International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 1277703 · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2688482

SailCor - Compact Coronagraph for the Helianthus sub-L1 Mission with Solar Photonic Propulsion

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ABSTRACT

Helianthus is a technological development project funded by the Italian Space Agency for a Phase A study of a space weather station with solar photonic propulsion. Helianthus will have a synchronous orbit with the Earth-Moon barycenter, positioned at about 7 millions km from Earth towards the Sun, thus much closer to the Sun with respect to historical Space Weather instrumentation, which are typically orbiting the Earth or L1. This sub-L1 halo orbit is maintained by radiation pressure on a solar sail as the propulsion mechanism: once in flight, the spacecraft will have a huge square sail, about 40 m long. The scientific payload will be hosted at the center of the sail and will comprise remote-sensing and *in situ* instruments. Remote sensing: an X-ray detector to detect Solar Flares and SailCor, a coronagraph with a wide field of view. *In situ*: a plasma analyzer and a magnetometer. For this "Sailcraft", a scientific payload with reduced mass and envelope is under study. The maximum allowed mass for the entire scientific payload shall not exceed 5 kg. Both the X-Ray detector and the *in situ* instruments have a flight heritage. This study aims at developing a laboratory prototype of a coronagraph matching the constraints of mass and envelope of the Helianthus payload. SailCor is a 20 cm long coronagraph with a field of view ranging heliocentric heights 3-30 solar radii. The external occulter is mounted on an extendable boom that will be deployed once in flight. SailCor presents an innovative solution that combines the diffraction apodization by the external occulter and the internal occulter positioning so that no Lyot stop is required. The classical design of externally occulted coronagraphs foresees the positioning of an internal occulter as a conjugated element to the external occulter with respect to the primary objective. The function of the internal occulter is to block the image of of the diffraction from the external occulter edge. Then, a secondary objective generates the coronal image on the detection system. The SailCor solution takes advantage of the focusing effect that the entrance aperture of the instrument induces on the light diffracted by the external occulter. This effect is used to calculate the position of the internal occulter with respect to the primary focal plane. With this approach, there is no need for a Lyot stop and the detection system can be placed at the first focal plane, with a significant reduction of envelope and mass. This contribution describes the design of the prototype of SailCor, used in laboratory to experimentally define the geometry of the occultation system. The activity has been carried out in the INAF OPSys facility clean environment (ISO5/6) hosted at ALTEC S.p.A. (Torino). The source is a solar divergence simulator.

Keywords: Solar Corona, Coronagraph, Stray light, Diffraction, Solar Photonic Propulsion, Sailcraft, Laboratory measurements

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1. INTRODUCTION

1.1 Prologue

Since its origin on our planet, mankind has fought to stay alive, preserve itself and its social and technological advances. While in its first millennia the main menace was the presence of other aggressive species with more or less our identical objectives, throughout time we "evolved" and started fighting each other. Throughout the last decades we understood that a man vs man fight is a complete non-sense, while living on a very tiny spot in an incommensurately larger universe. The only logical objective would be to preserve the planet, and therefore our lives, by fighting the climate change and to ensure that we can continue monitoring its status with the technological systems we developed.

1.2 Scientific scenario

Space Weather is one of the new science fields that are dedicated to monitor space natural phenomena which could threaten life on earth or affect the correct functioning of our technological apparatus. The Sun is the main subject for Space Weather investigations. In fact, the most energetic events on our star are able to significantly affect life and technology on Earth. One of the most dramatic phenomena is a solar storm. Solar storms are spectacular eruptions of plasma and embedded magnetic fields from the solar surface through the external solar atmosphere (the solar corona) into the interplanetary space. They are large and energetic events which can expel up to 10^{16} g of coronal plasma at speeds ranging from 100 km/s to over 2500 km/s. They are often preceded by sudden and fast localized coronal irradiance increases, called flares.

When a solar storm (also known as Coronal Mass Ejection - CME) impacts the Earth's magnetosphere the most severe space weather events, known as geomagnetic storms, are produced.[1] Spectacular auroras becomes visible in high latitude regions, satellites for telecommunications and navigation systems may be strongly damaged by sudden induced discharges, power grids can collapse because of strong geomagnetically induced currents, some kinds of radio broadcasts are frequently disrupted by variations induced in the Earth ionosphere, and radiation hazards for astronauts and people on board transcontinental flights are also possible.

So far, Space Weather has been performed by monitoring the solar corona through instruments orbiting the Earth or positioned in the Lagrangian point L1 (e.g., LASCO coronagraphs[2] on board SOHO[3]).

Solar missions orbiting the Sun, such as STEREO[4] or Solar Orbiter[5] could be useful but are not continuously monitoring the solar corona and their telemetry can experience large latency. Therefore such missions, despite providing exciting new science to the community, cannot be considered reliable Space Weather sentinels.

Helianthus is a phase A study of a space weather station with solar photonic propulsion.[6–8] Its orbit will be synchronous with the Earth-Moon barycenter, positioned at about 7 millions km from Earth towards the Sun, thus much closer to the Sun with respect to historical Space Weather instrumentation. This sub-L1 halo orbit is maintained by exploiting radiation pressure on a solar sail as the propulsion/stabilization mechanism: once in flight, the spacecraft will have a huge square sail, with a side of about 40 m.

The sub-L1 position guarantees an early detection of solar eruptive events of about 1 hour in advance with respect to stations positioned in L1 or in geostationary orbits, see figure 1 for the observational geometry.

The scientific payload of Helianthus will be made of: an X-ray spectrometer to detect solar flares; SailCor, a coronagraph with a wide field of view; a plasma analyzer; a magnetometer. The maximum allowed mass for the entire scientific payload shall not exceed 5 kg. The two imaging devices (coronagraph and X-ray spectrometer) are of fundamental importance for the sake of remotely and timely mapping the status of the Sun and provide Earth stations with early warning of potentially disruptive events. The in-situ instrumentation has a flight heritage. The selected X-ray spectrometer had a flight heritage as well, nevertheless has been tested with a dedicated experimental campaign run at the XACT facility in Palermo (Italy)[9] in order to verify that is suitable for detecting solar flares signatures in the solar corona.

A first prototype of SailCor was designed and built. The present paper accounts for SailCor prototype design, construction, alignment and test campaign. SailCor's optical design and prototype manufacturing are described in sections 2 and 3, respectively. The measurement campaign is depicted in section 4.

2. SAILCOR OPTICAL DESIGN

The main challenge in externally occulted solar coronagraph design is the stray light reduction. A coronagraph aims at observing the solar corona, a mean that in the visible is more than 6 orders of magnitude fainter than the

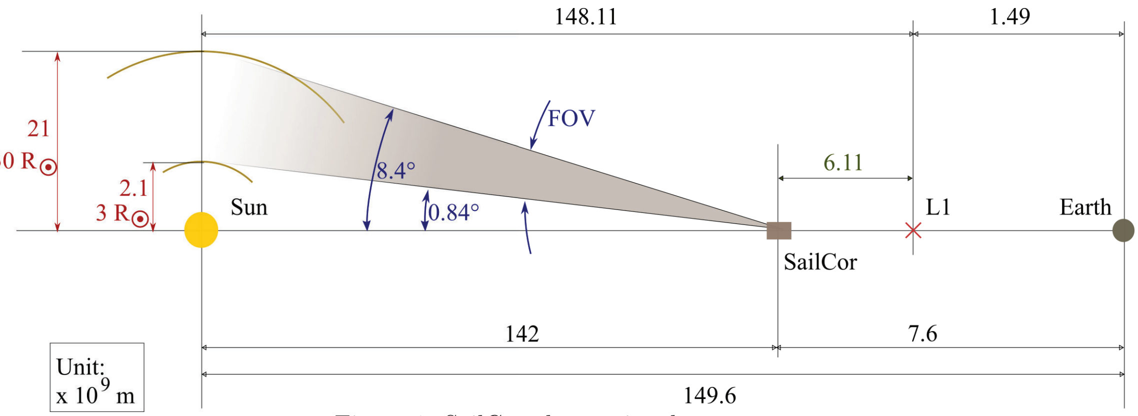

Figure 1: SailCor observational geometry.

photosphere, which is very close in angle. The photospheric light, diffracted by the occulters and scattered by the optics, can easily overwhelm the coronal light on the focal plane. Consequently, particular care shall always be reserved at stray light reduction in designing coronagraphs. In addition, SailCor is characterized by a couple of perhaps even more challenging constraints.

