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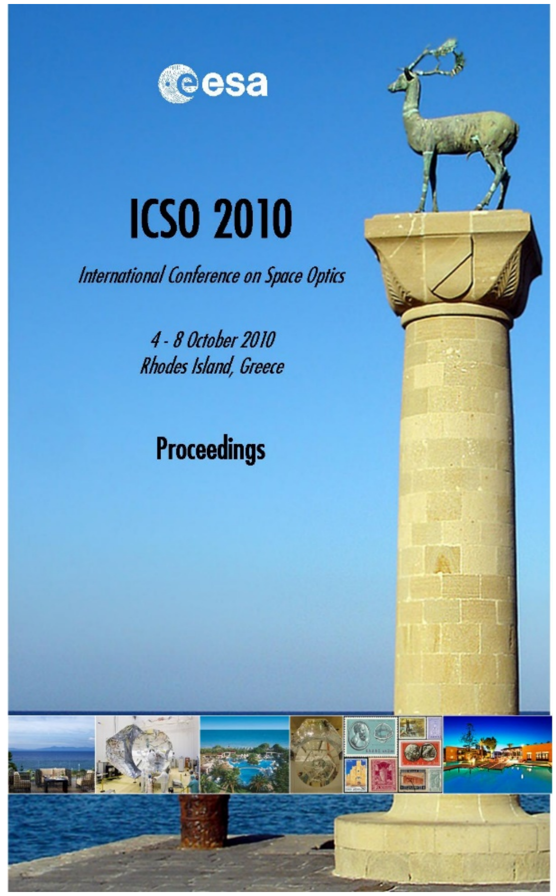

The STARTIGER'S demonstrators: toward a new generation of formation flying solar coronagraphs

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THE STARTIGER'S DEMONSTRATORS: TOWARD A NEW GENERATION OF FORMATION FLYING SOLAR CORONAGRAPHS

S. Vives[1], L. Damé[2], P. Lamy[1], A. Antonopoulos[3], G. Burton[4], G. Capobianco[5], G. Crescenzio[5], V. Da Deppo[6], M. Ellouzi[1], S. Fineschi[5], J. Garcia[1], C. Guillon[1], F. Landini[7], A. Marshall[4], A. Mazzoli[8], P. Rochus[8], T. Soilly[1], F. Stathopoulos[9], C. Tsiganos[3], K. Tsinganos[3], N. Waltham[4]
[1]Laboratoire d'Astrophysique de Marseille (LAM-CNRS), France. [2]Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS/IPSL-CNRS), France. [3]University of Athens (UoA/IASA), Greece. [4]Rutherford Appleton Laboratory, UK. [5]Osservatorio Astronomico di Torino (OATo-INAF), Italy. [6]University of Padova, Italy. [7]University of Firenze, Italy. [8]Centre Spatial de Liege (CSL), Belgium. [9]NTUA-UoA, Greece..

I. INTRODUCTION

STARTIGER stands for "Space Technology Advancements by Resourceful, Targeted & Innovative Groups of Experts & Researchers". STARTIGER is an ESA initiative within the Basic Technology Research Program (TRP) aiming at facilitating innovative and breakthrough research. The STARTIGER approach encourages the investigation of novel ideas, the aim being to achieve technology breakthroughs with the maximum likelihood of success in the shortest period of time (6 months or less).

In the framework of the ESA STARTIGER initiative, Laboratoire d'Astrophysique de Marseille (LAM, France) associated with Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS, France), and together with Centre Spatial de Liège (CSL, Belgium), Osservatorio Astronomico di Torino (INAF-OATo, Italy), University of Athens (UoA/IASA, Greece), and Rutherford Appleton Laboratory (RAL, UK), proposed to study the new generation of formation flying solar coronagraphs incorporating the most sophisticated capabilities to achieve diagnostics measurements in the solar corona in a unified, coordinated and progressive approach.

The solar corona is considered to be a laboratory of fundamental physical processes with extreme conditions common to solar and astrophysical plasmas physics. The advent of formation flying heralds a new era of coronal studies as it will allow deploying giant coronagraphs in Space capable of continuously observing the inner corona very near the solar limb under conditions approaching natural eclipses – a goal impossible with present Space and ground-based instruments.

