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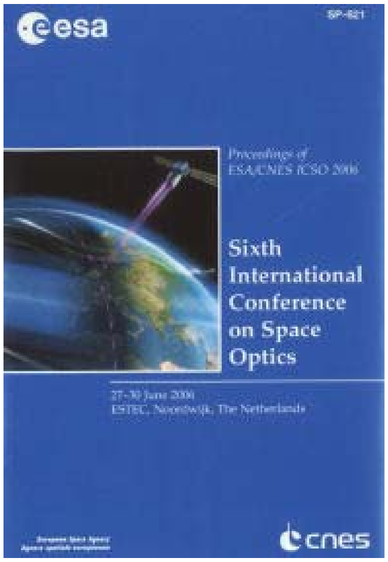

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PRELIMINARY OPTICAL DESIGN OF THE CORONAGRAPH FOR THE ASPIICS FORMATION FLYING MISSION

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ABSTRACT

Formation flyers open new perspectives and allow to conceive giant, externally-occulted coronagraphs using a two-component space system with the external occulter on one spacecraft and the optical instrument on the other spacecraft at approximately 100-150 m from the first one. ASPIICS (Association de Satellites Pour l'Imagerie et l'Interfromtrie de la Couronne Solaire) is a mission proposed to ESA in the framework of the PROBA-3 program of formation flying which is presently in phase A to exploit this technique for coronal observations. ASPIICS is composed of a single coronagraph which performs high spatial resolution imaging of the corona as well as 2-dimensional spectroscopy of several emission lines from the coronal base out to 3 $R_\odot$. The selected lines allow to address different coronal regions: the forbidden line of Fe XIV at 530.285 nm (coronal matter), Fe IX/X at 637.4 nm (coronal holes), HeI at 587.6 nm (cold matter). An additional broad spectral channel will image the white light corona so as to derive electron densities. The classical design of an externally occulted coronagraph is adapted to the detection of the very inner corona as close as 1.01 $R_\odot$ and the addition of a Fabry-Perot interferometer using a so-called "*étalon*". This paper is dedicated to the description of the optical design and its critical components: the entrance optics and the Fabry-Perot interferometer.

Key words: Coronagraph, Solar Corona, formation flying, visible, Fabry-Perot, etalon, optical design.

1. INTRODUCTION

Formation flying opens the possibility to conceive and deploy giant coronagraphs in space that are not affected by the limitations of classical externally-occulted coronagraphs presently limited in their performances by the distance between the external occulter and the front objective. The diffraction fringe formed by the external occulter and the vignetted pupil (which degrades the spatial resolution) prevent observing the inner corona inside typically 2-2.5 $R_\odot$ (where $R_\odot$ represents the solar radius). The only available images of the inner corona are those obtained with the SOHO/LASCO-C1 coronagraph but their contrast remains rather poor because of the high level of instrumental stray light. Routine images of the lower corona are also obtained with ground-based coronagraphs but their quality is affected by seeing and atmospheric conditions, and their useful fields of view rarely exceed a few tenth of solar radii. For completeness, we mention the images taken on the occasions of (rare) total solar eclipses whose quality remains unsurpassed.

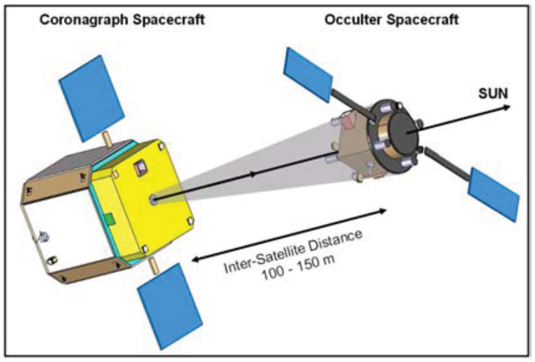

Figure 1. ASPIICS on a two-component space system with the external occulter on one spacecraft and the optical instrument on the other spacecraft at 100-150 m from the first one. Formation flying configuration studied by CNES/PASO (2005).

