ASPIICS: an externally occulted coronagraph for PROBA-3. Design evolution.

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ABSTRACT

PROBA-3 is a mission devoted to the in-orbit demonstration of precise formation flying techniques and technologies for future ESA missions. PROBA-3 will fly ASPIICS (*Association de Satellites pour l'Imagerie et l'Interferométrie de la Couronne Solaire*) as primary payload, which makes use of the formation flying technique to form a giant coronagraph capable of producing a nearly perfect eclipse allowing to observe the sun corona closer to the rim than ever before. The coronagraph is distributed over two satellites flying in formation (approx. 150m apart). The so called Coronagraph Satellite carries the camera and the so called Occulter Satellite carries the sun occulter disc. This paper is reviewing the design and evolution of the ASPIICS instrument as at the beginning of Phase C/D.

Keywords: PROBA-3, ASPIICS, solar physics, coronagraph, formation flying, in-orbit demonstration.

1. INTRODUCTION

1.1 Mission objectives

PROBA-3 is a mission devoted to the in-orbit demonstration (IOD) of precise formation flying (F²) techniques and technologies for future ESA missions. It is part of the overall ESA IOD strategy and it is implemented by the Directorate of Technical and Quality management (D/TEC) under a dedicated element of the General Support Technology Programme (GSTP). In order to complete the end-to-end validation of the F² technologies and following the practice of previous Proba missions, PROBA-3 includes a primary payload that exploits the features of the demonstration. In this case it is a giant 150 m sun coronagraph capable of producing a nearly perfect eclipse allowing observing the sun corona closer to the rim than ever before or in any planned mission. The coronagraph is distributed over the two satellites flying in formation.

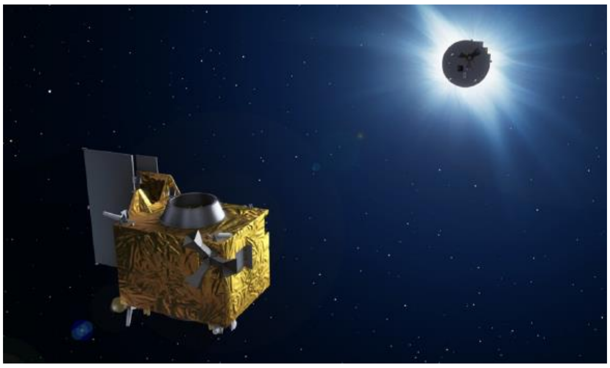

Figure 1. PROBA-3 artist impression (courtesy of ESA).

The so called coronagraph satellite (CSC) carries the "detector" and the so called occulter satellite (OSC) carries the sun occulter disc. A secondary payload will be embarked on the occulter satellite, it consists of the DARA solar radiometer.

1.2 Science objectives

Although recent space solar missions probed the solar corona in a wide range of heights, the region within the sonic point (around 2 – 3 solar radii from the solar center), where the solar wind is accelerated and coronal mass ejections (CMEs) are initiated remains extremely difficult to observe with spatial resolution and sensitivity sufficient to understand these phenomena. Progress on this front requires eclipse-like conditions for long periods of time. The rare minutes of total eclipses of the Sun currently present the only opportunities for a seamless view of the corona. This does not allow studying the coronal dynamics and eruptive phenomena during a sufficient amount of time to analyze its magnetic structure and the ubiquitous processes of dissipation of the free magnetic energy. Space-borne coronagraphs were designed and flown to provide a continuous coverage of the external parts of the corona but their over-occulting system did not permit to analyze the part of the white-light corona where the main coronal mass is concentrated. The proposed PROBA-3 Coronagraph System, also known as ASPIICS (the French acronym meaning "*Association de Satellites Pour l'Imagerie et l'Interférométrie de la Couronne Solaire*"), with its novel design will be the first space coronagraph to cover the range of radial distances between 1.08 and 3 solar radii (from the solar center) where the magnetic field plays a crucial role in the coronal dynamics, thus providing continuous observational conditions very close to those during a total solar eclipse, but without the effects of the Earth's atmosphere. The ASPIICS unprecedented field of view makes it uniquely suited for studies of the solar corona, as it will fill the crucial observational gap between the fields of view of low-corona EUV imagers and conventional space coronagraphs. ASPIICS will combine observations of the corona in white light and polarization brightness with images of prominences in the He I 5876 Å line. The brightness in white-light images depends only on the coronal electron density (Thomson scattering of photospheric light by free electrons in the corona) integrated along the line of sight (LOS) with a weighting factor depending on the position of the scattering element along the LOS. We thus can avoid disentangling temperature and density information contained in low-corona EUV images.

ASPIICS will provide novel solar observations to achieve the two major solar physics science objectives: to understand physical processes that govern the quiescent solar corona, and to understand physical processes that lead to coronal mass ejections (CMEs) and determine space weather. This investigation is focused on the following objectives that can be addressed by answering a set of science questions (as specified in the Science Requirements Document):

- Understanding the physical processes that govern the quiescent solar corona by answering:
  - What is the fine scale nature of the solar corona?
  - What processes contribute to the heating of the corona?
  - What processes contribute to the solar wind acceleration?
- Understanding the physical processes that lead to CMEs and determine space weather by answering:
  - What is the nature of the structures that form the CME?
  - How do CMEs erupt and accelerate in the low corona?
  - What is the connection between CMEs and active processes on the solar surface?
  - Where and how can a CME drive a shock in the low corona?

2. INSTRUMENT DESIGN

2.1 Overview, design evolution

The PROBA-3 coronagraph optical design follows the general principles of a classical externally occulted Lyot coronagraph. The external occulter (EO), hosted by the Occulter Spacecraft (OSC), blocks the light from the solar disc while the coronal light passes through the circular entrance aperture of the Coronagraph Optical Box (COB), accommodated on the Coronagraph Spacecraft (CSC). A general view of the Coronagraph System is shown in Figure 2.

Requirements

The key design drivers of the coronagraph are summarised as follows:

- To perform white-light coronagraph observations of the Sun corona in both natural and polarized light, with a field of view from 1.08 to 2.7 R_{sun} and with temporal resolution of 2 to 600 s. The term "white light" in this requirement corresponds to a band pass containing coronal continuum between 540 and 570 nm. For polarized light observations, three different polarizers should be used, with orientations of 0, +60, and –60 degrees.

- Within the above bandpass, the coronagraph shall achieve stray light to sun disk light ratios of less than 5 x 10^{-8} for radial distances between 1.08 R_{sun} and 2 R_{sun} and less than 10^{-8} for radial distances above 2 R_{sun}. The signal-to-noise ratio in both white-light and polarized images should be at least 20.
- To perform narrow-band imaging of prominences and the surrounding coronal material in the He I D3 emission line at 587.6 nm ($\Delta\lambda$=1.0 nm), at the cadence of 30 s and spatial resolution of 5.6 arc sec.
- To perform white-light (coronal continuum between 540 and 570 nm) coronagraphic observations of the corona in natural and polarized light, with the field of view from 1.05 to 4 R_{sun} with spatial resolutions of 5 arc sec over the entire field of view.
- To perform high-cadence (2 s) observations of fine-scale structure at different heights (plumes, loops, rays, etc.) in white light (coronal continuum between 540 and 570 nm) with a reduced field of view.