In this article we describe the four demonstrators developed during the STARTIGER study conducted between September 2009 and March 2010:

- the "Formation Flight Metrology (FFM) demonstrator" addressing the crucial question of alignment and pointing in Space of long instruments (> 100 m) with an accuracy of a few arcsec. This demonstrator is directly relevant to the very success of the ESA's PROBA-3 formation flying demonstration mission;
- the "coronagraph demonstrators" addressing major questions for implementing new optical designs allowing large apertures with low stray light level (External Occulter Demonstrator), for developing advanced focal plane instrumentation (Liquid Crystal Polarizer Demonstrator), and detectors (Smart APS Demonstrator).

II. FORMATION FLYING METROLOGY (FFM) DEMONSTRATOR

A. Objectives and Description

The Formation Flying Metrology (FFM) Demonstrator is a scaled-model prototype of the metrology units involved in the alignment and pointing of the PROBA-3/ASPIICS coronagraph in Space [1]. Its main objective is to validate the performance of these metrology units. Fig. 1 defines the main axes of the system which have to be aligned, and gives all possible individual misalignments of the two satellites.

The peculiar configuration of this coronagraph imposes that the specifications be logically organized in the following order (which is in complete contrast to usage in classical instruments):

- absolute pointing of the formation (i.e. pointing of the instrument);
- relative pointing of the two spacecrafts (i.e. alignment of the formation).

The absolute pointing of the formation corresponds to the alignment of the "Formation Axis" with the "Sun Axis" (cf. Fig. 1). It can be measured by verifying the centering of the optical pupil of the instrument in the shadow cone formed behind the occulting disc (materializing the "Sun Axis"). The proposed solution, the "Shadow Position Sensor" (SPS), is based on measuring the penumbra around the entrance aperture of the coronagraph. Optimum pointing to the Sun is therefore achieved when the penumbra levels are balanced. The SPS gives a direct access to the absolute pointing of the formation and can be quantify in terms of relative positioning of one S/C compared to the other.

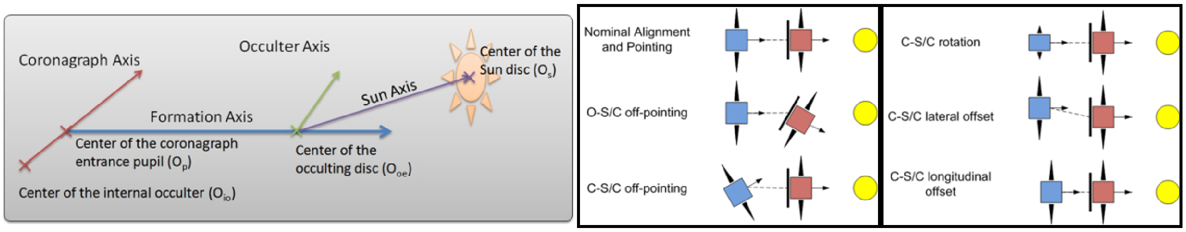


Fig. 1. LEFT: Definition of the axes of the ASPIICS coronagraph. The "Sun axis" is considered as the absolute reference. **RIGHT**: Possible individual misalignments of the two satellites. The satellite on the left is the Coronagraph S/C (C-S/C), the satellite facing the Sun (circle) is the Occulter S/C (O-S/C).