- The field of view (FOV), which shall be wide in order to monitor a large part of the heliosphere but with a lower limit close enough to the solar limb in order to catch emerging CMEs.
- Mass and dimension must be very limited. Mass shall be below 5 kg and dimensions shall be consequently the minimum possible.

A possibility in constraining mass and dimension, while guaranteeing a low stray light level, is offered by some recent advances in solar coronagraph stray light analysis. A numerical work of Gong and Socker[10] introduced (in 2004) the concept of the focusing effect induced by the entrance aperture on the light diffracted by the external occulter.
This paper, while describing the design and manufacturing of the SailCor prototype, aims at experimentally validating the *focusing effect* of the entrance aperture on the light diffracted by the external occulter.
The optical effect, and its beneficial consequence on the design of a coronagraph, are schematized in Fig. 2. In Fig. 2 a) the traditional[11] two stages externally occulted coronagraph is schematized: a first "Imaging section" produces the image of the solar corona and of the external occulter (EO) at two distinct focal planes; the light of the solar corona is imaged on the primary focal plane (PFP), the light diffracted by the EO edge on the plane where the internal occulter (IO) is located.
The detector cannot be placed at PFP: the spurious radiation diffracted and scattered by the EO edge is focused after PFP and an optical stop/trap before the detector plane would produce an excessive over-occultation at low heliocentric heights. Therefore, a second stage, called "Relay section" in figure 2 a), is needed. This stage re-images the solar corona on the detector plane, leaving space to insert the IO on the focal plane of the spurious radiation from the EO edge.
Please be aware that the present description is over-simplified for the sake of clarity. The actual relay section is more complicated: O2 is separated into two optical elements in order to permit the positioning of the so called "Lyot stop": an optical element used to block the radiation diffracted by the EA edge and focused by the primary optics. Just to simplify the description, we can consider the relay section as a single optical element. In 2 b) the light diffracted by the EO edge is blocked by IO. In this simplified scheme, the diffractive effect of EA collimates the radiation emerging from the EO edge (for illustrative purposes, in figure the red radiation becomes green), the image of EO is shifted and is coincident with PFP. If the condition depicted in figure 2 b) is verified, then the "Relay section" can be avoided, as shown in 2 c). IO can be positioned before the detector plane in order to intercept the radiation produced by the EO edge.

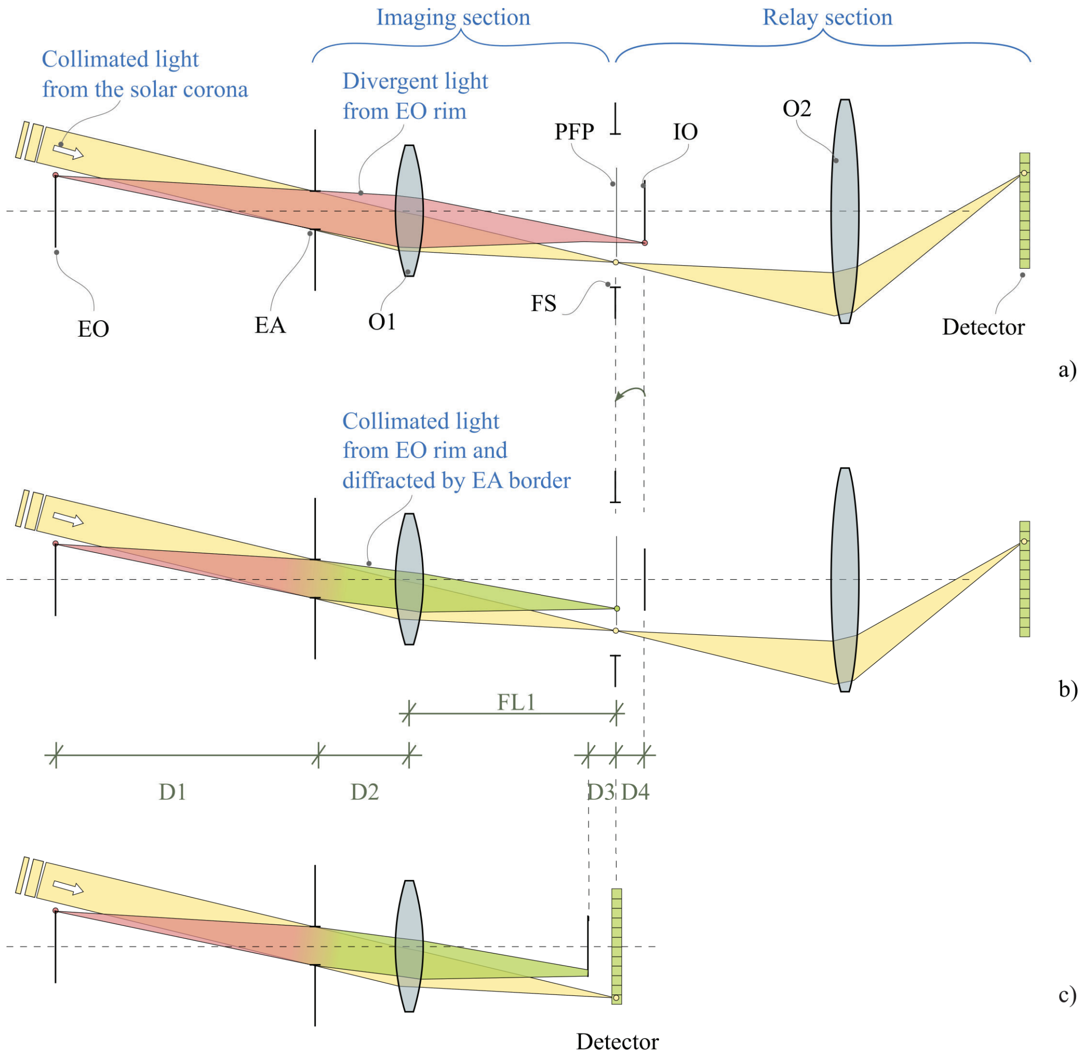

Figure 2: Simplified optical concept of an externally occulted coronagraph: from the top to the bottom, the physical effect permitting to avoid the use of the Relay section is schematized. EO, external occulter. EA, entrance aperture. O1, first objective lens. FS, field stop. PFP, primary focal plane. IO internal occulter. O2, second objective lens. a) traditional two stages coronagraph. b) The diffractive effect of EA (for illustrative purposes, collimation of the red radiation into a collimated green radiation). c) Condition in which the "Relay section" can be avoided.

