SWAP onboard PROBA 2, a new EUV imager for solar monitoring ⋆

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Abstract

SWAP (Sun Watcher using Active Pixel system detector and image processing) is a solar imager in the extreme ultraviolet (EUV) that has been selected to fly in 2006 on the PROBA 2 technological platform, an ESA program. SWAP will use an off-axis Ritchey Chrétien telescope equipped with an EUV enhanced active pixel sensor detector (coated APS). This type of detector has advantages that promise to be very profitable for solar EUV imaging. SWAP will provide solar coronal images at a 1 min cadence in a bandpass centered on 17.5 nm. Observations with this specific wavelength allow detecting phenomena, such as solar flares or EIT-waves, associated with the early phase of coronal mass ejections. Image processing software will be developed that automatically detects these phenomena and sends out space weather warnings. Together with its sister instrument LYRA, also onboard PROBA 2, SWAP will serve as a high performance solar monitoring tool to be used in operational space weather forecasting. The SWAP data will complement the solar observations provided by instruments like SOHO-EIT, and STEREO-SECCHI.

Key words: Instrumentation: detectors, Space vehicles: instruments, Techniques: image processing, Telescopes, Sun: corona, Sun: UV radiation
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1 PROBA 2, a micro-satellite as solar observatory

PROBA 2 is a follow up of the successful PROBA 1 (Teston et al., 1999) program, in orbit since October 2001. The spacecraft is a micro-satellite not larger than a domestic washing machine with a weight of 100 kg. It will be launched in the second half of 2006 as a piggy back payload, to reach a heliosynchronous polar orbit stabilized at 10:30. PROBA 2 has two main mission objectives: (i) perform an in-flight demonstration of a series of new spacecraft technologies and (ii) support a scientific mission of a set of selected instruments. As on PROBA 1, the platform technology demonstrations are in the field of avionics, spacecraft attitude control, power system and spacecraft propulsion. In addition, also the payload instruments contain important technological innovations (see below).

As its secondary scientific objective, PROBA 2 will be an observatory for studying the UV and EUV variability of the Sun. The two major components of the scientific payload are SWAP (Sun Watcher using APs detectors and image processing) and LYRA (LYman Alpha Radiometer). LYRA (Hochedez et al., 2004) is a small, compact solar UV radiometer, equipped with newly developed diamond detectors which are blind to the visual light. LYRA will monitor the variability of the solar irradiance in four ultraviolet pass bands, carefully selected for their relevance to aeronomy, space weather and solar physics. Both SWAP and LYRA are developed under the technical management of Centre Spatial de Liège (CSL, Belgium). After launch they will be operated from the Royal Observatory of Belgium (ROB, Brussels) as principle investigator's institution. Two more instruments are onboard for measurement of the local plasma environment of the spacecraft: the 'Thermal Plasma Measurement Unit' (TPMU) and the 'Dual Segmented Langmuir Probe' (DSLP).

SWAP has been proposed as a successor of the Extreme ultraviolet Imaging Telescope (EIT) onboard the joint ESA-NASA mission SOHO (Delaboudiniere et al., 1995). SWAP will continue the systematic 'CME watch' program (CME=coronal mass ejection) of the ageing EIT instrument for systematic detection of space weather related solar events. SWAP will have a higher image cadence than EIT (1 min versus 12 min) and a 20% larger field of view. Both SWAP and LYRA will be operated as solar monitoring instruments but it is important to realize that the PROBA 2 orbit only offers Sun visibility during slightly more than 50% of every orbit of 95 min.

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2 Technical innovations

As a part of a technology demonstration mission, SWAP contains several technical innovations which are necessary to stay within the very strict resource budget: SWAP mass is limited to 10 kg, with a mean power dissipation lower than 5 W. The SWAP telescope is based on a novel off-axis Ritchey-Chrétien scheme (Defise et al., 2004). The off-axis design leads to several advantages: (i) smaller and lighter primary mirror for a given pupil area (no central obscuration); (ii) smaller aluminum foil filter thus reduced risk of mechanical damages; (iii) easy and efficient baffling system without protruding parts. The optics and focal plane assemblies will be mounted on an optical bench designed to provide mechanical stability and insensitivity to thermal variations, better than 50 micrometers between the two mirrors of SWAP.