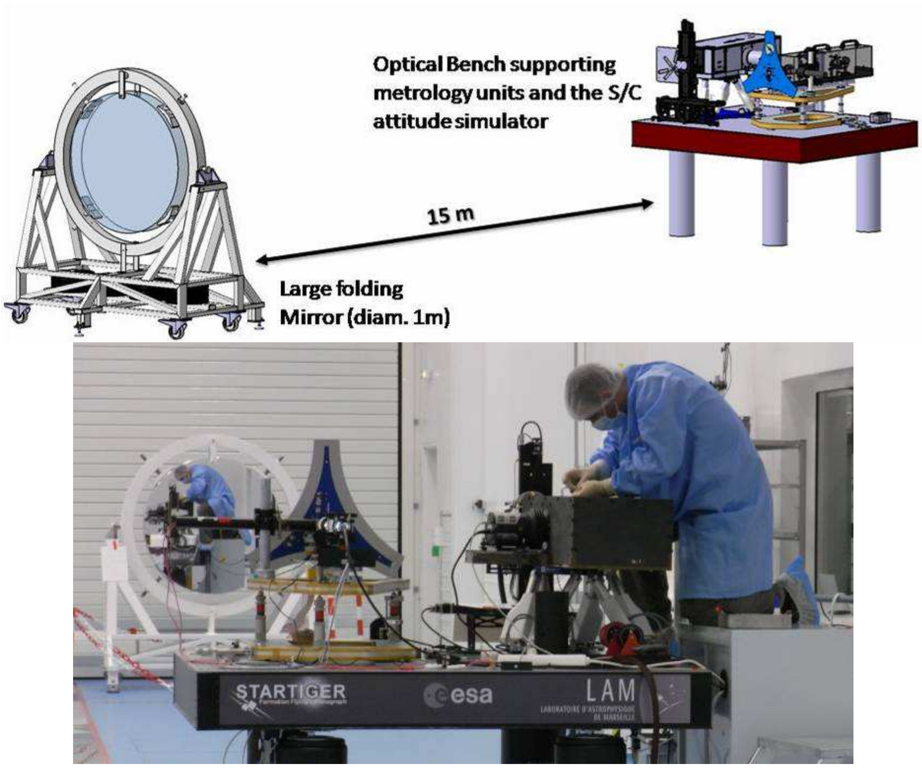


Fig. 2. TOP: Overview of the FFM demonstrator showing the 15 m distance between the 1 m diameter folding mirror and the optical bench (i.e. 30 m baseline) which supports the metrology units (SPS and OPS), the S/C attitude simulator (based on the hexapod technology), and calibration units (stability). **BOTTOM**: Photo during integration of the set-up in LAM premises.

The alignment of the formation corresponds to the alignment of the "Coronagraph Axis" (the optical axis of the coronagraph) with the "Formation Axis". It can be measured through the coronagraph itself, and its verification can be achieved by quantifying the positioning of the occulter in the field-of-view of the coronagraph. The proposed solution, the “Occulter Position Sensor” (OPS), is based on several light sources on the rear side of the occulting disc which are directly imaged by the coronagraph scientific channel.

In the FFM demonstrator both pointing and alignment of the formation have been implemented allowing to test all possible configurations (as shown in Fig. 1) and their relevant combinations. Note that the attitude of the Coronagraph S/C with respect to the other is done with an hexapod. This technology appears to be the most convenient and flexible solution to provide simultaneously the 6 degrees of freedom (DoFs) required for the demonstration while providing the capability to change the position of the center of rotation.

On top of the hardware part of the FFM demonstrator, a full numerical simulation has been developed in order to derive the 3D-coordinates and orientations of the two space from the measurements made by the SPS and the OPS metrology units. More details about this simulation are given in [2;3].

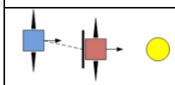
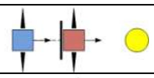
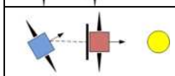
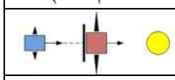
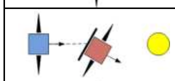
B. Main Results

Table 1 summarizes the measured relative positioning and pointing of the two S/Cs with the FFM demonstrator as well as the corresponding specifications imposed to the metrology system. PROBA-3/ASPIICS formation flying specifications are also given.

The C-S/C lateral displacements have been measured with both units SPS and OPS. The best results have been obtained with the SPS: the typical residual error (corresponding to >90% of the detection) is about 10 µm. Fig. 3 shows the statistical and spatial distributions of the errors. Note that we did not work in the best case, since the gradient of the penumbra projected by the EOS was lower by a factor ~5 with respect to the one in Space.

The C-S/C off-pointing is derived from the OPS measurements. In case of off-pointing, the LED pattern of the OPS is shifted on the coronagraph focal plane. The main limitation is the accuracy on the detection of the spot centroids. The typical error measured is 0.05 pixel (at 1σ) and 0.2 pixel (at 3σ). The centroid detection method has been optimized by tuning the following parameters: centroid computation algorithms, size of the spot (defocus), and shape of the light source (point source and various extended shapes).

