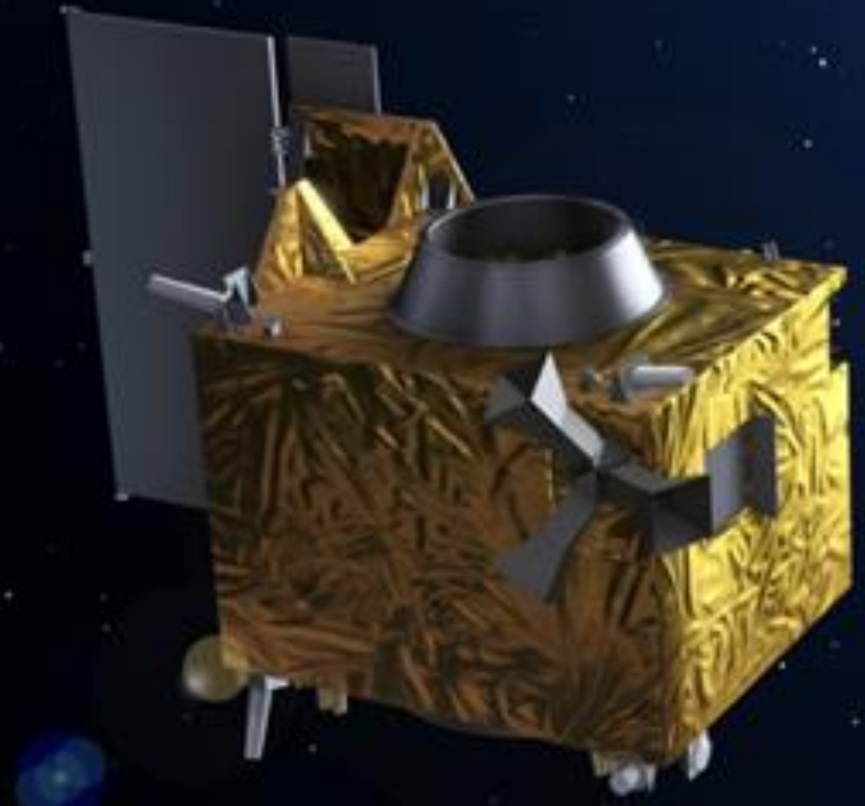
ASPIICS
Formation Flying Coronagraph



Proba-3 mission: the ASPIICS coronagraph and the total solar irradiance monitor DARA.

Marek Stęślicki and the Proba-3 SWT

General objectives

The Proba-3 project aims:

- To develop and demonstrate in-orbit the formation flying (FF) techniques and associated technologies,
- To develop and validate the engineering approach, ground verification tools and facilities required by formation flying,
- To provide scientific data using a giant coronagraph payload for the observation of the sun corona

Proba 3 mission objectives

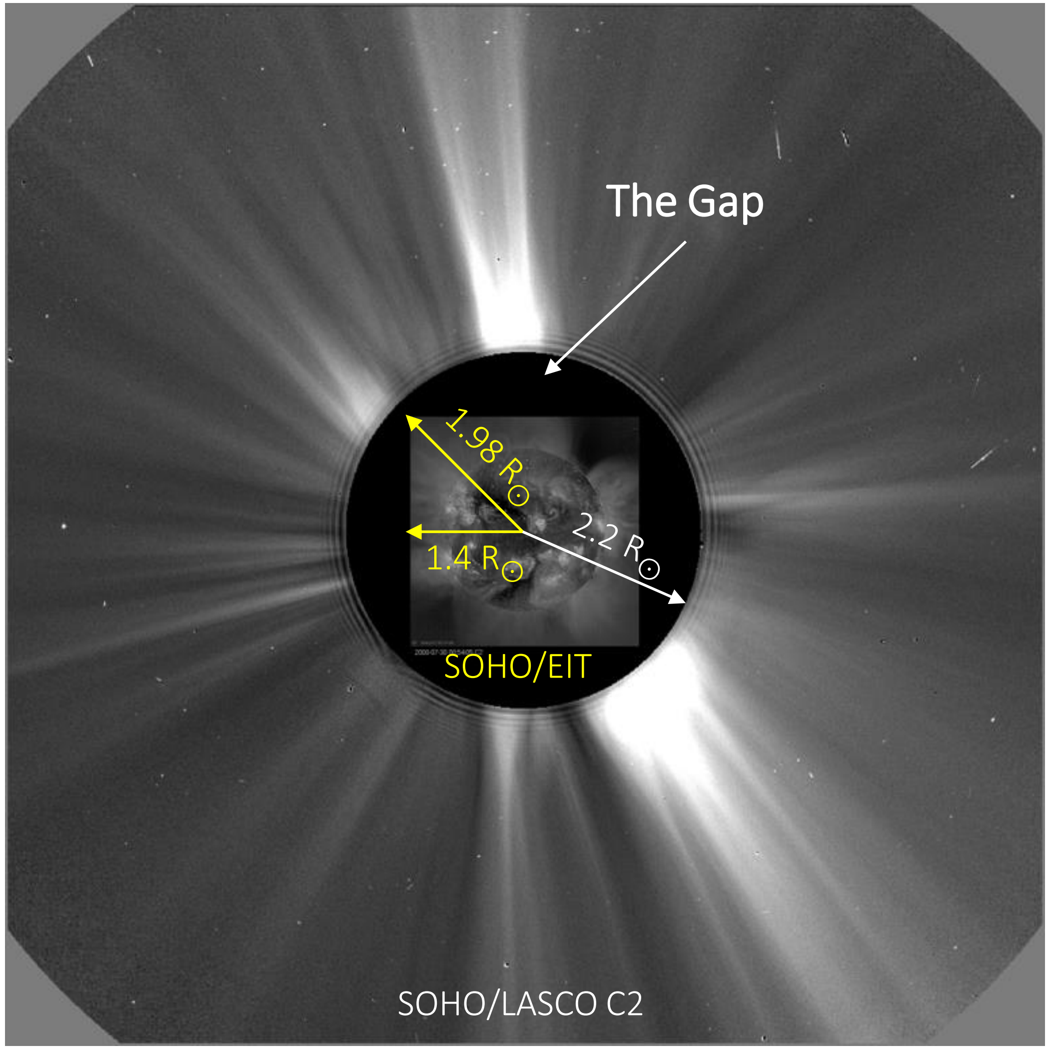
Proba-3 is a mission for in-orbit demonstration (IOD) of breakthrough concepts approaches. It addresses the objectives of the Agency’s IOD strategy, i.e. the demonstration of:

- Technology and products, e.g. metrologies, new GNSS receivers, new GNSS ASIC, new CMOS detectors, new gyros, etc.
- Techniques, for research or services, e.g.:
  - precise formation flying, with incapacitated target, in elliptical orbit, GNSS navigation beyond LEO
  - coronagraphy for science, for in-orbit operations, etc.
- Mission architecture and system concepts,
- Industrial capabilities: from new companies and/or in new Member States

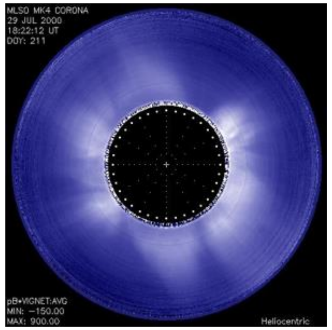
Imaging observations of the solar corona

Between the low corona (typically observed by EUV imagers) and the high corona (typically observed by externally occulted coronagraphs), there is a region where observations are difficult to make.

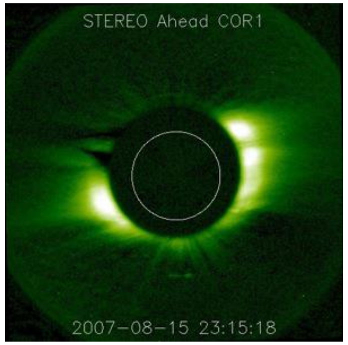
An externally occulted coronagraph allows for a good straylight rejection. However, the inner edge of its field of view is limited by the telescope length.



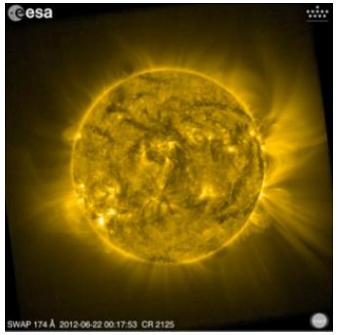
How to close The Gap?



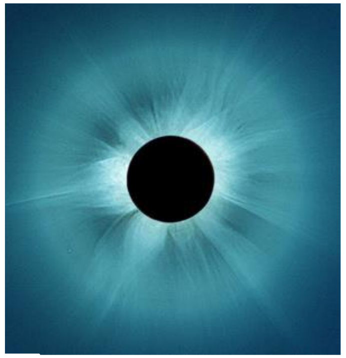
- **Ground-based coronagraphs** (straylight)



- **Internally occulted space-borne coronagraphs** (straylight)

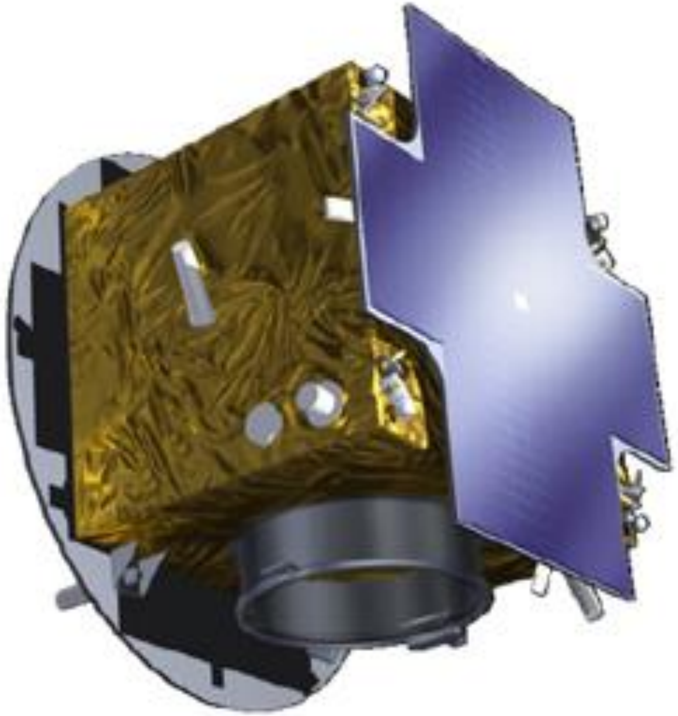


- **Wide field-of-view EUV imagers** (very long exposure times)



- **Total solar eclipses** (are rare and last only several minutes)

The PROBA-3 mission



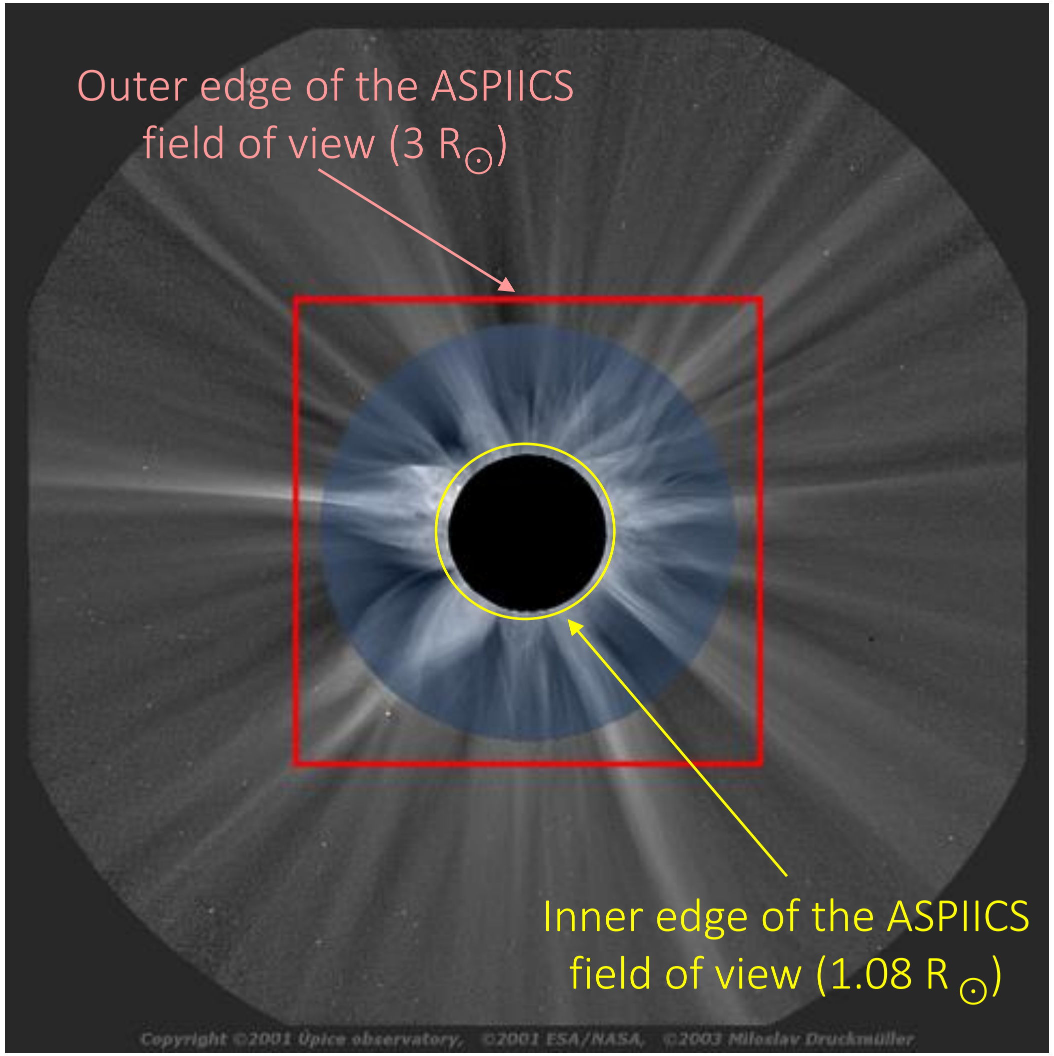
An artificial total eclipse created using two spacecraft in flight formation.

