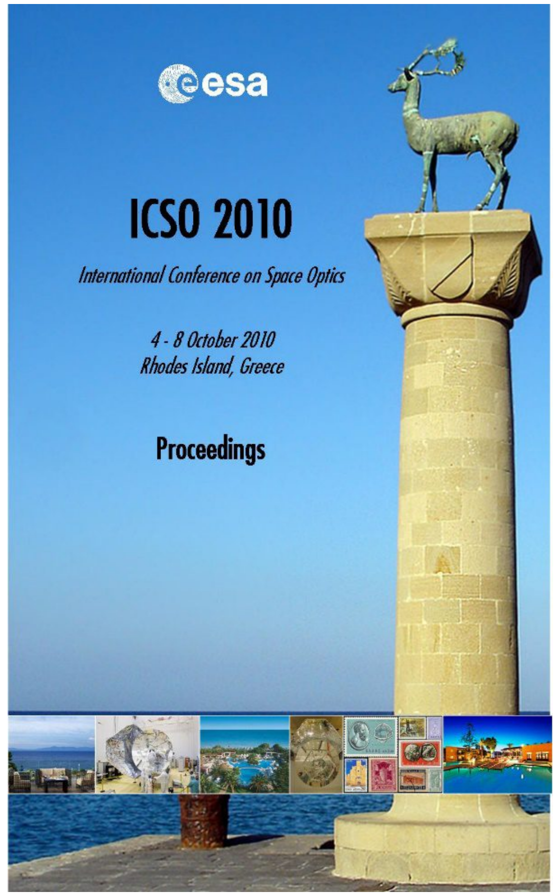
International Conference on Space Optics—ICSO 2010

Rhodes Island, Greece

4–8 October 2010

Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas



Stray light rejection in giant externally-occulted solar coronagraphs: experimental developments

M. Venet, C. Bazin, S. Koutchmy, P. Lamy

International Conference on Space Optics — ICSO 2010, edited by Errico Armandillo, Bruno Cugny, Nikos Karafolas, Proc. of SPIE Vol. 10565, 105651W · © 2010 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2309186

STRAY LIGHT REJECTION IN GIANT EXTERNALLY-OCCULTED SOLAR CORONAGRAPHS: EXPERIMENTAL DEVELOPMENTS

M. Venet[1], C. Bazin[2], S. Koutchmy[2], P. Lamy[1]
[1]*Laboratoire d'Astrophysique de Marseille, 38 rue Frédéric Joliot-Curie, 13388 Marseille cedex 13, France.*
E-mail: melanie.venet@oamp.fr, philippe.lamy@oamp.fr
[2]*Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 Paris, France.*
E-mail: bazin.cyrille@neuf.fr, koutchmy@iap.fr

I. INTRODUCTION:

The advent of giant, formation-flight, externally-occulted solar coronagraphs such as ASPIICS (Association de Satellites Pour l'Imagerie et l'Interférométrie de la Couronne Solaire [1,2,3,4]) selected by the European Space Agency (ESA) for its third PROBA (Project for On-Board Autonomy) mission of formation flying demonstration (presently in phase B) and Hi-RISE proposed in the framework of ESA Cosmic Vision program, presents formidable challenges for the study and calibration of instrumental stray light. With distances between the external occulter (EO) and the optical pupil (OP) exceeding hundred meters and occulter sizes larger than a meter, it becomes impossible to perform tests at the real scale. The requirement to limit the over-occultation to less than 1.05 R_{sun}, orders of magnitude to what has been achieved so far in past coronagraphs, further adds to the challenge. We are approaching the problem experimentally using reduced scale simulators and present below a progress report of our work.