Table 1. Formation Flying required specifications for ASPIICS/PROBA-3 and achieved performances.

	Items	**FF Specification**	**Metrology Specification**	**SPS/OPS measures**
	C-S/C lateral positioning	± 3.16 mm	± 15 µm	± 10 µm [1] ± 250 mm [2]
	C-S/C longitudinal positioning	± 70 mm	± 10 mm	± 200 µm [1] ± 72 mm [2]
	C-S/C off-pointing	± 24 arcsec	± 0.51 arcsec	± 0.33 arcsec [2]
	C-S/C rotation	± 0.5 deg	± 2 arcmin	± 1.5 arcmin [2]
	O-S/C off-pointing	± 0.5 deg	± 0.1 deg	Not measured

[1] SPS measurements done with the FFM but scaled for 150 m. [2] Idem for OPS.

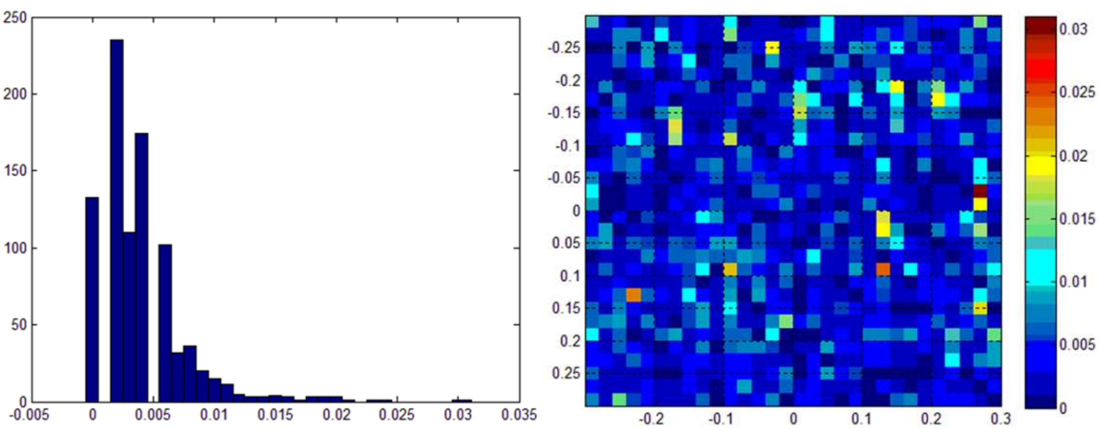


Fig. 3. **LEFT**: Statistical distribution of the residual error on the measurement of the C-S/C lateral displacement. Units are mm in x and the rate in y. **RIGHT**: Spatial distribution of these errors on an area of 600x600 µm. Each pixel is 10 µm. All units are mm.

III. EXTERNAL OCCULTER SCALED-MODEL DEMONSTRATOR

The most critical issue in the design of a solar coronagraph is the reduction of the stray light due to diffraction and scattering of the solar disk light from the optics and in particular from the external occulting disc. On top of the complete stray light analysis of the instrument [4], intensive laboratory tests have been performed in order to select the most optimized shape for the occulting disc.

Since it is practically impossible to realize a full-scale model for laboratory tests, we designed a test set-up able to measure the stray light behind a section of the whole occulter. The section of such a large occulter (1.5 m diameter) can be approximated by a small straight edge occulter.

A complete overview of the set-up is shown in Fig. 4 (left): the source is an "artificial Sun" (i.e. a collimator that simulates the angular aperture of the real solar disk). Light from the source enters a class 100 clean room through an aperture. In the clean room, the stray light measurement set-up is assembled. The detector is a photodiode (Newport 818-SL), with a baffle mounted in front. The baffle holds a 0.45 mm pin-hole, to allow a high resolution sampling. A light trap is placed very near to the detector, in order to prevent direct "solar" disk light from being scattered everywhere inside the room. Stray light measurements are performed behind the linear occulter along a direction perpendicular to the occulter edge.

