PROBA 3 INSTRUMENT CORONAGRAPH

PAYLOAD REQUIREMENTS AND DEFINITION DOCUMENT

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reference/*réference*	P3-EST-RS-7007
issue/*édition*	1
Revision/*révision*	1
date of issue/*date d'édition*	27-08-2009
status/*état*	Second Issue
Document type/*type de document*	Requirement Specifications
Distribution/*distribution*	Public document

ESA-ESTEC
European Space Agency, Noordwijk, The Netherlands

APPROVAL

Title *Titre*	Payload Requirements and Definition Document	issue *issue* -1	revision *revision* 1

Author *Auteur*	PROBA 3 team	date *date* 27-08-2009

approved by *approuvé by*	Agnès Mestreau-Garreau Philippe Escoubet	date *date*

CHANGE LOG

reason for change /*raison du changement*	issue/*issue*	revision/*revision*	date/*date*
First issue	1	0	05-06-2009
Second issue: addition of ARaSS	1	1	27-08-2009

CHANGE RECORD

Issue: draft Revision: 0

reason for change/*raison du changement*	page(s)/*page(s)*	paragraph(s)/*paragraph(s)*

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1. INTRODUCTION

The purpose of the Payload Requirements and Definition Document is to provide an overall description of the instrument conveniently called "Coronagraph" as resulting from the past phases of payload study.

2. ACRONYMS

CCB	Coronagraph Control Box
CCD	Charge Coupled Device
CME	Coronal Mass Ejection
CEB	Camera Electronic Box
COB	Coronagraph Optical Box
CSC	Coronagraph SpaceCraft
CU	Calibration Unit
EO	External Occulter
FDM	Front Door Mechanism
FF	Formation Flying
FFSS	Formation Flying SubSytem
F-P	Fabry-Perot
FPM	Fabry-Perot tilt Mechanism
FWM	Filter Wheels Mechanism
GNC	Guidance Navigation Control
ISD	Inter Satellite Distance
MAIV	Manufacture Assembly Integration and Verification
MLI	Multi Layer Insulator
OSC	Occulter SpaceCraft
PDD	Payload Definition Document
S/C	SpaceCraft
SHM	Shutter Mechanism
TBC	To Be Confirmed
TBD	To Be Determined
TMA	Tri Mirror Anastigmatic

3. APPLICABLE AND REFERENCE DOCUMENTS

[AD1] PROBA 3 Product Assurance Requirements
P3-EST-RS-1005 1.1

[AD2] PROBA 3 ARaSS Definition Document
P3-EST-TN-7003 1.2

[RD1] PROBA 3 Mission Requirements Document (MRD)
P3-EST-RS-1006

[RD2] Summary of PROBA3 Mission Analysis for Coronagraph Instrument

P3-EST-TN-7002 1.0

4. PREFACE AND SCIENTIFIC GOALS

The ESA PROBA 3 technology mission is aimed at demonstrating Formation Flying techniques and technologies. It is composed of two small spacecrafts flying in formation in a highly elliptical Earth orbit. Both spacecrafts accommodate FF flying technologies in order to demonstrate FF configurations and performances required for future missions (metrology, propulsion, GNC). The objectives include also the validation of FF at system level by the accommodation of a guest payload to critically evaluate the effect of formation flying on scientific observations. The baseline of the project is a "giant" white-light, externally-occulted solar coronagraph as the payload. One spacecraft hosts the occulting disk and the other the coronal imager/coronagraph. The spacecraft fly in formation with a separation of 150 meters. The mission is designed for a life-time of 2 years.

Although solar physics missions have probed the corona in several temperatures and heights, the region within 3 solar radii where the solar wind and CMEs are born remains extremely difficult to observe with sufficient spatial resolution and sensitivity to understand these phenomena. Progress on this front requires eclipse-like conditions for long periods of time and these are precisely offered by the PROBA 3 coronagraph. This mission is focused on the following

The science instrument questions to be answered are:

- **Understanding the physical processes that govern the solar corona** by answering:
  - What is the fine scale nature of the solar corona?
  - What processes contribute to the heating of the corona and what is the role of waves?
  - How and where does the solar wind originate?
  - What processes contribute to the acceleration of the slow and fast solar winds?
- **Understanding the physical processes that lead to CMEs and space weather** by answering:
  - What is the nature of the structures that form the CME?
  - What is the connection between CMEs and active processes on the solar surface (flares, prominences...)?
  - How do CMEs erupt and accelerate in the low corona?
  - Where and how can a CME drive a shock in the low corona?