The co-alignment of the two spacecraft's is of course critical for the performances of the instrument. This is not under the control of the coronagraph system but it shall be correctly taken into account to ensure that sufficient margins are taken in order to cover all misalignment risks. The alignment of the instrument with the spacecraft platform shall remain within acceptable limits in order to ensure that the co-alignment of the spacecraft's, performed by external metrology systems, will always provide the correct observation condition. Also, the thermal environment of the Coronagraph shall be correctly defined in order to ensure that the optical bench thermal control system is always fully performing. The radiator for the detector shall remain hidden from Sun and Earth as much as possible in order to limit the recovery time from detector heating.

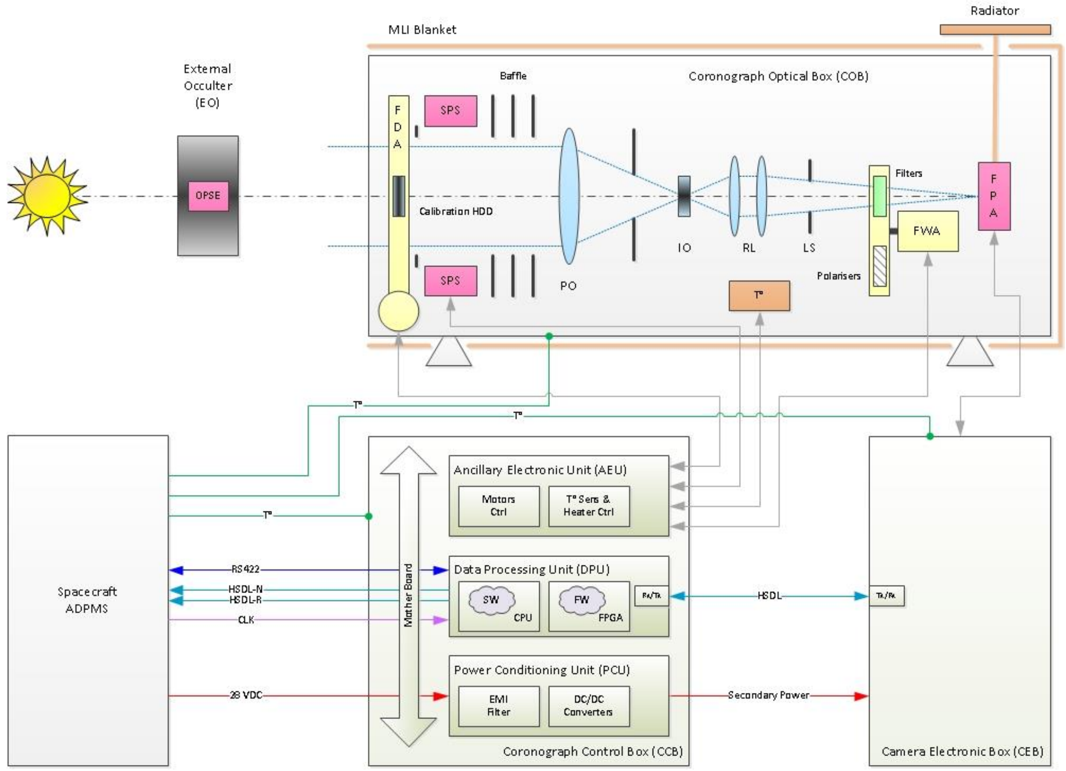

Figure 2. Coronagraph system functional block diagram.

Design evolution

The PROBA-3 coronagraph system design, as established in Phase B by a team led by *Laboratoire d'Astrophysique de Marseille* (LAM), was previously described in [8]. The present paper is presenting the design evolution of the ASPIICS instrument as at the beginning of Phase C/D.

Nonetheless, mostly because of the quite significant re-deployment of the consortium resources (and participating countries) between Phase B and Phase C/D, the following design changes will be considered:

1. Focal Plane Assembly & Camera Electronic Box: we decided to change the 2k x 2k CCD baselined in Phase B for a 2k x 2k CMOS APS sensor. The CCD was a major cost driver to be procured outside the PROBA-3 participating states. The proposed CMOS APS sensor is a direct heritage from the Solar Orbiter programme and is developed within the participating states (Belgium). Also, the proposed team demonstrates experience heritages for this type of sensor. The Camera Electronic Box (CEB) needs of course to be adapted to the new sensor.
2. Shutter Mechanism: as a direct consequence of using CMOS APS instead of CDD, the need for a shutter is no longer justified and it has been removed from the baseline.
3. Optical Layout: in order to accommodate the new detector with a pixel pitch of 10 µm (CCD was 15 µm), the coronagraph optical design has to be reviewed. It is also desirable to introduce telecentricity at the level of the filters to avoid chromatic effects across the field of view.
4. Mechanical accommodation: revising the optical layout will affect dimensionally nearly all elements of the COB. Right after the optical layout, this is therefore a priority task of the Bridging Phase.
5. Coronagraph Control Box: revisiting the CCB is necessary because of the loss of heritage from the previous team who baselined the CCB on a Solar Orbiter unit.
6. Shadow Position Sensor, Front Door Assembly and Coronagraph Control Box: the present design does not satisfy the system requirement to allow Shadow Position Sensor (SPS) measurements even when the coronagraph instrument is not operating. Design adaptations to the SPS and/or FDA and/or CCB are necessary to permit the use of the SPS when the rest of the coronagraph system is not operating.

2.2 Detection chain

The Focal Plane Assembly (FPA) is located at the back of the telescope optics and is housing the front-end of the electronics of the coronagraph camera. It consists of an APS image sensor, the proximity electronics of the APS, a harness from the FPA to the Camera Electronic Box (CEB), the FPA mechanical parts, and a radiator and its thermal strap. The FPA design concept is illustrated on Figure 3. The newly-proposed image sensor is a CMOS APS, manufactured by CMOSIS (Belgium). It has been developed for the PHI instrument of Solar Orbiter. No additional qualification testing or other development aimed at improving the performance of the proposed sensor will be envisaged in the context of this mission.

Table 1. Image sensor specifications.

Resolution	2048 x 2048 pixels
Pixel pitch	10 µm
Spectral range	400 to 800 nm
Sensitivity	55 – 65 @ 610 nm
Full well	114 ke$^-$
Dynamic range	11 bits (66 dB)
Power dissipation	0.57 W / 0.36W (active/idle)
Frame rate	10 FPS
Radiation tolerance	TID > 70 kRad
	SEL high
	SEU : 10E11 protons/cm² @ 10 MeV

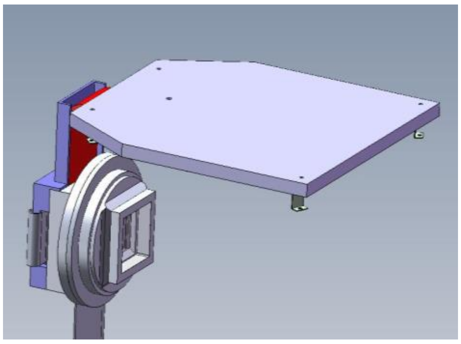

Figure 3. Coronagraph system focal plane assembly with radiator (Phase B design).