- The formation flying is maintained over 6 hours in every 20-hour orbit: around a factor 100 improvement in the duration of uninterrupted observations in comparison with a total eclipse.
- A technological challenge: the distance between the spacecraft is 150 m, and the accuracy of their positioning should be around a few millimeters!

ASPIICS characteristics

- 6 channels:
  - 1 white light,
  - 3 polarized light,
  - 1 narrow-band filter
    centered at the Fe XIV line at 5303 Å,
  - 1 narrow-band filter
    centered at the He I D3 line at 5876 Å.
- 2048x2048 pixels
  - **2.8 arc sec per pixel**
- Outer edge of the field of view:
  - **2.99 $R_\odot$**
  - **4.20 $R_\odot$** in the corners
- 60 s nominal cadence
  - 2 s using a quarter of the field of view

ASPIICS will cover The Gap between the typical fields of view of EUV imagers and externally occulted coronagraphs!



Outer edge of the ASPIICS field of view (3 $R_\odot$)

Inner edge of the ASPIICS field of view (1.08 $R_\odot$)

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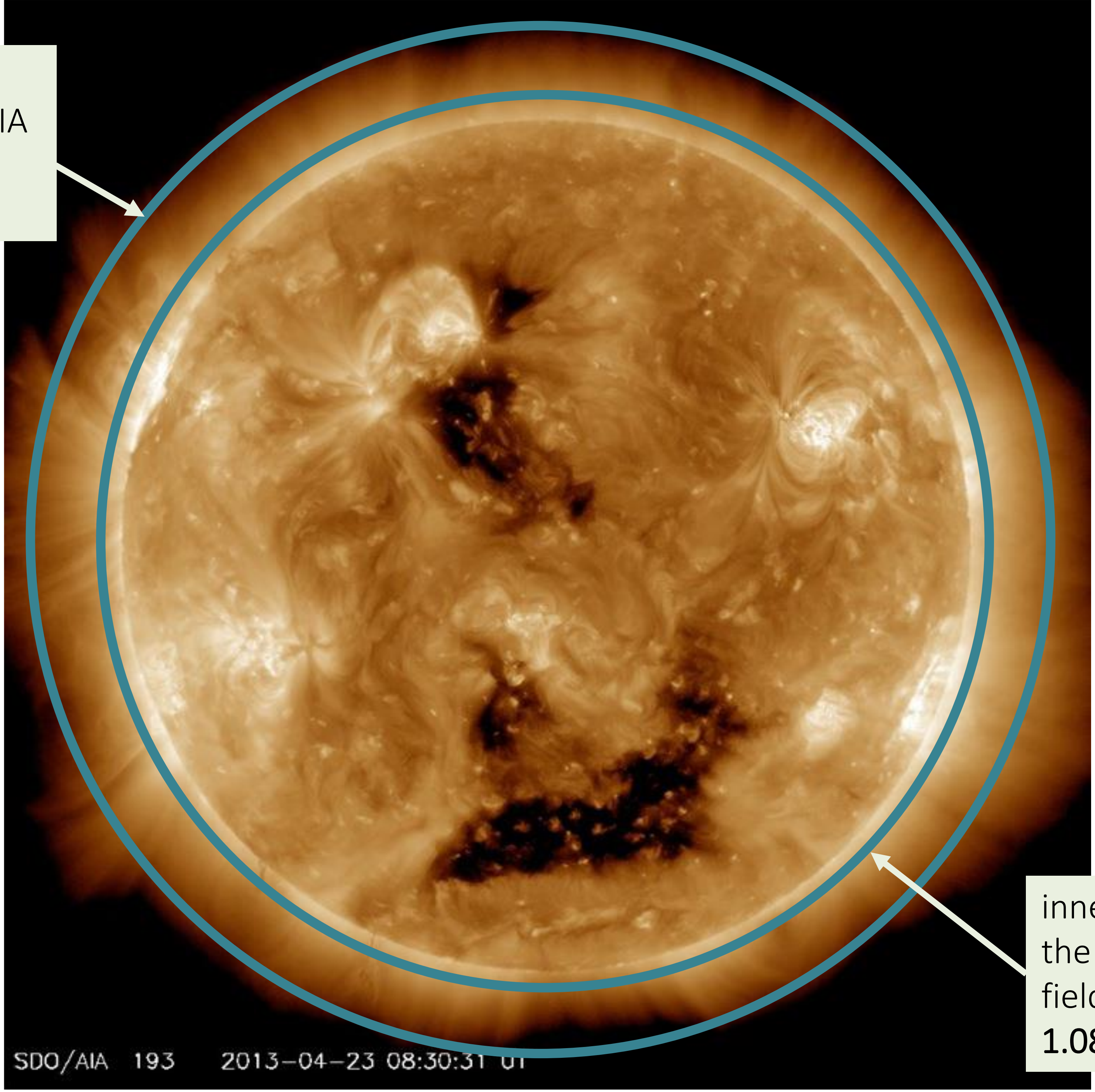
outer edge
of the SDO/AIA
field of view:
1.27 $R_\odot$



inner edge of
the ASPIICS
field of view:
1.08 $R_\odot$

The position of the inner Edge of the ASPIICS field of view allows for a significant overlap with SDO/AIA.

ASPIICS scientific objectives

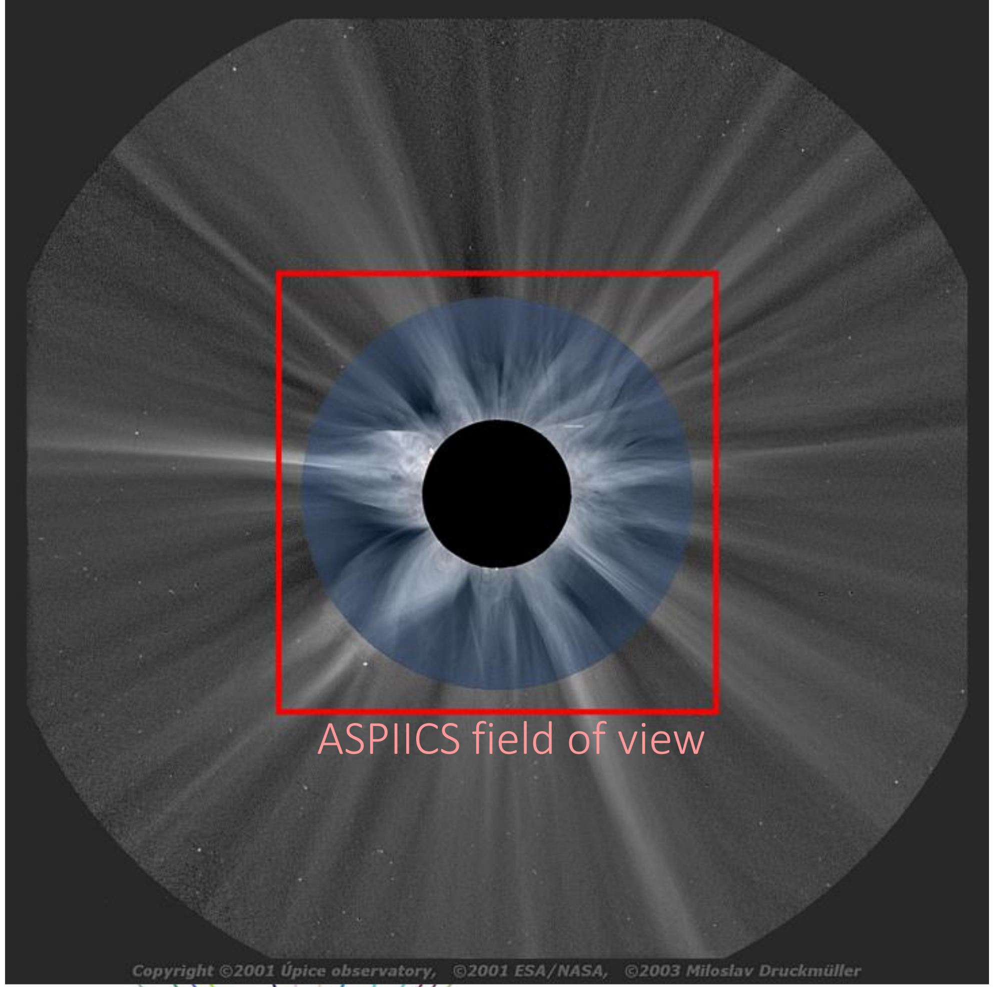
The top-level scientific objectives of ASPIICS are:

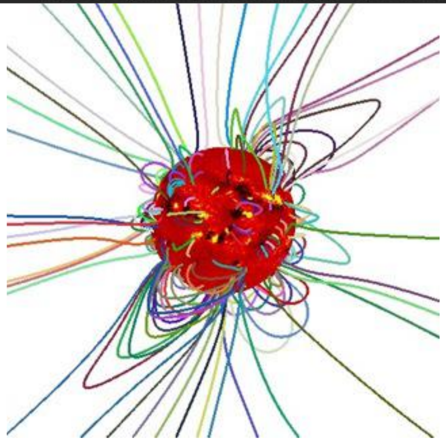
- Understanding the physical processes that govern the quiescent solar corona by answering the following questions:
  - What is the nature of the solar corona on different scales?
  - What processes contribute to the heating of the corona and what is the role of waves?
  - What processes contribute to the solar wind acceleration?
- 2. Understanding the physical processes that lead to CMEs and determine space weather by answering the following questions:
  - What is the nature of the coronal structures that form the CME?
  - How do CMEs erupt and accelerate in the low corona?
  - What is the connection between CMEs and active processes close to the solar surface?
  - Where and how can a CME drive a shock in the low corona?

Coronal magnetic field

- The magnetic field often plays a dominant role in the structuring and dynamics of plasma in the solar corona
- However, the coronal magnetic field cannot be routinely measured at the moment. Instead, it is extrapolated from photospheric magnetograms.
- The extrapolated field is strongly model dependent.
- The extrapolated field cannot always reproduce the complex magnetic configuration of the solar corona.

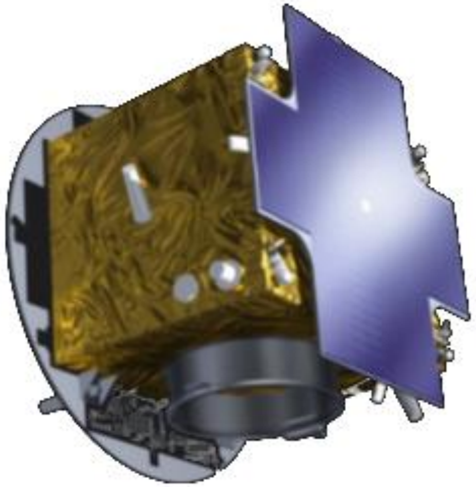
ASPIICS will answer questions about the structuring and dynamics of the solar corona on different scales, as well as constrain coronal magnetic field models.