Heliospheric Imagers such as Solo/HI,[12] STEREO/SECCHI HI[13] and PSP/WISPR[14] are already based on the single stage coronagraph principle, but they both are observing a portion of the heliosphere (they have linear occulters) and have a very high inner FOV.
In order to experimentally validate the single stage solution for a coronagraph that observes the whole solar corona, a laboratory demonstrator has been conceived. Its optical design has been thought by aiming at obtaining an acceptable spatial resolution while minimizing the stray light. The objective consists of a cemented doublet.

The optical parameters of SailCor are summarized in table 1.

Table 1: SailCor optical parameters

Field of View	0.84° - 8.4°
Focal length (FL1 in 2 b))	85 mm
Entrance aperture	20 mm diameter
EO - EA distance	800 mm
IO - detector distance	< 5 mm
Spectral band	500 - 600 nm

3. SAILCOR LABORATORY PROTOTYPE

The measurement campaign was run in September 2022 at the Optical Payload System (OPSys),[15,16] a laboratory of the INAF Astrophysical Observatory of Torino hosted by ALTEC S.p.A. in Torino (Italy). The facility is equipped with an optical bench in an ISO5/6 environment in front of a solar divergence simulator.
The EO for the flight model of SailCor will be mounted on an extendable boom that will be deployed once in orbit. In laboratory, in this phase, there is no need for such a complication. The EO assembly and the objective have been mounted on an optical rail.
A sketch of the set-up is shown in figure 3. The detector was positioned on the optical bench. The IO system

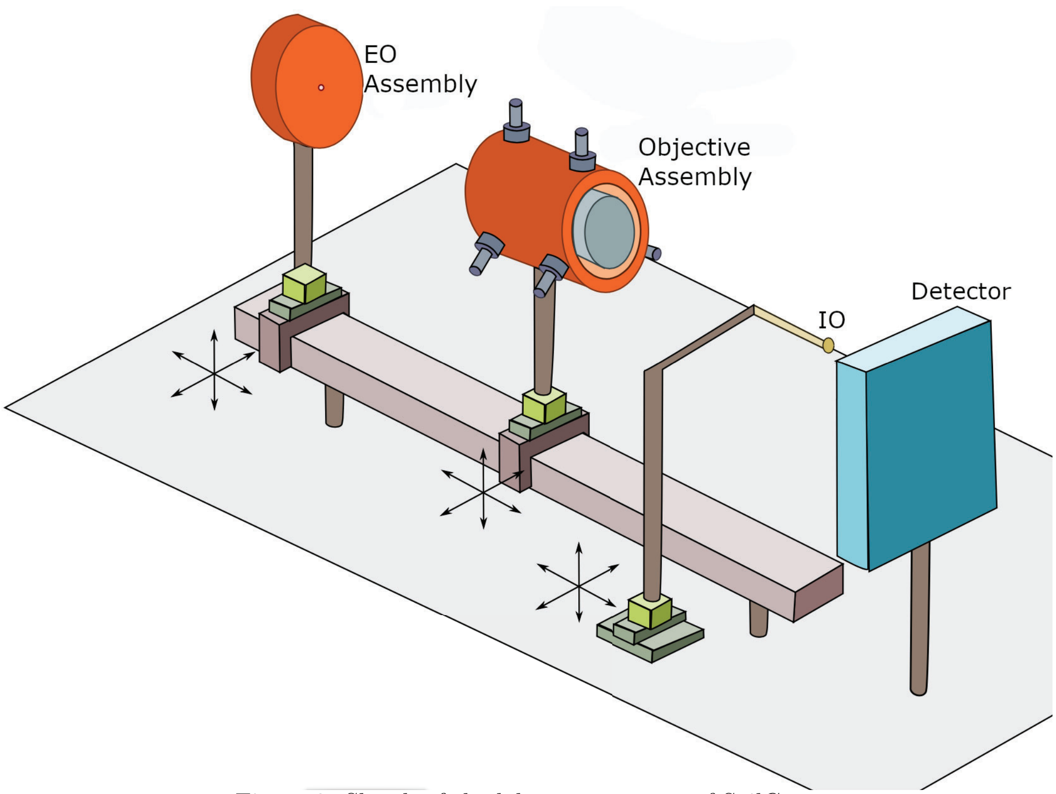

Figure 3: Sketch of the laboratory set-up of SailCor.

was mounted on a 3-axis translation stage positioned on the bench. In the following, a paragraph is dedicated to each one of the elements of the experimental set-up.

3.1 External Occulter

Many works on solar coronagraphy are dedicated to the study of external occulters and their apodization in order to reduce the stray light generated by the occulter edge. The light diffracted by a simple knife edge external occulter, scattered by the telescope optics, overwhelms the coronal signal on the focal plane.[17] As experience has demonstrated,[18–24] a suitable optimization of the external occulter geometry may lower the stray light level by at least 2 or 3 orders of magnitude.
The apodization can be based onto two main optimization principles: occultation and light redirection.

- Occultation. The simplest approach consists in a second disk, in the shadow of the first (with respect to the solar disk) that blocks the radiation diffracted by the first disk edge and limits the scattering from eventual dust on the first disk; then a third disk, in the shadow of the second one, blocks the diffraction produced by the second disk edge, and so on. A natural extension of the multiple occulters is a multithread shaped as a frustum of a right cone, or as a barrel. In case of an infinite number of occulters, each in the shadow of the previous one respect to the solar disk light, the multithread is smoothed down to a polished surface.
- Light redirection. The principle is used by the serrated edge occulter. A series of tiny teeth all around the occulter edge spreads the solar disk light out of the instrument pupil.

From the cited literature contributions[18–24] it is clear that an apodization is mandatory for externally occulted coronagraphs and that the most effective optimization principle is occultation. In many cases, the multi-threaded or polished frustum of a right cone turns out to be the best solution (see for instance the cases of SOHO/LASCO-C2[22] and Solar Orbiter/Metis[23]) but several space-borne solar coronagraphs are still using the multiple disk solution. A general recipe does not exist because many factors linked to the mission type are influencing the selection: a solution shall be found by investigating case by case. In the case of SailCor we selected the occultation principle as field of investigation and a series of different EOs have been compared in terms of stray light reduction performance. The EOs are listed in table 2. All the occulters, except for the sand blasted one, have been coated

Table 2: List of EOs that have been compared in terms of stray light reduction.

Type	Description	Geometry
Simple disk	Single occulting disk with knife edge.	Disk diameter 45 mm
Triple disk	Three equally spaced disks with knife edge.	1^{st} disk diameter 45 mm, 2^{nd} disk diameter 44 mm, 3^{rd} disk diameter 43 mm, disks spacing 50 mm.
Polished cone	Truncated right cone, lathe polished surface.	1^{st} surface diameter 45 mm, Last surface diameter 43 mm, Length 100 mm.
Multithreaded cone	Truncated right cone, lathe dug thread.	
Sandblasted cone	Truncated right cone, external surface sandblasted.	

with a hand crafted black paint, made of a suspension of coat powder in shellac.
The full series of EOs is shown in figure 4. A picture of the assembled set-up is shown in figure 5.

3.2 Objective assembly

The objective is the doublet described in section 2. It has been manufactured by Optec S.p.A. (Parabiago, Italy) and is hosted in a commercial cinematic mount, as shown in the 3D rendering of figure 6.

The ray-tracing on the objective lens is shown in Fig. 7. In this study the lens has been tested in an extended spectral band 500 - 800 nm. The spot diagram in such an extended spectral region is presented in Fig. 8. As already pointed out, the purpose of this objective is not to produce sharp images of the solar corona but to demonstrate that is possible to take advantage of the focusing effect of the entrance aperture to the sake of cutting a stage of the classical external coronagraph design.

