 20 lines per inch Nickel mesh grid filter used as entrance wavelength selection filter of SWAP

Following this new front filter selection, a depressurization test of the SWAP instrument has been performed to validate the two instrument filter's resistance to the pressure variation they have to survive during launch. The air evacuation from the SWAP housing 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.

Figure 3 shows the 0.25 m vacuum chamber of CSL used for this test. Figure 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 was 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.

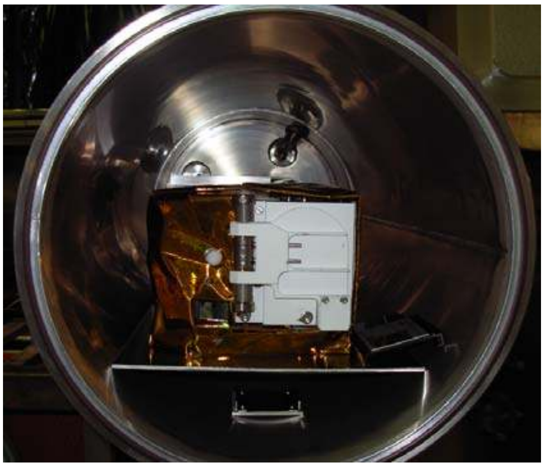


Figure 3. Depressurization test chamber

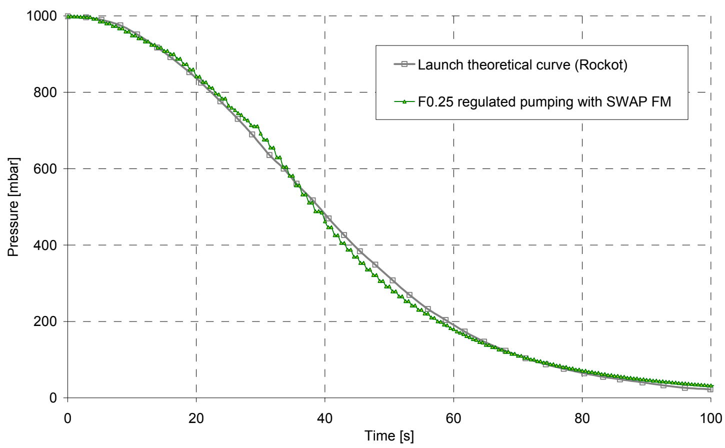


Figure 4. Depressurization slope

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 November 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 December 14 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 (Figure 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).

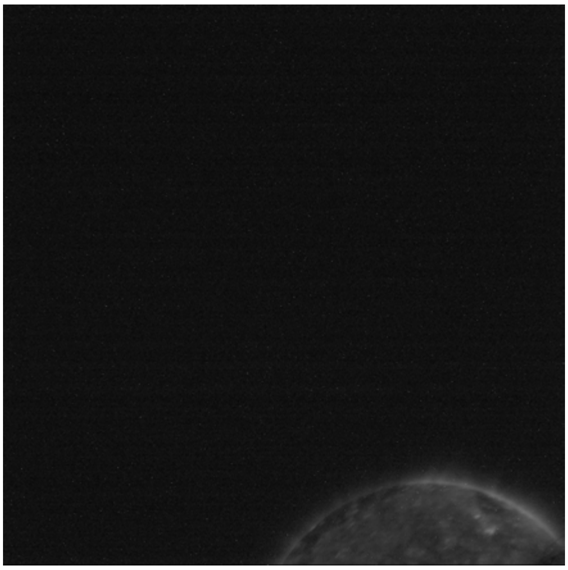


Figure 5. SWAP first light

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.

For this reason, the SWAP detector is 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.

Figure 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.