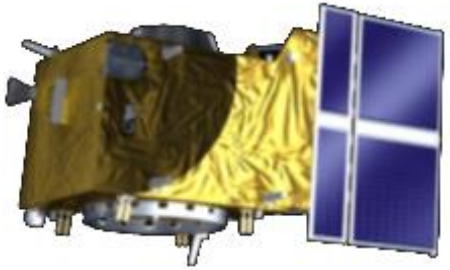

MHD model
of the coronal
magnetic field

Mission overview

- The Proba-3 mission consists of two spacecraft, the Coronagraph and the Occulter spacecraft, flying in a close proximity (about 150m with accuracy of a few mm)
- The giant coronagraph is implemented by one satellite occulting the sun and the other satellite flying a telescope

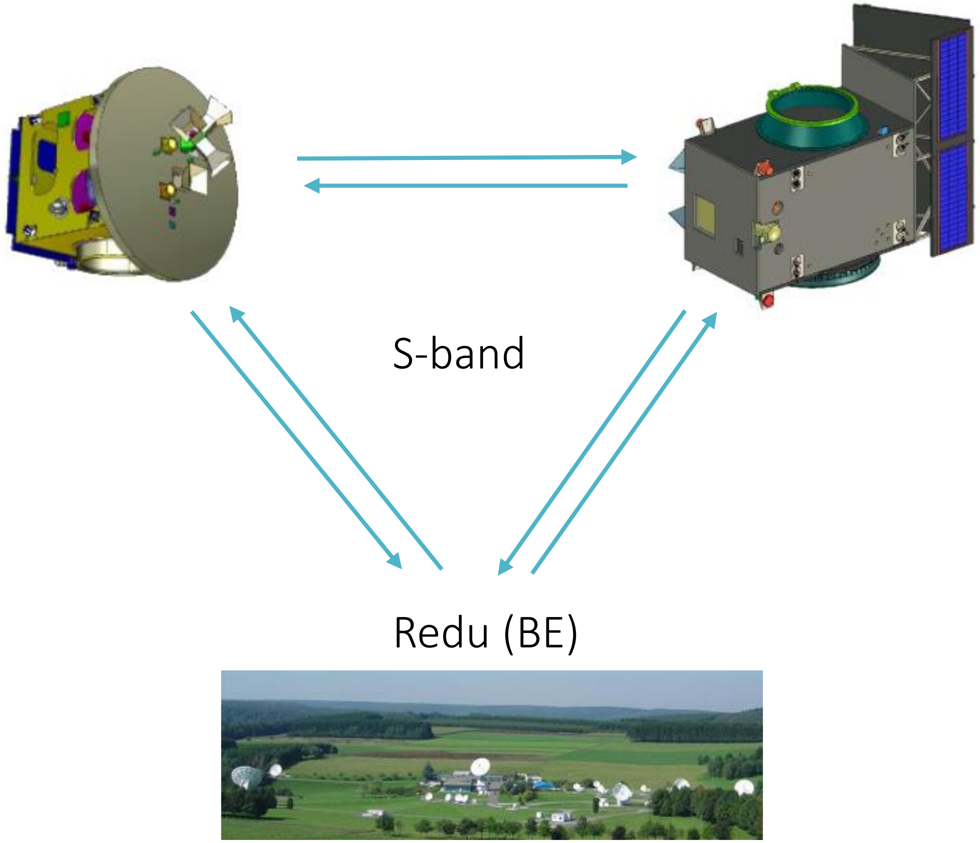


Occulter
Space**C**raft
OSC



Coronagraph
Space**C**raft
CSC

Mission overview



Launch 2019

Occulter
200 kg
120 Mb/orbit

Coronagraph
340 kg,
9 Gb/orbit

S-band

Redu (BE)

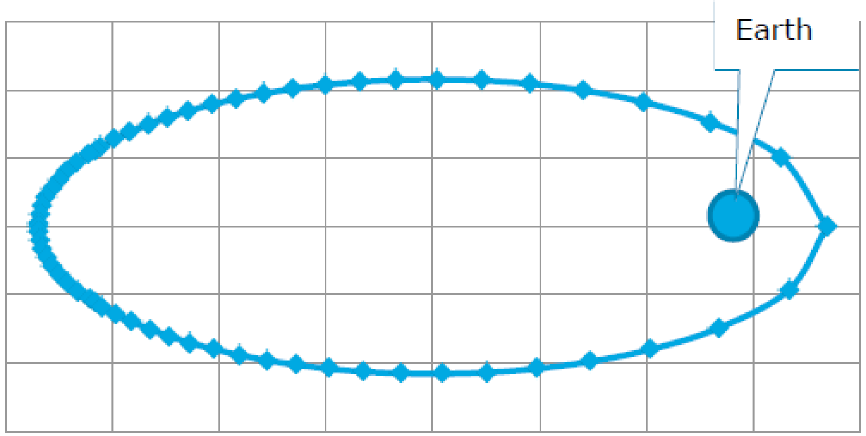
Proba-3 Orbit

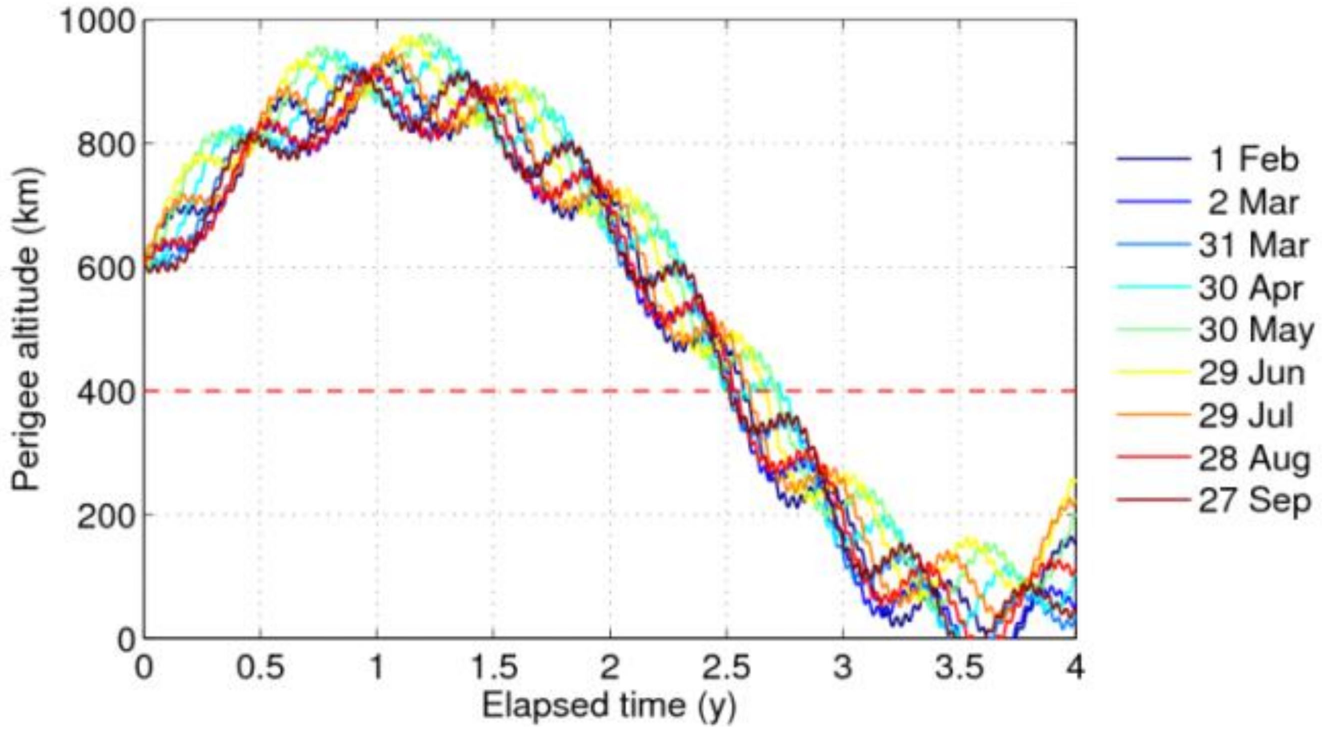
- PROBA-3 orbit is the result of a complex trade-off that takes into account many contrasting requirements:

Requirement	Preference
Need of low gravity gradient environment (to exercise FF demonstration without large fuel penalty)	High altitude
Limit radiation	High inclination, appropriate Argument of Perigee (~180 deg)
Accessibility by low cost launcher via direct launch	Low altitude, low inclination, appropriate AoP
Visibility from Redu as main tracking station	High inclination
Natural de-orbit within 25 years (to comply with debris avoidance regulations)	Low altitude, appropriate RAAN

- Best compromise is High Elliptical orbit of intermediate inclination with tuned AoP and RAAN to match requirements

Orbit characteristics





Perigee altitude decays naturally after ~2.5 yrs due to Lunar-solar perturbation

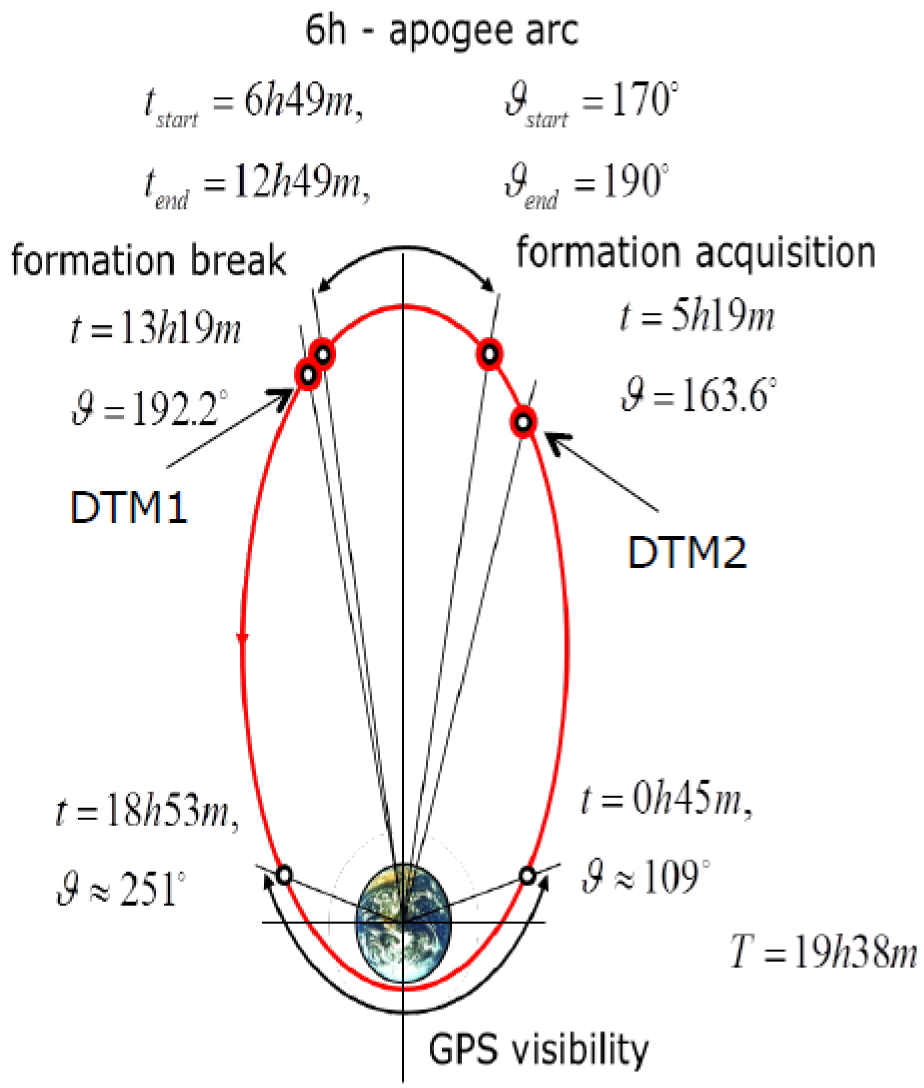
Parameter	Value
Perigee height	600 km
Apogee height	60530 km
Semi-major axis	36943 km
Eccentricity	0.8111
Inclination	59°
RAAN	84°
AoP	188°
Orbital period	19h38m

Routine orbit

- Coronagraphy around apogee:
  - Spacecraft are in fine formation (for 6 h around the apogee)
  - 0.5h after the 6h, the formation is broken by prop maneuver (DTM1)

- Outside the apogee arc:
  - Spacecraft are in “free drift” (safe) configuration
  - Relative GPS nav. around perigee.
  - Formation acquisition maneuvers (DTM2) and instrument preparation take place on the ascending arc

