OPTICAL PERFORMANCE OF THE PROBA-3/ASPIICS SOLAR CORONAGRAPH

S. Vives(1), **A. Mazzoli**(2), **F. Landini**(3), **R. Melich**(4), **C. Escolle**(1), **J.-Y. Plesseria**(2), **C. Guillon**(1), **and P. Levacher** (1)
(1)*Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France, +33 491 056 931, sebastien.vives@oamp.fr*
(2)*Université de Liège – CSL (Centre Spatial de Liège), Avenue du Pré-Aily, 4031 Liège, Belgique, +32 4 382 46 00, amazzoli@ulg.ac.be*
(3)*INAF – Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy, +39 055 2055221 flandini@arcetri.astro.it*
(4) *Institute of Plasma Physics ASCR, v.v.i. - TOPTEC, Sobotecka 1660, 51101 Turnov, Czech Republic, +420 776 783 952, melichr@ipp.cas.cz*

Abstract:
PROBA-3 is a technology mission of the European Space Agency (ESA), devoted to the in-orbit demonstration of formation flying techniques and technologies. Presently in phase B, PROBA-3 will implement a coronagraph (called ASPIICS) that will exploit the capabilities and validate performance of formation flying. ASPIICS is distributed on two spacecrafts separated by 140m with the external occulting disk hosted by one spacecraft and the imaging optical system on the other one. ASPIICS will perform high spatial resolution imaging of the solar corona from the coronal base (1.04 solar radii) out to 3 solar radii. It will observe two different coronal regimes: the continuum (between 540 and 570nm) and the HeI D3 emission line (at 586.4nm). On top of the description of the optical design and the expected performance of this peculiar solar coronagraph, this article will focus on the innovative solutions and methods developed for ASPIICS (during the phase B) to evaluate the optical performance of such a giant instrument. Indeed, even if ASPIICS will observe the corona in eclipse-like conditions, the reduction of the stray light remains critical and challenging: the coronal signal is about 10^6 to 10^8 lower than the direct solar disk signal.

Keywords: *PROBA-3, ASPIICS, optical design, stray light, solar coronagraph.*

1. Introduction

Formation flying (FF) 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 performance by the distance between the external occulter disk and the front objective. When this distance is small, the diffraction fringe formed by the external occulter and the vignetted pupil (which degrades the spatial resolution) prevent for observing the inner corona inside typically 2–2.5Rsun (where Rsun represents the solar radius).
ASPIICS is a solar coronagraph that was proposed to ESA for the technology mission of the European Space Agency (ESA) PROBA-3, devoted to the in-orbit demonstration of formation flying techniques and technologies. PROBA-3/ASPIICS successfully passes its Preliminary Design Review (PDR, end of phase B) in April 2013.

ASPIICS is distributed on two spacecrafts separated by 140m with the external occulting disk hosted by one spacecraft and the telescope on the other one. ASPIICS will perform high spatial resolution imaging of the solar corona from the coronal base (1.04 solar radii) out to 3 solar radii.
ASPIICS is developed by a consortium of European Institutes and Industries from Belgium, Czech Republic, France, Germany, Greece, Italy, Luxembourg and Russia. For more information about ASPIICS and its status, please refer to [1].

2. Optical Concept

2.1. Description

The ASPIICS optical design follows the general principles of a classical externally occulted Lyot coronagraph. The external occulter (EO), hosted by one spacecraft, blocks the light from the solar disk while the coronal light passes through the circular entrance aperture (50 mm diameter) of the optical telescope on the second spacecraft. As shown in Fig. 1, the primary objective (PO), located 200mm behind the entrance pupil, forms an image of the external occulter (EO) onto the internal occulter (IO). The image of the surrounding bright fringe is blocked by slightly over-sizing the internal occulter (1.04Rs instead of 1.02Rs). The Relay Lens (RL) re-images both the entrance pupil onto the so-called “Lyot Stop” and the corona image onto the CCD detector (protected by a glass window). The detector is a 2048x2048 with 15microns pixel size.

The effective focal length of ASPIICS is 1150mm with an overall length (from the entrance pupil to the detector plane) of 700mm.