The PROBA-3/ASPIICS (standing for "Association de Satellites Pour l'Imagerie et l'Interferometrie de la Couronne Solaire") mission is composed of two spacecrafts separated by about 100-150 m and forming a giant coronagraph: the external occulter is

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supported by one satellite while the second satellite hosts the optical system (Fig. 1).

ASPIICS (Vivès *et al.* (2006); Lamy *et al.* (2006)) will perform high spatial resolution imaging of the corona as well as 2-dimensional spectroscopy of several emission lines from the coronal base out to 3 $R_\odot$. The selected lines allow to address different coronal regions: the forbidden line of Fe XIV at 530.285 nm (coronal matter), Fe IX/X at 637.4 nm (coronal holes), HeI at 587.6 nm (cold matter). ASPIICS will address the question of the coronal heating and the role of waves by characterizing propagating fluctuations (waves and turbulence) in the solar wind acceleration region and by looking for oscillations in the intensity and Doppler shift of spectral lines. The combined imaging and spectral diagnostics capabilities available with ASPIICS will allow to map the velocity field of the corona both in the sky plane (directly on the images) and along the line-of-sight by measuring the Doppler shifts of emission lines in an effort to determine how the different components of the solar wind, slow and fast are accelerated. With a possible launch in 2011, ASPIICS will observe the corona during the maximum of solar activity, insuring the detection of many Coronal Mass Ejections (CMEs). By rapidly alternating high resolution imaging and spectroscopy, CMEs will be thoroughly characterized. In addition, ASPIICS will attempt to characterize the topology of the magnetic field in the corona.

2. OPTICAL CONCEPT

ASPIICS is an externally occulted coronagraph entirely protected from direct sunlight by remaining in the shadow of the external occulter hosted by another spacecraft. The classical design of an externally occulted coronagraph is adapted to both the detection of the very inner corona as close as 1.01 $R_\odot$ from the Sun centre with high spatial resolution (5 arcsec), and the addition of a solid "*étalon*" Fabry-Perot interferometer.

The design of the primary optics is critical because a high level of both aberrations and scattered light will prevent observing the very inner corona: this is discussed further in section 4.

Various instrumental solutions have been considered to cover the desired spectral measurements. Conventional slit spectrographs have the disadvantage that they give 1-D information while 2-D spectrographs (multislit, optical fibers, IFU) lead to complex and bulky instruments, incompatible with the present flight constraints. As described in section 5, the optical concept best suited to our problem is the "*étalon*" Fabry-Perot (F-P) interferometer. The method consists in analyzing the bi-dimensional distribution of line profiles by a set of quasi concentric fringes generated by the F-P. The interferogram may be viewed as resulting from a multislit spectrograph: all the spectral information is contained in the image, and there is no need to combine several images as in the scanning F-P to reconstruct the spectra.

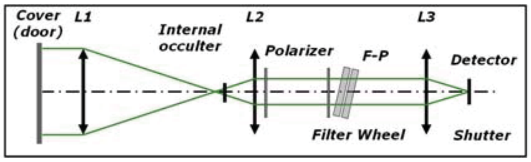

Figure 2. Basic scheme of the optical concept of the ASPIICS coronagraph with main opto-mechanical sub-systems.

3. OPTICAL DESIGN

The current optical design (Fig. 3 and 4) is based on a dioptric solution to achieve the required optical quality at the internal occulter and preserve instrumental polarization. However, the use of mirrors instead of lenses is also under consideration because such solution presents major technical advantages: a natural front baffle, protection of the first optics against contamination and thermal variations, straightforward folding (reducing the overall length). The following description also applies to a reflective design. Table 1 summarizes the main instrumental characteristics and performances.