In externally-occulted solar coronagraphs, the main source of instrumental stray light is the diffraction fringe surrounding the external occulter. Efforts have therefore concentrated on elaborating occulting systems that improve upon the baseline simple disk [5-9]. For occulters flown so far having dimensions of a few centimetres and EO-OP distances of less than a meter (e. g., Solwind, SMM, LASCO, SECCHI), there was no particular difficulties in performing laboratory tests, except the implementation of a solar simulator that correctly reproduces the geometric illumination conditions [9] and performing measurements of faint signals in the presence of a bright illuminating source. Three-disk systems have become the standard on US coronagraphs (Solwind, SMM, LASCO-C3, SECCHI-COR2), while a multithreaded occulter was selected for the french LASCO-C2 based on its superior rejection performances [9]. For ASPIICS, the implementation of an occulter having a diameter of ~1.5 m on a satellite imposes severe practical constraints (handling, cleanliness, vibration) and rules out disks, either single or multiple, with knife edges. As electro-eroded short truncated cones have been experimentally shown to have performances similar to the multithreaded EO flown on LASCO-C2 [9], such a simple and robust design has been adopted as the baseline solution for ASPIICS.

The optimization of the intrinsic performances of an occulter may be first studied irrespective of the optical part of the coronagraph, by measuring for instance the level of stray light on the optical axis [9] or its radial distribution [10] at the foreseen distance of the optical pupil. However this covers only one aspect of the problem. Ultimately, it is the combination of EO and pupil of the coronagraph that controls and determines the stray light rejection performance, and this is intimately connected to the specified over-occultation (clearly, the larger this parameter, the easier the problem). This further split in three considerations: i) the total level of stray light that goes through the entrance pupil, ii) its radial distribution across the pupil, and iii) the image of the diffraction fringe superimposed on and contaminating the inner corona. The second consideration entails the illumination level of the external diaphragm delimiting the pupil whose diffraction is a secondary source of stray light. The third aspect needs further elaboration. In coronagraphs flown so far, this fringe is partly blocked by an inner occulter (IO) placed in the conjugated plane of the EO, henceforth not in the focal plane of the first objective. Therefore it is the defocused image of the unblocked outer ring of the fringe which is superposed on the corona. It is not yet clear whether an IO will be needed for ASPIICS (a radial compensating neutral filter that both reduces the gradient of the corona and the diffraction fringe has been baselined [4]) and a final decision on this question is precisely part of the present investigation. Whatever the final choice, the image of the fringe must be as sharp as possible to facilitate its blocking (if relevant) and limit its contamination of the corona, and further with the lowest possible intensity. The study and optimization of the occulting system must therefore involve at least the EO and the first objective of the coronagraph (equivalent to the Three-Mirror Anastigmat in the present ASPIICS optical design [4]). This represents a formidable challenge because of the involved dimensions. In a first step, we proceed at a reduced scale, but still with dimensions much larger and over-occultation much smaller than achieved so far in past experimental works.

II. EXPERIMENTAL STUDIES:

ASPIICS has a typical EO-OP distance of 150 m and an EO of 1.5 m in diameter preventing a laboratory simulation at full scale. We decided to work at a reduced scale of typically 1/15 as a compromise between practical dimensions and adequate representation of ASPIICS, in particular its over-occultation, far smaller than considered in previous similar investigations. Two experimental setups have been implemented, one using the real Sun at a high altitude observatory, the other a laboratory solar simulator.