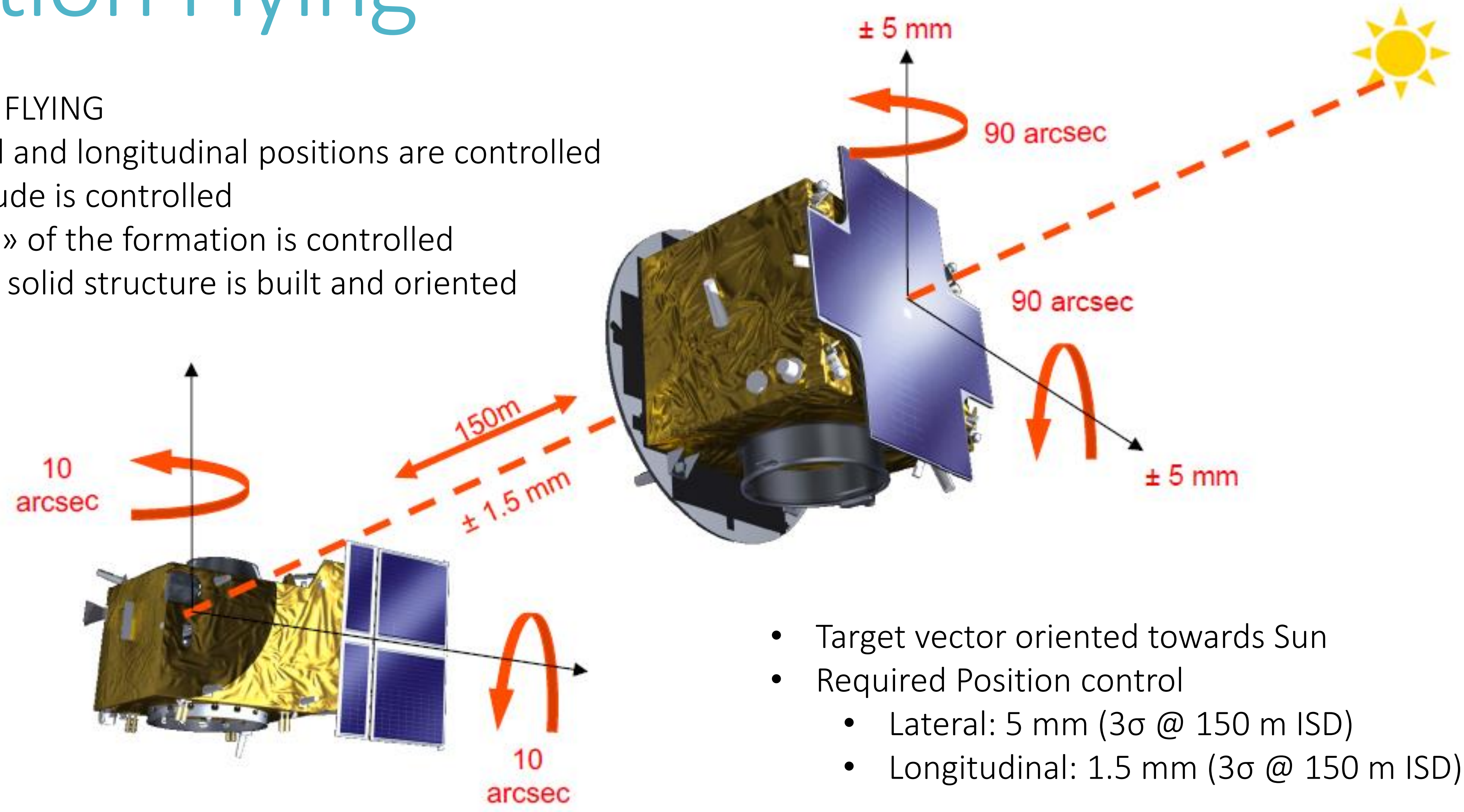
Data downlink takes place in any point of the orbit depending on GS visibility (in average 6-h per orbit)



Formation Flying

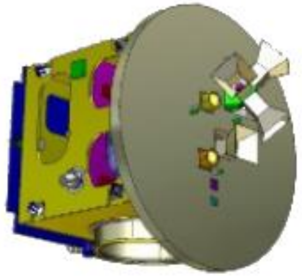
PRECISE FORMATION FLYING

- The relative lateral and longitudinal positions are controlled
- The absolute attitude is controlled
- The « line of sight » of the formation is controlled
- A virtual large and solid structure is built and oriented

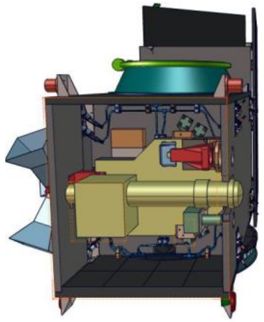


- Target vector oriented towards Sun
- Required Position control
  - Lateral: 5 mm (3σ @ 150 m ISD)
  - Longitudinal: 1.5 mm (3σ @ 150 m ISD)

Spacecrafts

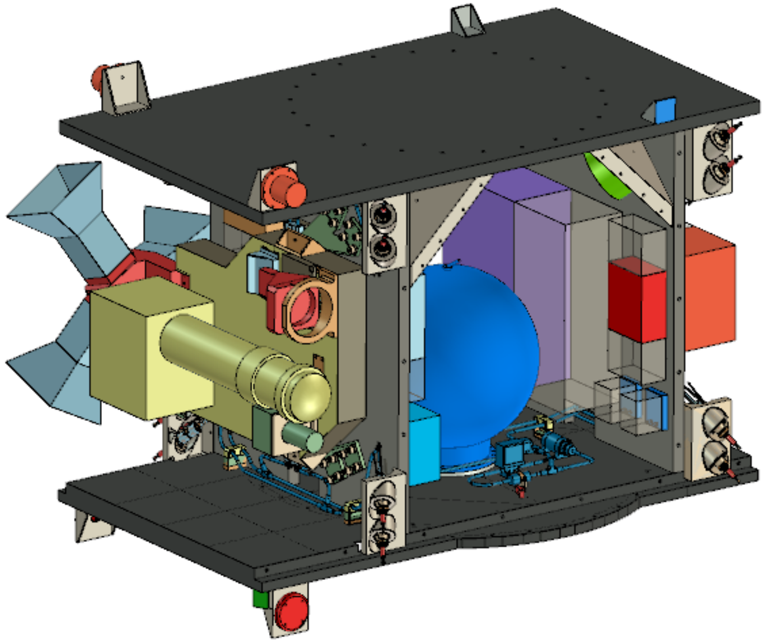


- Mass (wet): 231 kg
- Dimensions: envelop: 1.42m x 1m x 1.42m
- ADPMS (combined power & computer)
- Power: solar array 200W
- Ah Li-ion battery
- Propulsion: 12x2 10-mN cold gas
- TTC&Comms: S-band
- FF technologies:
  - Inter satellite Link (ISL),
  - Optical metrology including a camera Vision based sensor and corner-cubes,
  - OPSE LEDs
- AOCS: Reaction wheels, star tracker, sun sensor, GPS, gyros

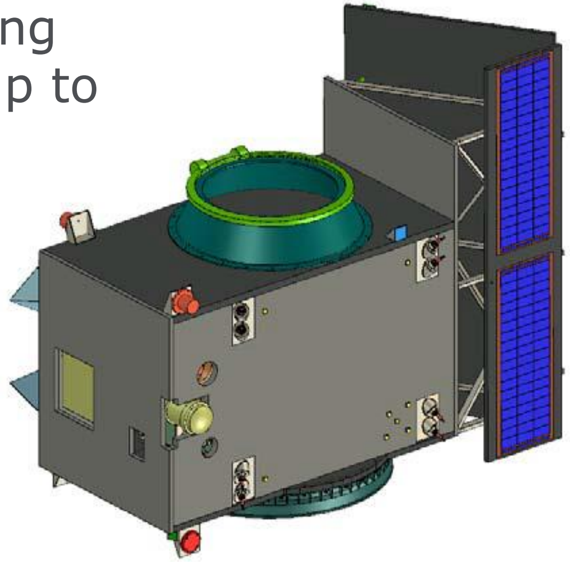


- Mass (wet): 283 kg (incl. margins)
- Dimensions: envelop: 1.65m x 1.1m x.1.95m
- ADPMS (combined power & computer)
- Power: Solar array 300 W
- Ah Li-ion battery
- Propulsion: 2x8 1-N monopropellant
- TT&Comms: S-band
- Coronagraph instrument
- FF technologies:
  - Inter satellite Link,
  - optical metrologies including a coarse lateral sensor, a fine lateral sensor
- AOCS: reaction wheels, star tracker, sun sensor, GPS, gyros

Coronagraph Spacecraft

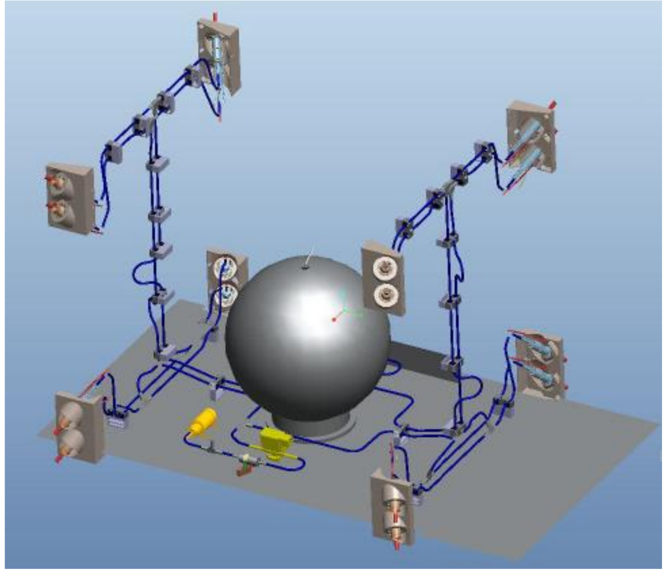


Power handling capabilities up to 300 W

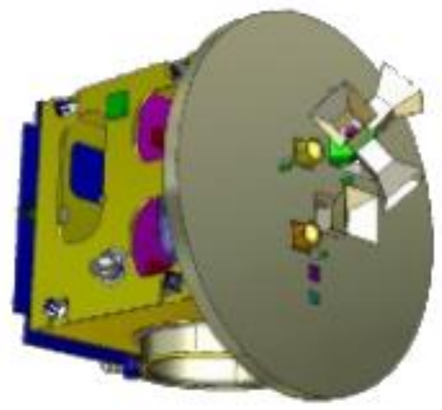


Single side-deployable Solar Array to avoid penumbra from Occulter disk

8X2 1-N monopropellant thrusters for 6 DoF control of the SC

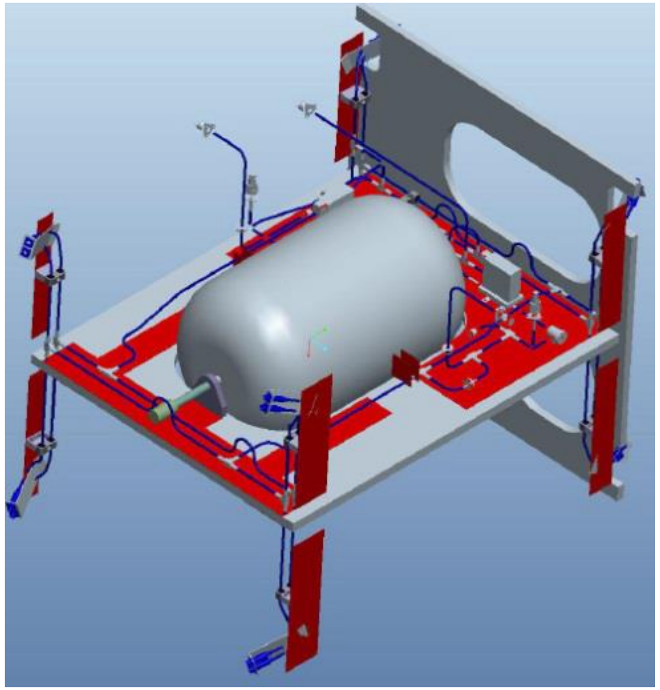


Occulter Spacecraft



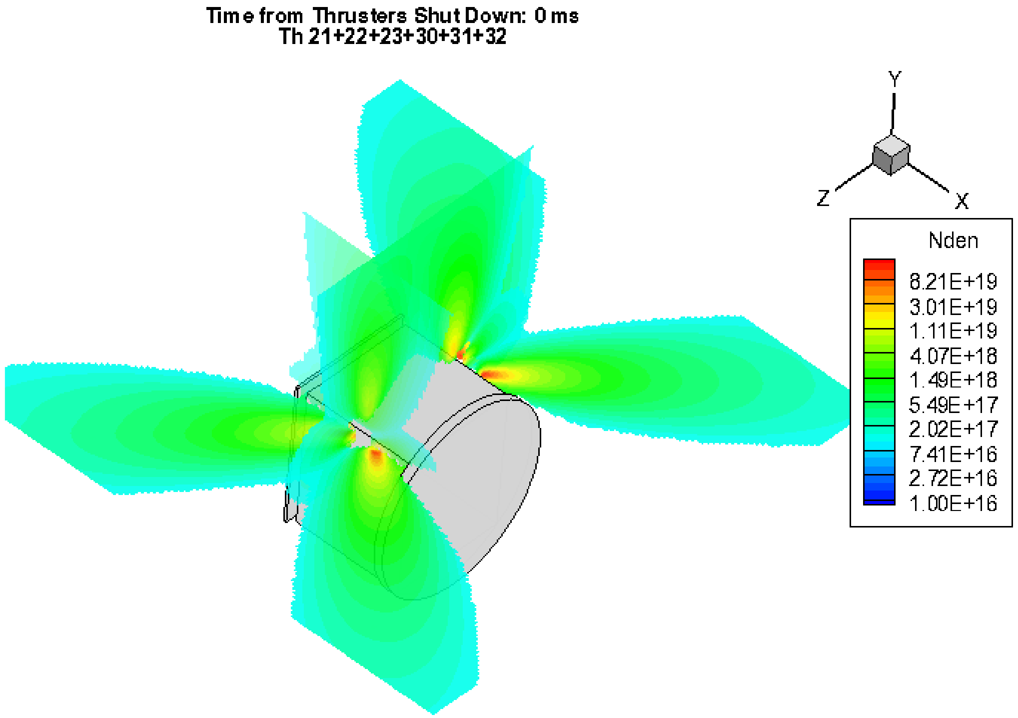
- All SC body shall be behind the disk to avoid straylight to the Coronograph
- Fixed Solar Array
- Disk is black-painted on the Coronagraph side and white painted on the Sun side