All our results are relative to the unobstructed flux and to the razor edge stray light reduction performances, which is easy enough to calculate even considering the whole solar disk as a source. Indeed the razor edge behaves as a perfect theoretical straight edge. As shown Fig. 4 (right), our measurements demonstrate that an optimization of the occulter shape improves the stray light reduction performances of a simple disk, and that a cone is the best solution, even if the cone has to be fairly compact along the optical axis. Our measurements show also that such a system is relatively insensitive to tilt (within 2 arcmin) and scratches (at least up to 20 µm deep) on the conic surface. In order to improve its efficiency, the cone has to be as long as possible, compatibly with the stability and alignment requirements of the spacecrafts. We tested also some toroidal shapes, but they are less efficient than the conic ones.

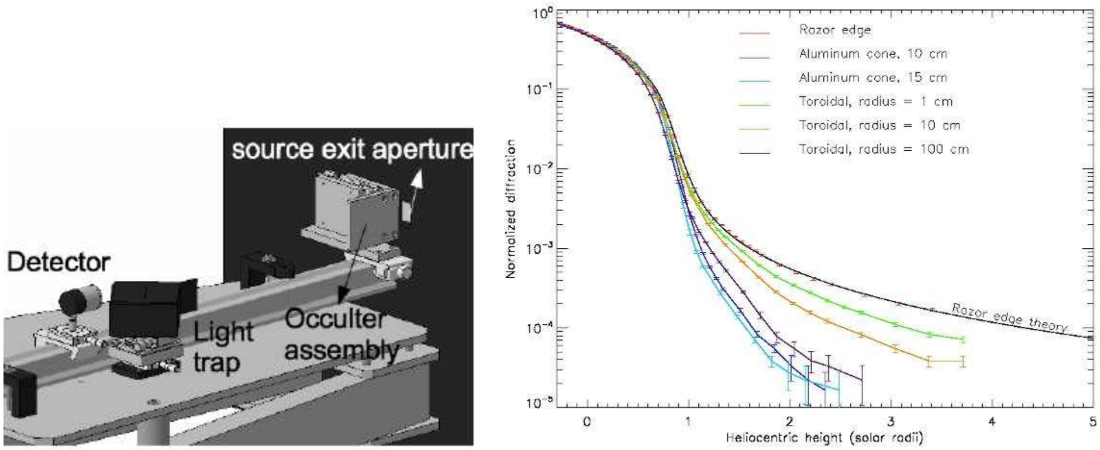


Fig. 4. LEFT: 3D-view of the set-up. **RIGHT**: Diffraction profile along the direction perpendicular to the occulter edge for various occulter shapes: three toroidal occulters, two Aluminum cones of different lengths and the theoretical razor edge curve.

IV. LIQUID-CRYSTAL TUNABLE-FILTER POLARIZER (LCTP) DEMONSTRATOR

The Liquid Crystal Tunable-filter Polarizer (LCTP) is a key element in our quest for enhanced science capabilities of future space coronagraphs. It allows to select and to finely tune a narrow spectral range throughout a large visible-light bandwidth region with, in addition, polarization capabilities. And, compared to previous techniques (Fabry-Perot etalon or tunable Fabry-Perot), without involving any mechanisms or moving parts.

The LCTP consists in a combination of a Liquid Crystal (LC) Tunable Filter and a LC Polarization Rotator. The filter we used is a customized version of a standard product line of Meadowlark Optics. It consists of multiple liquid crystal variable retarders, invariant retarders, and polarizers all protected in a temperature-controlled housing. Varying the voltages applied to the liquid crystals shifts the pass band without any mechanical motion or vibration of the optics. The filter realized (Fig. 5) has a full width at half maximum of 0.15 nm at a wavelength of 530.3 nm. The center wavelength of the bandpass is tunable in 0.01 nm steps from 528.64 nm to 533.38 nm. The free spectral range between neighboring transmission bands of the filter is more than 2.7 nm. Dimensions are less than Ø5 cm x 10 cm for a 17.8 mm clear aperture filter.