The sensor is configurable through a SPI line. The pixel array of the sensor requires to be clocked externally. The output of the sensor is analogue. The sensor is powered from the secondary voltage of the CCB. The APS proximity electronics is a front-end printed circuit board aimed at supporting the image sensor electrically but also mechanically. It contains elements for biasing (capacitors, resistors), decoupling (capacitors), and communication to the CEB (drivers, buffers). A radiator is used to cool down passively the FPA so that the sensor can operate in a lower temperature range for noise reduction purposes. The radiator will be connected to the mechanical housing by means of a thermal strap.

2.3 Optics

Lens objective

The Coronagraph optical system consists in a Primary Objective (PO) that forms an image of the external occulter onto the internal occulter (IO), and a Relay Lens (RL) that re-images both the entrance pupil onto the so-called "Lyot Stop" and the corona image onto the detector.

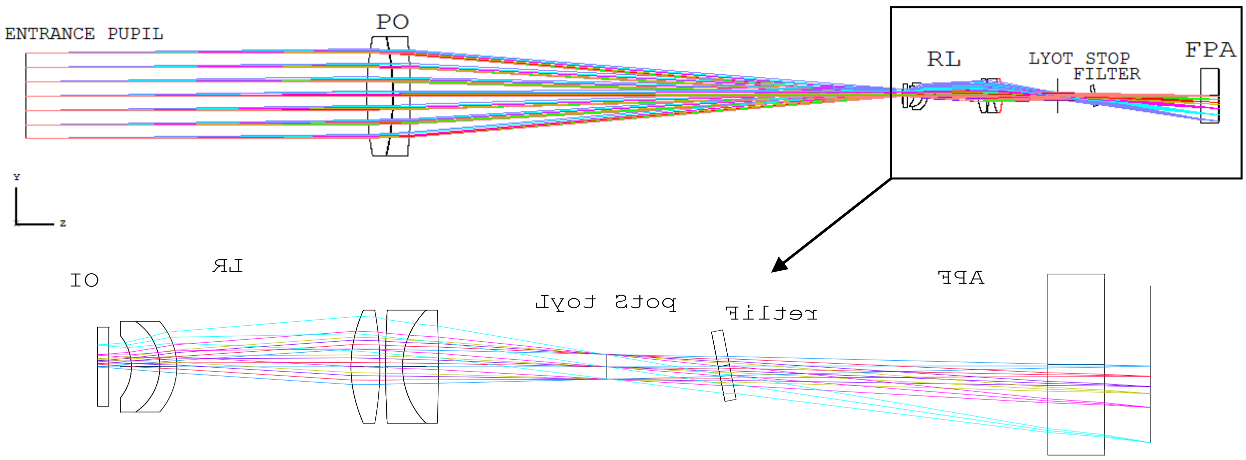

Figure 4. Coronagraph System Lens Objectives.

Radiation hard glasses are used to avoid any darkening effects and with the same optical performance as classical glasses. The first lens of the PO is not coated while all other lenses of the Lens Objectives are covered by an AR coating with reflectivity < 2%. In term of surface quality, the PO lenses shall present a microroughness < 0.5 nm RMS and the RL lenses a microroughness < 2 nm RMS. The high surface quality and cleanliness of the PO are critical to reduce the stray light from scattering inside the PO of the Sun light diffracted by the external occulter. The PO barrel is held inside the PO tube which is part of the instrument tube. The tube holding the two barrels of the RL is interfaced to the Equipment Box.

Optical design evolution

As the design is non-telecentric in the image space (Figure 4) it gives a shift of the spectral response from the centre to the edge of the FOV. The design options proposed here involve a telecentric design of RL objective where two main modifications are applied to the original design to make the RL telecentric and to accommodate the new detector with 2048 x 2048 pixels of 10 µm (instead of 15 µm). The design is optimized for these new constraints while trying to minimize the modifications with regard to the original design.

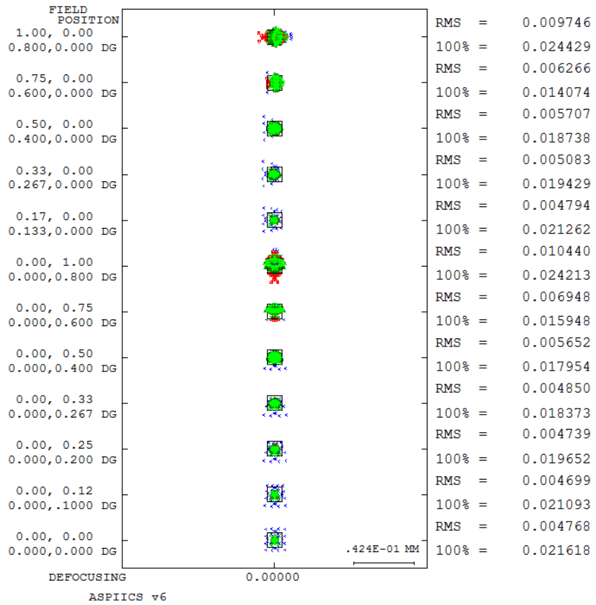

Figure 5. Image spot diagram obtained with the updated telecentric optical design.

Internal occulter

The Internal Occulter (IO) is located on the image of the External Occulter through the Primary Objective (PO). The IO consists in a neutral density to limit the high dynamics induced through the image by the Sun disc and corona. The transmission of the IO is variable with the field angle from 1Rsun to 3Rsun and the density value is evaluated with the photometric budget of the instrument and the exposure time dynamics. Four regions are necessary (Figure 6):

- Between 0 and 0.3 R_{sun}: the IO transmits the light of the OPSE emitters.
- Between 0.3 and 1.04 R_{sun}: the occulter blocks the light with a high density (OD > 4).
- Between 1.04 and 3 R_{sun}: the optical density is linearly decreasing from d = 2 at 1.04 R_{sun} to d = 0 at 3 R_{sun}.
- Beyond 3 R_{sun}: the optical density stays constant and equal to 0.

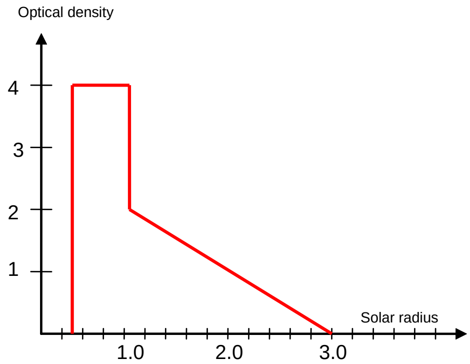

Figure 6. Optical density on IO as function of field angle (in solar radius).

The IO is made of a circular window in fused silica with a diameter of 14 mm and a thickness of 2 mm. The variable optical density covers the entrance face of the IO. The scale ratio between Solar radius and physical units at the IO location is derived from the optical design.

Filters & polarisers

The filters consist in one narrow-band filter and one broad-band filter with the following characteristics:

Table 2. Filter & polarisers specifications.

	Narrow band filter	Broad band filter	Polarisers
Clear aperture	≥ ∅13 mm	≥ ∅13 mm	≥ ∅13 mm
Useful range	centred on He I D3 line (587.6 nm) FWHM: 2 nm ± 0.1 nm	540 – 570 nm	540 – 570 nm
Temperature drift	< 0.02 nm/°C	N.C.	N.C.
Transmission	> 25% over useful wavelength range ; > 50% at central wavelength	> 70% over useful range	> 40%
Extinction ratio	N.A.	N.A.	1:10,000 or better
// polarisation reflection	N.A.	N.A.	< 0.25%

The filters are made of thin layer coats assembled with rad hard BK7 double side polished Glass Windows(GW). V-type AR coatings will be applied on the GW for waveband 540-570nm with a reflectivity <0.3% per side.