A. Experimental studies at Pic-du-Midi observatory

Using the Sun is obviously a must for studying externally occulting systems as the illumination conditions are the real ones. A prerequisite is a "dark" or "coronal" daytime sky which can only be found at high altitudes. The Pic-du-Midi observatory was selected based on a long history of collaboration with one of the authors (S. K.), the availability of an equatorial mount and the relative ease of access. The optimal sky conditions only prevail during the winter and early spring seasons; later on, continental aerosols rise to the height of the observatory and create a prominent aureole which is detrimental to our measurements. A possible source of "pollution" is however flying snow flakes as will be illustrated below. The optical configuration is quite simple as illustrated in Fig. 1, and depending upon the various combinations that have been tested, the EO-OP distance varied from 6.5 to 7 m. Our experiment was set up on the equatorial mount of the coronagraph dome, the occulter on a first bench near the upper edge at the maximum extent compatible with the dome and the imaging system on a second bench fixed to the back of the mount (Fig. 2). The alignment (positioning in space) of the occulter was performed using a laser temporarily placed in front of the objective and targeting a mirror fixed on the back of the occulter. The entrance diaphragm of the imaging camera and the camera itself were accurately centered on the shadow of the occulter, first by visual inspection and then, by imaging the diffraction fringe to reach perfect balance. Several campaigns took place from 2005 until 2008 to test different configurations and occulters: a single disk (serving as reference), a serrated disk, a polished barrel 13 mm thick, and two truncated cones of 40 arcmin cone angle in line with the work on LASCO-C2, a multithreaded one with 20 disks and a smooth one obtained by electro-erosion [9], see Fig. 3. Their diameter varied from 112 to 95 mm, yielding over-occultation

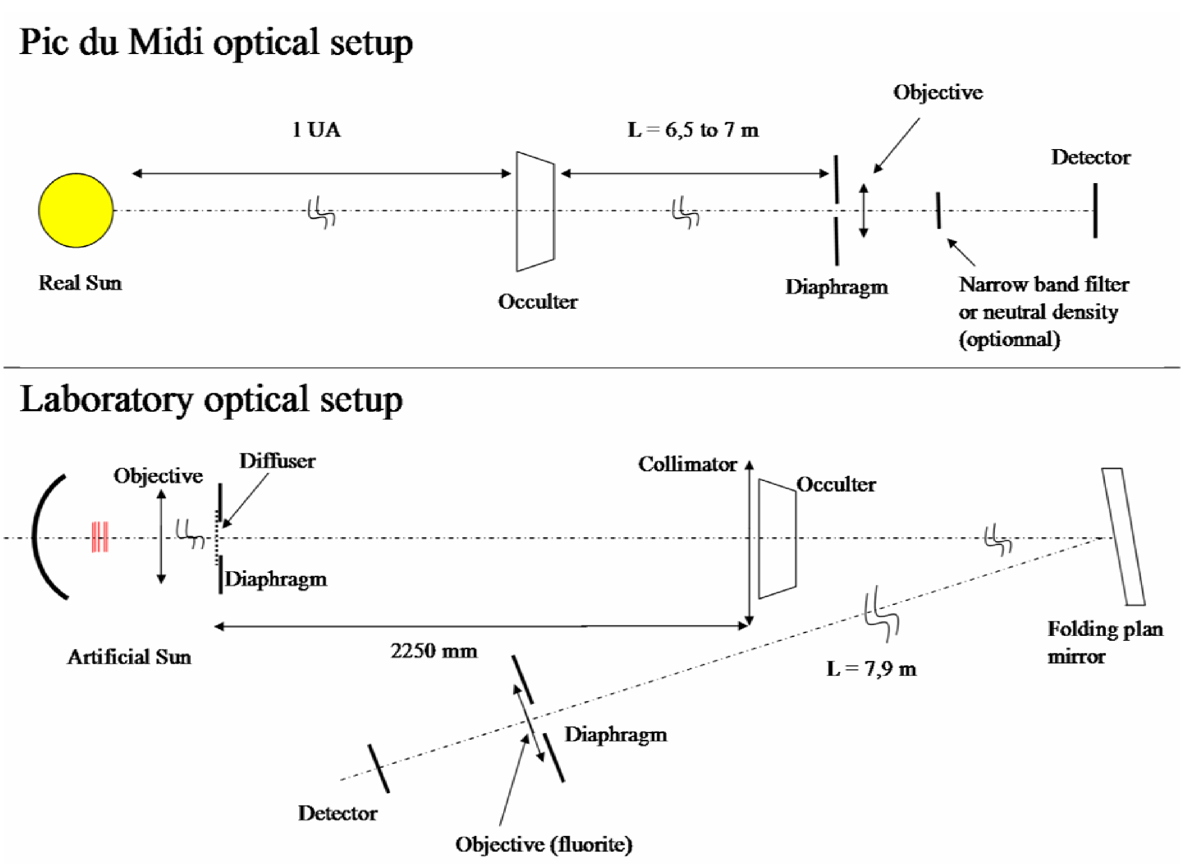


Fig. 1: Optical setups at Pic-du-Midi observatory (top panel) and at the Institut d'Astrophysique de Paris (bottom panel).