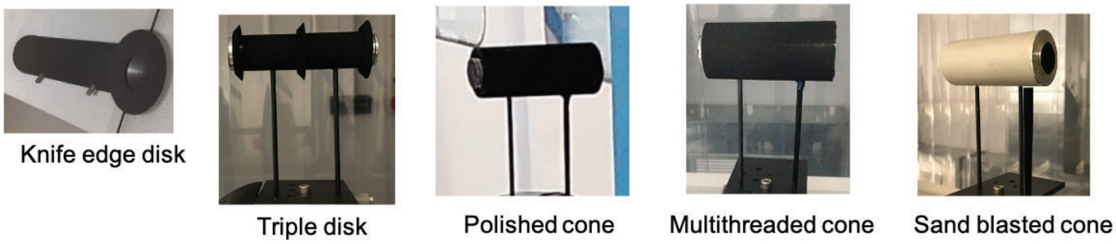

Figure 4: The full series of manufactured EOs.

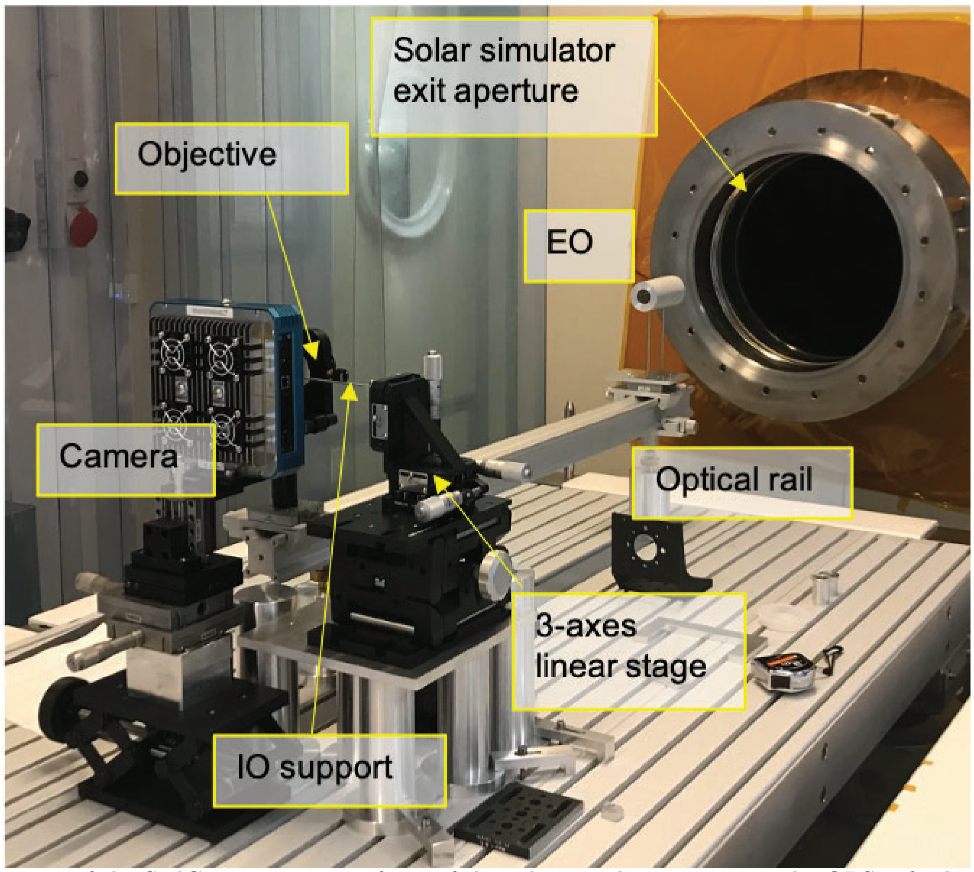

Figure 5: Picture of the SailCor prototype in front of the solar simulator source at the OPSys facility in Torino.

3.3 Detector

The available detector for the tests was the Apogee CCD camera ALTA F6, with sensor Kodak KAF-1001E, sensor area 1024 x 1024 pixel^2, pixel size 24 μm, dynamic range 16 bit. The sensor is located about 26 mm behind the camera front mechanical aperture.
It is not the camera that will be used in flight, and there is no need for it to be, since the scope of the laboratory set-up is to experimentally demonstrate that the Entrance Aperture indeed introduces a "*focusing effect*" as described in section 2 and that a single stage compact design is feasible for an externally occulted coronagraph. A selection for the flight camera will be performed in the coming phases of the mission.

Figure 6: 3D rendering of the objective assembly.

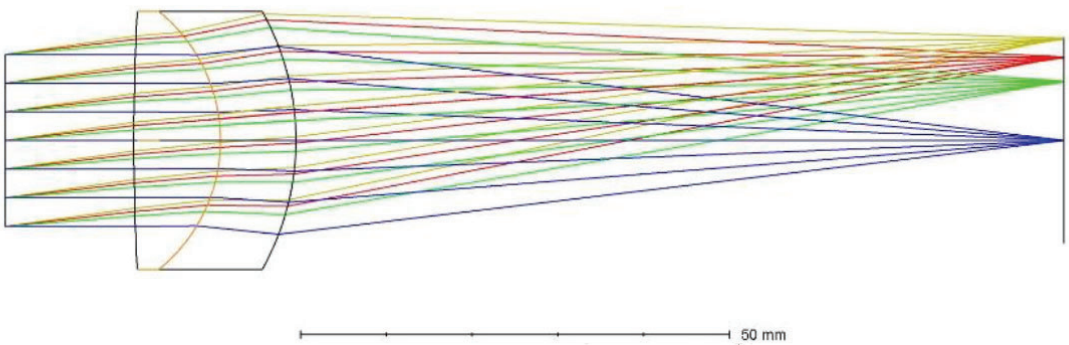

Figure 7: Ray tracing on the objective lens.

3.4 Internal occulters

As described in section 2, in order to verify the focusing effect of the EA, the IO shall be positioned slightly before the primary focal plane, that is the plane of the camera sensor.
A scheme of the IO positioning is shown in figure 9. A pylon with diameter 3 mm was mounted externally to the camera except for the terminal part that holds the tiny disk of the IO. That part was to be inserted into the camera with the IO almost in contact with the sensor surface.
As shown in figure 5, the pylon was installed onto a 3-axis linear translation stage that is fixed to the optical bench. The micro-translations allow a fine tuning of the IO both along and perpendicularly to the optical axis. The movement along the optical axis, in particular, was tremendously useful in exploring several positions of the IO with respect to the primary focal plane position in order to determine the most effective one. The objective with the entrance aperture, the IO mount and the camera are shown in figure 10 (a), a zoom on the IO, obtained by removing the camera, is shown in figure 10 (b). By considering the focusing effect of the entrance aperture, an IO positioned at about 1 mm from the sensor would need to have a diameter of 5.3 mm in order to overoccult the EO image by 0.1 mm. In order to explore field of IO dimensions and positions, 4 IOs have been manufactured, with diameter 4 mm, 5.3 mm, 6.5 mm, 8 mm. The full series of manufactured IOs is shown in picture 11. With the available camera it is actually impossible to achieve such a proximity between IO and sensor, since the camera is equipped with a protective window positioned at 7.9 mm from the actual sensor. With the current set-up