12X2 10-mN cold gas thrusters for 6 DoF control of the SC



Slide on scattering from nitrogen cloud

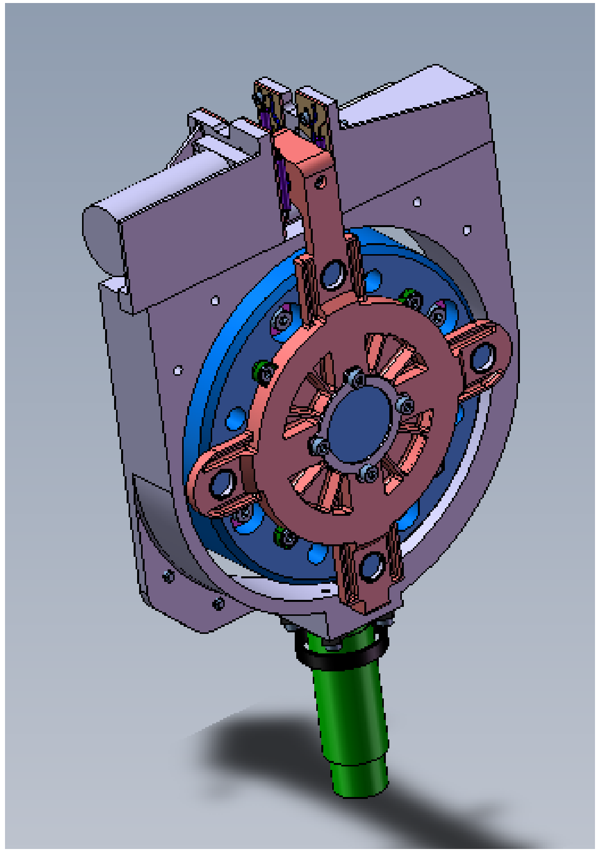
Worst case nitrogen density around OSC:



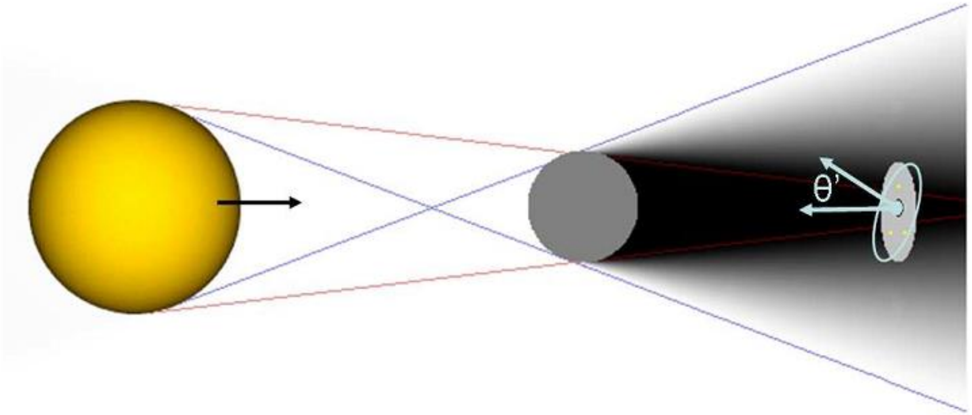
Assuming density is 10^{20} molecules per cm^3 everywhere, and considering Rayleigh scattering, estimate of flux entering ASPIICS ~ 10^{-14} (normalised to flux from direct Sun)

Negligible compared to other source of straylight

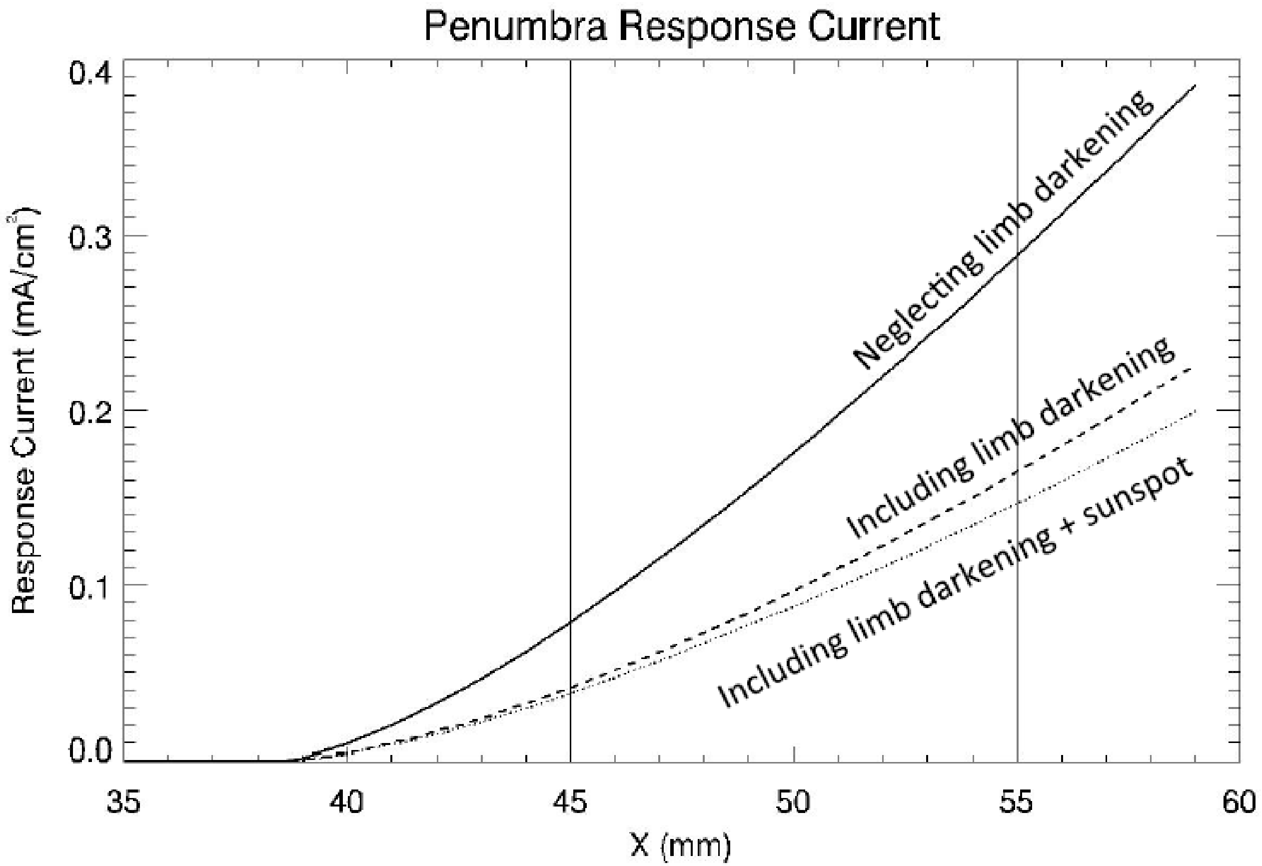
Shadow Position Sensor

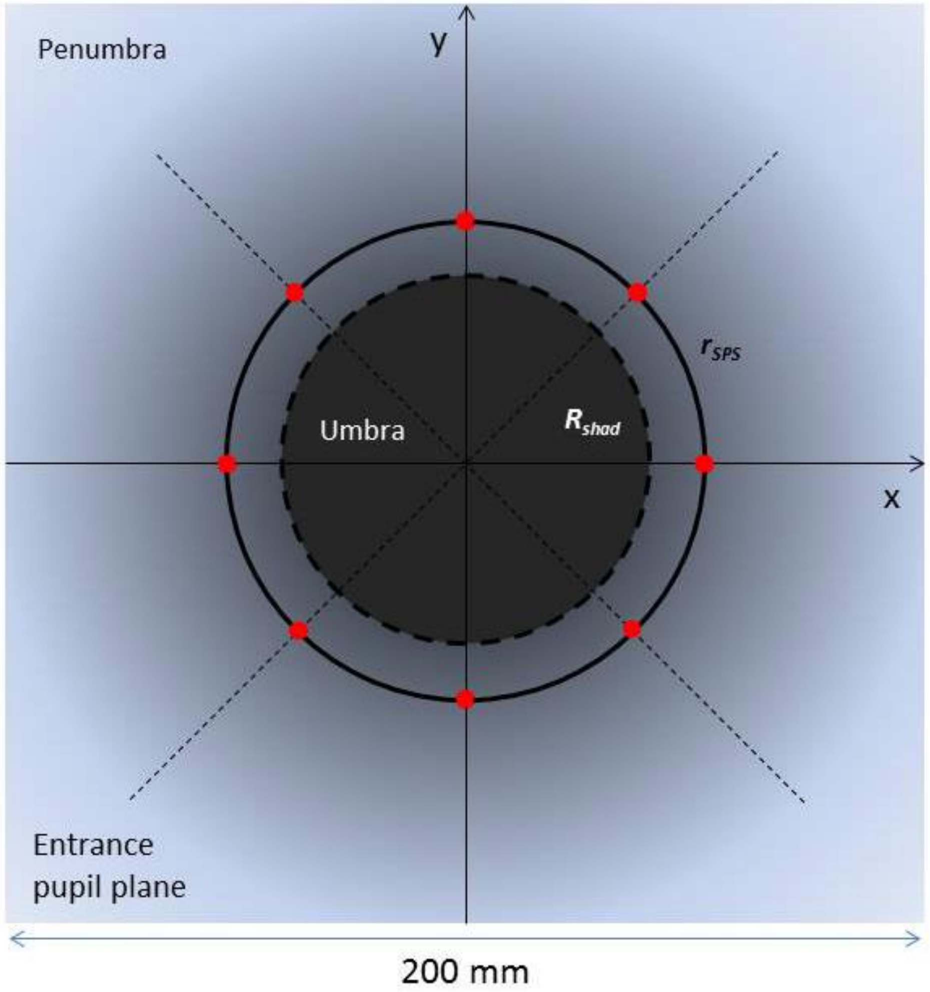


- 8 photo-diodes mounted close to the instrument aperture, along 2 concentric circles
- A lateral or longitudinal position error of the formation means a displacement of the diodes within the umbra and penumbra regions created by the occulter disk
- The variation of light intensity on the diodes is processed to estimate the displacement with great accuracy