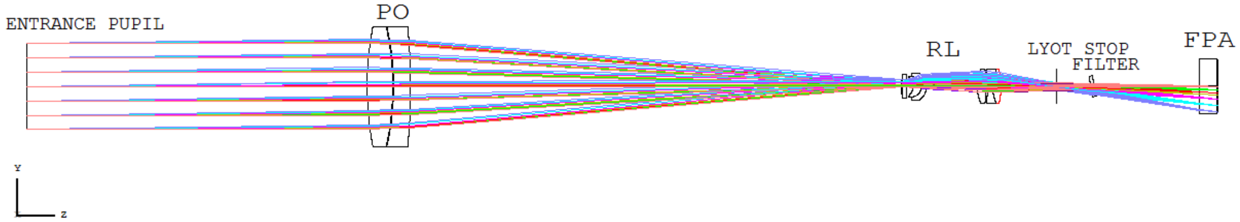

Figure 1. Overall layout of the ASPIICS optical design.

The primary objective has an effective focal length of 300mm and is composed of two separated lenses made of BK7G18 and SF6G05. The two lenses are made of radiation hard glasses to avoid any darkening effects while the optical performance are strictly equivalent to those achieved by classical glasses (e.g. BK7 and SF10). The separation (of 0.5mm at the edge) allows to cope with the differential thermal dilation between the two lenses and allows mounting the two lenses in a common barrel. The primary objective has been optimized for finite distance object (144 m) for a field-of-view corresponding to the outer edge of the external disc (i.e. ~1.02 Rsun).

As shown in Fig. 2, the relay lens is composed of 2 sets of lenses: a doublet (made of BK7 and SF2); followed by a BK7 lens (with one aspherical surface) and a doublet (made of SF2 and BK7). The Lyot Stop blocks the light diffracted by the edges of the pupil. Filters and polarizers (mounted on a wheel) can be inserted after the Lyot Stop. Note that they are tilted by 11 degrees to avoid ghosts.

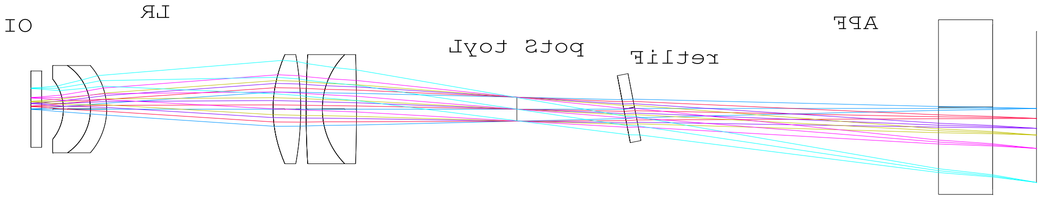

Figure 2. Layout of the imaging unit of the ASPIICS optical design.

2.2. Image quality

The optics of ASPIICS shall produce diffraction limited images in both planes of the internal occulter and the focal plane. Indeed the image quality specification is divided in two in order to meet the two main functions of the coronagraph:

1. Image of the corona on the detector which is required to observe the corona with the specified spatial resolution (about 2.8 arcsec/pixel) over the whole FoV (about +/-2.7Rsun)
2. Image of the external occulter onto the internal occulter which is required to reduce the stray light in the instrument.

Fig. 3 shows the image quality at the focal plane for an object at infinity up to 0.8deg (i.e. 3Rsun). On the right hand-side, the spot diagram is given for four wavelengths (0.540 µm, 0.555 µm, 0.570 µm and 0.588 µm). The boxes are 30µm square (i.e. 2x2 pixels). On the left hand-side, the plot shows the variation of the RMS spot radius across the FOV for the same four wavelengths.
The specifications are met for a circular FoV of 2.7Rsun and only the corners of the detector (up to 3Rsun) are slightly out-off specification.

