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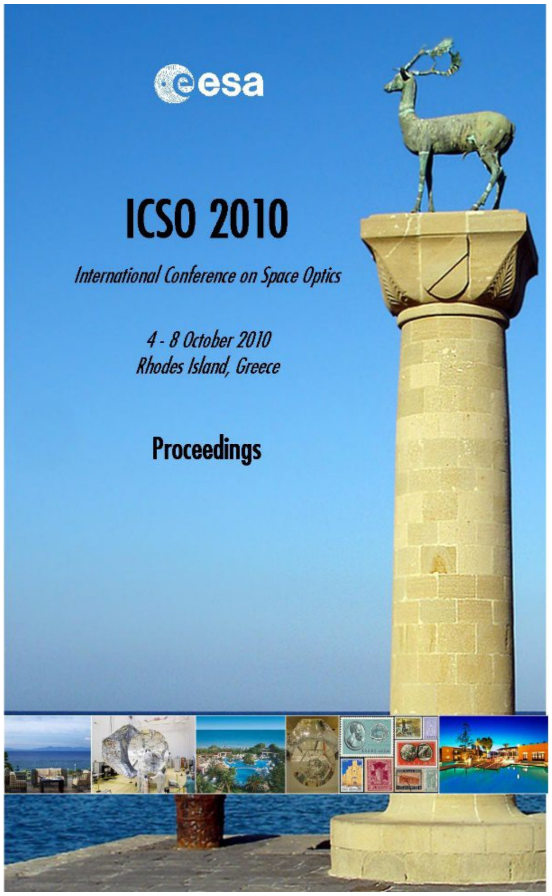

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PERFORMANCES OF SWAP ON-BOARD PROBA2

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I. SWAP ON PROBA2:

The PROBA2 [1] 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 [2]. The mission is tracked by the ESA Redu Mission Operation Center.

The Sun Watcher using Active Pixel System detector and Image Processing [4][5][6][8] (SWAP) is a compact instrument on PROBA2 that observes the Sun in extreme ultraviolet (EUV) at 17.4nm and demonstrates the performance of the CMOS-APS technology in space environment. It also demonstrates the use of a two-mirror off-axis optical system with multilayer coatings for the EUV imaging of the Sun. The SWAP field of view is larger than EIT [3][7] to follow 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, 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.

II. 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. The SWAP door-opening sequence has then been run, six weeks after launch. On December 14 2009, at 07:43, following sets of reference images (dark and LEDs), the detector has been annealed for 24 hours at +50°C, the spacecraft off-pointed (3-arcdeg) to avoid Sun EUV light directly hit the detector surface at the time the door was opened, and the SWAP door (which can open only once and never reclose) has been opened. The door-opening sequence has then been followed by a second annealing sequence of 12 hours to ensure residual contaminants on the optical surfaces would leave the instrument cavity.

First light was obtained 12 hours later (Fig. 1). Dark and LEDs reference images were taken before and after this first light to quantify a possible direct degradation by Sun illumination. The Sun pointing and the spacecraft stability were not fully adjusted at the time of the first light, but the image proved that the instrument was working nominally (EUV filters, mirrors, detector, and electronic). Spacecraft stabilization and pointing quickly result in better images (Fig. 2).