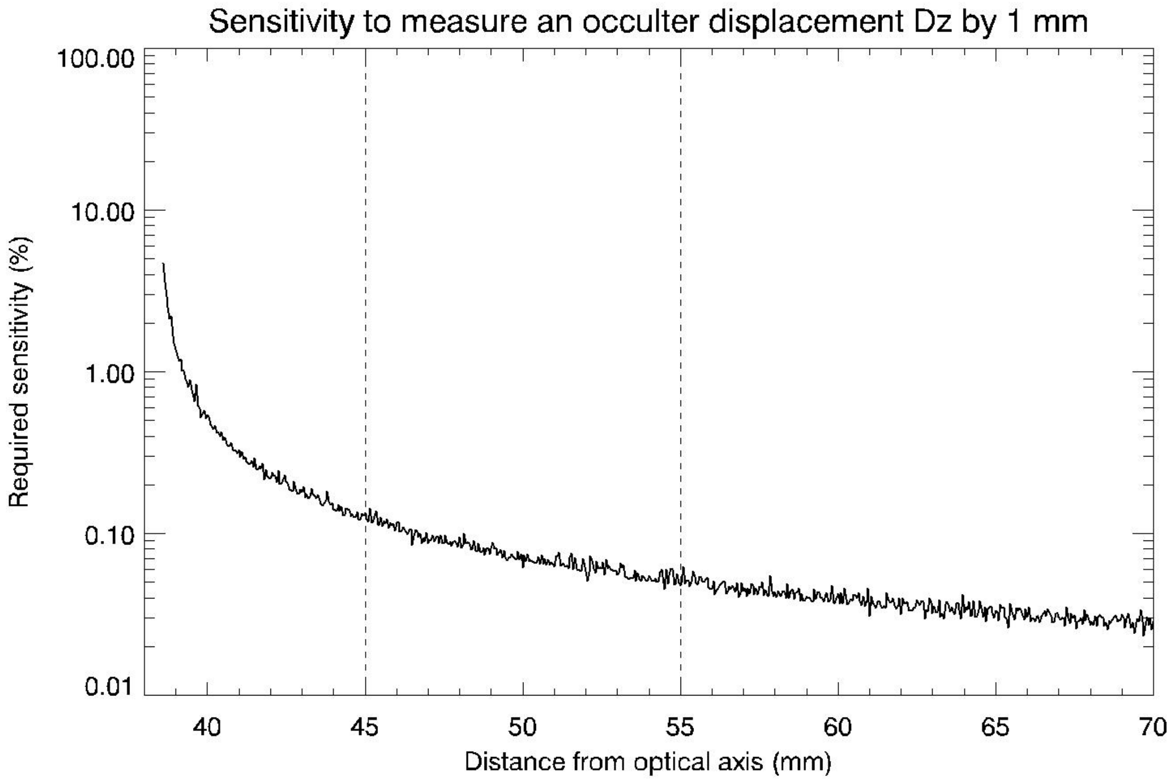


SPS output currents





SPS required sensitvites

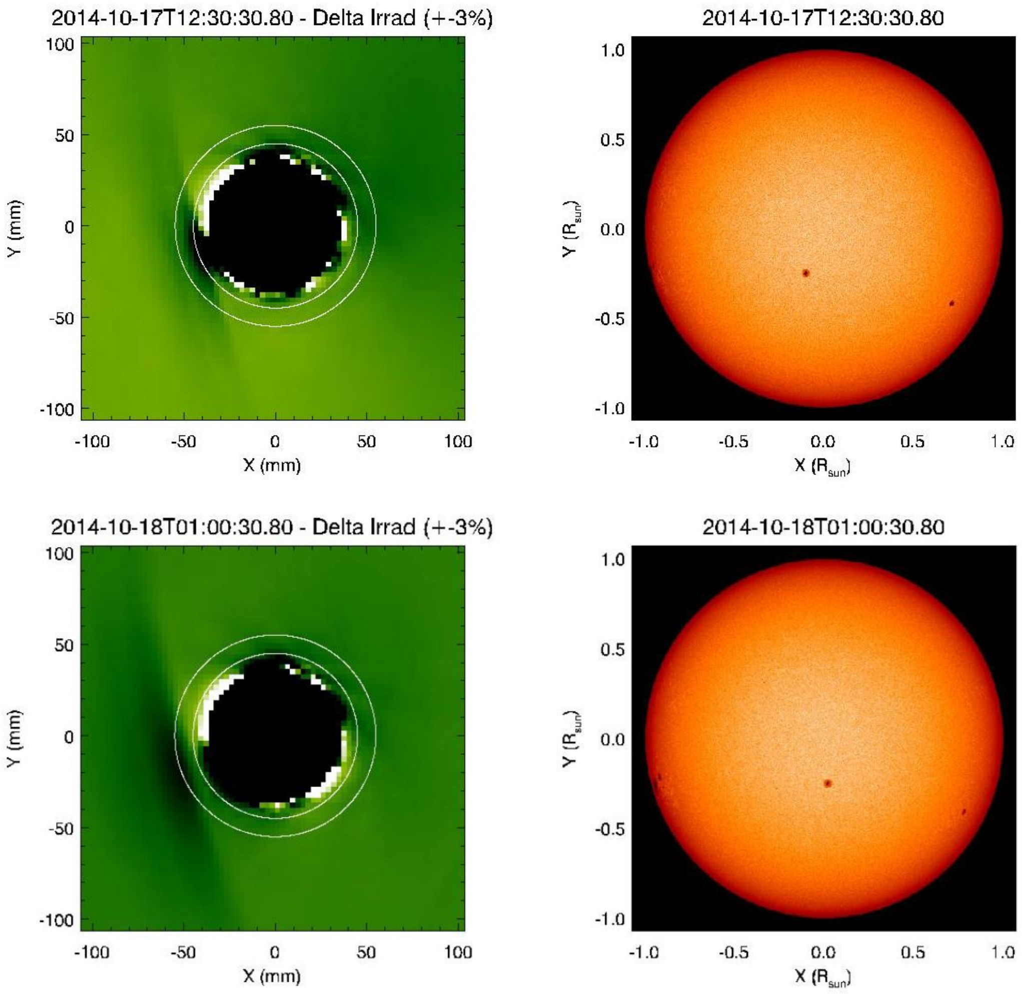


Bemporad (2014)

The required sensitvites to detect the minimum lateral displacement in agreement with performance requirements is 0.45% ~0.5% with SPSs at 55 mm (the minimum required sensitvity decreases going farther from the optcal axis because the slope of the current curve increases much slower than the absolute value of the current to measure);

The required sensitvity to detect the minimum longitudinal displacement in agreement with performance requirements is 0.048% ~0.05% for SPSs at 55 mm.

Effects due to sunspots

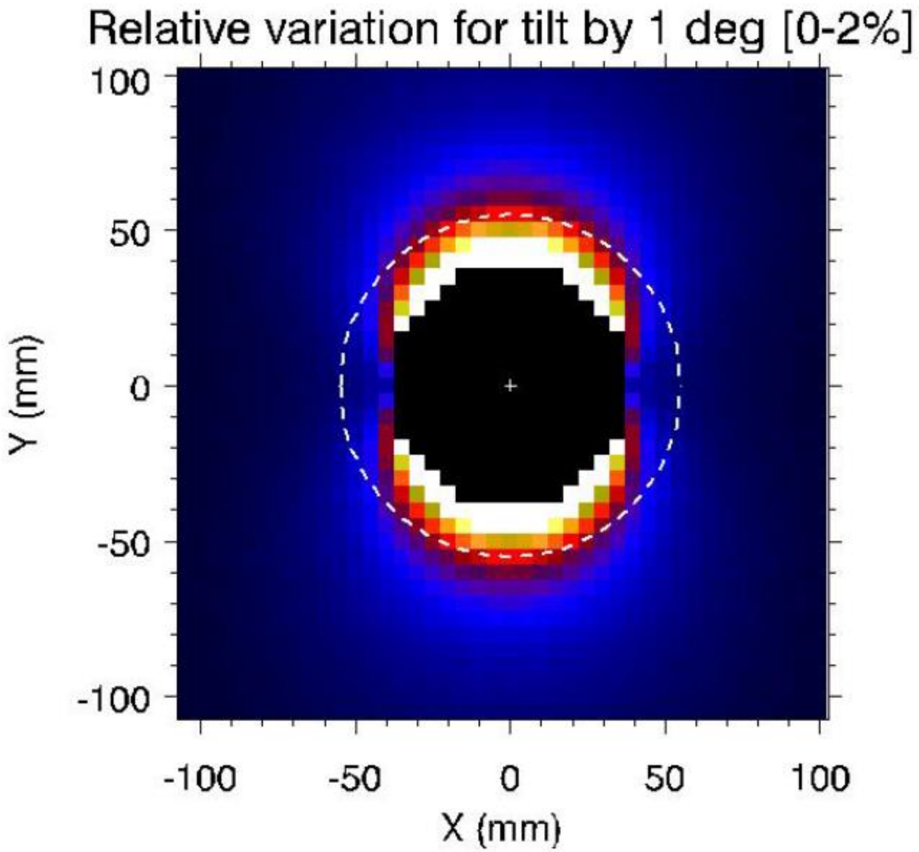


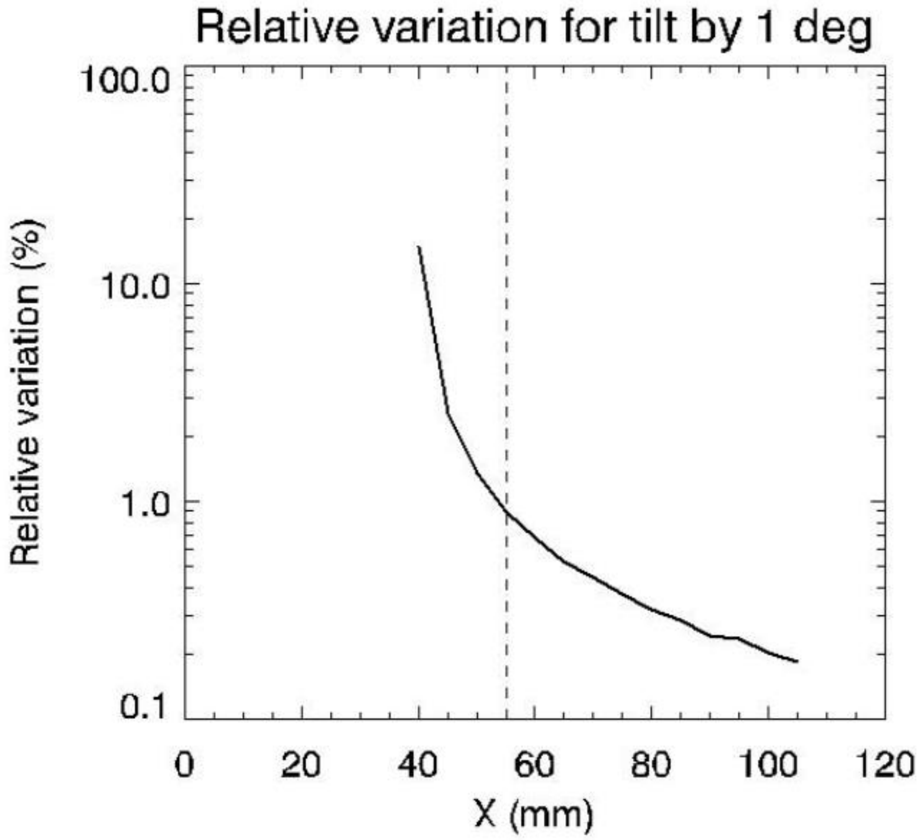
Bemporad (2014)

At these high levels of accuracy required, even the appearance of a sunspot at the limb of the Sun will be important, because will modify locally the penumbra illuminaton by up to ~3%.

The Figures show an example (based on real SDO/HMI data) of the relative variaton of the penumbra distributon during a sunspot appearance with respect to the pre-sunspot distributon.

Effects due to EO tilt

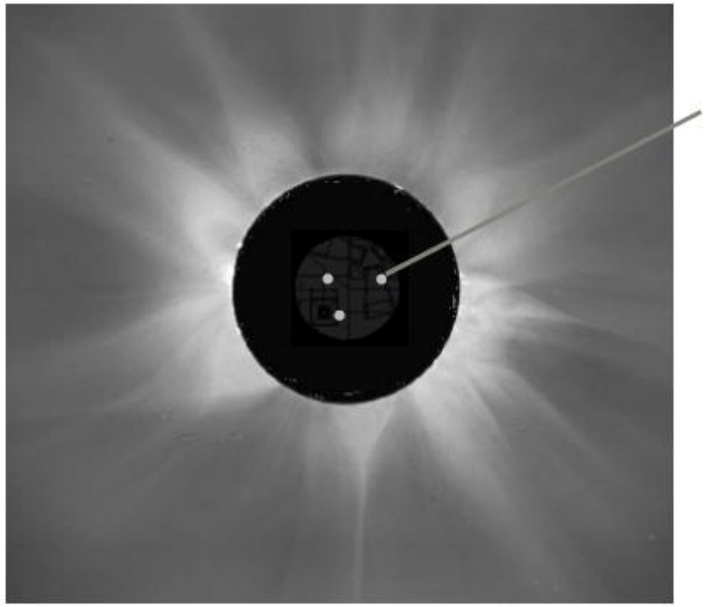




Bemporad (2014)

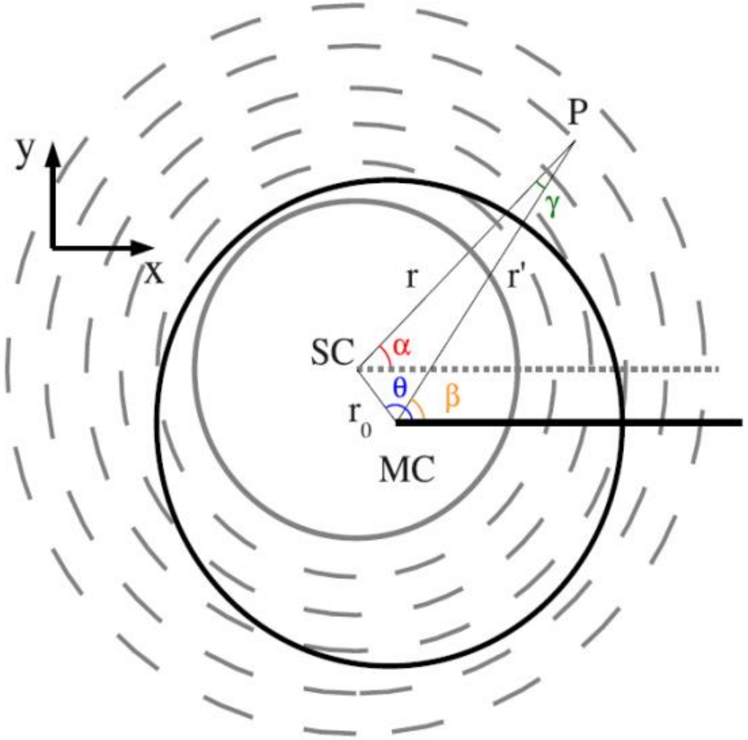
Occulter Position Sensor

- 3 LEDS mounted on the occulter disk
- Imaged by the instrument during Corona observation
- Downlinked to ground with the rest of the image to perform post processing and verify the lateral position of the occulter with respect to the Coronagraph