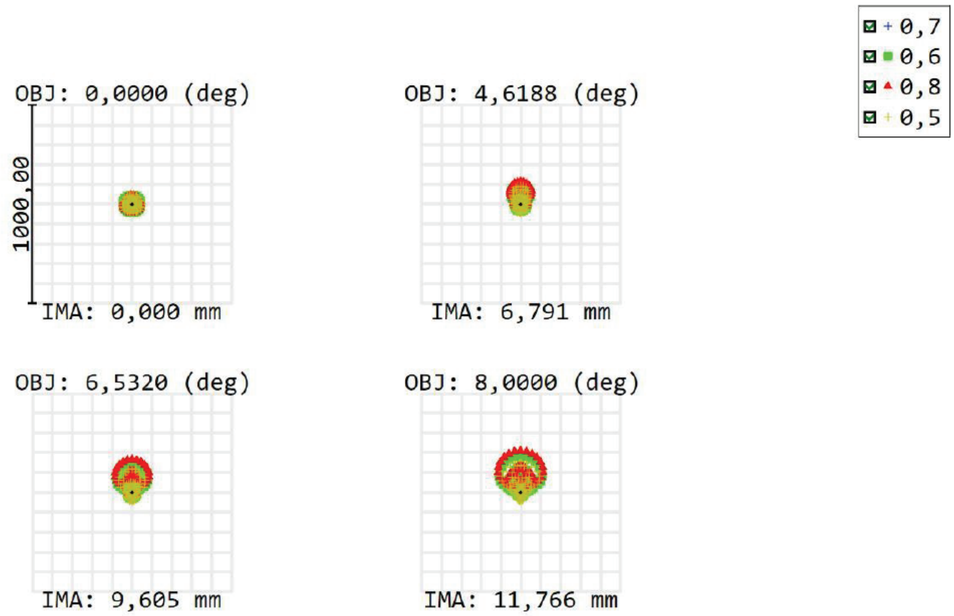

Figure 8: Spots diagram on the focal plane, produced by the the objective lens.

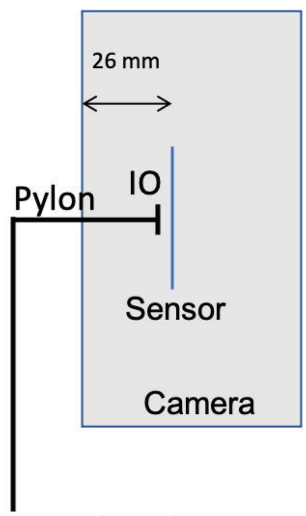

Figure 9: A sketch of the IO positioning principle.

it is therefore not possible to reach an acceptable stray light suppression. Nevertheless, we can experimentally demonstrate for the first time that the Entrance Aperture acts as a "*focusing element*" (see section 2) for the light diffracted by the EO edge and that allow for anticipating the position of IO before the primary focal plane.

4. STRAY LIGHT MEASUREMENTS

A series of stray light acquisitions has been taken with the 5.3 mm diameter IO and by alternating all the EOs. Each measurement has been repeated with and without the EA in order to experimentally demonstrate its "focusing effect" (see section 2). The multithread EO is omitted from the results because the EO surface is characterized by several discontinuities which scatter light and produce a stray light level out of control. The multithread occulter was hand crafted by lathe machining. The test will have to be repeated with an occulter

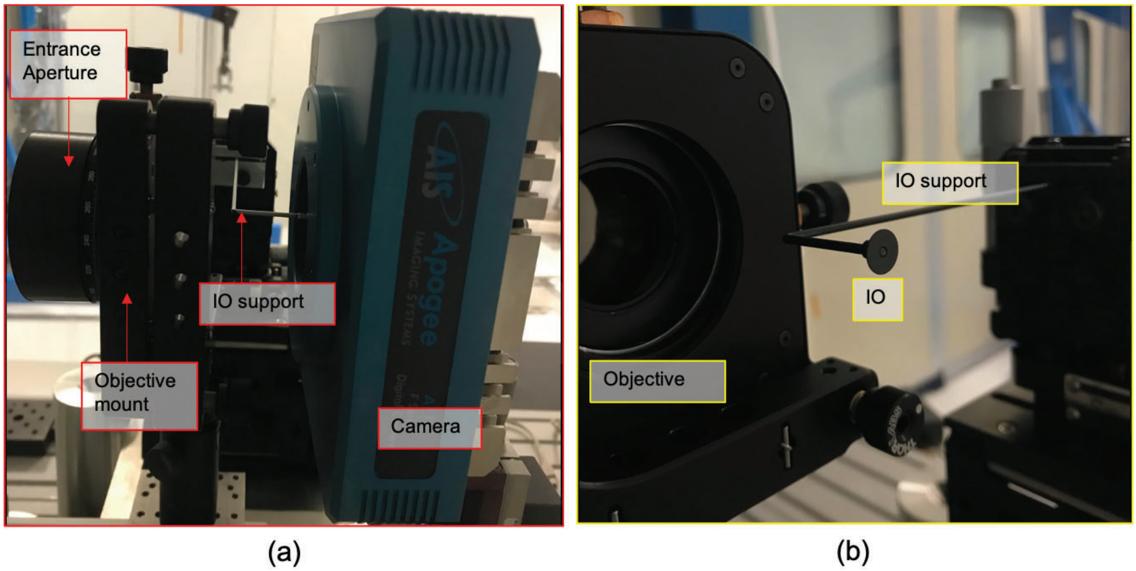

Figure 10: (a) Objective assembly with the entrance aperture, IO support and camera. (b) Zoom on the IO by removing the camera.

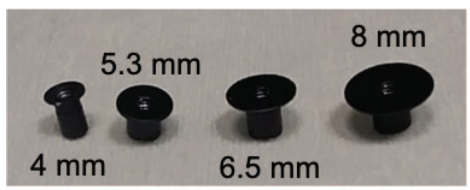

Figure 11: The full series of manufactured IOs. Diameters are specified by labels.

manufactured with a different method (e.g. with Computer Numerical Control machines) and coated with a paint characterized by smaller carbon grains.
All stray light images have been normalized to the mean solar disk brightness. The mean solar disk brightness has been obtained by taking images of the solar divergence simulator without EO and IO, by drawing a region of interest (ROI) over the solar disk and computing the average.
A comparison of stray light images taken with and without EA in the case of the simple disk as EO is shown in figure 12. As expected, the stray light suppression is not enough in order to guarantee an observation of the solar corona, for which a level in the range of 10^{-9} is needed. This is due partially to the scarcely effective single disk as an EO and partially to the impossibility of placing the IO as close as possible to the sensor. The image is dominated by stray light. Nevertheless, it is possible to notice that the halo around the occulter is reduced in the configuration with the EA, shown in figure 12 (b).
In the case of a triple disk EO, shown in figure 13, the impact of EA is much more evident. In this case the images are much less dominated by stray light. Some stray light features from the laboratory setup can be identified, such as the bright spots in the top part, the support of the EO and the base that holds the EO support, at the bottom. The stray light level is lower, though still far from acceptable in order to observe the solar corona.
Nevertheless, the images offer the possibility of demonstrating that the EA impact is mainly limited to the light diffracted from EO, which is a further confirmation of the "focusing effect" of the EA itself. In fact, in both frames of figure 13, the image portions affected by the diffraction from the EO holding pylon and from the pylon base can be easily identified and there is not a significant improvement in using or not the EA as there is for the halo around IO.
By considering the case of the polished cone EO we obtain the plain demonstration of the "focusing effect" of the EA. The images for the polished cone are shown in figure 14. Despite the not ideal laboratory configuration,