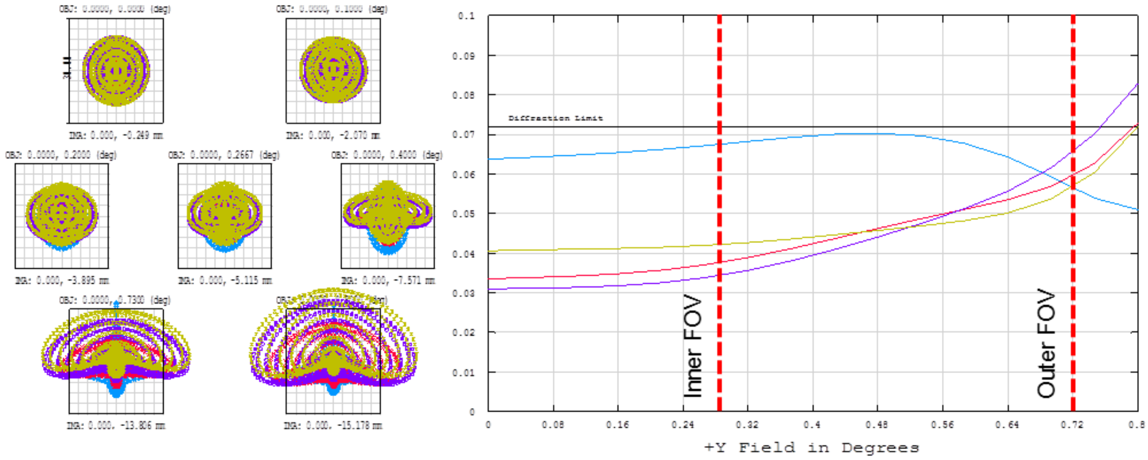

Figure 3. Image quality in the image plane: spot diagram (right) and RMS spot radius versus FoV for four wavelengths (left).

Fig. 4 shows the image quality at the internal occulter plane for an object located at 144m. Indeed, the internal occulter is the conjugated plane of the external occulter. The optimization has been made for a ring of about 1.02Rsun corresponding to the edge of the external occulter.

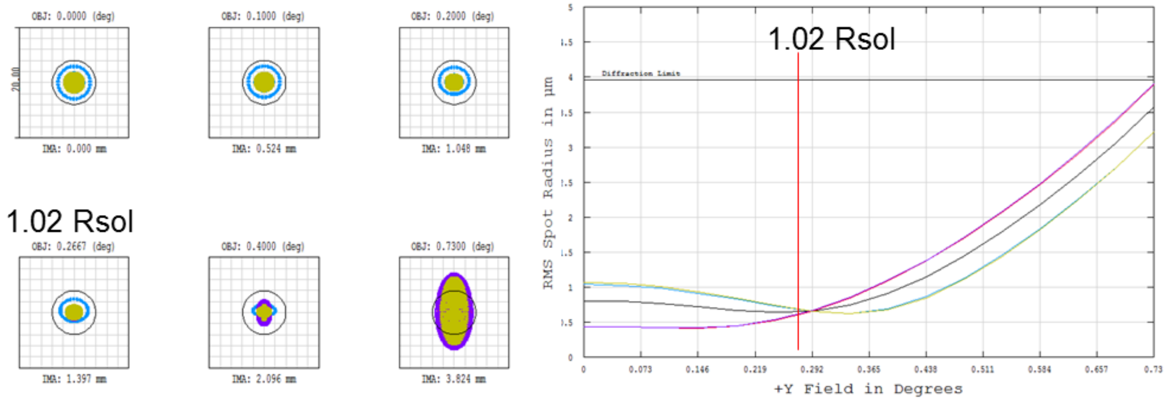

Figure 4. Image quality at the internal occulter: spot diagram (right) and RMS spot radius versus FoV for four wavelengths (left).

2.3. Optical design simplification

Initially ASPIICS incorporated a Fabry-Perot to perform 3D-diagnostic of the corona [2,3]. However the limited resource available on the PROBA-3 platforms led us to descope the Fabry-Perot. This descoping allowed drastic simplifications of the optical design. In particular, the pupil diameter has been reduced (from 140mm to 50mm) allowing to replace the Three-Mirror Anastigmat (TMA) by a lens objective (doublet). The doublet preserved the image quality: even if intrinsically it offers lower image quality, by taking into account the manufacturing and alignment errors, the doublet is comparable to the TMA. By using a doublet, the overall optical train can be implemented on-axis and the whole mass is reduced by about 30%. The use of a doublet relaxes the thermal stability requirements of the optical bench.

3. Stray light Performance

The major source of stray light is the diffraction by the external occulter (EO) edge of the direct Sun light. Indeed, the intensity of the Sun is several orders of magnitude higher than the corona in visible light; and even if the external occulter blocks the direct Sun light, the light diffracted by its edge remains a major concern and this contribution must be estimated. A computation has been made in two steps:

1. Diffraction by the external occulter based on the Fresnel-Kirschhoff theory at the pupil and the primary objective level.
2. Propagation of the diffracted light in the instrument with ASAP.

The ASAP model has been also used to define baffle design, and search for ghosts. These aspects are not addressed in this paper.