III. IN-FLIGHT PERFORMANCES:

A. 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 (compression factor of 2.5 to 3).

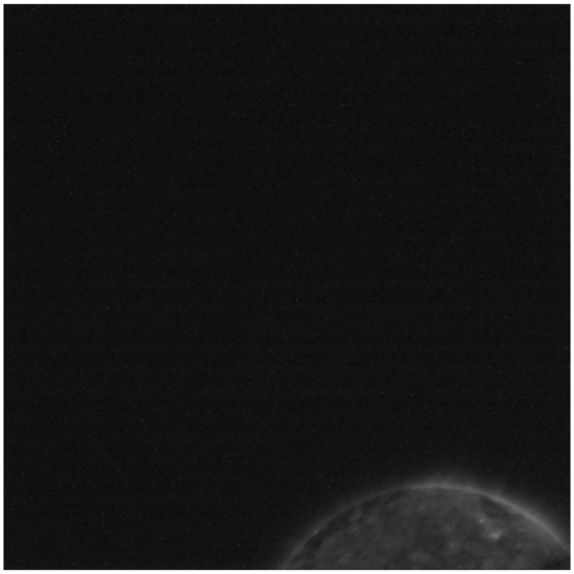

Fig. 1. SWAP first light

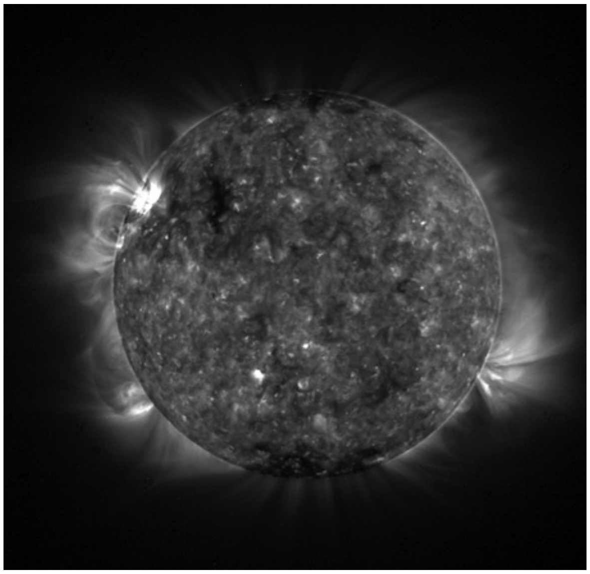

Fig. 2. SWAP typical image

B. 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. In the operational range, which is around 0°C, approximately 1DN per degree has to be counted for (Fig. 3). To cope with this temperature effect and the particularity of the APS sensor, whose pixels all behave independently of the others, individual pixel dark current polynomial fitting (3 parameters per pixel) has been performed to derive a detector dark current map for each image versus its temperature. This dark current map is then removed from the images to improve the image quality.