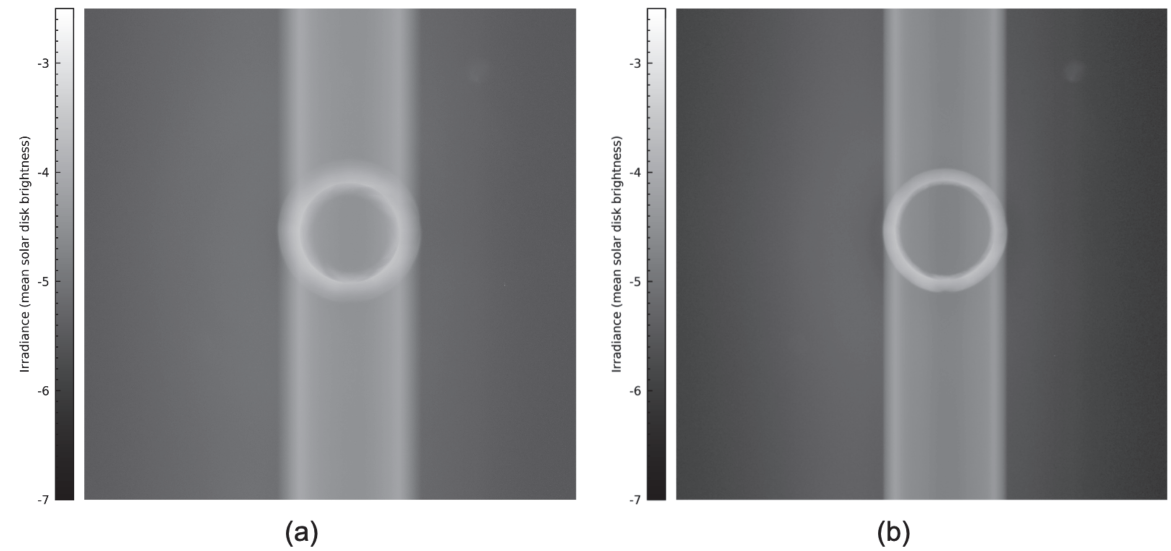

Figure 12: Stray light images with the simple disk EO. Units are mean solar disk brightness irradiance in log scale. (a) Without EA. (b) With EA.

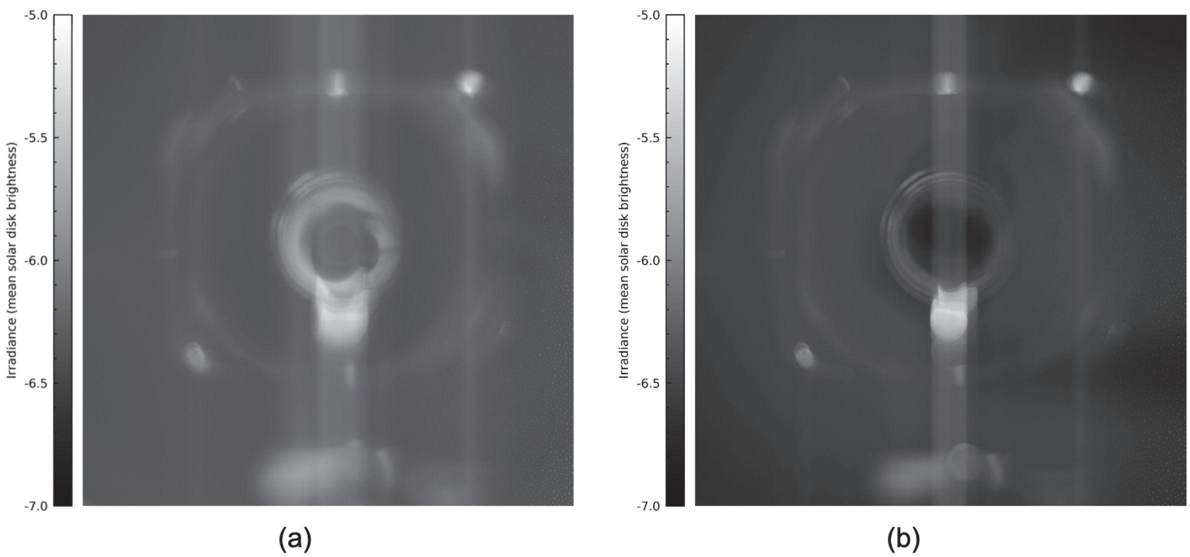

Figure 13: Stray light images with the triple disk EO. Units are mean solar disk brightness irradiance in log scale. (a) Without EA. (b) With EA.

the overall level of stray light is in the range of 10^{-8}, which is closer to the required level in order to observe the solar corona.

The result shown in figure 14, in comparison with those in figures 13 and 12 is also a further confirmation of the goodness of the polished cone as optimization shape for the EO. A final test has also been performed with the same IO by using the sand blasted EO. The results with and without EA are shown in figure 15. While guaranteeing the now usual confirmation of the "focusing effect" of the EA, the result is also suggesting a potential improvement for the EO shape. The stray light level is lower with respect to the triple disk case, and slightly worse with respect to the polished cone case. Though, it shall be considered that the sand blasted cone is not blackened, while the polished is. An idea for a future set-up improvement could be to blacken a sand

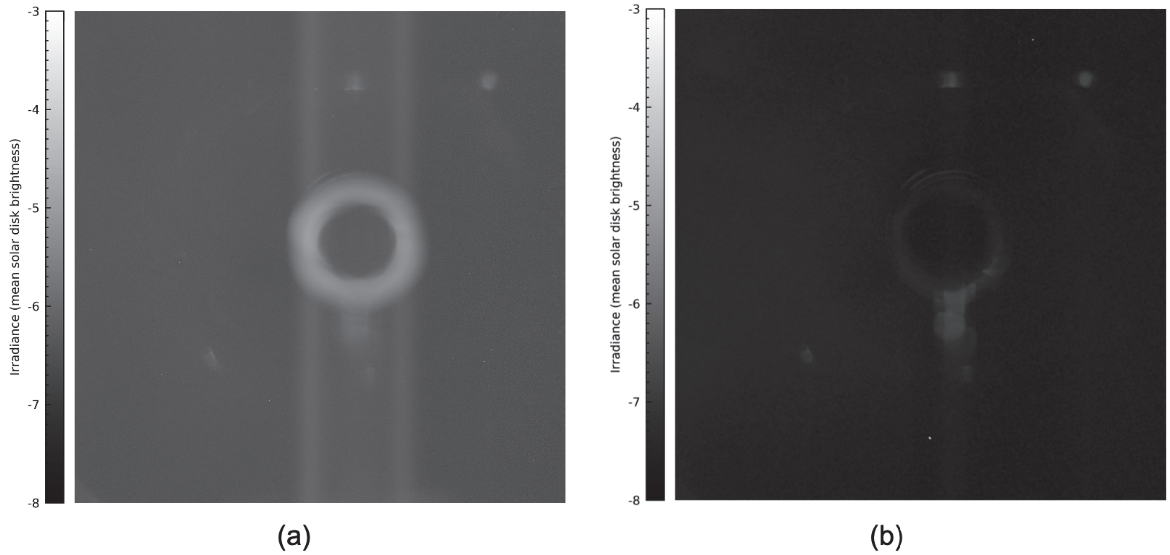

Figure 14: Stray light images with the polished cone EO. Units are mean solar disk brightness irradiance in log scale. (a) Without EA. (b) With EA.