In addition to the filters, the filterwheel holds 4 identical polarisers but mounted with different orientations. The selected polariser is a sandwich comprising the polariser substrate glued from both sides to glass windows. The polariser itself is made in nanoparticle technology (for example ColorPol®, Polarcor™) on soda lime glass (0.28mm) substrate, showing a high contrast, temperature resistivity and good aspect ratio to fit into a filter wheel. Polariser Core Plates (PCP) (0.28mm thick) will be assembled with rad hard BK7 double side polished Glass Windows (GW) The baseline procedure will produce Polariser parallel <10 arc min and thickness controlled to ±0.1 mm. V-type AR coatings will be applied on GW for waveband 540-570nm with reflectivity <0.3% per side.

High density filter

A high density diffuser (HDD) combining a neutral density and a diffusive surface is used to produce a flat field on the detector plane when lit by the Sun, with a flux compatible with the dynamics of the coronagraph. The HDD is located in the lid of the Front Door Assembly. The optical and mechanical designs of the HDD will be studied and optimized with respect to the desired optical performance, mechanical, physical, environmental constrains and interface requirements.

2.4 Mechanical structure

The coronagraph structure is based on a tube and a box mounted on 3 feet (Figure 7). The feet are made of Titanium alloy and consist of 3 bipods (more exactly 2 bipods and 2 monopods). They ensure isostatic mounting to decouple mechanically the optical box from the spacecraft optical bench. The feet also ensure thermal insulation to limit heat load from and towards the optical bench. The monopods are located under the tube and the bipods on the equipment box sides. The tube holds the first part of the optical elements. The entrance pupil is located at the very front of the instrument to avoid any mechanical element in front of it. In the centre of the tube, the primary objective is inserted. This objective images the Corona on an intermediate focus and the external occulter on the internal occulter. It is important to maintain the internal occulter at an accurate position to ensure that it continuously covers the external occulter image. A suitable distance is maintained between the pupil and the primary objective in order to protect the lenses from direct view of bright elements in space, to protect it from radiation and to ensure that the temperature between the objective and the internal occulter remains stable and uniform. The full tube is thermally controlled by a heater. At the front of the tube, the Front Door Assembly is inserted in order to protect the tube interior and more particularly the front lenses from contamination. In flight the door will also reduce the risk of long exposure to direct Sun (un-occulted), this can be detrimental for the detector and cause important increase of temperature. The door will also be used in flight for calibration of the optical system. In the middle of the cover lid, a diffuser (including optical density) will spread the light of the Sun in the entire field of view in order to distribute it uniformly on the detector. A number of vanes are inserted in the tube in order to prevent straylight from source out of the field of view to enter the optical system.

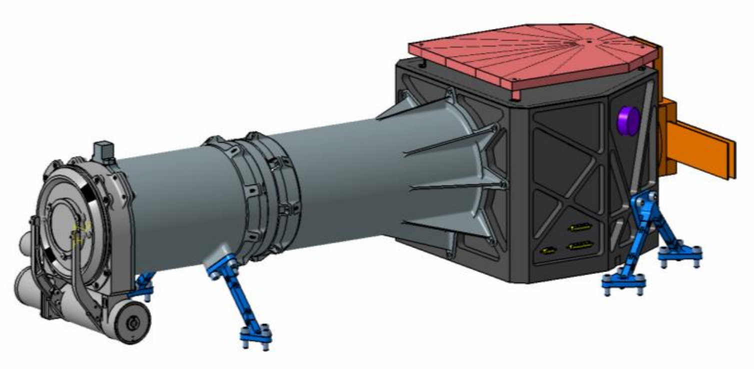

Figure 7. Coronagraph COB overview.

The second part of the structure is a box holding the different optical elements. The first element is the Relay Lenses which re-image the Sun Corona on the detector. This Relay Lenses is a set of lenses in a lens barrel. It also re-images the entrance pupil on the Lyot Stop in order to remove the straylight from the pupil edge.

The equipment box also contains the filter wheel. This wheel holds the filters and polarisers for the different observation modes. The filters in the wheel are tilted in order to ensure that no ghost is generated by the flat surfaces. The Focal Plane Assembly is mounted on the back wall of the box. It includes a detector matrix and included thermal links to connect it to an externally mounted radiator. This ensures passive cooling of the detector down to operational temperature. Flexi-cables are ensuring the electrical connection of the detector towards the Camera Control Box. On the top of the box a radiator is installed, mounted by insulating feet on the box cover. This radiator is exposed to space in order to evacuate the heat from the detector. The Equipment Box is also thermally regulated.

2.5 Mechanisms

Filter Wheel Assembly

The Filter Wheel Assembly (FWA) is a 6-position mechanism designed to position filters or polarisers within the science beam between the relay lens (RL) and the focal plane assembly (FPA). The FWA carries two filters and four polarisers. The FWA is also used as a support for the Lyot Stop assembly (TBC), which is located in front of the filters/polariser within the beam at the secondary pupil. The FWA is mounted inside the Equipment Box (EQB) of the COB and is controlled by the CCB. The FWA design uses heritages from the Planetary Fourier Spectrometer module Scanner of MARS and VENUS EXPRESS missions and the Pointing Unit of the MERTIS experiment of the BEPI COLOMBO mission.

Front Door Assembly

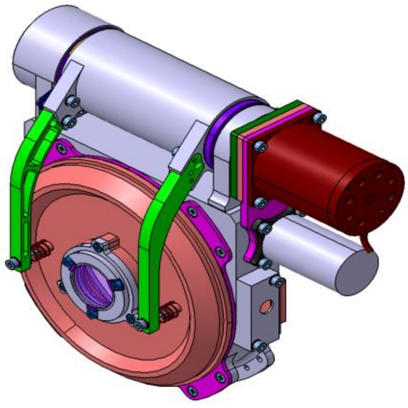
Figure 8. Front Door Assembly (FDA).

The Front Door Mechanism is designed to protect telescope optics from contamination on the ground, during launch and some flight operations and to avoid thermal loads of inner part of coronagraph. It will be placed at the end of the COB's Tube. The Front Door Assembly (FDA) is designed to have three operational positions and one failsafe position. During flight, the Lid is pressed position protects the optics and detector from direct sun light. During the non-observation phases of Coronagraph instrument, the Lid is in the closed position. Before and after the Coronagraph observation the Lid is moved by stepper motor via gearbox to the Open position. In any case of malfunction of the FDA the Failsafe position can be used. It is actuated by the Wax actuator.

2.6 External occulter

The external occulter (EO) is a critical element for every coronagraph and is the major stray light source. The external occulter shape must be optimized in order to reduce the light that is diffracted by its edge and then scattered by the telescope optics. The issue is so delicate that dedicated preliminary investigations have been performed and are described in [3] and [4], to which we recommend to refer for more detailed information. According to the preliminary studies, the current baseline optimization is a truncated cone (see Figure 9), from 70 to 100 mm long and with a semi-angle that has to respect the following constraints:

- the truncated cone surface must be in the shadow of the EO outer edge with respect to the solar disk light.
- The cone surface must be as close as possible (compatibly with pointing uncertainties) to the line connecting the IEO outer edge and the pupil edge.