The SWAP sensor will be a new CMOS (complimentary metal oxide semiconductor) APS detector from Fillfactory N.V. (Belgium), recently developed as an improved version of the STAR1000 sensor (Dierickx et al., 1997) for high-accuracy star tracking. SWAP will be equipped with the first CMOS APS detector used in space for solar physics. The sensor will consist of 1024x1024x18μm active pixels, that can be operated linewise independently. In contrast to a CCD, a CMOS detector does not transport the charges from pixel to pixel during a read-out. This brings the advantage that SWAP will not need a shutter, leaving the one-shot door as the only mechanism of the telescope. Furthermore, the sensor provides non-destructive read-out functionality which will be used for 'Correlated Double sampling' to lower the static sensor noise. The sensor surface is covered by a scintillator coating for EUV sensitivity. Besides the sensor, the focal plane will include the proximity electronics required to readout the sensor and to drive the calibration diodes. An additional feature is the decontamination heater that will be periodically used to outgas eventual condensation on the sensor, which is passively cooled by a radiator viewing

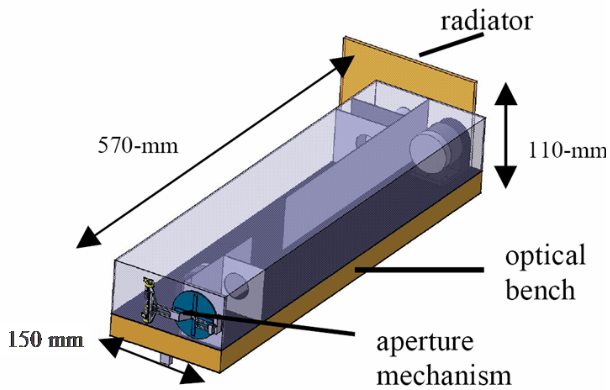

Fig. 1. SWAP sensor box

cold space, in order to lower the thermal noise.

The proximity electronics is connected to a c-PCI card that is directly plugged in the central computer of PROBA 2. This card is called the MCPM (Memory, Compression and Packetisation Module) and will provide the storage (max 500 MByte) for the acquired data. The close integration of the instrument electronics and the central PROBA 2 computer has the advantage that spare CPU resources of the platform can be used to run the SWAP onboard software. Besides driving the instrument electronics, this software will also do image compression and automatic event detection. For the image compression a choice is foreseen between JPEG (lossy) and LZW (lossless). To optimize the compression, several preprocessing steps are applied on the data such as removal of cosmic ray hits and weak pixel compensation. More importantly, the compression is preceded by a re-coding step that reforms the original 12bit image to 8bit. This step is lossy in the mathematical sense but lossless in the physical sense, as the data alteration is smaller than the uncertainty resulting from the photon shot noise. The combination of the preprocessing and recoding steps, together with the JPEG compression, results in compression factors of a factor 7.5 with very acceptable data quality. Relatively good data quality is maintained up to compression factors 15. On top of the image compression, the total volume of required telemetry can optionally be further reduced through image prioritization. This means that the SWAP onboard software will be able to do simple event recognition and send the images that e.g. show a flare event with first priority to the telemetry. The remaining, lower priority, data is then only sent as far as more telemetry remains available.

3 SWAP images

The aspheric mirrors are polished from zerodur with a micro-roughness below 0.5 nm. The EUV reflectivity and spectral selection is provided by specific multilayer coatings deposited on the mirrors. The mirrors will be coated by Institut d'Optique Théorique et Appliquée(IOTA, France). The coating is a mutilayer composed of 30 alternating layers of 2 different materials (Mo/Si) optimized for the best near normal reflection in the 1.3 nm band centered on 17.5 nm. First results of efficiency measurements made on test sample mirrors are shown in Fig. 2. The peak reflectance of 40.5% is well above the performance of the EIT mirrors (Delaboudiniere et al., 1995).