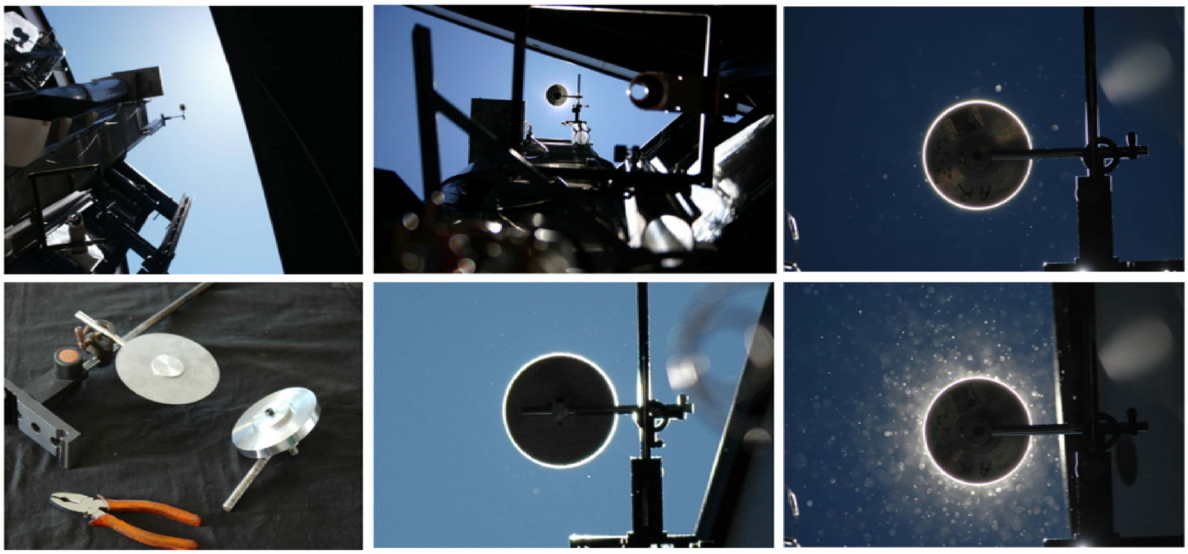


Fig. 2: Top panels: two views of the setup at Pic-du-Midi observatory and an image of the diffraction by the barrel occulter. Bottom panels: the serrated disk and the polished cone (left), an image of the diffraction by the serrated disk (center) and an image of the diffraction by the simple disk with a flurry of flying snow (right).