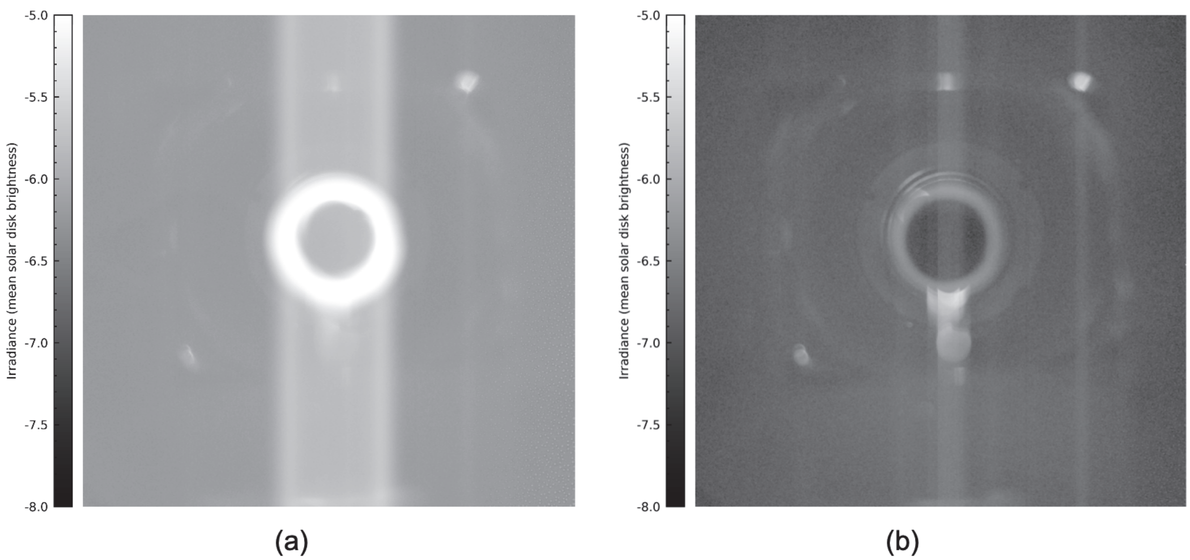

Figure 15: Stray light images with the sand blasted cone EO. Units are mean solar disk brightness irradiance in log scale. (a) Without EA. (b) With EA.

blasted cone and include its performance in the comparison list. A further proof of the EA effect is given by the image ratio between the case without EA and the case with EA. An example is shown in figure 16 for the sand blasted EO. It is evident that the huge impact of EA is around the IO shadow. There is a minimum impact (the ratio is around 1) in correspondence of stray light features due to the set-up, such as the bright spots at the top of the image.
Measurements were also performed with the other IOs (see figure 11) and results are in agreement with those just shown.
A choice of the most suitable IO will be made during a new test campaign in which a camera without protective

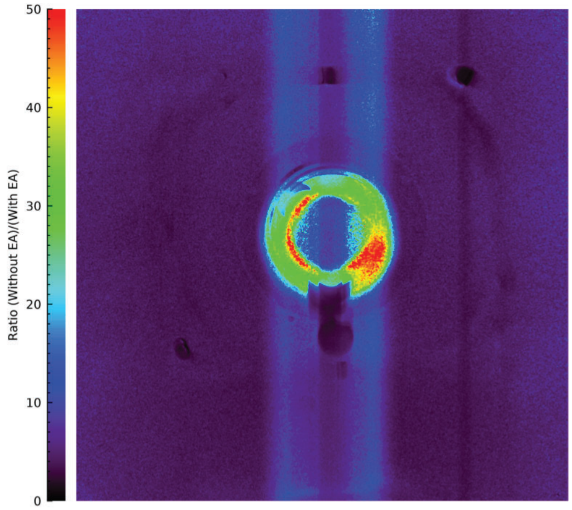

Figure 16: Ratio of images shown in figure 15 (a) and (b).

window will be implemented.

5. CONCLUSIONS

We designed, manufactured, built and tested a prototype of SailCor, a compact and light weight coronagraph for the phase A of Helianthus. Helianthus is a space weather mission which will be positioned in a sub-L1 orbit on a spacecraft with solar photonics propulsion.
A first test campaign was run on the prototype in order to validate the principle that a single stage coronagraph is feasible. The classical externally occulted coronagraph design foresees a three stage concept and two focal planes. The single stage coronagraph is based on the focusing effect of the EA on the light diffracted by the EO edge. The effect allows to position the IO before the primary focal plane and to remove the second and the third stage, resulting in a much more compact and light design.
The focusing effect of the EA was experimentally proven for the first time for a coronagraph that observes the whole corona. The stray light level is promising, despite being higher than foreseen due to some intrinsic limitation of the set-up (the camera has a protective window that prevent for positioning the IO too close to the sensor).
In conclusion, our results constitute the experimental basis that allows to design and manufacture single stage externally occulted coronagraphs for space weather monitoring.
The experimental set-up will be improved for a further test campaign. In particular:

- A detector without protective window will be used in order to place the IO closer to the sensor.
- The pylon that holds IO will be designed in order to block the stray light generated by the pylons that support EO.
- A black box will be designed, manufactured and installed around objective and camera in order to keep the environmental stray light pollution as low as possible.

ACKNOWLEDGMENTS

This work is performed jointly under the Implementing Agreement between the Italian Space Agency and DIAEE – Sapienza University of Rome n. 2019-28-HH.0 - CUP n. F84I19001070005 related to R&D activities on solar photonic propulsion. The Implementing Agreement is based on the Framework Agreement between ASI and "La Sapienza" n. 2015-1-Q.0.

REFERENCES

[1] Temmer, M., "Space weather: the solar perspective," *Living Reviews in Solar Physics* **18** (jun 2021).

[2] Brueckner, G. E., Howard, R. A., Koomen, M. J., Korendyke, C. M., Michels, D. J., Moses, J. D., Socker, D. G., Dere, K. P., Lamy, P. L., Llebaria, A., Bout, M. V., Schwenn, R., Simnett, G. M., Bedford, D. K., and Eyles, C. J., "The Large Angle Spectroscopic Coronagraph (LASCO)," *Sol Phys* **162**, 357–402 (Dec. 1995).

[3] Domingo, V., Fleck, B., and Poland, A. I., "The SOHO Mission: an Overview," *Sol Phys* **162**, 1–37 (Dec. 1995).

[4] Kaiser, M. L., Kucera, T. A., Davila, J. M., St. Cyr, O. C., Guhathakurta, M., and Christian, E., "The STEREO Mission: An Introduction," *Sp Sc Rev* **136**, 5–16 (Apr. 2008).

[5] Müller, D., St. Cyr, O. C., Zouganelis, I., Gilbert, H. R., Marsden, R., Nieves-Chinchilla, T., Antonucci, E., Auchère, F., Berghmans, D., Horbury, T. S., Howard, R. A., Krucker, S., Maksimovic, M., Owen, C. J., Rochus, P., Rodriguez-Pacheco, J., Romoli, M., Solanki, S. K., Bruno, R., Carlsson, M., Fludra, A., Harra, L., Hassler, D. M., Livi, S., Louarn, P., Peter, H., Schühle, U., Teriaca, L., del Toro Iniesta, J. C., Wimmer-Schweingruber, R. F., Marsch, E., Velli, M., De Groof, A., Walsh, A., and Williams, D., "The Solar Orbiter mission. Science overview," *A&A* **642**, A1 (Oct. 2020).