5. PAYLOAD REQUIREMENTS

5.1 Science goals and performance requirements

The PROBA 3 coronagraph is conceived so as to fully exploit the unprecedented access to the inner solar corona offered by formation flight.

The PROBA 3 payload will consists of a Coronagraph and an Absolute Radiometer and Sun Sensor (ARaSS).

Coronograph:
Conceptually, it is a classical, white light, externally-occulted Lyot coronagraph, but adapted to the formation flying configuration: the coronal imager/coronagraph is carried by one S/C (called the

"Coronagraph S/C") entirely protected from direct sunlight by remaining in the shadow of the occulting disk hosted by the other spacecraft (called the "Occulter S/C"). The inter-satellite distance of 150 m allows reaching the corona close to the solar limb with very low stray light and almost no vignetting that otherwise degrades the spatial resolution.
The coronagraph is therefore designed to obtain high-resolution images of the solar corona (continuum and coronal emission lines) over a field of view of 1.02-4 Rsun in both unpolarized and polarized light, as well as 2-dimensional spectroscopy of several visible coronal emission lines to perform diagnostic measurements of the properties of the coronal plasma. The coronagraph should be capable of detecting low contrast features and emission lines up to 4 Rsun in the corona.

Optical concept	Externally occulted white light coronagraph
Field of View	1.04 Rsun – 3 Rsun (goal 1.02 Rsun – 4 Rsun)
Spatial Scale	< 3 arcsec /pix
Spectral Range	3 emission lines: Fe XIV (530.3nm), He I (587.6nm), Fe X (637.4nm). Continuum: 540-570nm

Fig. 1 *– optical requirements*

Absolute Radiometer and Sun Sensor:
The Absolute Radiometer and Sun Sensor will be an experiment on board of the Occulter spacecraft and with the scientific goal to achieve high accuracy and long-term stability measurement of the Total Solar Irradiance. All data concerning the Absolute Radiometer and Sun Sensor are described in [AD2].

5.2 Interface Requirements and description

The coronagraph payload is composed of:

- an external occulting disk accommodated on the OSC (not part of the AO but the establishment of the geometrical and optical specifications are part of the AO)
- a coronagraph instrument accommodated on the CSC
- a Shadow Position Sensor accommodated on the CSC
- a Occulter Position Sensor with LEDs accommodated on the OSC
- a Absolute Radiometer and Sun Sensor accommodated on the OSC(part of the AO)

The coronagraph payload maximum resources are given in the following table:

	From Coronagraph S/C	From Occulter S/C
Volume	1000 x 800 x 300 mm	TBD
Mass	25 kg (TBC)	1 Kg (TBC)*
Power	35 W (TBC) (4W in non operating mode)	1 W (TBC)
Data Rate Volume	8 Gbits / day	0 (TBC)

* Without the external occulting disk.

The [AD2] describes the definition and interface requirements of the Absolute Radiometer and Sun Sensor.

External Occulter disk (not part of AO):
The size of the occulting disk will be finalised in cooperation with the instrument provider. The disk edge and optical properties will be reviewed by the instrument provider; however it is planned that the occulting disk shall be built with traditional structural materials and processes (edge, paint ...).
The shape of the disk will also be finalised with the instrument provider. In phase 0/A it was defined as circular to maximise visibility of the full corona. During phase B design activities, some protrusion may be required, their accommodation will be discussed with instrument provider to minimise perturbations to the observations.

Coronagraph instrument
The Coronagraph Detector shall be thermally decoupled from the S/C platform.
Data provided by the Coronagraph Detector shall be compressed without loss, stored in the S/C mass memory and then transmitted to ground, in real time or after the observation phase.

Shadow Position Sensor (part of the AO):
A Shadow Position Sensor (SPS) shall be used to verify that the Coronagraph Detector's entrance pupil is centered within the shadow cone of the Occulter Disk.

Occulter Position Sensor (part of the AO):
An Occulter Position Sensor (OPS) shall be used to check the accuracy of the Formation Flying by providing information on the position of the Occulter S/C in the field of view of the Coronagraph Detector.
Four (TBC) LEDs shall be accommodated on the Coronagraph-facing side of the Occulter S/C.
When switched ON, the LEDs shall provide information on the position of the occulter disk in the field of view of the Coronagraph Detector. (By comparing the position of the barycentre of the LED images with the reference pixel, the Coronagraph Detector will be able to estimate the accuracy of positioning of the Occulter Disk w.r.t. the optical axis of the Coronagraph Detector.)