A bandpass centered at 17.5 nm was chosen because it covers the brightest spectral lines of iron ions emitted by the solar corona in a low and medium activity state and very well accords with high reflectivity of the Mo/Si coating and maximal transparency of aluminum filters after the cut-off of 17.0 nm. This band is fruitfully exploited for more than 3 years in the solar telescope

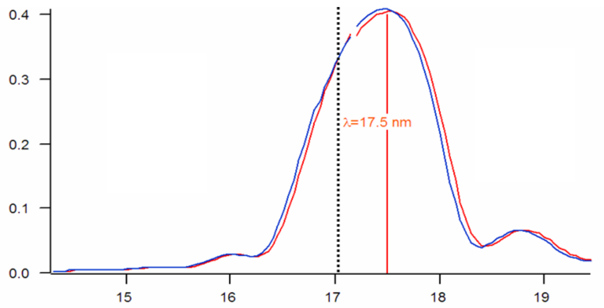

Fig. 2. Reflectivity (1 bounce) provided by the multilayer coating on a test sample. The bandpass is $\tilde{1}.3$ nm, with peak reflectivity of 40.5 % (source: IOTA). The separation between the two lines correspond to the range of incidence angles on the mirror (1 and 4 degrees). The dashed line outlines the aluminum cut-off of the front filter below which no photons enter the telescope.

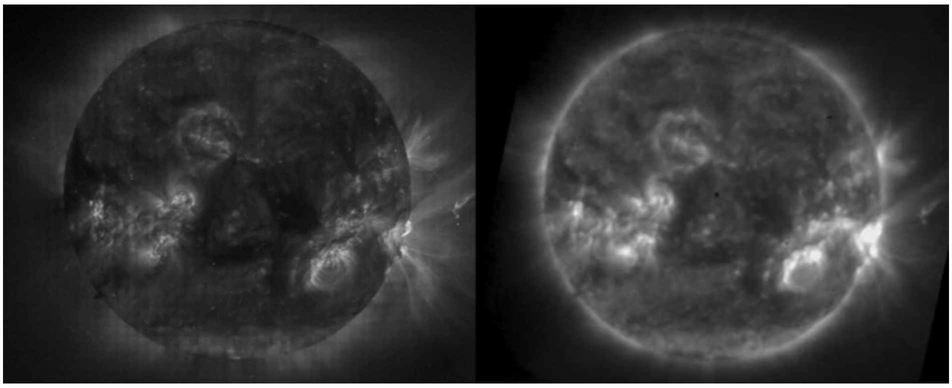

Fig. 3. EIT 19.5 nm bandpass (left) compared with SPIRIT 17.5 nm bandpass (right) with only 25 sec difference in observation time. The dynamic range in the EIT 19.5 nm bandpass is slightly larger than in the SPIRIT 17.5 nm bandpass (e.g. the contrast between active regions and coronal holes. Both images show an ejection at the right hand side of the image.

SPIRIT onboard the Russian CORONAS mission (Zhitnik et al., 2002). In Fig. 3 we show a comparison between the images in the EIT 19.5 nm channel and the SPIRIT 17.5 nm. Besides the obvious difference in spatial resolution, which is not related to difference in central wavelength, the two images show a good correspondence. In general, the dynamic range of a signal from dark coronal holes to bright active region cores appears smaller at 17.5 nm than at 19.5 nm, which better fits to our 12 bit coding scale.

Estimations of the telescope throughput based on the CHIANTI code (assuming ionization equilibrium) for spectral line intensities (Dere et al. (1997), Young et al. (2003)) convolved with the test mirrors reflectivity function show (Table 1) that the main part of a signal corresponds to FeIX-XI ions with maximum excitation temperatures log Tmax = 5.9-6.1. This range corresponds to the smooth maximum of the Differential Emission Measure functions for quiet Sun, coronal holes and active regions. For quiet Sun it gives 20% more signal

Table 1
Preliminary estimation of the relative contribution of different spectral lines with maximum excitation temperature Tmax in the SWAP bandpass.

	log T max	Quiet Sun	Active Region	Coronal hole	Flare
O VI	5.5	0.7%	0.5 %	4.7 %	2.6%
Fe VIII	5.8	0.5%	0.3%	1.6%	0.5%
Fe IX	5.9	38.2%	31.6%	57.5%	26.0%
Fe X	6.0	51.4%	54.6%	31.8%	35.1%
Fe XI	6.1	8.9%	11.5%	2.3%	7%
Fe XII	6.2	0.3%	0.4%	0.0%	0.3%
Fe XX	6.9	0.0%	0.0%	0.0%	14.3%

than traditional FeXII 19.5 nm band (log Tmax = 6.2) or FeIX-X 17.1 nm band (log Tmax = 5.8-6.0). In flares there is a significant (14%) contribution of FeXX ion lines (log Tmax= 7.1), which is much less than the contribution of the FeXXIV line in the EIT 19.5 nm channel. Low temperature FeVIII and OVI ions give very small input. According to the SPIRIT results (Slemzin et al., 2004), the SWAP 17.5 nm band will be effective for observation of CME-associated phenomena such as EIT waves, dimmings, off-limb ejecta (see also Fig. 3), etc.