3.1. Diffraction by the External Occulter

The evaluation of the diffraction pattern on the pupil plane was performed by means of the Fresnel-Kirchhoff diffraction theory. The solar disk can be schematized as a finite set of non-coherent source points. Using 419 points to describe the full disk allows achieving a typical precision of +/-1% on the computation of the diffraction pattern. We neglected all the intensity variations on the solar disks (e.g., Sunspots), except for the limb darkening effect.

Fig. 5 shows the normalized profile of the light diffracted by the external occulter in the entrance pupil plane considering a simple occulting disk. The profile is almost constant (about 6.10^{-4} with respect to the Sun disk brightness) over the entire entrance pupil.

The previous computation has been made assuming a simple disk as occulting system. However, ASPIICS will incorporate a conic occulter edge that will reduce the amount of light diffracted toward the entrance pupil. Experiments to optimize occulter edge shape have been made in the past (in particular during the second Startiger initiative, see [4,5]). In the region 1Rsun to 1.1Rsun, it is possible to reduce by a factor 2 to 5 the light diffracted towards the pupil by using conic shape occulter. This is shown in Fig. 6 which plots the ratios between the simple knife-edge (simple disk) and some other occulter shapes (including the cones). The experiments were performed with a set-up replicating a portion of the large occulter (about 1.5m), approximated by a straight edge. The stray light in the solid angle subtended by the ASPIICS pupil was measured.

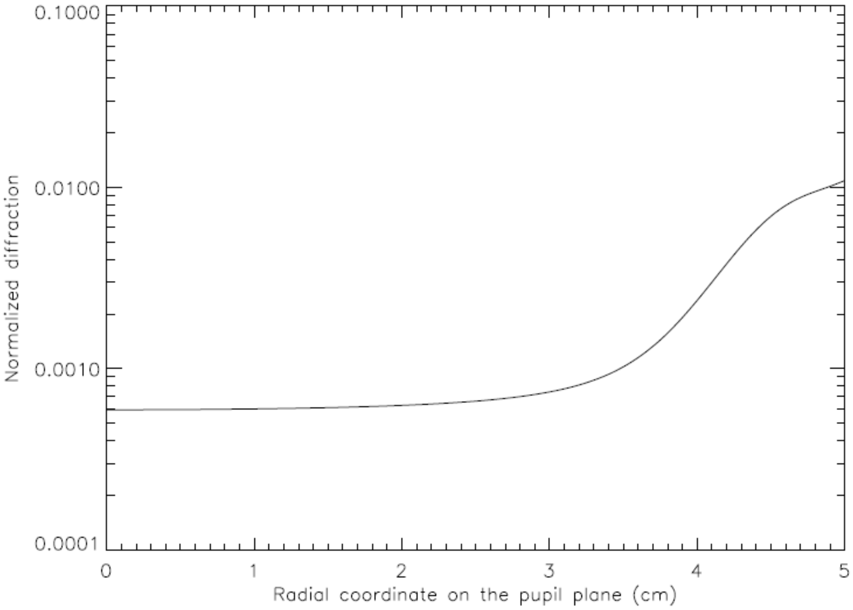

Figure 5. Normalized profile of the light diffracted by the external occulter in the entrance pupil.