Absolute Radiometer and Sun Sensor (part of the AO see [AD2]):
The accommodation of an Absolute Radiometer and Sun Sensor (ARaSS) is foreseen.
The ARaSS is used to measure the visible irradiance of the solar disk and to provide independent/additional information on the Sun pointing of the Occulter S/C.

5.3 Formation Flying Requirements

The scientific requirements on the flying formation are defined so as to:

i. provide observational conditions close to those obtained during ground-based total solar eclipses (very low stray light level combined with a high spatial resolution in the very inner corona); this translates into a specification for the distance between both S/C (inter-satellite distance).

ii. insure a nominal occultation of the entrance pupil of the coronagraph by the external occulting disk; this translates into a specification for the relative longitudinal positions of the two S/C;

iii. maintain the entrance pupil of the coronagraph centered in the shadow of the external occulter; this translates into a specification for the relative lateral positions of the two S/C.

The Inter-Satellite Distance (ISD) will be set at about 150 m (variable to correct for seasonal variations) and is compatible with scientific requirements. The nominal occultation of the Sun is 1.02 ± 0.01 R_{sun} (where R_{sun} corresponds to the Sun apparent angular radius, about 0.25°). This specification allows deriving both relative lateral and longitudinal positioning.

θ_o = 1.02 ± 0.01 R_{sun}		Value at 3σ
Specifications of the formation	Inter-Satellite Distance (ISD)	**150 m**
	Lateral positioning	0 ±3.4 mm
	Longitudinal positioning	150 m ±74.2 mm

***Fig. 2** – attitude requirements*

6. CORONAGRAPH DESCRIPTION

6.1 Optical description

The optical design follows the general principles of a classical externally occulted Lyot coronagraph (as shown Fig. 3). The external occulter (D1) blocks the light from the solar disk while the coronal light passes around the occulting disk then enters through the circular aperture of the coronagraph. The primary objective (O1) forms an image of the external occulter onto the internal occulter (D2). The image of the surrounding bright fringe is blocked by slightly over-sizing the internal occulter. The secondary objective (O2) re-images the entrance pupil (A1) onto the so-called "Lyot Stop" (A3) that blocks the light diffracted by the edges of the pupil. Finally, the corona image is formed by a camera (O3) onto the focal plane (F).

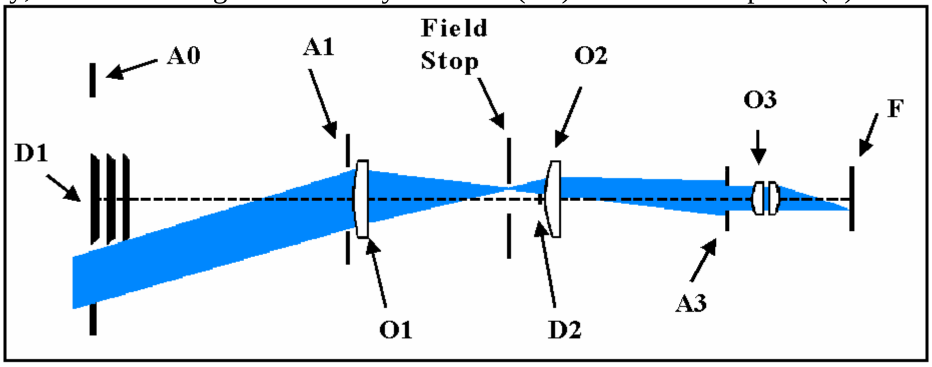

***Fig. 3** - Basic scheme of a classical externally occulted Lyot coronagraph already successfully used for all space borne coronagraphs. Performances are directly driven by the distance between the external occulter (D1) and the entrance pupil (A1).*

6.2 Example of a PROBA 3 coronagraph

The above classical design could be adapted to the PROBA 3's coronagraph to both detect the very inner corona as close as 1.04 Rsun from the Sun centre with high spatial resolution. The following sub-paragraphs describe a possible design and shall not be considered as requirements.

6.2.1 Optical PROBA 3 coronagraph configuration

The external occulter (EO) blocks the light from the solar disk while the coronal light passes through the circular entrance aperture. An unobstructed three-mirror anastigmat (TMA) solution is selected to limit the optical aberrations (diffraction limited at the internal occulter plane) and the total length of the instrument, while allowing a F-number of F/7. The internal occulter is located after the focal plane of the 3-mirror objective. The dioptric objective (L2) produces a real telecentric image of the entrance pupil at the Lyot stop with a magnification of about 10. The collimated beam leaving L2 passes through a narrow-bandpass Fabry-Pérot (F-P) interferometer, a set of blocking filters and polarizers mounted on a wheel. Each blocking filter isolates a specific emission line, and blocks all but a single transmitted interferometer order. The broadband filter allows obtaining polychromatic images of the corona (the Fabry-Pérot is then removed from the optical path). The final image is formed by a telephoto lens system onto the CCD detector such that a circular field-of-view with a radius of about 3 Rsun forms an inscribed circle on the 2k x 2k pixels detector where one pixel subtends less than 2.8 arcsec on the corona.