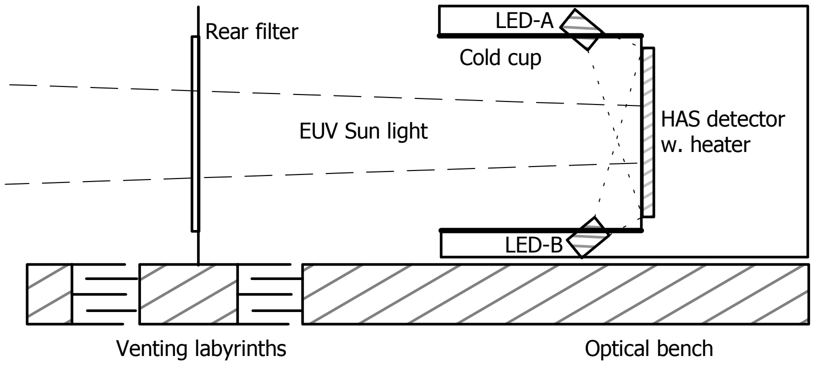


Figure 6. SWAP focal plane assembly and detector cavity. A cold cup surrounds the detector, on which is mounted a heater, and includes two UV calibration LED. Dedicated labyrinths are place around the focal filter to ensure air evacuation during launch.

The SWAP door-opening sequence (shown in the Figure 7) has been run six weeks after launch, ensuring that no air remained 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.

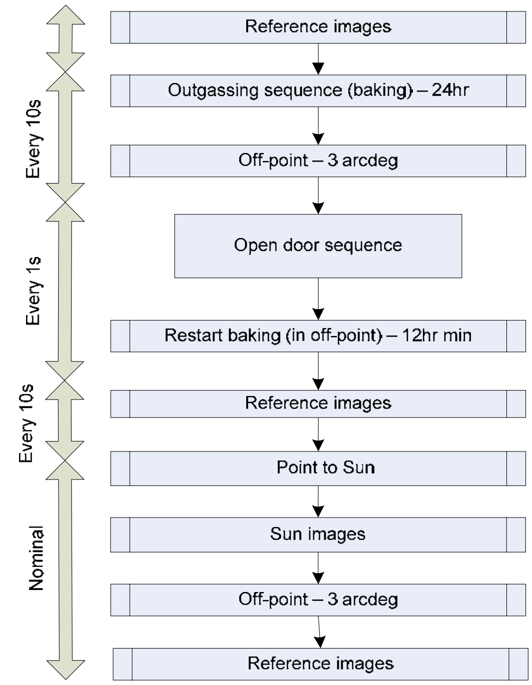


Figure 7. SWAP door-opening sequence (as run in flight)

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 three 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 pointing to center the Sun in the SWAP images, the large angle rotation of the spacecraft (4 every 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 10 s and maximum cadence to 18 s. 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.