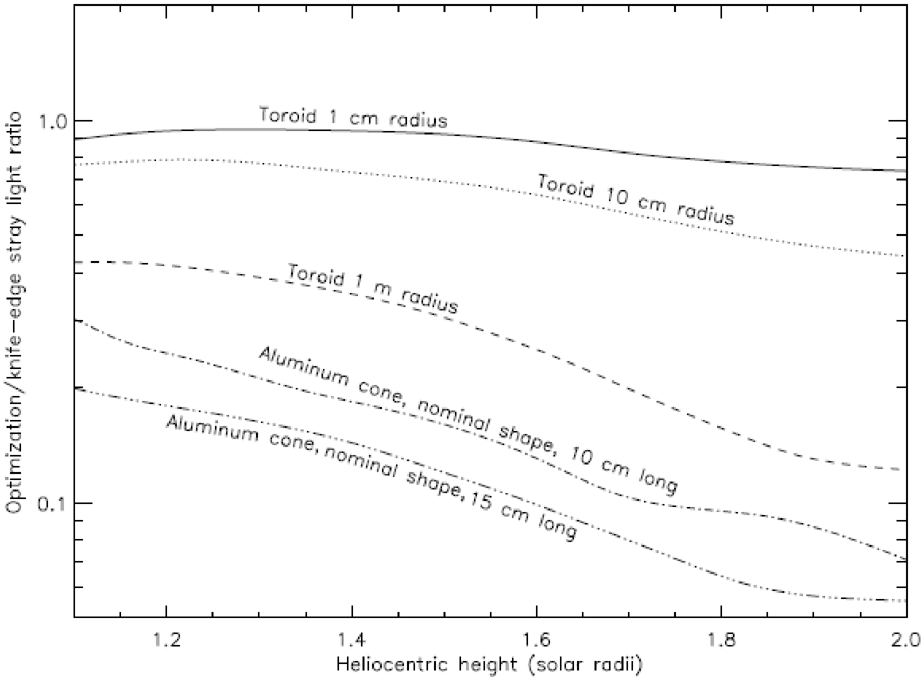

Figure 6. Ratios of light diffracted towards the entrance pupil between different occulter shapes (including cone) and the knife-edge reference.

3.2. Instrumental Stray light

The study was performed with the ASAP® ray tracing software. A view of the mechanical model with the optical elements used for the stray light analysis is shown in Fig. 7. This model was used to assess the expected final stray light level on the detector taking into account: optics scattering, ghosts, scattering and reflections by mechanical parts, etc.

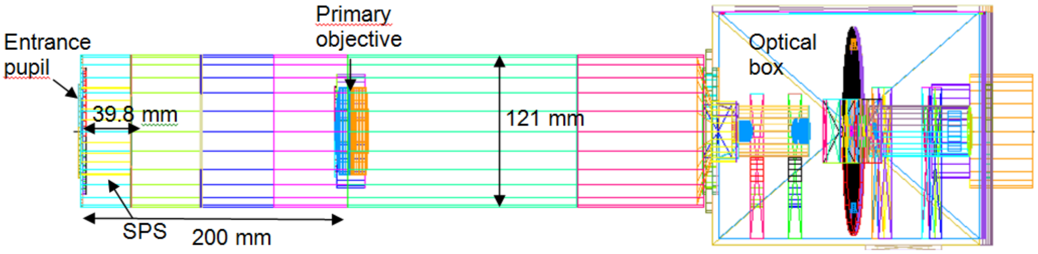

Figure 7. ASAP Model of the ASPIICS coronagraph.

Several sources have been considered: in particular, the external occulter (using the computation described in Section 3.1 and simulated by a series of point sources located on the edge of the EO), Earth and Moon up to 15 degrees of the line of sight, and reflections and scattering on the rear side of the external occulter.

The model allowed us to propagate the diffracted light through all the optics up to the detector taking into account all effects (scattering, ghosts, etc.). It appears that the scattering of the Primary Objective drives the stray light level between 1 and 2Rsun. Indeed, the internal occulter (IO) blocks the direct light from the external occulter but the part which is scattered before (i.e. by the PO) produces a pattern on the detector as shown in Fig. 8. Therefore the critical parameter is the micro-roughness of each surface of the primary objective.