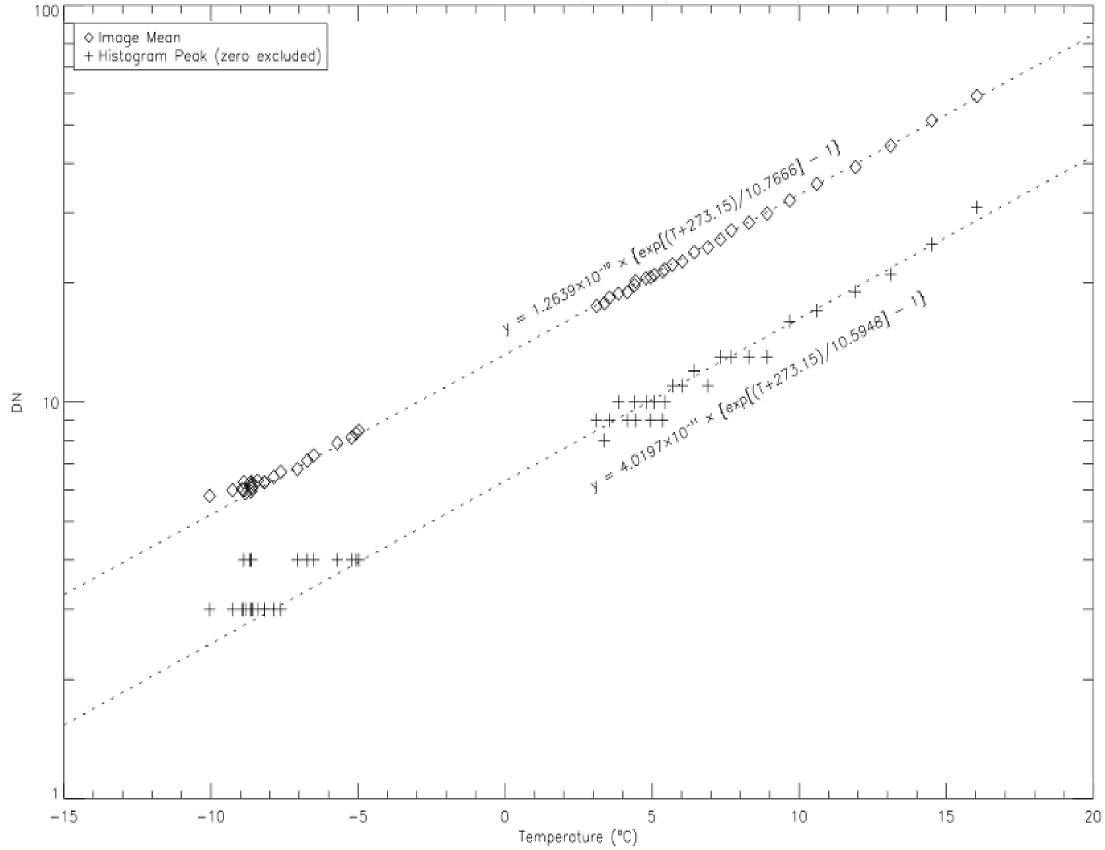

Fig. 3. Dark current (mean and histogram peak)

C. Detector linearity

The detector linearity is characterized by comparing the signal density (in DN) of all the pixels for two images of different exposure duration. In the corresponding density plot, one then have a map where each pair shows the number of pixels that had those values in the two respective images, which can be visualized with blue for lowest density and red for highest density of pixel value pair. Because the detector is nonlinear, the density best fit goes away from the linearity line as the signal level increases. Fig.4 shows the density plot of LED signal in pixels in 6-s images against signal in pixels in 3-s images. If the detector were linear, the density should be located along the line (y = 2x). Because the detector is nonlinear, the density curves away from the line as the signal level increases (up to 5%). The spread near the top of the graph is due to pixels that were not saturated in the 3-s image reaching saturation in the 6-s and falling far below the expected curve. A 5% non-linearity if good considering SWAP is using a commercial (non-scientific) detector.