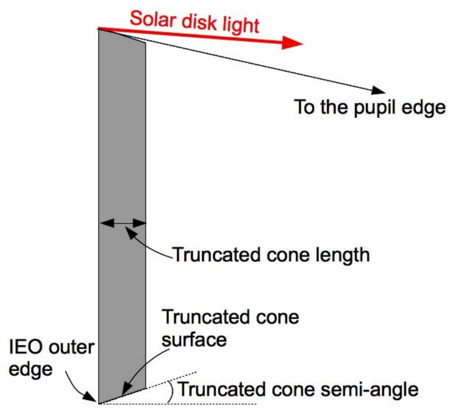

Figure 9. Not-to-scale sketch to emphasize the main geometrical parameters of the optimized EO.

According to the investigation results, such an optimization will at least halve the level of diffracted light inside the entrance pupil of the coronagraph [5]. The EO outer edge shall be as regular as possible, in order to prevent solar disk light scattering from manufacturing imperfections. The EO surface must be black coated and with a lambertian surface finishing. The preliminary studies did not account for the edge finishing, for the coating and for the surface finishing of the truncated cone, so these last requirements are based on the designers' experience. In order to confirm the manufacturing parameters, a further experimental investigation is being organized.

2.7 Formation flying metrology

Shadow position sensor

The Shadow Positioning Sensors (SPS), together with the Occulter Position Sensors Emitter (OPSE) form the ASPIICS metrology unit. The SPS are photodiodes mounted around the entrance pupil of the coronagraph and determine the absolute pointing of the instrument (i.e. the formation) by sensing small displacements of the penumbra cast by the external occulter located in the Occulter S/C. When the formation is nominal (i.e. the axis of the formation points to the Sun center), the shadow/penumbra falls equally on all the sensors, and the entrance pupil of the instrument is centered in the shadow cone of the occulting disc. When the formation is off-pointed, the shadow/penumbra changes (loss of circular symmetry) on the coronagraph entrance pupil. The changing signal from the SPS is used by the algorithm of the metrology software to evaluate the S/Cs off-pointing. The SPS also insures the safety of the coronagraph, by detecting direct solar illumination before it reaches the entrance pupil. The formation flying PROBA-3 performance specifications are summarised in Table 3.

Table 3. Formation flying requirements.

Inter-satellite distance (ISD)		144.2 m (± 2 m seasonal variations)
Absolute displacement error (ADE)	Lateral:	± 3.16 mm (3σ) with 20 arcsec APE
	Axial:	± 70 mm (3σ)

The Shadow Position Sensors (SPS) provide information with the above sensitivity on the alignment of Formation Axis with respect to the Sun Axis and the alignment of the Coronagraph Axis with respect to the Formation Axis. The SPS consists of 2 x 4 sensors distributed on two concentric circles (∅ 42 mm and ∅ 52mm respectively), mounted on a flex-rigid PCB and provided with their proximity electronics (pre-amplifiers, signal conditioning circuits, etc.…) and temperature sensors - The SPS are assembled in a mounting flange fixed to the COB Tube and including the first vane of the Coronagraph baffle (see Figure 10). The requirements on the accuracy in the S/Cs alignment should be achieved with 4 photodiodes but the choice to select an 8 sensors option was driven by redundancy constraints. The SPS shall measure lateral displacements of the shadow of the occulting disc in a square area centred on the optical axis of the coronagraph with a side of +/- 50 µm (nominal square and within an unobstructed field of view (UFOV) ≥ 1° half-cone angle. After in-flight calibrations, the SPS system shall be able (at nominal Inter Satellite Distance (ISD) ± 500 mm) to deliver absolute information of the shadow position, in the nominal square area, with a resolution of 3.0 µm (1sigma) and a accuracy of 7.0 µm (1sigma), on each transverse axis. Because of the great amount of information and the expected storage memory and telemetry ratio the shadow position measurement are expected to be performed with a cadence of 10 Hz. The SPS will give in output a differential, fully symmetrical signal of 2.5V (5V between the 2 outputs) for the maximum illumination within a bandwidth at -3dB limited to [0, 60 Hz]. The proximity electronic circuit is expected to have a dynamic able to acquire a flux of 8% of the full Sun without saturation. This is fundamental to avoid critical damages to the detection system.

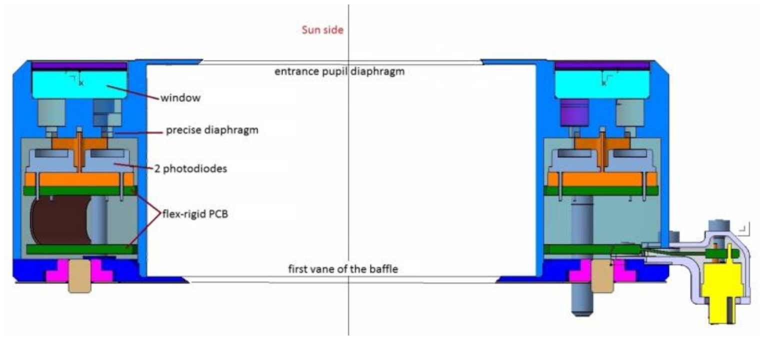

Figure 10. Shadow position sensor (SPS).

The photodiodes have a diameter of ~2.5mm and will operate with 0V. A simulation based on this sensor and typical solar emission profile shows a maximum signal current of 0.956 mA through a 2mm diaphragm when exposed to the full sun. Once integrated, the space qualifying tests to verify the complete sequence of the formation-flying (F^2) metrology will be held in the OPSys facility (ALTEC, Turin, Italy) with the final SPS setup mounted on the flying telescope. The main task of the tests and calibrations is to reconstruct the actual behaviour of each photodiode under nominal and off-pointing illumination conditions and to check the metrology algorithms in order to extrapolate the linear movements of the S/Cs from the SPS measurements.These measurements shall return the expected sensitivity to the F^2 alignment, with the required accuracy and resolution and will be a critical issue for the validation of the metrology algorithms.

Photodiode sensors with a diameter of ~2.5mm will operate with 0V. A responsivity profile obtained with this sensor at 0V is shown in Figure 11. A simulation based on this sensor and typical solar emission profile shows a maximum signal current of 0.956mA through a 2mm diaphragm when exposed to the full sun.

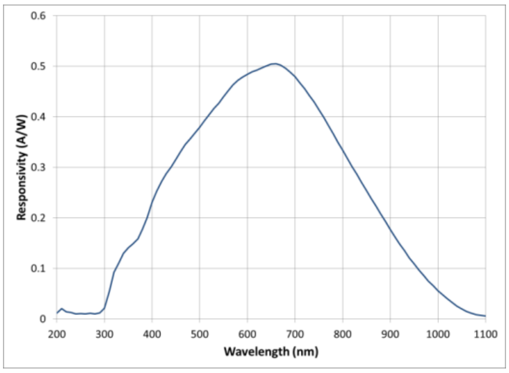

Figure 11. Responsivity plot of SensL MicroFB-30035 operated at 0V bias.

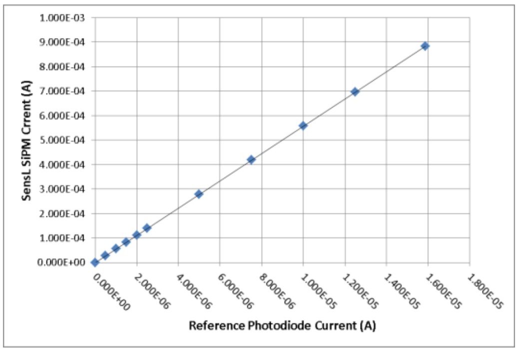

Figure 12. Linearity of SensL sensor to input light flux.