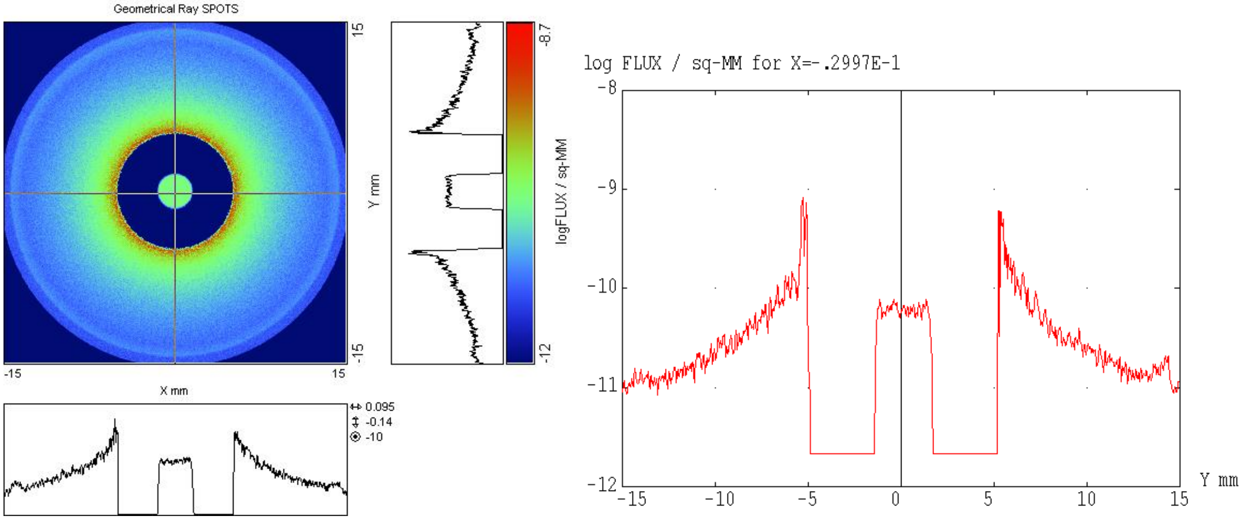

Figure 8. Spatial distribution (left) and profile (right) of occulter diffracted light scattered by the optics on the detector.

Fig. 9 shows the final expected performance considering a micro-roughness of 0.5nm RMS for each surface. In this case the expected stray light level is compliant with the specification (red lines). Note that if we degrade all surface roughness by a factor 2 (i.e. 1nm RMS), only the very inner part is significantly affected and the specification is not met below 1.2Rsun.

Several investigations and prototyping are foreseen to assess the typical micro-roughness that can be achieved on the Primary Objective lenses.

4. Conclusions

We demonstrated in this paper that the proposed optical design for ASPIICS will allow observing the very inner corona (from 1.04Rsun) with an unprecedented spatial resolution. Indeed ASPIICS will fully take advantage of the formation flying technique.

We presented the drastic simplification of the optical design which then meets both the scientific requirements and the available resources on-board PROBA-3.

We also presented a stray light analysis which combines the Fresnel-Kirchhoff diffraction theory and classical ray-tracing computation. Thanks to this innovative approach, we were able to assess the stray light in this giant instrument.

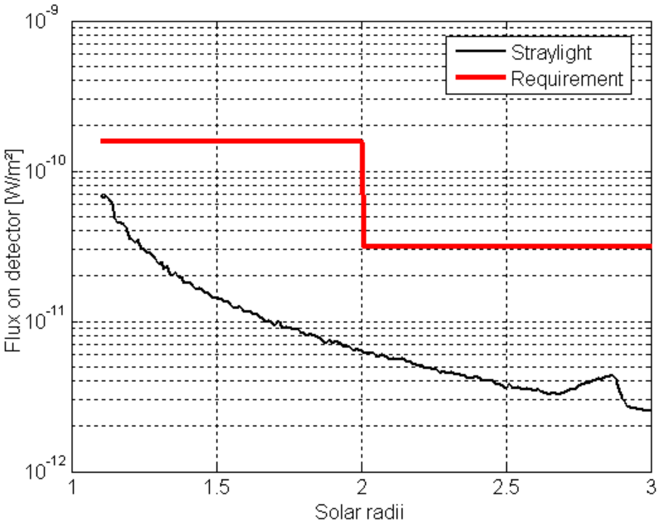

Figure 9. Scattered light on detector due to EO diffraction and PO micro-roughness (0.5 nm).

5. Acknowledgments

The Belgian contribution to this work has been funded by the Belgian
Science Policy Office (BELSPO)

6. References

[1] Plesseria, J.-Y., et al., "Design and development of ASPIICS, an externally-occulted solar coronagraph for PROBA-3 mission", 2013, this proceeding.

[2] Lamy, P., Vives, S., Damé, L., Koutchmy, S., "New perspectives in solar coronagraphy offered by formation flying: from PROBA-3 to Cosmic Vision", Proc. SPIE 7010, 70101H (2008)

[3] Lamy P.; Damé L.; Vives S.; Zhukov A., "ASPIICS: a giant coronagraph for the ESA/PROBA-3 Formation Flying Mission", SPIE Proc., Volume 7731, pp. 773118-773118-12 (2010)

[4] Landini F.; Mazzoli A.; Venet M.; Vives S.; Romoli M.; Lamy P.; Rossi G., "Measurements and optimization of the occulting disk for the ASPIICS/PROBA-3 formation flying solar coronagraph", SPIE Proc., Volume 7735, pp. 77354D-77354D-15 (2010)

[5] Landini F., Vives S., Venet M., Romoli M., Fineschi S., "External occulter laboratory demonstrator for the forthcoming formation flying coronagraphs", Applied Optics, Vol. 50, No. 36 (2011).