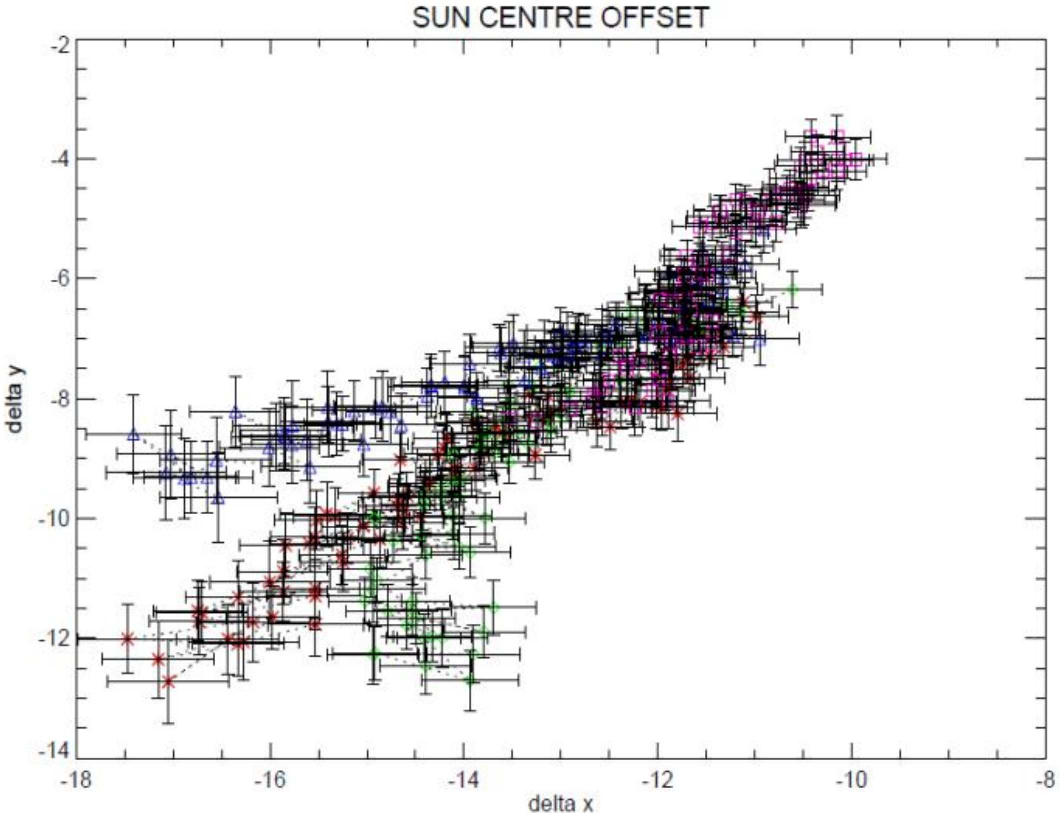


OPSE images on the detector

Centering the Sun-disk using the K-Corona Polarization

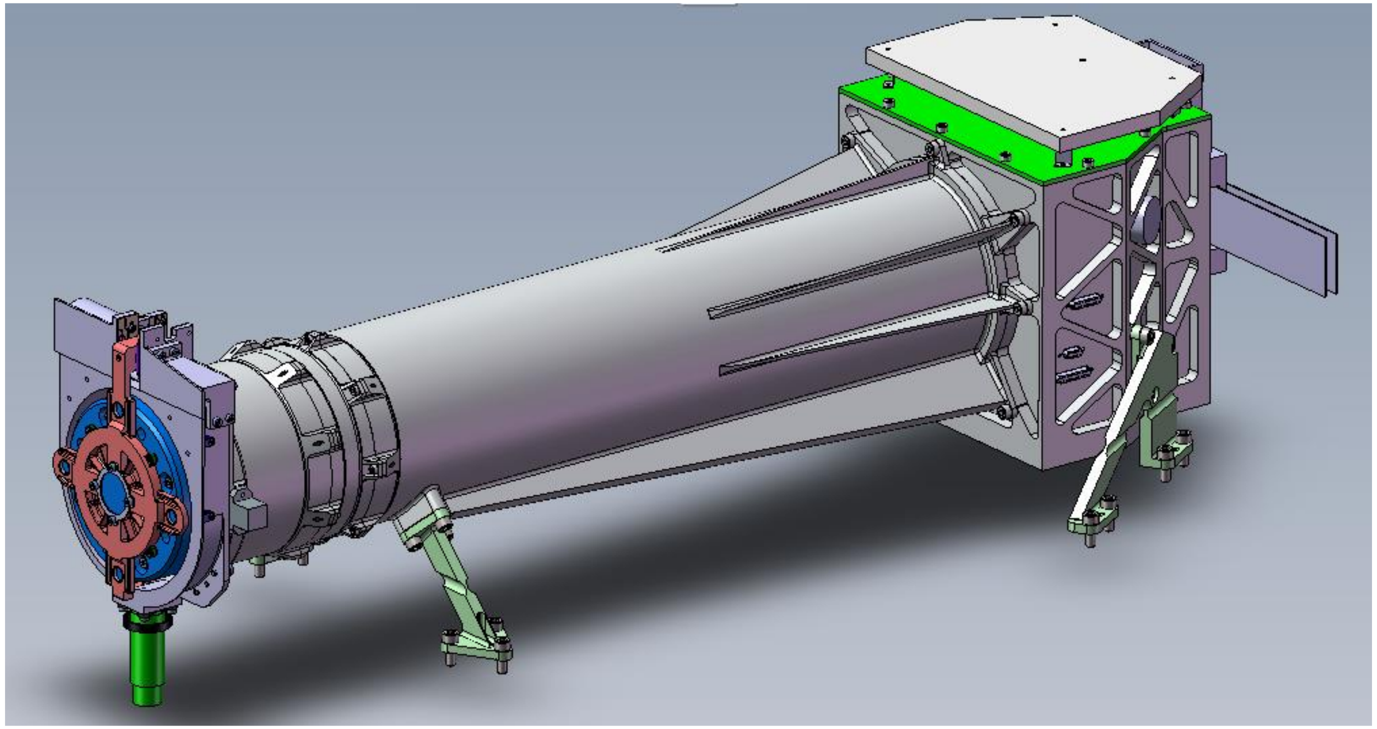


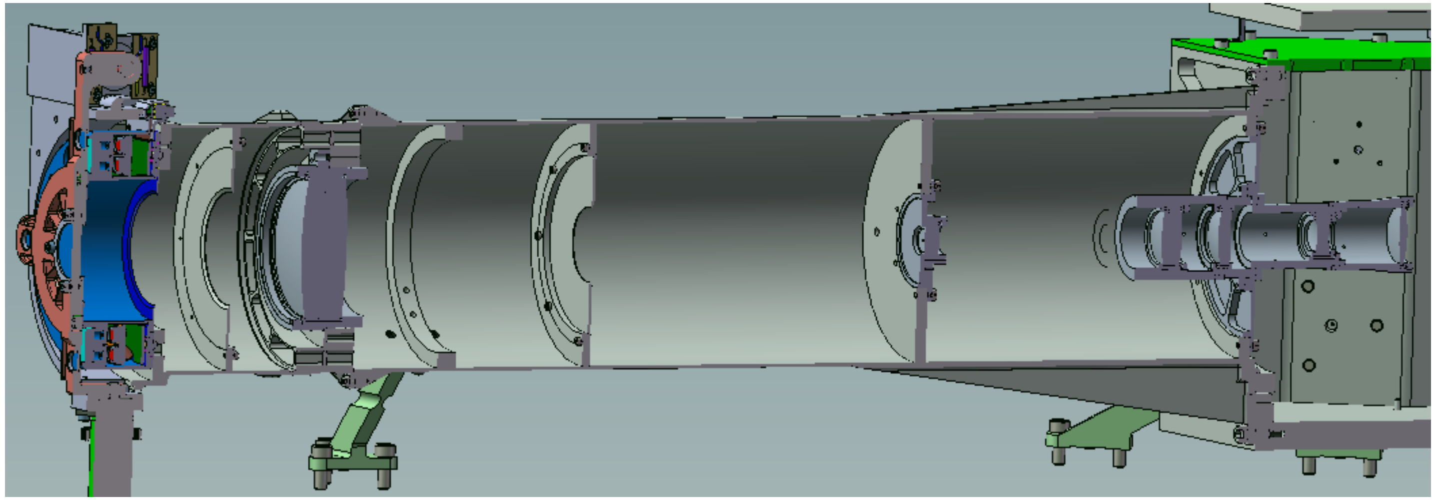
2006 Eclipse K-Corona Polarizaton



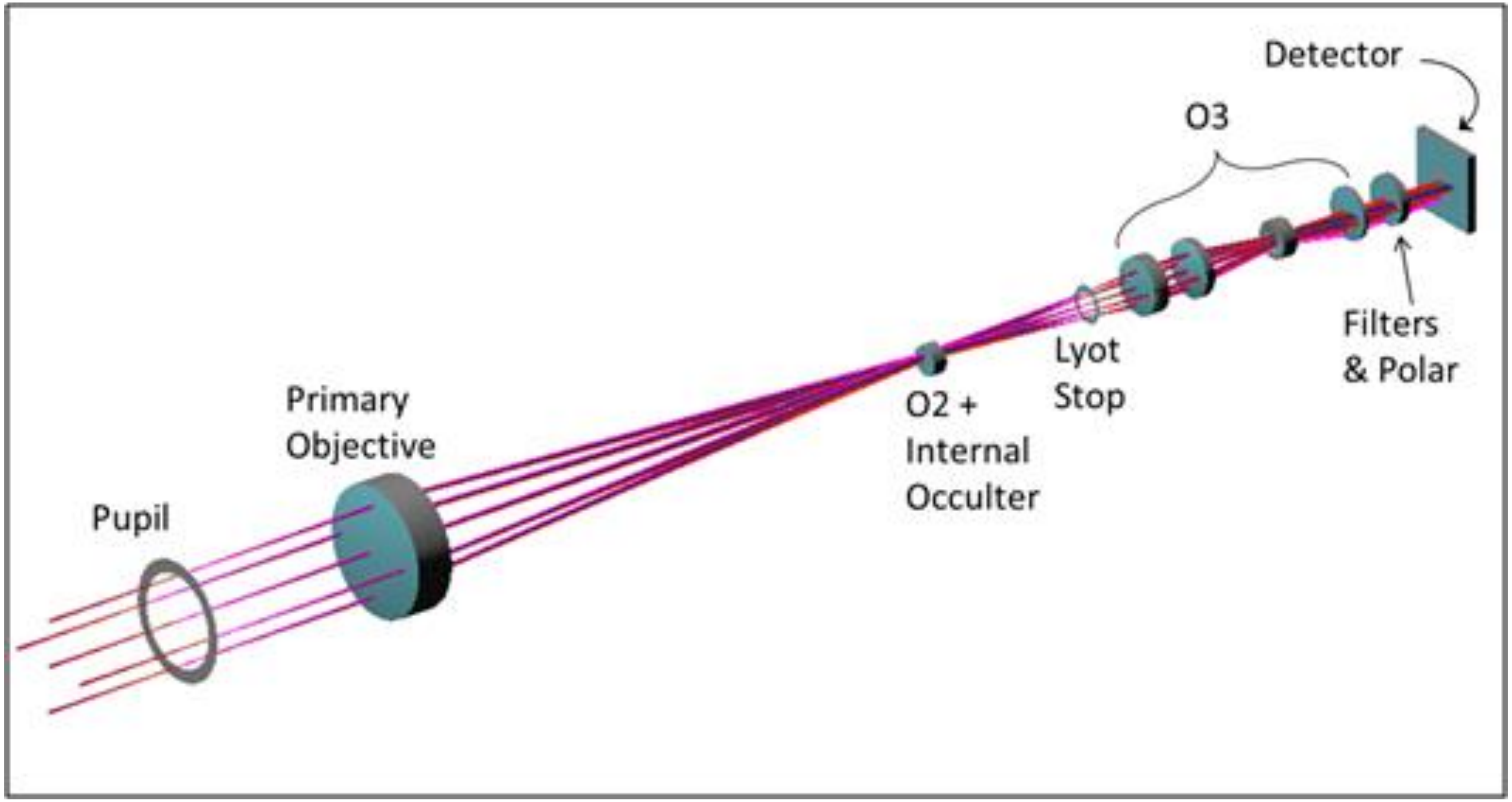
Silvano FINESCHI

COB Design





Optical Design



Straylight

The light from the solar disk is mostly blocked by the external occulter, but a small part of it is diffracted by the edge of the occulter and reaches the entrance pupil.