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

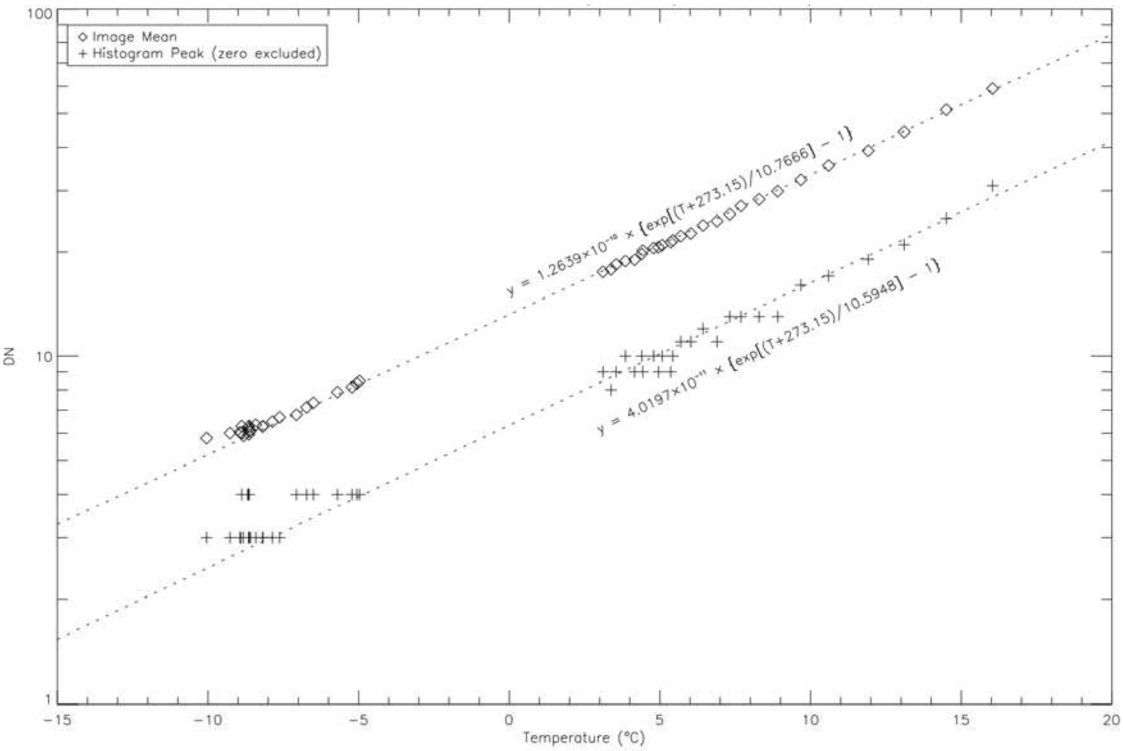


Figure 8. SWAP dark current vs. temperature (image mean and histogram peak).

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 in Figure 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 Figure 6. Nevertheless, these patterns are sufficient to monitor the detector evolution and quantify its response.

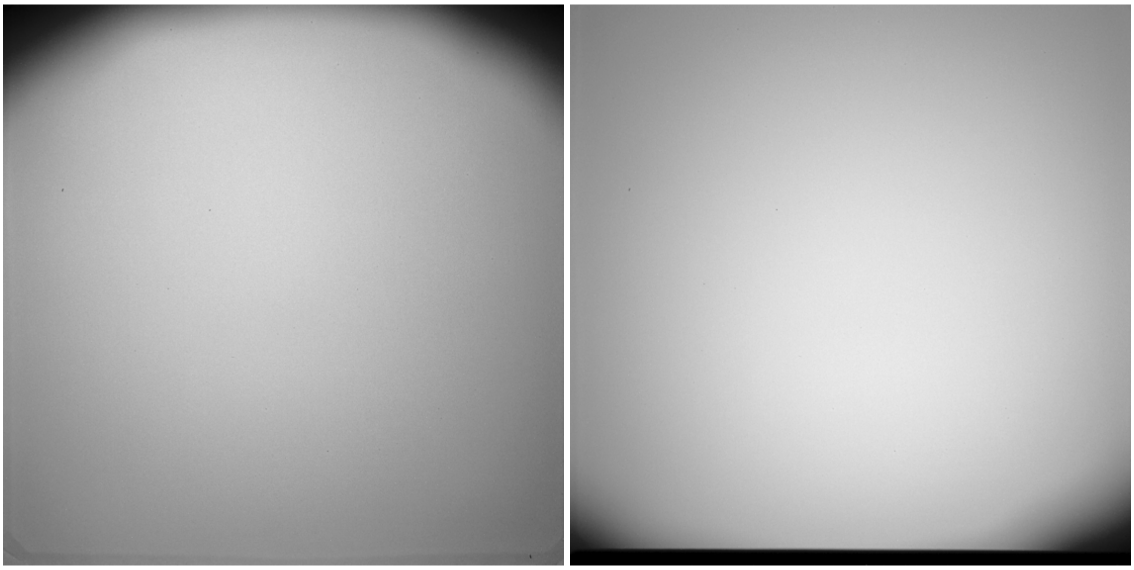


Figure 9. SWAP UV calibration LED-A and LED-B images

Since the instrument switch-on in November 2009, series of 3-seconds correlated double sampling (CDS), also named « NDR » (for Non Destructive Readout), dark and LED images have been taken at regular intervals and also before- and after- annealing sequences. The mean value of the LED and dark images has been computed and plotted versus time, together with the detector temperature (Figure 10).