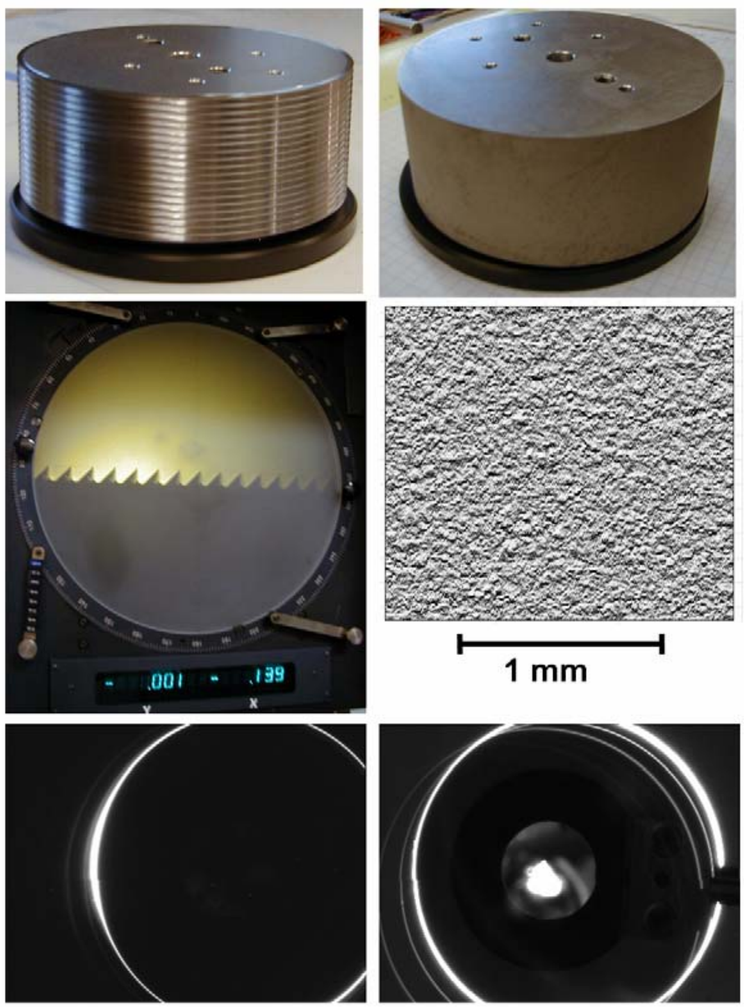


Fig. 3: Top panels: the multithreaded (left) and electro-eroded conic (right) occulters. Mid panels: an enlarged projected view of a section of the multithreaded occulter (left) and an enlarged view of the surface of the electro-eroded occulter illustrating its rugosity (right). Bottom panels: Images of the diffraction by the multithreaded (left) and electro-eroded conic (right) occulters obtained with the same exposure time (the discontinuities at the middle of the left arc of the fringes result from a defect of the detector).

ranging from 1.06 to 1.4 Rsun. We found that both centering and alignment were becoming more and more critical as the over-occultation decreased, making the situation significantly different from the cases of presently flown coronagraphs. The polished barrel gave disappointing results while the serrated disk confirmed its excellent anticipated performances (Fig. 2). The two conic occulters required very accurate co-alignment of their own axis with the optical axis and this turned out very challenging with the present setup, with only manual adjustments. As illustrated in Fig. 3, we could not achieve a proper balance of the fringes. In addition, we used a CCD Starlight camera to achieve accurate photometric measurements and this required introducing a narrow-band filter which in turn resulted in multiple reflections. Note that this was not the case with the other occulters as we then used a Canon EOS camera capable of achieving an exposure time of 1/4000 sec thus avoiding the need of neutral density or narrow-band filters.

The operational difficulties in carrying out this program in winter time, the complexity of using a setup atop an existing coronagraphic instrument and the practical difficulties of performing the alignments in acrobatic conditions led us to change our approach and turn to a laboratory solution.

B. Laboratory experimental studies

The dimensions we are dealing with led us to completely re-think the concept of testing occulters in the laboratory compared to what has been implemented for past coronagraphs. The solar simulator developed for LASCO-C2 has an overall length of about 10 m [9] ; adding an extra 10 m behind the occulter would bring the overall length to 20 m. In addition the collimating lens representing the Sun would have to be ~250 mm in diameter to correctly illuminate the occulter, an extremely large value. We therefore changed our approach and decided to move the EO close to the collimating lens simulating the solar disk to reduce the overall dimension (Fig. 1). The drawback is the simultaneous imaging of the lens with its intrinsic scattered light (internal defects, dust contamination, stray reflections). This is however not a limiting factor for our investigation as diffraction fringes are always quite bright (of course such an optical configuration would be inappropriate to testing a full coronagraph) and as the artefacts from the collimating lens are characterized by a fixed pattern which can be subtracted. The optical setup implemented at the Institut d'Astrophysique de Paris is illustrated in Fig. 1. The illumination system is classical and creates a uniform disk having the angular extent of the Sun at the focus of the collimating lens (F = 2250 mm, Dia = 150 mm). A folding mirror had to be introduced to bring the EO – OP distance to 7920 mm, compatible with the size of the laboratory. The imaging system is composed of a high quality fluorite triplet objective (manufactured by Televue, F = 600 mm) diaphragmed by an aperture of 20 mm diameter, and a Canon 20D still camera. Two occulters have presently been studied so far:

- A single disk with a diameter of 95.1 mm, a short sector of which was serrated.
- A truncated cone of 40 arcmin cone angle with a diameter of 94.9 mm and an height of 40 mm, obtained by electro-erosion (i.e., similar to that used at Pic-du-Midi). A short knife-edge has been glued tangentially to allow a direct comparison.

The resulting occultation amounts to 1.025 and 1.023 Rsun respectively, a negligible difference for our present purpose. Fig. 4 displays the resulting images of the diffraction patterns of the occulters (the outer bright ring corresponds to the diffraction by the collimator). There is an arc of diffuse stray light roughly centred on the pylon holding the occulters and possibly connected to it. The salt and pepper appearance results from scattering by defects or dust particles stuck to the collimator. But altogether these effects do not hamper the analysis of the fringes. This is best carried out after performing a polar transform whose origin is at the center of the occulters (Fig. 5). The fringes are not totally regular, a probable result of the utmost sensitivity to centering and alignment (for the cone) at the present level of over-occultation in spite of careful adjustments. The serrated section on the disk leads to a (slight) reduction of the fringe intensity as expected. The fringe of the cone exhibits a short

Fig. 4: Images of the diffraction fringe of the simple disk (left panel) and of the cone, both focused (middle panel) and focused at infinity (right panel).

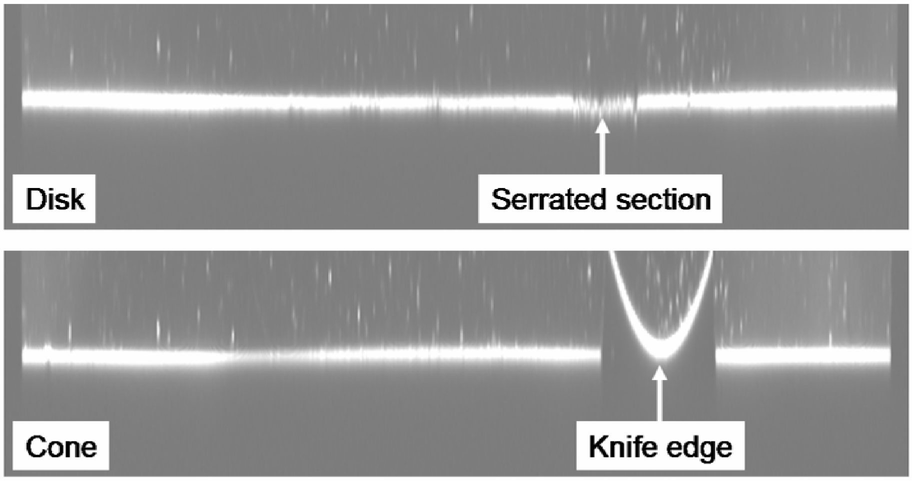


Fig. 5: Images of the diffraction fringes after the polar transformation

section of rather abrupt decrease of intensity being too local to be explained only by a misadjustment. A local variation of surface properties is also difficult to conceive. Averaged radial profiles of the fringes have been calculated excluding irrelevant portions (the serrated section for the disk and the knife-edge for the cone); in the case of the knife-edge, the section has been limited to a few central lines to limit the impact of increasing radial distance. Fig. 6 displays the original profiles and after normalization to the maximum intensities and recentering for an easier comparison. The distance scale is in millimetres as measured on the detector, i.e., in the focal plane of the Televue objective, the origin being at the center of the occulters. Note that this scale is about ¾ of that of the first focal plane of ASPIICS, that is the conjugated plane of its external occulter [4]. The FWHM of the disk and cone are remarkably similar and amounts to 42 µm, while that of the knife-edge appears slightly narrower, 35 µm. This implies that, for the total occulters, the total energy contained in their fringe is directly proportional