[6] Palmeri, F., Tortorici, D., Laurenzi, S., Circi, C., Santonicola, M. G., Pizzarelli, M., Pizzurro, S., Pellegrini, R., and Cavallini, E., "Structural design of booms for the solar sail of Helianthus sailcraft," 73rd International Astronautical Congress, IAC 2022, Paris (France) 18-22 September 2022 (submitted).

[7] Santonicola, M. G., Toto, E., Laurenzi, S., Circi, C., Pizzarelli, M., Simone Pizzurro, R. P., and Cavallini, E., "High-Performance Polyimide Membranes for Use in Solar Sail Propulsion," 73rd International Astronautical Congress, IAC 2022, Paris (France) 18-22 September 2022 (submitted).

[8] Bassetto, M., Niccolai, L., Boni, L., Mengali, G., Quarta, A. A., Circi, C., Pizzurro, S., Pizzarelli, M., Pellegrini, R. C., and Cavallini, E., "Sliding mode control for attitude maneuvers of helianthus solar sail," *Acta Astronautica* **198**, 100–110 (2022).

[9] Noce, V., Varisco, S., Landini, F., Haudemand, H., Candia, R., Barbera, M., Lo Cicero, U., Frassetto, F., Zangrilli, L., Caracci, V., Loreggia, D., Collura, A., and Fineschi, S., "The Space Weather X-Ray spectrometer for the Helianthus sub-L1 mission with solar photonic propulsion," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* (2022, in press).

[10] Gong, Q. and Socker, D., "Theoretical study of the occulted solar coronagraph," in [*Optical Systems Degradation, Contamination, and Stray Light: Effects, Measurements, and Control*], Chen, P. T. C., Fleming, J. C., and Dittman, M. G., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5526**, 208–219 (Oct. 2004).

[11] Evans, J. W., "Photometer for measurement of sky brightness near the sun," *Journal of the Optical Society of America (1917-1983)* **38**, 1083 (Dec. 1948).

[12] Howard, R. A., Vourlidas, A., Colaninno, R. C., Korendyke, C. M., Plunkett, S. P., Carter, M. T., Wang, D., Rich, N., Lynch, S., Thurn, A., Socker, D. G., Thernisien, A. F., Chua, D., Linton, M. G., Koss, S., Tun-Beltran, S., Dennison, H., Stenborg, G., McMullin, D. R., Hunt, T., Baugh, R., Clifford, G., Keller, D., Janesick, J. R., Tower, J., Grygon, M., Farkas, R., Hagood, R., Eisenhauer, K., Uhl, A., Yerushalmi, S., Smith, L., Liewer, P. C., Velli, M. C., Linker, J., Bothmer, V., Rochus, P., Halain, J. P., Lamy, P. L., Auchère, F., Harrison, R. A., Rouillard, A., Patsourakos, S., St. Cyr, O. C., Gilbert, H., Maldonado, H., Mariano, C., and Cerullo, J., "The Solar Orbiter Heliospheric Imager (SoloHI)," *Astron. Astrophys.* **642**, A13 (Oct. 2020).

[13] Howard, R. A., Moses, J. D., Vourlidas, A., Newmark, J. S., Socker, D. G., Plunkett, S. P., Korendyke, C. M., Cook, J. W., Hurley, A., Davila, J. M., Thompson, W. T., St Cyr, O. C., Mentzell, E., Mehalick, K., Lemen, J. R., Wuelser, J. P., Duncan, D. W., Tarbell, T. D., Wolfson, C. J., Moore, A., Harrison, R. A., Waltham, N. R., Lang, J., Davis, C. J., Eyles, C. J., Mapson-Menard, H., Simnett, G. M., Halain, J. P., Defise, J. M., Mazy, E., Rochus, P., Mercier, R., Ravet, M. F., Delmotte, F., Auchere, F., Delaboudiniere, J. P., Bothmer, V., Deutsch, W., Wang, D., Rich, N., Cooper, S., Stephens, V., Maahs, G., Baugh, R., McMullin, D., and Carter, T., "Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)," *Space Sci. Rev.* **136**, 67–115 (Apr. 2008).

[14] Vourlidas, A., Howard, R. A., Plunkett, S. P., Korendyke, C. M., Thernisien, A. F. R., Wang, D., Rich, N., Carter, M. T., Chua, D. H., Socker, D. G., Linton, M. G., Morrill, J. S., Lynch, S., Thurn, A., Van Duyne, P., Hagood, R., Clifford, G., Grey, P. J., Velli, M., Liewer, P. C., Hall, J. R., DeJong, E. M., Mikic, Z., Rochus, P., Mazy, E., Bothmer, V., and Rodmann, J., "The Wide-Field Imager for Solar Probe Plus (WISPR)," *Space Sci. Rev.* **204**, 83–130 (Dec. 2016).

[15] Fineschi, S., Crescenzio, G., Massone, G., Capobianco, G., Zangrilli, L., Antonucci, E., and Anselmi, F., "OPSys: optical payload systems facility for testing space coronagraphs," in [*Solar Physics and Space Weather Instrumentation IV*], Fineschi, S. and Fennelly, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8148**, 81480W (Oct. 2011).

[16] Capobianco, G., Fineschi, S., Massone, G., Landini, F., Casti, M., Bellomo, A., Deffacis, M., Romoli, M., Antonucci, E., Andretta, V., Naletto, G., Nicolini, G., and Spadaro, D., "OPSys: optical payload systems facility for space instrumentation integration and calibration," in [*International Conference on Space Optics — ICSO 2018*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11180**, 111807M (July 2019).

[17] Newkirk, Gordon, J. and Eddy, J. A., "A Coronograph Above the Atmosphere," *Sky & Telescopes* **24**, 77 (Aug. 1962).

[18] Newkirk, Gordon, J. and Bohlin, D., "Reduction of scattered light in the coronagraph," *Ap Opt* **2**, 131 (Feb. 1963).

[19] Fort, B., Morel, C., and Spaak, G., "The reduction of scattered light in an extended occulting disk coronograph.," *A&A* **63**, 243–246 (Feb. 1978).

[20] Lenskii, A. V., "Theoretical Evaluation of the Efficiency of External Occulting Systems for Coronagraphs," *Sov Astr* **25**, 366 (June 1981).

[21] Koutchmy, S. and Belmahdi, M., "Improved measurements of scattered light level behind occulting systems.," *Journal of Optics* **18**, 265–269 (Jan. 1987).

[22] Bout, M., Lamy, P., Maucherat, A., Colin, C., and Llebaria, A., "Experimental Study of External Occulters for the Large Angle and Spectrometric Coronagraph 2: LASCO-C2," *Ap Opt* **39**, 3955–3962 (Aug. 2000).

[23] Landini, F., Romoli, M., Capobianco, G., Vives, S., Fineschi, S., Massone, G., Loreggia, D., Turchi, E., Guillon, C., Escolle, C., Pancrazzi, M., and Focardi, M., "Improved stray light suppression performance for the solar orbiter/METIS inverted external occulter," in [*Solar Physics and Space Weather Instrumentation V*], Fineschi, S. and Fennelly, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8862**, 886204 (Sept. 2013).

[24] Landini, F., Baccani, C., Schweitzer, H., Asoubar, D., Romoli, M., Taccola, M., Focardi, M., Pancrazzi, M., and Fineschi, S., "Scaled model guidelines for solar coronagraphs' external occulters with an optimized shape," *Optics Letters* **42**, 4800 (Dec. 2017).