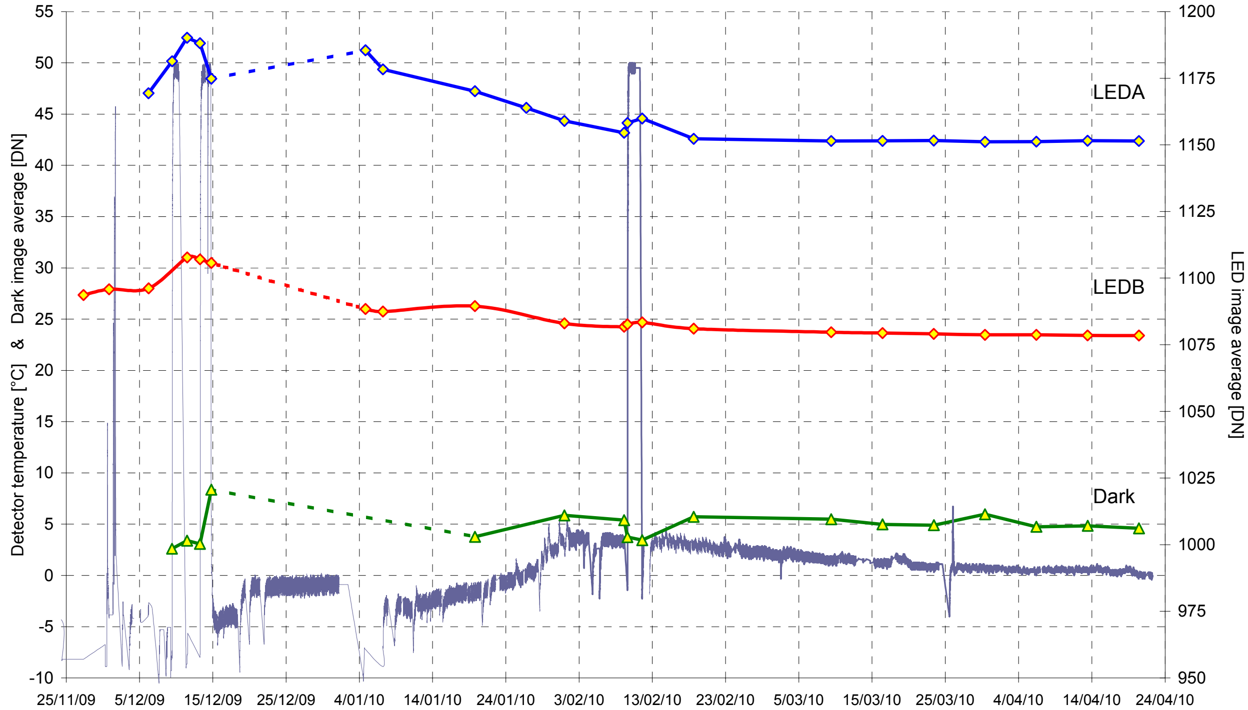


Figure 10. Evolution of temperature and detector response to LEDs and dark images

As shown in Figure 11, not only the dark images but also the LED image mean value is related to the detector temperature. Indeed, the LEDs temperature is following the detector temperature. The detector is indeed very close to the LEDs and is thermally linked to them by the cold cup. Furthermore the 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.

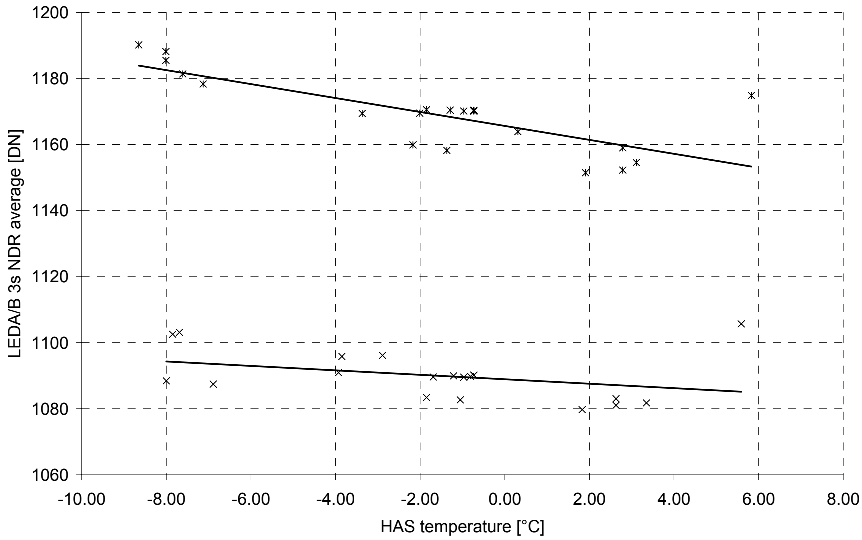


Figure 11. Detector response to LEDs vs. temperature

Since the SWAP door-opening, 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 will be 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).