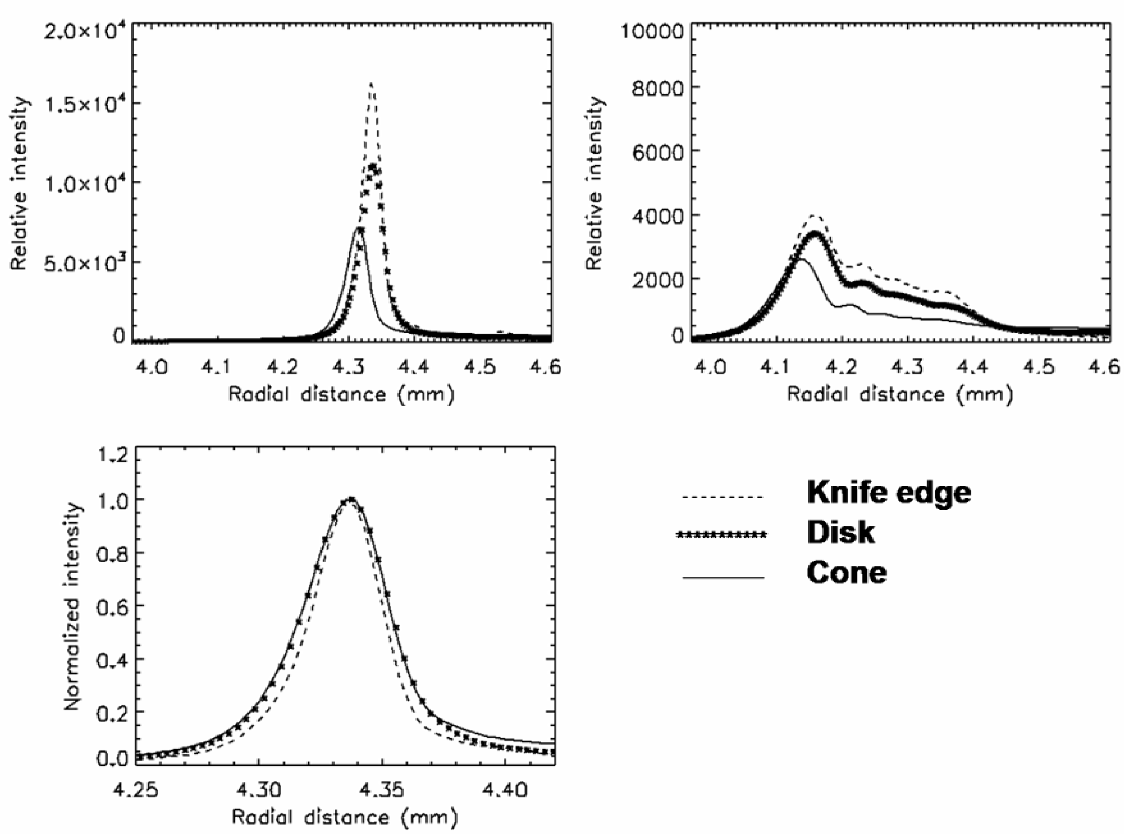


Fig. 6: Averaged radial profiles of the fringe corresponding to the knife-edge, the simple disk and the cone. The top panels correspond to focused (left) and defocused (right) cases. The bottom panel display the (focused) profiles after normalization and centring.