The external occulter (EO) blocks the light from the solar disk while the coronal light passes through the circular entrance aperture (100 mm diameter). The L1 two-element design forms the image of the EO onto the internal occulter with reduced geometric and chromatic aberrations to provide more efficient inner occultation. The internal occulter is slightly oversized to block the bright diffraction fringe surrounding the EO. The amount of over-occultation results from the compromise between the stability of the formation, attitude of the spacecraft hosting the coronagraph and the vignetting which determines the spatial resolution in the inner part of the corona. A rotating polarizer is located right after the internal occulter, so very close to an image plane, and in the unfolded part of the beam to avoid instrumental polarization. The combination of L1 and L2 forms an afocal system which produces a real image of the entrance pupil at the Lyot stop. The collimated beam leaving L2 is sent through a narrow-bandpass Fabry-Perot (F-P) interferometer and a set of blocking filters mounted on a wheel. Each blocking filter selects a specific emission line spectral interval and blocks all but a single transmitted interferometer order. A large band filter allows to transmit several orders thus yielding polychromatic images. The final image is formed by a telephoto lens system on a detector

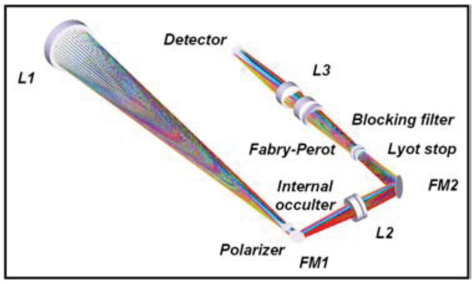

Figure 3. Preliminary optical layout of the ASPIICS coronagraph using dioptric components: 3D-view.

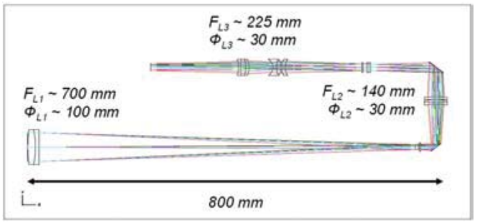

Figure 4. Preliminary optical layout of the ASPIICS coronagraph: overall dimensions.

Table 1. Coronagraph Instrument Characteristics and Main Optical Performances.

Coronagraph Performances	
FOV	1.01-3 $R_\odot$
Spatial resolution	2.5 arcsec/px
Spectral resolution	≈26500
Wavelength	530.3 nm; 587.6 nm; 637.4 nm; 540-570 nm
Calibration Lamp	546.1 nm
Primary objective	
Clear Aperture	100 mm
Focal length	700 mm
F-number	F/7
Glasses	2-element (BK7 + SF10)
Fabry-Perot Interferometer	
Clear Aperture	30 mm
Spacer thickness	300μm
Reflector coating	91%
Detector	
Dimension	2k×2k
Pixel size	13.5 μm

located behind a mechanical shutter. The layout is such that a circular field of view with a radius of 3 $R_\odot$ forms an inscribed circle on the 2k × 2k pixels CCD detector where one pixel subtends 2.5 arcsec in the corona. Two plane mirrors M1 and M2 fold the optical path in order to limit the overall length of the instrument. The coronagraphic part (before the internal occulter) is axially designed to limit aberrations and then preserve image quality at the internal occulter.

4. PRIMARY OBJECTIVE

The primary objective (L1) must achieve high image quality and low scattering level. L1 is the most critical optical component as far as stray light is concerned, therefore all its surfaces will be superpolished to limit scattered light and the two elements are in optical contact to minimize multiple reflections between the internal faces. Furthermore, the combination of glasses, BK7 and F2, has already been used for the primary objective of the successful SOHO/LASCO-C2 coronagraph. The image quality at the primary focal plane also drives the over-occultation. Indeed, the internal occulter will be sized to block the diffraction fringe around the external occulter. Preliminary simulations show that optical aberrations represent between 15 to 30% of the over-occultation (the rest is due to spacecrafts misalignments). Thus reducing aberrations provides both better occultation and better tolerancing for formation flying constraints.