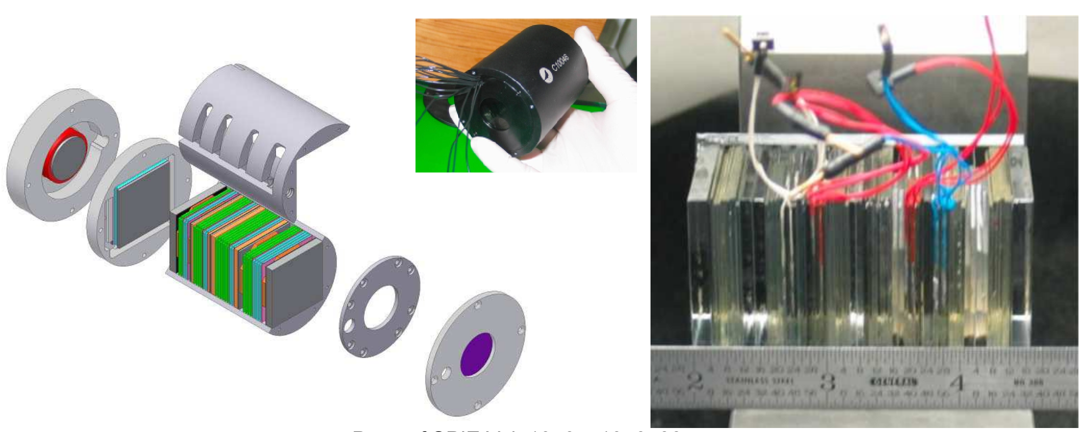


Fig. 5. Principle, assembly (stack of liquid crystal variable retarders) and housing of the LCTP realized.

Spectral and polarimetry tests of the assembly have been carried in laboratory and performances are along expectations: finesse of 25, free spectral range of 2.5 nm and a spatial resolution of 5 arcsec. These are comparable, contrast and S/N ratios also, to Fabry-Perot with an almost similar throughput and the advantage of no mechanisms, full coronal image in the same bandpass, and polarimetry capability. Further, in case of power failure, the zero power corresponds to the center line (530.3 nm) position.

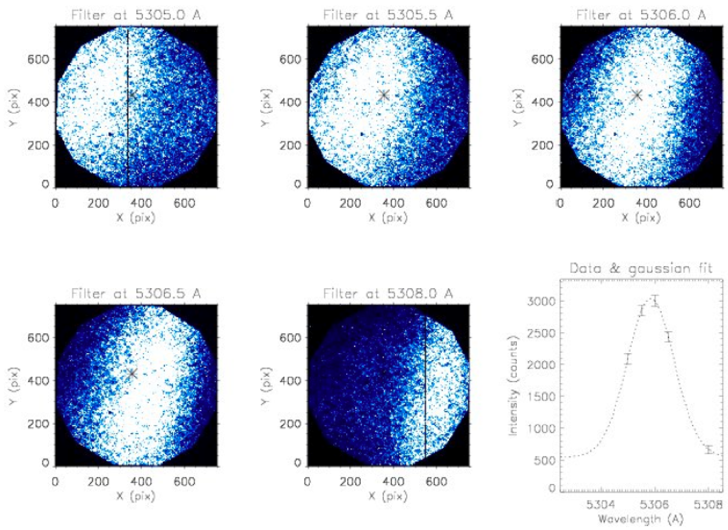


Fig. 6. Laboratory spectral performance test of the LCTP assembly: proper reconstitution of the line profile.

V. SMART CMOS ACTIVE PIXEL SENSOR DEMONSTRATOR

We undertook a study to compare the merits of employing a CMOS Active Pixel Sensor (APS) detector in place of the baseline concept of a science-grade CCD-based camera system . The APS, although not having the photometric efficiency, dynamic range and read out noise capability of today's best CCD-based solutions, offers the advantages of a more compact, lower mass and lower power system and with better resilience to the effects of space radiation.

We selected the Cypress HAS2 APS (Fig. 7) as offering the most mature, space-qualified and radiation-tested solution to our science and instrument requirements. The HAS2 is a 1024 x 1024 pixel sensor with 18 µm pixel pitch, manufactured on a 0.35 µm CMOS process. It offers programmable x- and y- window addressing, rolling shutter operation and non-destructive readout modes. Non-destructive readout enables an image to be read several times while still integrating. This allows true correlated double sampling to remove reset noise and also provides a means to increase dynamic range. More information on the Cypress HAS2 APS are given in [8].