Figure 12 shows dark images mean values (10 seconds CDS) over 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 0.5 DN. This proves 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[9].

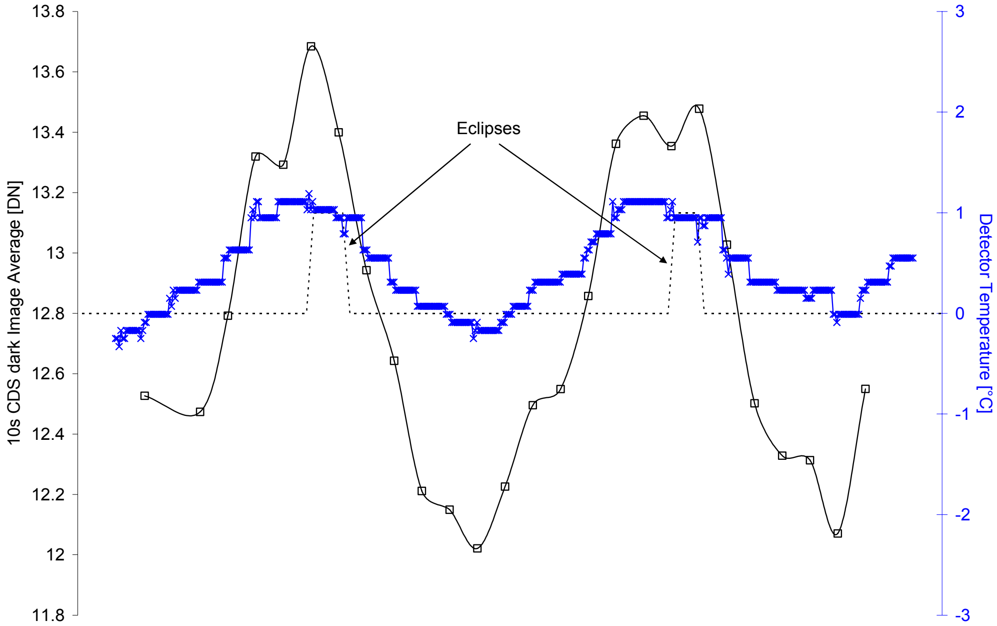


Figure 12. Dark images over two orbits with a 3 arcdeg off-point

Very long exposure images also showed that the off-limb corona does not get bigger with increasing exposure time. This proves that the instrument is not limited by stray-light. The observation limit of the corona is thus determined by the dark current.

4.5 Bright pixels and Cosmic rays

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

As PROBA2 flies in 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 while passing the SAA (example in Figure 13). The spacecraft moves at a speed 25 000 km/h, thus crossing the SAA is a matter of only a few minutes.

One particular event has been observed on 13 January 2010 (Figure 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 cosmic rays.

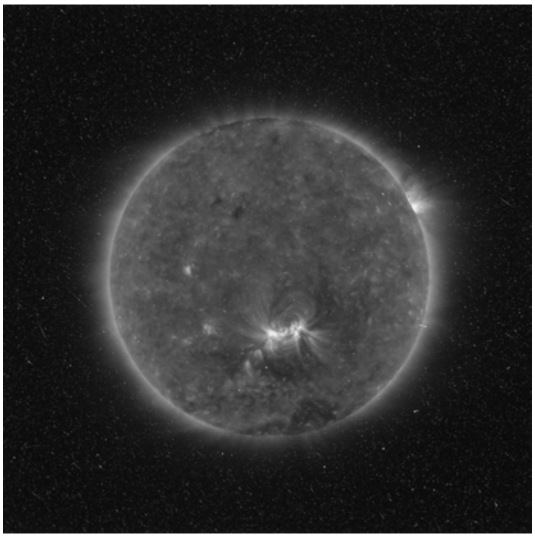


Figure 13. Typical SWAP image showing lots of cosmic rays during passage of the SAA