With an F/7 focal ratio, L1 provides good image quality over a 1.5° field diameter at the internal occulter. Spots are better than 3 arcsec that corresponds to an over-ocultation of about 0.3%. The focal length of L1 drives the total length of the instrument and it appears to be a practical limit since the corresponding total length of the instrument is about 1 m. Lower focal ratio degrades image quality. As an example, the over-occultation due to aberrations amounts to 0.6% with an F/3 focal ratio (total length divided by approximately 2). Using mirrors will also reduce total length. However, to achieve the required optical quality, L1 has to be replaced by a combination of two or three off-axis mirrors with complex shapes (instead of a single on-axis two-element with spherical surfaces). Using mirrors lead to a compact design (length reduced by a factor 2) at the expense of the simplicity of the instrument (optics manufacturing, alignment).

5. FABRY PEROT INTERFEROMETER

For ASPIICS, we propose a solid "*étalon*" F-P interferometer which does not require any internal adjustments unlike the tunable F-P which uses a scanning mechanism. Using an *étalon* F-P allows to avoid problem of F-P adjustment (interferometer cavity

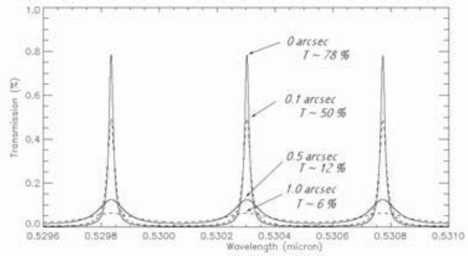

Figure 5. Evolution of the transmission and of the finesse as functions of the tilt angle between surfaces of the F-P (in arcsec).

length and parallelism) at the expense of the instantaneous coverage of the full FOV. This problem is compensated by a tilting mechanism (which increase the spatial resolution) and by the fact that the line profile is contained in a single image while a tunable F-P needs a combination of several images to reconstruct the line profile. Significant cavity length drift could result in variations of the effective passband central wavelength, and a lack of parallelism could reduce the instrument finesse and consequently broadens the transmission profile (Fig 5).

The baseline Fabry-Perot (F-P) interferometer operates at the main emission line of 530.3 nm (Fe XIV). The fringes have an instrumental profile ($\delta\lambda$) of typically 0.02 nm (FWHM), narrower than the width of the line ($\approx$0.1 nm), so that the observed profiles are not significantly affected by the instrumental function and directly give the real profiles of the coronal emission line to a very good accuracy. The free spectral range (FSR) will be approximately 0.5 nm, a compromise between the expected shifts of the line, the transmission peak, and the rejection of the continuum corona, leading to an effective finesse of about 25. The set of fringes will be decentered compared with the solar disk and the F-P will work in low orders producing dense fringes and resulting in a higher spatial resolution (see Fig. 6). The *étalon* will be mechanically tilted to displace the set of fringes and increase the resolution. There is obviously a compromise between the number of fringes (instantaneous spatial resolution), the number of tilted positions (real spatial resolution) and the width of the fringes (spectral resolution).

Although the baseline F-P is optimized for a single wavelength (530.3 nm), it is possible to accommodate additional wavelengths by selecting a coating covering a wider spectral range. The only downside aspect is that the AR-coating is not quite as good as for a single wavelength. Table 2 shows the main characteristics of the F-P for the selected emission lines (including the calibration line of Hg at 546.1 nm).

When an *étalon* is tilted, the effective finesse and the peak transmission are both reduced. This is due to beam walk-off, which results in a reduced number of reflections in the cavity. The magnitude of the effect depends on the ratio of *étalon* aperture to mirror separation (the larger the aperture, or the smaller the mirror separation, the smaller the degradation of finesse and transmission). In our case the mirror separation is very small (about 300 μm), and tilting to 20° has little effect on finesse and transmission as shown in Table 3. Tilting also changes the FSR because the spacer thickness is not constant.