A linearity plot of the output of a SensL sensor to input light flux is shown in Figure 12. The SensL sensor will perform linearly over the required range of operation of the SPS. The SPS head electronics consists of a pre-amplifier and voltage buffer amplifier. The first stage, front end amplifier uses a usual current to voltage converter operating in transimpedance amplifier mode. The second stage of amplification consists of 2 amplifiers delivering 2 symmetrical voltages to be carried out to the AEM thanks to twisted shielded pairs. Eight such pre-amplifiers are installed inside the SPS head mounted on the PCB.

Occulter position sensor emitters

The OPSE system consists of a set of three light emitting heads mounted on the External Occulter disc. Their images produced by the Coronagraph form a pattern that uniquely defines the position along the transverse axes, with respect to the instrument coordinate system. Moreover an estimate of the inter-satellite distance (ISD) and of the orientation of the External Occulter can also be derived. (NB: the OPSE images are processed on ground. Therefore the information delivered by the OPSE is not usable onboard in real time.) The 3 OPSE Heads are accommodated on the Coronagraph-facing side of the Occulter disc, close to the disc centre (so limiting the size of the density hole in the centre of the Internal Occulter in the Coronagraph). Ideally, for appropriate discrimination, the 3 OPSE Heads should be located more than 75 mm apart and within a diameter of 400 mm. Each of the 3 OPSE Head includes two nominal/redundant pairs of LEDs individually wired (so four LEDs in total per OPSE Head). For a given pair, the two LEDs have slightly different central wavelengths so reducing the risk of falling out of the Coronagraph band pass because of the LED wavelength drifting with temperature (typically -0.2 nm/°C at +25 °C). At least one of the two LEDs must emit in the band pass of the continuum filter (540-570 nm, TBC) of the coronagraph. The two LED models baselined in Phase B are VS575N and VS590N from OPTRANS CORP (Japan), which emit respectively at 575 nm and 590 nm at room temperature and, by extrapolating down the predicted EO temperature (around -120°C), they are therefore believed to emit within the Coronagraph useful range. Nonetheless, the LEDs shall be characterised in temperature during Phase C/D, and the temperature of the rear side of the Occulting Disc will be better evaluated.

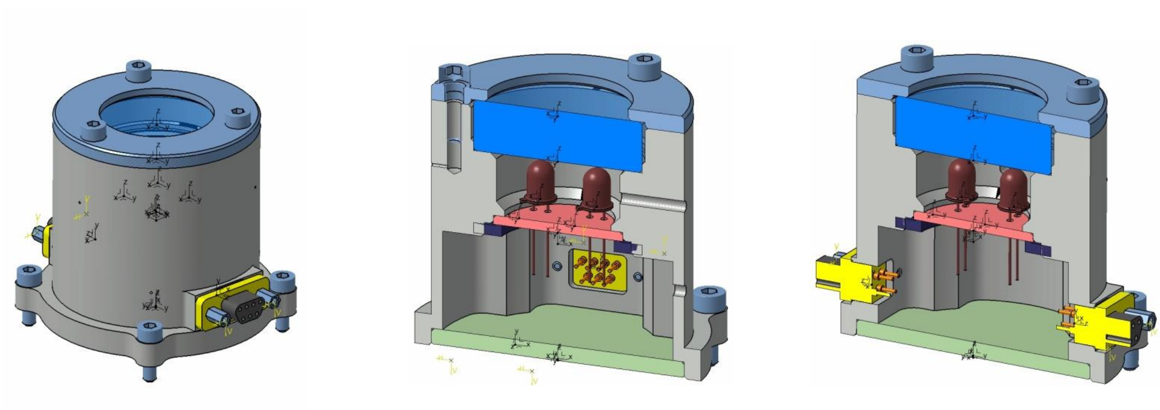

Figure 13. Occulter position sensor emitter head (OPSE), preliminary design reproduced from Phase-B Design Report, courtesy of LAM.

2.8 Electronics and software

Camera electronic box

The Camera Electronic Box (CEB) is dedicated to controlling the FPA. The electrical circuitry of the CEB contains all of the electronics and printed circuit board related to the command and control of the FPA and of its proximity electronics from the CCB. The CEB electronics contains the following electronic functions: FPGA to control the detector, buffering (conditioning) analogue video signal, Analogue-to-Digital converter (30MSPS), housekeeping circuitry, voltage regulators, LVDS drivers and receivers, memory (optional), connector to interface FPA, connectors to interface CCB (one SpaceWire compliant connector (ECSS-E-ST-50-12C) and one secondary power supply connector). The SpaceWire interface in the firmware for the CEB&FPA read out electronics will consist of the space wire CODEC IP core and will be integrated into the FPGA (Remote Memory Access Protocol is considered as an option).

Coronagraph control box

The Coronagraph Control Box (CCB) is the electronic controller of the coronagraph. It consists of an electronic box including:

- A data processing unit (DPU), hosting
  - The CCB On-board Software (inside Microsemi RTAX 2000)
  - The Data Compression Firmware (inside Xilinx Virtex5)
- An ancillary electronic unit (AEU) driving
  - the COB mechanisms,
  - shadow position sensors and
  - the COB thermal hardware (temperature sensors and heaters)
- A power conditioning unit (PCU)
- A mother board
- A mechanical housing

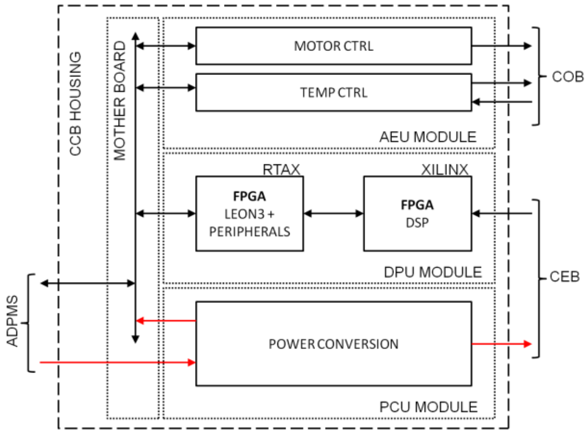

Figure 14. Coronagraph Control Box (CCB).

The Coronagraph Control Box (CCB) preliminary architecture and interconnection among functional blocks is depicted (Figure 14). The CCB receives primary power and telecommands from the Spacecraft ADPMS. It operates an On-Board Software and an Image Data Compression Firmware (IDC).

The DPU (Digital Processing Unit) module equips the Coronagraph with all its control and data processing capabilities. It is the brain someway. The DPU design is based on a LEON processor coupled to an in-flight reprogrammable FPGA. The processor is in charge of the overall control while the reprogrammable FPGA is in charge of the data processing. The reprogramming capability enables on-demand in-flight data processing algorithm reconfigurations. The LEON processor is implemented on a rad-tolerant, one-time programmable Microsemi RTAX FPGA. The reprogrammable FPGA is a rad-tolerant SRAM-based XILINX VIRTEX5 FPGA. Connections between both FPGA are of two kinds. The first one is the data link, for moving processed data among cache and storage memories, and for configuring the parameters of cores loaded to reconfigurable FPGA. The second one is the configuration link (presumably, parallel variant) enabling access to configuration memory space of RAM based FPGA. It can be used for partial (or full, if necessary) and dynamic (online) reconfiguration of functionality. It can be also used for improving dependability of system by employing some external scrubbing techniques on Xilinx FPGA (interesting, although not obligatory as internal scrubbing is also possible).