A breadboard was designed for evaluation of the HAS2. One of our prime objectives was to demonstrate that we could effectively increase image dynamic range by operating the HAS2 is non-destructive readout mode [9]. The concept relies on reading out multiple frames non-destructively over the course of an exposure. Bright features can be sampled in the earlier frames before the onset of saturation while faint features can be sampled with good signal-to-noise in later frames. Appropriate scaling of the data as a function of exposure time allows the reconstruction of a single image with significantly greater dynamic range than could be obtained in a single readout. The principal components are the HAS2 APS, a new radiation-tolerant external video amplifier with integral 14-bit ADC (National Semiconductor LM98640) and two ACTEL FPGAs. The video amplifier allows programmable gain and offset adjustment, and provides a higher performance ADC than the HAS2's on-chip 12-bit converter. One FPGA contains a waveform generator and sequencer which provides all the control clocks and timing needed to operate the APS and ADC. We read the APS at 5 Mpixels/s. The second FPGA contains a FIFO buffer memory and a SpaceWire interface running at 200 Mbits/s. The SpaceWire link is used to program the APS and waveform generator, provide commanding for reading out the APS and for the return of digitized video data.

Evaluation of the HAS2 has started and we have so far confirmed both normal and non-destructive readout modes and nominal operation of the sensor. Quantum efficiency, dark current and fixed-pattern noise characteristics have yet to be confirmed. Our immediate plan is to implement an operating mode in which we read, for example, ten non-destructive images at regular intervals over a specified exposure period. Appropriate weighting and co-addition of the image data is anticipated yielding a final image with ten times the dynamic range of any one single image and, thus, recovering from one of the primary deficiencies of the APS compared to the best science-grade CCDs.

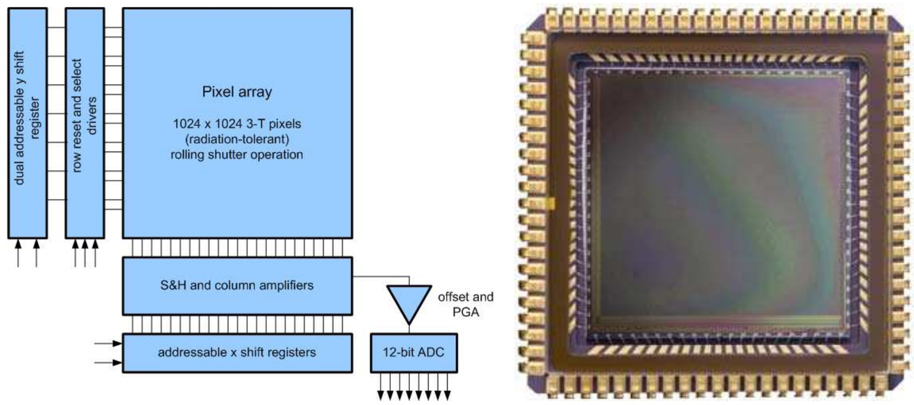


Fig 7. LEFT: Cypress HAS2 APS - schematic. **RIGHT**: Cypress HAS2 APS - photo.

VI. CONCLUSION

This new STARTIGER initiative "Toward A New Generation of Formation Flying Solar Coronagraph" has delivered on expectations: more than 80% of the initial objectives have been achieved in the very challenging timeframe of 6 months period.

The STARTIGER study allowed (i) to validate the two major metrology concept units, Occulter Position Sensor and Shadow Position Sensor, required to control to arcsec the future formation flying demonstration mission PROBA-3; and (ii) to demonstrate three crucial technologies for the development of solar coronagraphy in Space, namely, external occulting disk optimization for ultra low scattering, narrow filter-mechanism free tunable polarizer using Liquid-Crystal and Smart APS detector of the next generation. On top of the direct application of most of these results on the ASPIICS ESA/PROBA-3 mission, this will pave the way toward the next generation of solar coronagraph missions in Space, in particular the Solar Orbiter very soon [5] and, more promising even, the ESA Cosmic Vision large Formation Flying mission HIRISE with its 30 cm UV-vis-NIR coronagraph and a 280 m inter-satellite distance [6;7].

ACKNOWLEGMENTS

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In particular we would like to thank the ESA STARTIGER study's managers, Dominic Doyle and Peter de Maagt, for their efficient support and permanent good spirits during the whole study.

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