The field of view (FOV) covered by SWAP (54 arcmin) will be 20% larger than the FOV covered by EIT (45 arcmin) (see Fig. 4). Moreover, the spacecraft will allow for off-pointings from the strict sun centering to allow for far-off disc imaging.

First estimations of the overall telescope throughput show that full well is achieved for active regions after an integration time of 20 sec. As a baseline, the SWAP image acquisition rate will be at 1 image per minute.

4 Science and space weather services

The SWAP design will allow to image the various solar drivers of space weather such as coronal holes, flares and last but not least coronal mass ejections. Thanks to its enlarged field of view and higher cadence, SWAP will be better suited than EIT to catch eruptions above the limb. Also on-disc signatures of coronal mass ejections, such as EIT waves and dimmings will be better

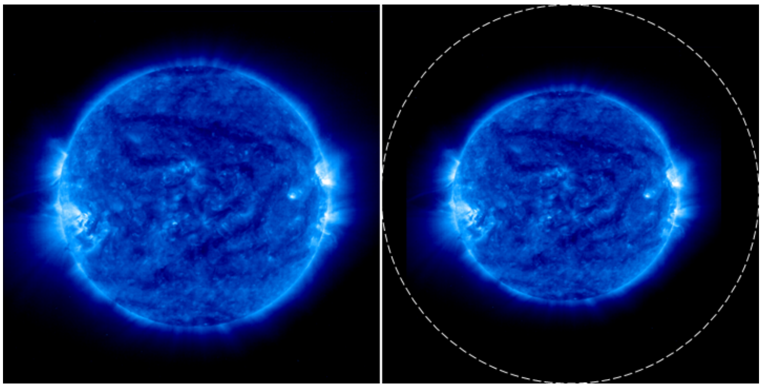

Fig. 4. The 20 % larger field of view of SWAP is shown on the right. The circle corresponds to 1.67 solar radii. The corners of the SWAP field of view correspond to 2.36 solar radii. On the left we show for comparison the original EIT image that was used as input.

observed. With the nominal EIT cadence of 12 min, an EIT wave is typically observed in 3-4 images. This is sufficient to detect the event and to determine its source, but it is not sufficient to do a much deeper scientific analysis. SWAP will have an order of magnitude more images per event which will make it possible to track the front of the wave, determine its dispersive proporties and study the interaction of the EIT-wave with coronal structures such as active regions or coronal holes.

Automated processing pipelines will be developed, which will, on the basis of feature/event recognition techniques, automatically detect the above mentioned space weather driving events and report these to the space weather community through the SIDC (Berghmans et al., 2002). The SIDC is a regional warning center of the International Space environment Service and a Service Development Activity of ESA's Pilot Project for Space Weather Applications (also called SWENET). Both SWAP and LYRA will be operated as solar monitoring instruments but it is important to realize that the PROBA 2 orbit only offers Sun visibility during slightly more than 50% of every orbit of 95 min.

The PROBA 2 mission, with SWAP and LYRA, will overlap significantly with the NASA STEREO mission. The EUV imagers of the STEREO/SECCHI (Moses and et al, 2000) mission (NASA) will have a similar spectral bandpass at 17.1 nm, making SWAP a potential third eye of this 2-spacecraft mission. Also joint campaigns with SOHO (if still active), Solar-B or ground based instruments can be foreseen.

5 The Road ahead

Despite a non optimal orbit and very limited platform resources, a solar payload will be operated on a technology demonstration micro-satellite. SWAP and LYRA have been designed to provide valuable inputs for space weather monitoring and new data for scientific research.

SWAP and LYRA will demonstrate the feasibility of key-technology that will be highly beneficial in the context of the Solar Orbiter ESA mission. New detectors, new compact optical scheme and on-board processing are essential elements for this ESA mission scheduled for the 2011-2013 time frame.

SWAP will have an open data policy. Analysis software and data will be distrubed through the website http://swap.oma.be. We welcome interested colleagues to analyse the SWAP data, to plan special observation campaigns or to join the co-investigators team.

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