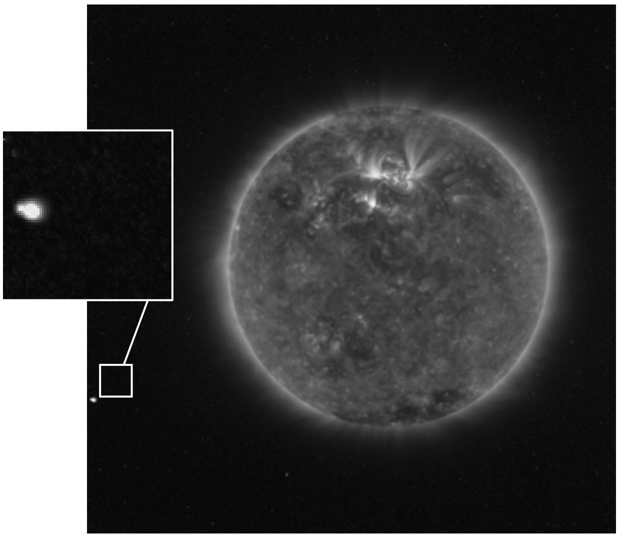


Figure 14. High energy cosmic ray hit the SWAP detector on January 13 2010

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 Figure 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 is shown in Figure 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.

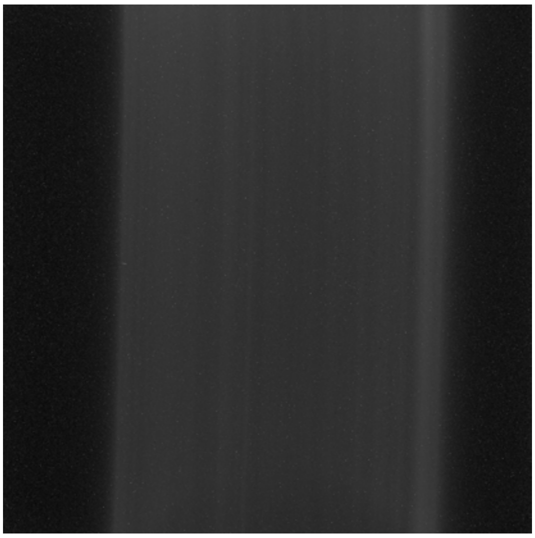
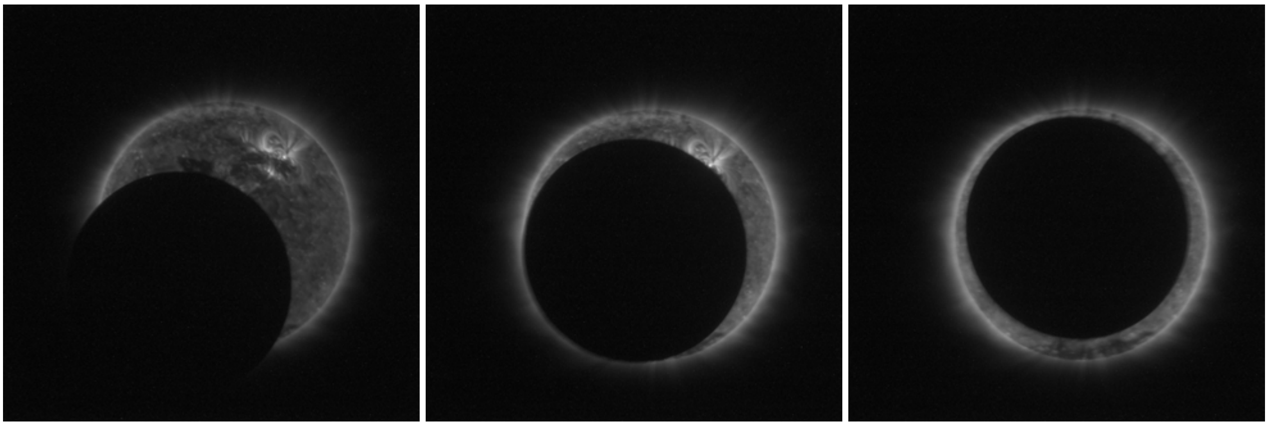