to their peak values. The cone achieves the best performance but not by much, a modest gain of ~1.6 compared to the simple disk. The peak value reached by the knife-edge is somewhat puzzling as it exceeds that of the simple disk, although by only a factor 1. 4; in terms of total energy, this translates to a factor of only 1.2 taking into account the different FWHM. A slight contribution from the cone itself may possibly explain this result. The modest gain of the electro-eroded cone with respect to the simple disk is at odd with the results reported on the LASCO-C2 occulters for which gains of 50 to 100 have been measured [9]. In our opinion, this is a direct consequence of operating at completely different over-occultations, 2.2 Rsun for C2 and 1.025 Rsun for ASPIICS. Finally, we investigated the impact of the defocusing of the fringe when the objective is set to infinity as the case in a coronagraph. Fig. 4 displays the defocused image in the case of the cone. Note the appearance of a faint external ring surrounding the main fringe which is reminiscent of the multiple ring systems conspicuous on the LASCO-C2 images. It is better seen on the averaged profiles and Fig. 6 further allows assessing how much extra over-occultation would have to be introduced by the inner occulter to partially or fully block the defocused image of the fringe coming from the external occulter. But ultimately we need an accurate radiometric calibration to compare the fringe level with that of the solar corona and decide whether an internal occulter is indeed necessary.

III. CONCLUSION:

After these extended tests, the impression prevails that, with the very limited over-occultation required by ASPIICS to see the corona “down to the solar limb”, we are entering a new world in the design and optimization of externally occulted coronagraphs, and more specifically of their occulter. Our laboratory tests conducted at a reduced scale of ~1/15 suggest that the behaviors of the different types of occulter tend to level-off and that very large gains obtained at over-occultation of ~2 Rsun [9] no longer apply at very small over-occultations. Centering and alignment further become highly critical, with much reduced tolerances. While studies of limited linear sections of occulters may still have some value for parameter optimization [10], they are insufficient to assess the performances that ASPIICS could achieve. We plan to develop and improve our method with the aim of reducing the scaling factor with respect to the real dimensions of ASPIICS, possibly down to 1/10.

REFERENCES

[1] X. Leyre, M. Sghedoni, S. Vivès, P. Lamy, E. Pailharey, “Concept of formation flyer for the ASPICS solar coronagraphic mission”, *Proc. SPIE*, vol. 5899, 221-229, 2005.

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

[3] P. Lamy, S. Vivès, S. Koutchmy, J. Arnaud, "Chromospheric and Prominence Physics with the ASPIICS Formation Flying Coronagraph", in *The Physics of Chromospheric Plasmas*, ASP Conf. Series 368, 2007.

[4] P. Lamy, et al., “ASPIICS: A giant, white-light and emission line coronagraph for the ESA PROBA-3 formation flight mission”, this conference.

[5] J. D. Purcell and M. J. Koomen, “Coronagraph with improved scattered-light properties,” *J. Opt. Soc. Am.* 52, 596–597, 1962.

[6] G. Newkirk, D. Bohlin, “Reduction of scattered light in the coronagraph,” *Appl. Opt.* vol. 2, 131–140, 1963.

[7] B. Fort, C. Forel, and G. Spaak, “The reduction of scattered light in an external occulting disk coronagraph,” *Astron. Astrophys.* 63, 243–246, 1978.

[8] S. Koutchmy and M. Belmahdi, “Improved measurements of scattered light levels behind occulting systems,” *J. Opt.* 18, 5–6, 265–269, 1987.

[9] M. Bout, P. Lamy, A. Maucherat, C. Colin, and A. Llebaria, “Experimental study of external occulters for the Large Angle and Spectroscopic Coronagraph 2: LASCO-C2”, *Appl. Opt.*, vol. 39, 3955-3962, 2000.

[10] F. Landini, et al., "Measurements and optimization of the occulting disk for the ASPIICS/PROBA-3 formation flying solar coronagraph", *Proc. SPIE* 7735-156, 2010.