Due to the offload of intensive processing tasks to the reconfigurable FPGA, a processor with a modest processing power and moderately clocked (LEON3-FT @ 25MHz) is sufficient to control the instrument and to communicate with the platform of the spacecraft. While managing all of the electrical subsystems of the coronagraph, the DPU is however not implementing all of the electronic functions. In particular, the discrete parts necessary to perform the power distribution and monitoring electronic functions like amplifiers or switches are place inside the AEU (Ancillary Electronic Unit). The DPU receives it required secondary power supplies from the motherboard. These are small voltages, high currents, ranging from 1V to 5V, in order to power the FPGAs and the memories. The DPU communicates with the other CCB units also from the motherboard on a dedicated data bus. A unique cutting-edge feature of the DPU is its dynamic partial hardware reconfiguration capability. Dynamic partial reconfiguration is the process of reprogramming the contents of just the part of the FPGA configuration memory which is implied in the data processing while the rest of the device remains operational. It is achieved using a SRAM-based XILINX VIRTEX FPGA. The basic principle underlying the whole dynamic partial reconfiguration concept is the division of the FPGA design into two parts: a static part and a reconfigurable part. The static part remains unchanged and unaffected by all partial reconfigurations. It can be considered, from the project hierarchy perspective as a top-level logic. The most suitable configuration interfaces for partial reconfiguration are ICAP and SelectMAP due to their speed of operation. Their theory of operation is exactly the same.

CCB DPU on board memory comes in two flavours:

- Volatile, RAM, used mainly for software execution, operation system purposes, caching (128MB SDRAM)
- And non-volatile, FLASH, used for storage (raw data from full scientific observation session, bit streams for FPGA configuration, telemetry logs, software applications, 22GBs NAND-Flash).

The PCU (Power Conditioning Unit) will be used to supply secondary power to all of the modules of the Coronagraph system (DPU, AEU, CCB, CEB and COB). It will consist of two main parts: a set of input EMI filters and a set of DC/DC converters. Separate EMI filters will be used close to each DC/DC converters in charge of powering the electronic equipment and the electro mechanisms. To ensure proper operation of the Coronagraph five different values of output voltage are planned. For driving the motors 12 V is proposed. For other subsystems, four voltages values are proposed: 1V; 2,5V; 3,3V and 5 V. The output voltage regulation accuracy will be ±1% (for 3,3V and higher outputs). Expected ripple level of any output voltage will be below 50mVPP.

On-board Software

The on-board software will run onto the LEON3FT processor implemented on an RTAX-2000 antifuse FPGA and it consists of the low-level software and of the high-level software.

The bootstrap software is part of the low-level software and is responsible for the initial CPU initialization, performing memory tests and jumping to the start-up software. During initial development stages this software will be replaced by automatically generated images of mkprom2 utility. The bootstrap is written in assembly language.

The start-up software is part of the low-level software and is responsible for handling a basic set of commands and providing some patching functionalities from the ground. It is proposed to keep this software as simple as possible. Therefore it will be based on simple closed loop pattern with additional interrupt handlers. No operating system will be used in this part of software. Additionally it is worth to mention that from the logical point of view startup software will be divided into bootloader and startup application. This division will provide possibility to update startup software application in a safe and reliable way. The start-up software is written in C language.

The device drivers are part of the low-level software and are distributed together with the operating system port for the LEON3. If ever some Coronagraph device drivers were not commercially available, they would be developed on purpose.

A minimum set of device drivers are necessary for initial software modes (e.g. UART, flash memory driver) at start-up. Device drivers will be developed for both start-up software and application software. It is assumed that application software executed in the RTEMS environment will reuse subset of hardware drivers developed for low-level start-up code. This will be realized by adding wrappers that will provide OS API for hardware drivers. Thanks to such an approach, the amount of possibly duplicated code will be minimum.

The high-level software is the application software. It consists mainly of the state machine and functional tasks running under RTEMS for operating autonomously the Coronagraph and fulfilling all of the functional requirements.

Selected functional tasks:

- TC Handler: Task responsible for handling spacecraft telecommands. This task will be mostly responsible for TC verification and further routing to target SW modules.
- TM Provider: Task responsible for aggregation of TM packets and their transmission to spacecraft.
- FPGA reconfiguration manager: Task responsible for executing FPGA dynamic reconfiguration.
- CCB operational mode manager: Task responsible for management of transitions between different operational modes.

- Observation plan manager: Task responsible for autonomous operations required for given observation plan.
- Observation manager: General task responsible for providing functionalities associated with current observations.
- Observation data provider: Task responsible for managing flash memory holding observation data.

2.9 Image data compression

The Image Data Compressor (IDC) consists of an IP Core firmware to be implemented on a reconfigurable space-grade Xilinx FPGA (Virtex-4QV or Virtex-5QV), located in the CCB DPU. Such a state-of-the-art FPGA technology provides an excellent on-board payload data processing platform, featuring qualification for space applications, exceptional radiation hardness (Virtex-5QV), very high reliability (configuration memory scrubbing ensures immunity to Single Event Effects) under extremely harsh radiation environments over long operational periods, dynamic partial reconfiguration for in-flight adaptability, high performance and very high density. Reconfigurable SRAM FPGA technology offers unique advantages over both one-time programmable (OTP) FPGAs and ASICs due to its ability to support planned, mode-dependent functional alterations as well as unplanned updates. Operationally, there is the major system advantage that allows upgrades after launch, greatly enhancing mission profile and extending valuable system life time. An adaptable instrument based on an adaptable on-board payload data processing platform could be adjusted to unforeseen events such as changes or extensions in the scientific objectives, resulting in a superior scientific data yield and a reduced risk of a total instrument loss. Moreover, dynamic adaptability offers the possibility to timeshare resources in a Time Space Partitioning (TSP) manner, when dedicated functions are not necessary at the same time, resulting in significant savings in mass, power, hardware resources and design complexity.