Table 2. Main performances of the P-F (free spectral range, FSR; reflectivity finesse, F_r; effective finesse, F_e; and F-P peak transmission, T) calculated over the whole scientific spectral range. The reflector coating is considered constant over the bandpass.

	Fe XIV	Hg	He I	Fe X
in nm	530.3	546.1	587.6	637.4
FSR (nm)	0.47	0.50	0.57	0.68
F_r	33.3	33.3	33.3	33.3
F_e	26.1	26.4	27.1	27.8
T (%)	78	79	81	83

Table 3. Tilting effect on the P-F performances (spacer tickness, d; free spectral range, FSR; effective finesse, F_e; and F-P peak transmission, T) calculated for tilts between 0° and 20°.

Tilt	0°	5°	10°	15°	20°
d (μm)	299	298	294	289	281
FSR (nm)	0.47	0.47	0.48	0.49	0.50
F_e	26.1	26.0	25.9	25.8	25.6
T (%)	78.3	78.2	77.9	77.6	77.0

6. CONCLUSION

The present optical design of ASPIICS is based on dioptric solution to preserve image quality (particularly at the internal occulter) and stray light rejection at the expense of the compactness of the instrument. Further studies are in progress to adapt mirrors and/or reduce length with a different configuration. Up to now the use of a tunable F-P interferometer was not considered because of its apparent complexity although it allows to drastically improve the spatial sampling. This alternative will be considered in the immediate future. Finally, we are also participating to the phase A industrial study for the PROBA-3 mission in order to accommodate ASPIICS at best.

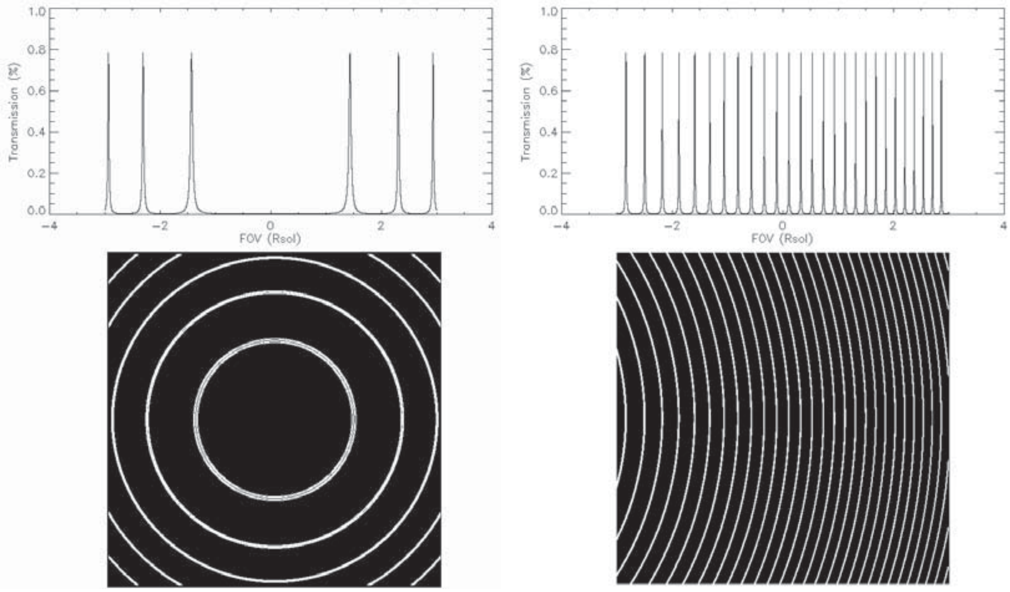

Figure 6. When the Fabry-Perot works at normal incidence, fringes are centered on the optical axis (at left) but there is a few number of rings within the FOV ($\pm 3\ R_\odot$). Tilting the F-P by 10° (at right) increases the number of fringes what improves the instantaneous spatial coverage.

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