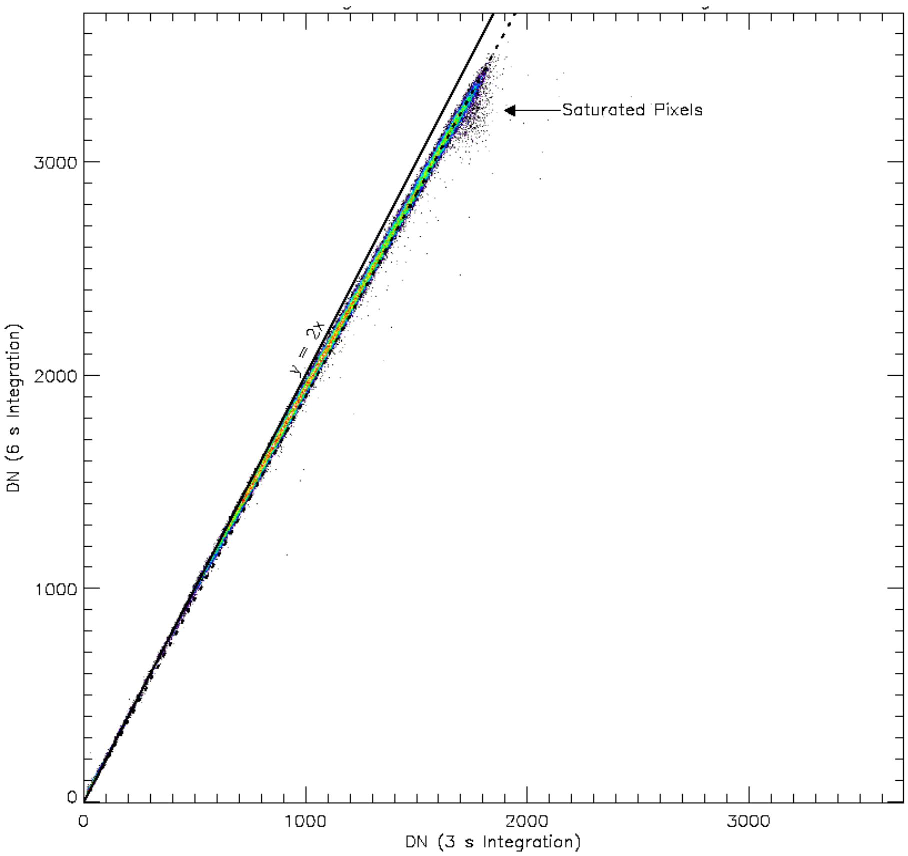

Fig. 4. Linearity plot of 6-s against 3-s images

D. 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). Taking into account the detector temperature variation, the straylight level was then measured as less than 0.5 DN which is negligible. This analysis demonstrated that the LED images could be used for detector response monitoring, when used in off-point, without parasitic solar straylight.

To better quantify the straylight in the SWAP images, series of off-pointed imaged have been taken from 0 to 60-arcmin by steps of 5-arcmin, and from 60 to 180-arcmin by steps of 10-arcmin. The average of each image has been plotted versus the off-pointing angle together with the corresponding ray-tracing model curve [9], the being normalized w.r.t. the Sun-cantered image average (0-arcmin off-point). Fig. 5 shows the matching with the theoretical ray-tracing curve. The straylight level due to the out-of-the field Sun can thus be estimated to be less than 1% of the Sun average. The bump at 70-arcmin is due to lag effect of the detector scintillator coating which gives a remanent image of the Sun that was cantered on the previous image (due to in-flight image sequence constraints). The variations at angles larger than 60-arcmin depend on the dark image used for subtraction and therefore stands for the image noise / non-uniformity.