6.2.2 Mechanical Configuration

The optical components and the various equipments/subsystems are enclosed in the Coronagraph Optical Box (COB). This box is used as an optical bench. Its main objective is to maintain, during science operations, the optical axis direction with a very high accuracy and optical alignment, despite the variation of the thermal environment. The specification is in the range of a few arc-seconds.
The COB is constituted of composite panels made of aluminium honeycomb and carbon/cyanate or carbon/epoxy skins.
The electronics of the video camera has its own box called the "Camera Electronics Box" or CEB located closed to the detector to limit the cable length between them, and the associated noise.
A third box called "Coronagraph Control Box" or CCB contains the electronics for the functioning control of the coronagraph (mechanisms, thermal ...). This box may be integrated within the platform avionics.

6.2.3 Thermal configuration

The thermal concept is based on both passive and active control.
The COB requires a temperature of about 20°C stabilized at a few degrees. The COB is highly isolated from its surroundings, both conductively and radiatively, by implementing low conductance legs and MLI blanket. Note that some subsystems inside the COB may require more stringent stabilization (a few tens of degree). The detector requires a temperature under TBD with a stability of a few degrees when operating. The detector is cooled down by a passive radiator connected by a thermal bus and a cold finger.
The electronics boxes can dissipate their thermal power radiatively if they see the sky, or by conduction. They can therefore be thermally connected to the platform or isolated from it, but in the two cases they shall be warmed and controlled by an active system during a long non-operating phase.

6.2.4 Electrical configuration

Located on the C-S/C, the CCB commands, controls and synchronises the functioning of the following subsystems:

- the Camera Electronics Box (CEB),
- the image compression,
- the Motor Control Module (mechanisms) if required,
- the Servitude Control Module (FF subsystems, calibration unit, and housekeeping acquisition),

- the Thermal Control Module (used for the fine temperature control of the critical optical components and the detector),
- the Power Supply Module

Note that possible electronic commands and controls can also be implemented on the O-S/C for the FF subsystems.
The coronagraph will be provided the following I/F lines by the platform:

- Power lines, switched, protected against over current, and if possible regulated (TBC).
- Serial data links for data exchange: commands, image data, housekeeping data…
- Thermal lines connected to the heaters and temperature sensors.

6.2.5 Subsystems / mechanisms / calibration

The instrument is composed of the following subsystems:

- **Formation Flying Subsystems (FFSS)** which allow evaluating the quality of the formation flying in terms of both pointing and alignment.
- **Front Door Mechanism (FDM)** which protects the optics from particulate and molecular contamination.
- **Shutter Mechanism (SHM)** which defines the exposure time and protects the detector.
- **Filter Wheel Mechanism (FWM)** which is equipped with various blocking filters and polarizers.
- **Fabry-Perot Tilting Mechanism (FPM)** which rotates the Fabry-Perot etalon by a few tenth of degree allowing examining different areas.
- **Calibration unit (CU)** which allows calibrating (photometry and spectroscopy) the instrument.

6.2.6 Detector

The detector is base-lined on a conventional CCD detector array of 2048 x 2048 square pixels (15µm size). The need of a good quantum efficiency for the spectrometer channel leads to a back-thinned and back-illuminated CCD type.
The detector operating temperature shall be lower than TBD.

6.3 Orbit and Operations

PROBA 3 will be launched into a highly elliptical orbit with an orbital period of one day. An orbit will be divided between periods of formation flying, when coronagraphic observations will be possible, and periods of free flight when the formation will be broken.
In average, Formation flying operations will take place along an orbital arc centred on the apogee during a minimum period of 6 hours, but up to 12 hours in practise, during which FF experiments and science observations will be performed. The science operations will therefore be spread over the duration of the mission, nominally 2 years, and will amount to about 1000 hours cumulated (equivalent to 167 days or close to 6 months). The detailed mission timeline will depend on the earth/sun/orbit alignment which varies along the mission.

7. ARASS DESCRIPTION

See [AD2].