Figure 15. Flat fielding using spacecraft off-point movement



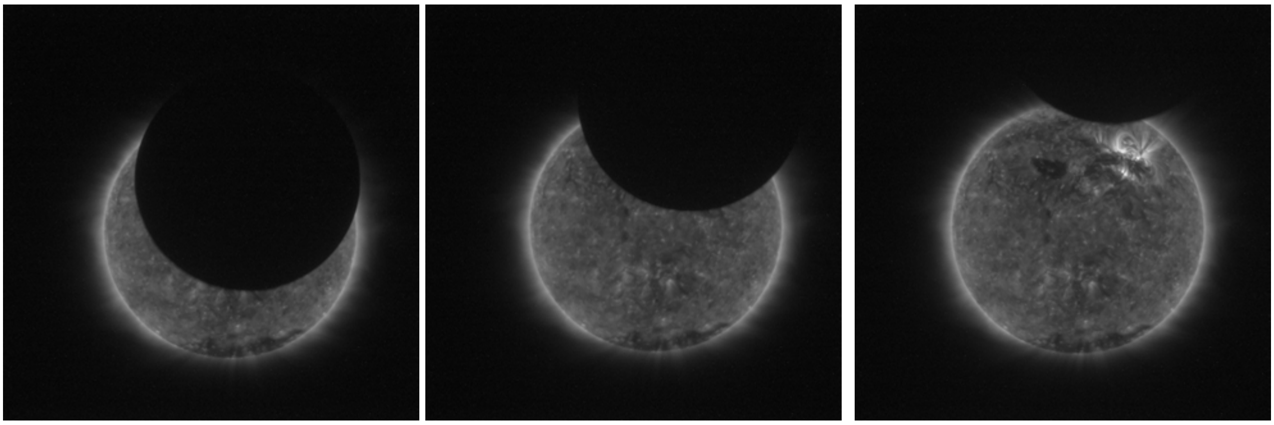


Figure 16. January 15, 2010 Annular Solar Eclipse

4.8 Image processing

The raw images are first reformatted, decompressed and saved into engineering (or Level-0) FITS files with a header containing all information on acquisition and processing times, spacecraft pointing and 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 Level-1) 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 on board.
- 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

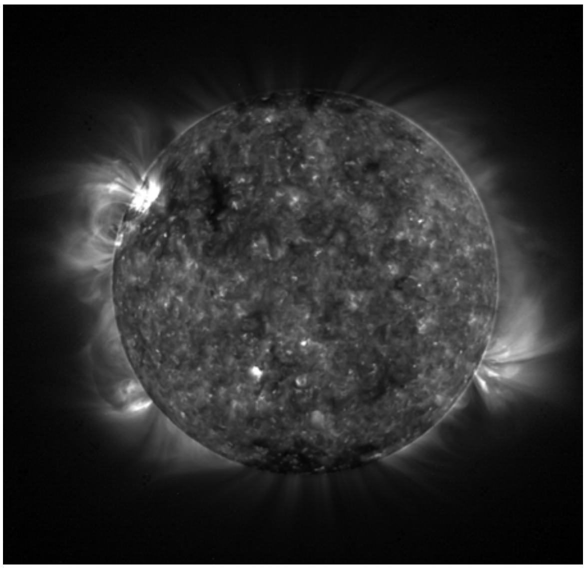


Figure 17. Processed image

- 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.

The image shown in Figure 17 received, apart from the nominal procedures, some extra processing to enhance the off-limb region.

An average of 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, sorted 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 used in the frame of space weather and solar science. It provides high temporal cadence up to 18 seconds (1 minute nominal), of 10 seconds exposure duration, with limited blooming due to CMOS detector, and onboard data processing and prioritization.

Data are available in near-real time (9 passes/24 hours with image priorities). Off-pointing capabilities (automatically) also provide the capabilities of CME tracking up to a few degrees by a flexible commanding from the PROBA2 Science Center.

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

ACKNOWLEDGEMENTS

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