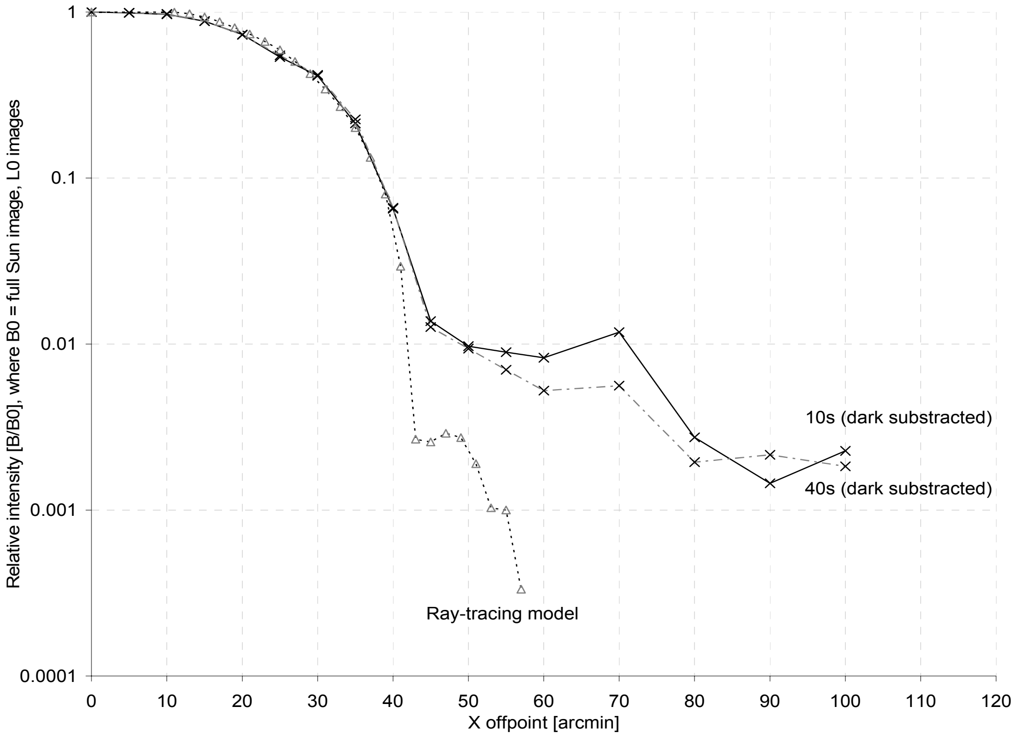

Fig. 5. Off-pointing image average after dark image subtraction

E. Detector response evolution

The detector response evolution is thus monitored using the two focal plane LEDs in an off-point mode to avoid Sun illumination (as there is no shutter in SWAP and door cannot be re-closed). Since the instrument switch-on in November 2009, series of 3-seconds correlated double sampling (CDS), dark and LED images have been taken at regular intervals and also before- and after- annealing sequences. The average image value has been plotted over time with the detector temperature (Fig. 6).