The Reconfigurable FPGA IDC IP Core implements an algorithm based on the CCSDS Image Data Compression (IDC) recommendation (CCSDS 122.0-B-1). The CCSDS-IDC recommended standard is both a lossless and lossy (rate-limited and quality-limited) compression algorithm designed specifically for use on board a space platform. This standard has sought a balance between the complexity of the algorithm and its performance, and thus it can be efficiently implemented by hardware. In addition, the algorithm permits a memory-efficient implementation which does not require large intermediate frames for buffering. The CCSDS-IDC recommendation supports gray-scale two-dimensional images with integer-valued pixels having a maximum dynamic range (bit depth) of 16 bits. The CCSDS-IDC consists of two functional parts: (a) a Discrete Wavelet Transform (DWT) unit that performs decorrelation and (b) a Bit Plane Encoder (BPE) unit which encodes the decorrelated data. To limit the effects of data loss that may occur on the communications channel, the DWT data are partitioned into segments, each loosely corresponding to a different region of the image. A segment is defined as a group of S consecutive blocks of 8×8 coefficients (1 DC and 63 AC). Each segment is compressed independently, so that the effects of data loss or corruption are limited to the affected segment. Partitioning the DWT data into segments has also the benefit of limiting the memory required. The segment size S can be adjusted to trade memory requirements for compression effectiveness (rate-distortion performance); smaller segments provide low memory requirements, but tend to reduce the compression effectiveness and reconstructed image quality. Encoding of a segment can terminate earlier as a trade-off between reconstructed image quality and compressed data volume. The architecture of the Reconfigurable FPGA IDC IP Core provides a powerful, cost-effective and highly integrated solution since it does not require any external memory. Furthermore, the high memory capacity of SRAM FPGAs allows implementation of strip-mode compression for large image widths (e.g. 2Kx2K) without limitation to small segment size values, thus offering higher compression rates and better rate-distortion performance. The characteristics of the Reconfigurable FPGA IDC IP Core architecture are summarized as follows:

- Single reconfigurable FPGA solution enabling: a) no extra memory chip procurement, b) no external memory cost, mass and power overhead, and c) no external memory interface implementation bottlenecks.
- Based on a memory efficient DWT architecture.
- High data-rate performance using pipelined data flows.
- Exploit algorithm inherent parallelism targeting the Bit Plane Encoder (BPE) bottleneck.
- High compression effectiveness using large segment size values leveraging FPGA embedded memory.

Compression effectiveness: CCSDS-IDC (with segment size S=256 or 128) provides lossless and high fidelity lossy compression up to compression ratio 8 without requiring any pre-processing. Throughput performance: The implementation of the CCDSD-IDC algorithm as an IDC IP Core targeting a space-grade SRAM FPGA is able to achieve much higher throughput than the 3MSamples/sec of PROBA-3 Phase B requirement. In fact, it is even able to perform on-the-fly compression, if it is acceptable by science operational requirements and permitted by other system level constraints (e.g. rates of CMOS APS, CCB I/F with S/C and CEB, etc.). It should be noted that CCSDS-IDC hardware implementation provides high performance allowing about two orders of magnitude less data processing execution time than the corresponding SW one.

3. DEVELOPMENT PLAN

3.1 Programmatics

A Phase B study, led by *Laboratoire d'Astrophysique de Marseille* (LAM), has been completed in spring 2013. This paper is presented whilst the ASPIICS project is transiting into Phase C/D/E1 on the basis of a new industrial structure reflecting the redistribution of resources allocated to this programme. ASPIICS is built by a European consortium including about twenty partners from seven countries (Belgium, Poland, Romania, Italy, Ireland, Greece, and The Czech Republic) under the auspices of the European Space Agency's General Support Technology Programme (GSTP) and the Czech Prodex Programme. The planned Phase C/D duration is 2½ years with an expected launch date in 2018.

3.2 Model philosophy

The model philosophy that we will apply to support the development of our instrument is summarised in Table 4. It serves both our internal needs for validating critical technologies and the needs expressed at Mission level to populate the spacecraft models. The principal "de-risking model" is the DM that will consist of a complete functional prototype of the telescope.

Table 4. Instrument model philosophy summary.

Model	Representativity	Internal Use	Upper Level Use
Development Model (DM)	Partially representative, depending on the technology to be validated	For validation of sub-unit key technologies, for developing and end-to-end breadboard of the COB, for F² metrology ancillary units validation	To support the Mission formation flying metrology needs
Structural-Thermal Model (STM)	Thermo/mechanical representative (mounting interface, mass properties, structural properties, thermal properties, envelope and shape, subsystems structural & thermal dummies, harness)	For math models correlation, to populate upper-level STM and support system level tests	To support the Mission STM programme
Engineering (Qualification) Model (EQM)	Flight representative (full flight design & flight standard with respect to electrical, optical, and mechanical parameters)	For qualification, to verify performances, functional interfaces and operational procedures, to validate functional interfaces at instrument level, and to populate and support system-level qualification	To support the Mission EM/EQM programme
Proto Flight Model (PFM)	Full flight design & flight standard	For acceptance testing, and to populate instrument FM	The flight hardware & software
Flight Spare (FS)	A sensible kit of spare components/ sub-assemblies (flight standard)	For quick replacement of failed/damaged flight hardware	For quick replacement of failed/damaged flight hardware

3.3 Verification plan

The qualification test baseline is derived from ECSS-E-ST-10-03C (protoflight test baseline), which is tailored according to the equipment category and to the specific programme's needs. The proposed test matrix is presented in Table 5.

Table 5. Instrument verification and test matrix.

Test Category	Test Content	STM	EM	EQM	PFM	Notes
General	Functional, performance	**-**	**T**	**T**	**T**	
	Life	**-**	**-**	**T**	**-**	
	Burn-in	**-**	**-**	**-**	**- / tbc**	N/A for COB, TBC for E-Boxes
Physical	Mass	**T**	**-**	**T**	**T**	
	Dimensions	**T**	**-**	**T**	**T**	
	COG	**A**	**-**	**A**	**A**	By analysis only
	MOI	**A**	**-**	**A**	**A**	By analysis only
Mechanical	Random vibration	**T**	**-**	T_{QQ}	T_{AA}/T_{QA}	AA for FM COB / QA for E-Boxes

Test Category	Test Content	STM	EM	EQM	PFM	Notes
	Sine vibration	**T**	**-**	**T**	**T**	
	Shock	**-**	**-**	**T**	**- / tbc**	TBC for E-Boxes
Thermal	Thermal vacuum	**-**	**-**	T_{QQ}	T_{AA}/T_{QA}	AA for FM COB / QA for E-Boxes
	Thermal Balance	**T**	**-**	**T**	**- / T**	
Electrical	EMC	**-**	**tbc**	**-**	**T**	TBC for EM E-Boxes
	Magnetic	**-**	**tbc**	**-**	**- / tbc**	On EM or PFM E-Boxes (TBC)
	ESD	**-**	**tbc**	**-**	**- / tbc**	On EM or PFM E-Boxes (TBC)

QQ = Qualification level and Qualification duration/cycles ; QA = Qualification level and Acceptance duration/cycles ;
AA = Acceptance level and Acceptance duration/cycles

4. SUMMARY

This paper presents the current status of ASPIICS, a solar coronagraph on the ESA's formation flying in-orbit demonstration mission PROBA-3. This instrument takes advantage of the possibility to place the external occulter on a companion spacecraft to perform high resolution imaging of the inner corona of the Sun as close as 1.08 solar radii. The instrument optical principle remains as simple as possible so that the emphasis can be placed on critical aspects such as formation flying control, stray light reduction and data handling. The image acquired will be compressed on board in an in-flight reconfigurable FPGA before being down-linked to ground for scientific analyses. ASPIICS is built by a European consortium including about twenty partners from seven countries (Belgium, Poland, Romania, Italy, Ireland, Greece, and the Czech Republic).

5. ACKNOWLEDGEMENTS

The ASPIICS project will be developed under the auspices of the ESA's General Support Technology Programme (GSTP) and the ESA's Prodex Programme thanks to the sponsorships of seven member states: Belgium, Poland, Romania, Italy, Ireland, Greece, and the Czech Republic.

ESA Director of Science and Robotic Exploration has appointed Dr Andrei Zhukov of the Royal Observatory of Belgium as Principal Investigator for the ASPIICS instrument.

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