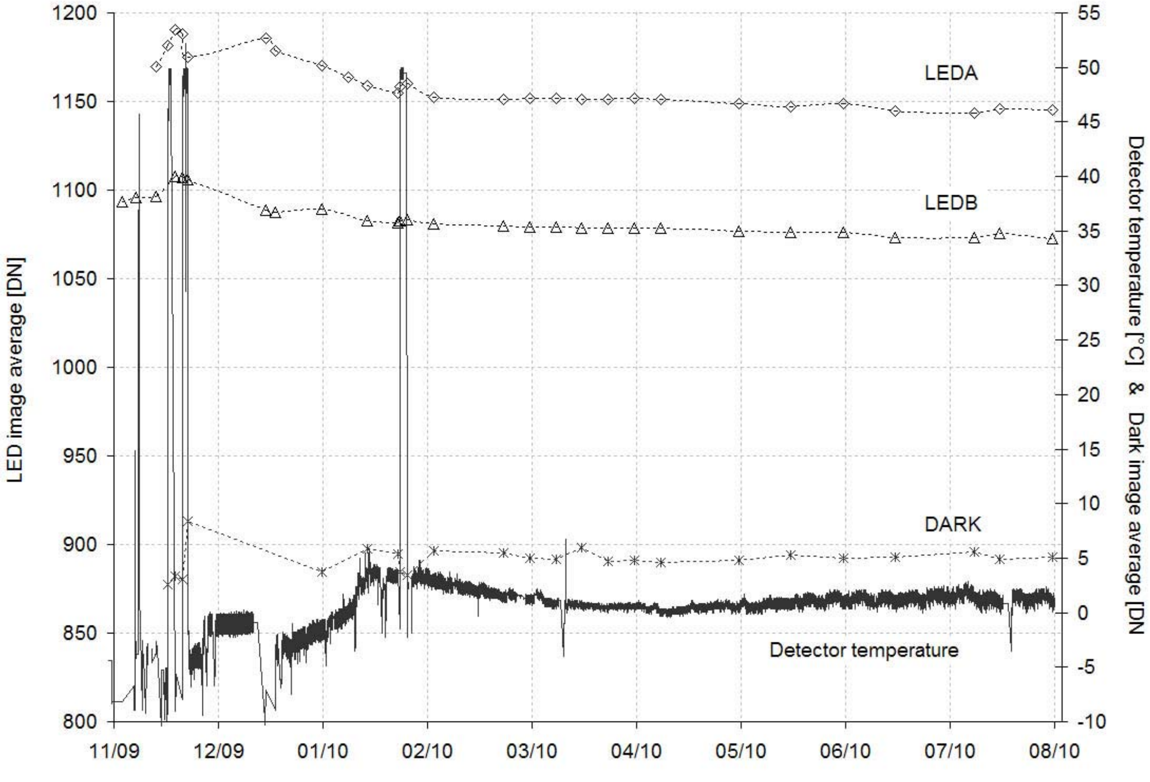

Fig. 6. Temperature and detector response evolution since launch

The correlation between LED image average value and the focal plane cavity temperature (monitored via the detector temperature sensor) is due to LED emissivity which is inversely proportional to its temperature. On view of these plots, we can however conclude that, up to now, the detector response convolved with LED emissivity is stable and that no degradation can be observed. Since launch, only two annealing sequences of the detector have been performed but without significant effect on the detector response to LED illumination. This indicates that the contaminant level is probably low. Nevertheless, annealing will be performed on a regular basis to ensure possible new contaminants are released.

F. Plate scale

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 Fig. 7. The eclipse was the opportunity to cross-check the SWAP plate scale (3247.37 [arcsec] along X axis, i.e. 54.123 arcmin, and 3238.16 [arcsec] along Y axis, i.e. 53.969 arcmin).

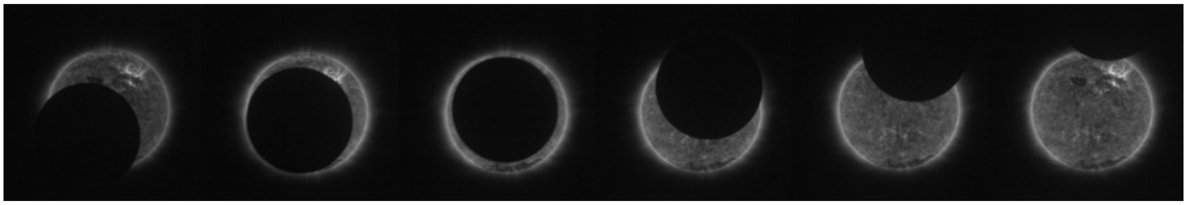

Fig. 7. January 15, 2010 Annular Solar Eclipse

G. 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 neighbouring 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 being sent to the ground, but a slight increase of these 'hot pixels' (0.5% in 6 months) may be due to the orbit pass through the South Atlantic Anomaly (SAA).

IV. IMAGE PROCESSING:

The raw images are first reformatted, decompressed and saved into engineering (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 on-board and on-ground processed to produce base science (Level-1) FITS files:

- On-board correction of 'bad' pixels replaced by their neighbours average, and of saturated or missing pixels.
- On-ground subtraction of dark current, image orientation and centring, normalization to the exposure time.

Additional extra processing is also performed to enhance the off-limb region.

An average of 750 daily images is taken with on-board compression and recoding. 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 and movies files for quick look purposes

V. CONCLUSIONS AND ACKNOWLEDGEMENTS:

SWAP is a successful technological demonstration instrument. Its first use a CMOS-APS for space solar science with specific scintillator coating. It also takes advantage of a low power passive thermal control providing nominal optical quality even at high operational temperature. Optical performances are also nominal (no grid effect, no visible straylight). In-flight performance analyses have been started during commissioning, and are continued to improve knowledge of the instrument behaviour and capabilities. SWAP is thus a preparatory instrument for other similar EUV Imagers, from which lessons will be derived and expertise gained with CMOS detectors camera will be re-used.

SWAP is also used in the frame of space weather and solar science, providing 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.

The SWAP instrument was developed by Centre Spatial de Liège (University of Liège, B) in collaboration with the Royal Observatory of Belgium (B). Support for calibration was provided by the Max Planck Institute for Solar System Research (D). Belgian activities are funded by the Belgian Federal Science Policy Office (BELSPO), through the ESA/PRODEX program.

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