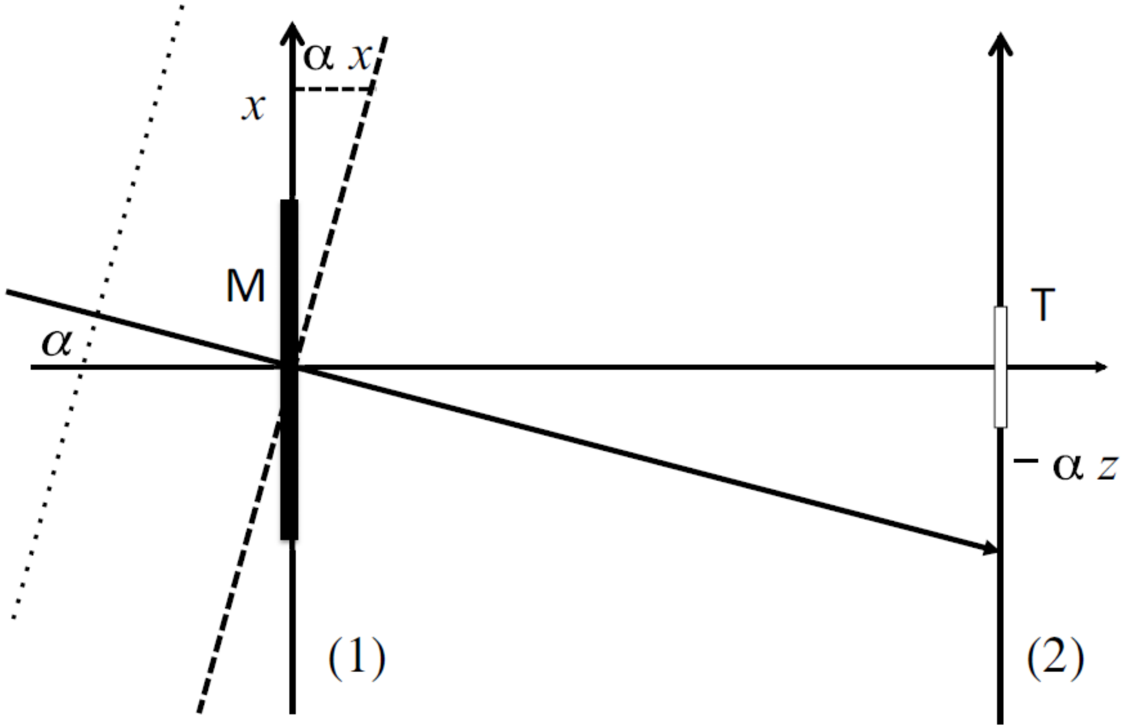
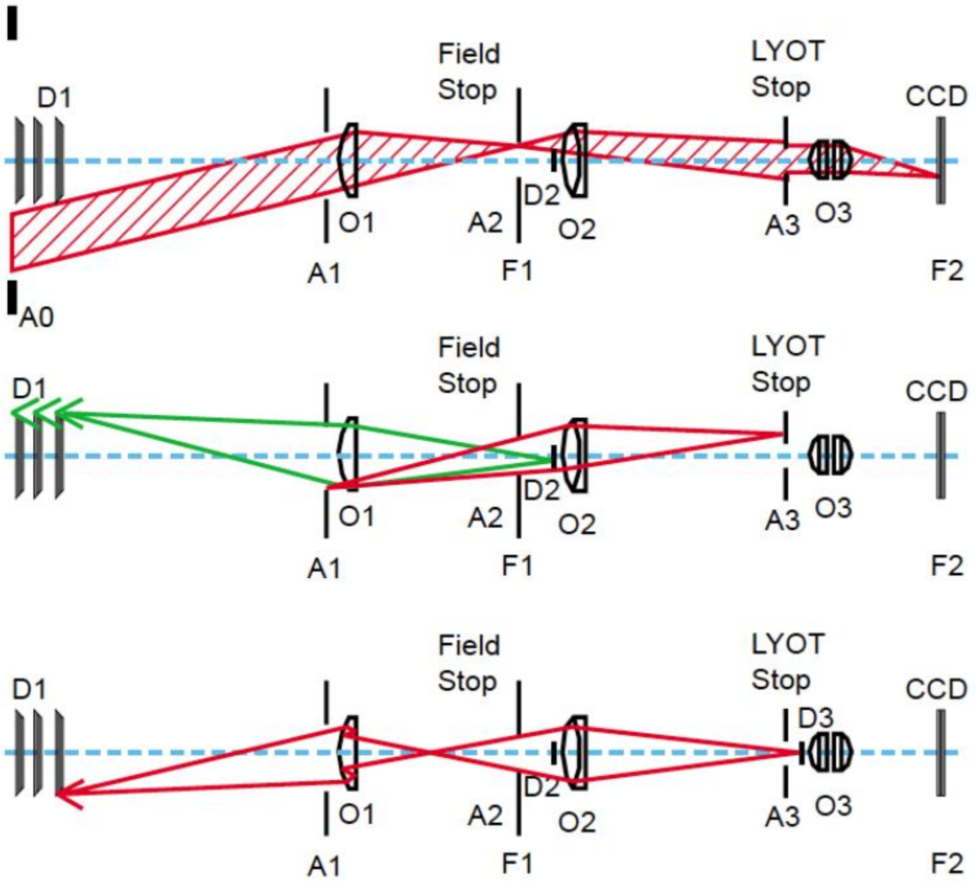


Fig. 1. Solar light coming from the (α,β) direction produces a tilted plane wave of equation $\exp(-2i\pi(\alpha x + \beta y)/\lambda)$ on the occulter M (plane 1). The Fresnel diffraction pattern is computed at the telescope aperture T, which is set at the distance z from the occulter (plane 2). The representation is a cut of the xOz plane.

Aime (2013)

Straylight blocking in externally occulted coronagraphs

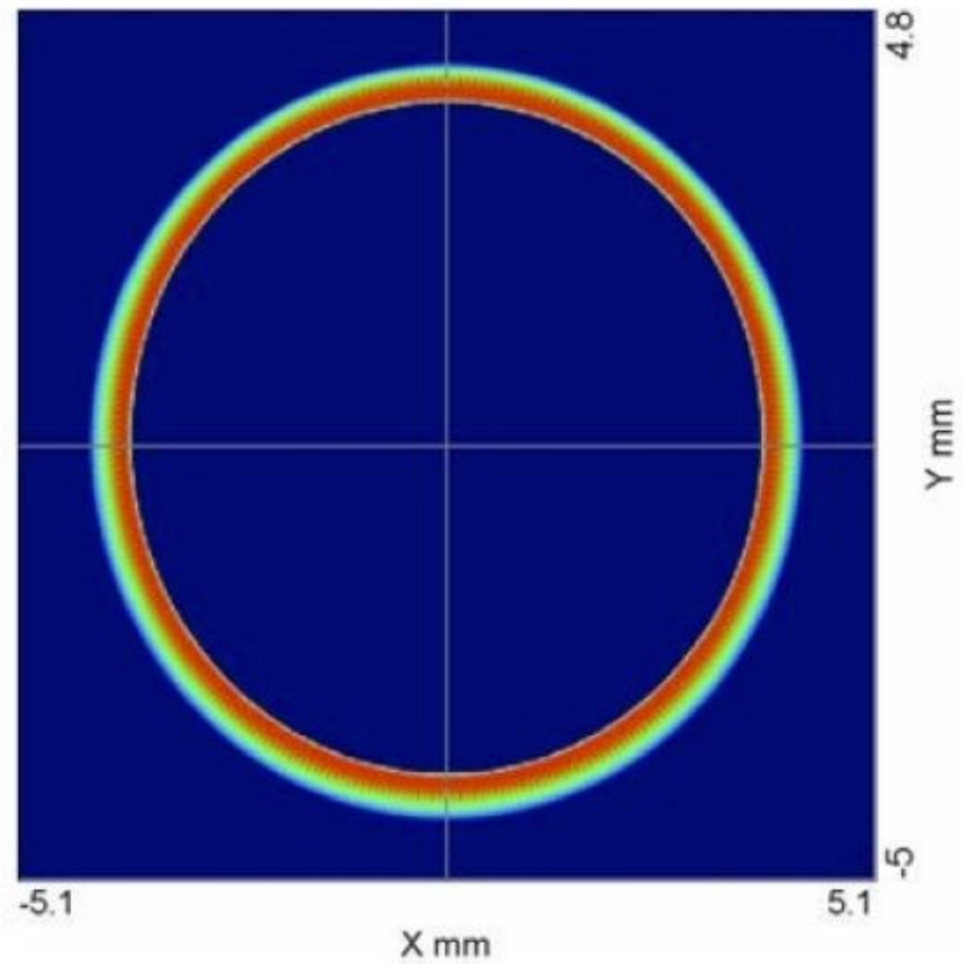


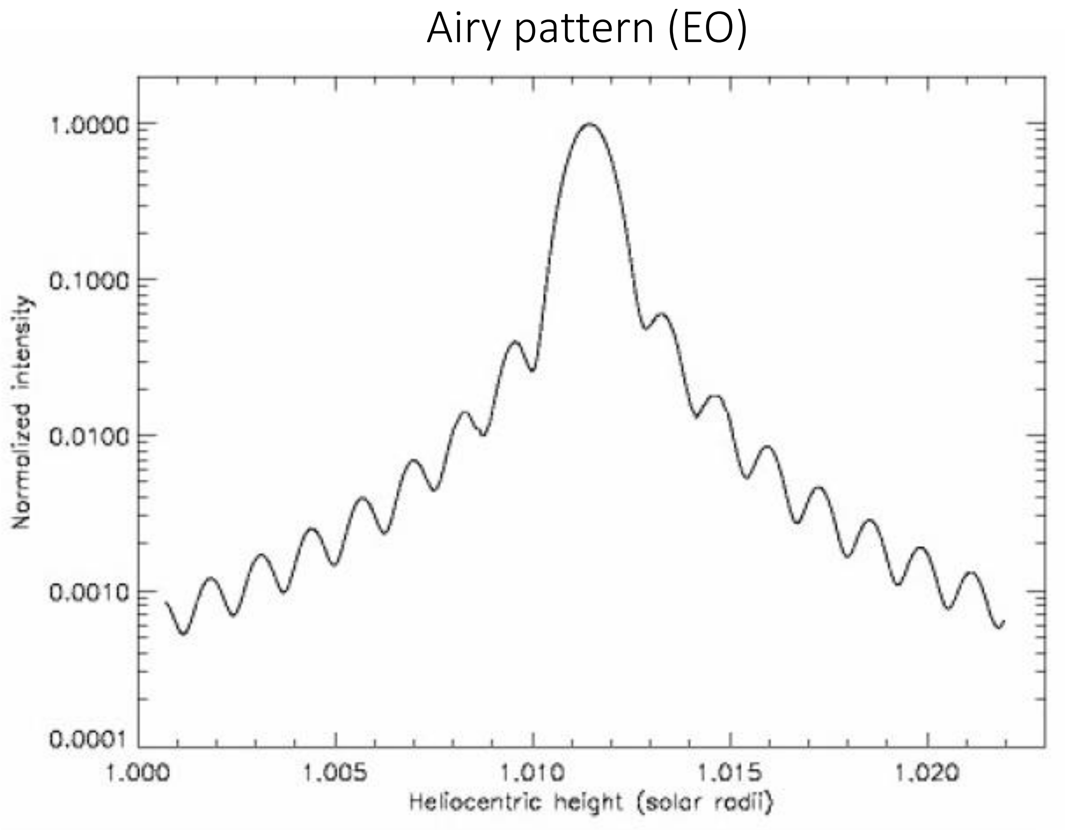
A0, front aperture
A1, entrance aperture
A2, field stop
A3, Lyot stop
D1, external occulter
D2, internal occulter
D3, Lyot spot

F1, primary focal plane
F2, secondary focal plane
O1, objective lens
O2, field lens
O3, relay lens

Howard et al. (2000)

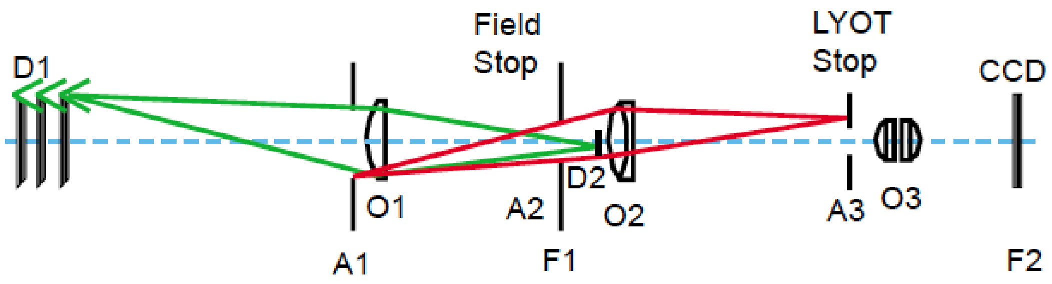
Diffraction Pattern





Landini et al. (2010)

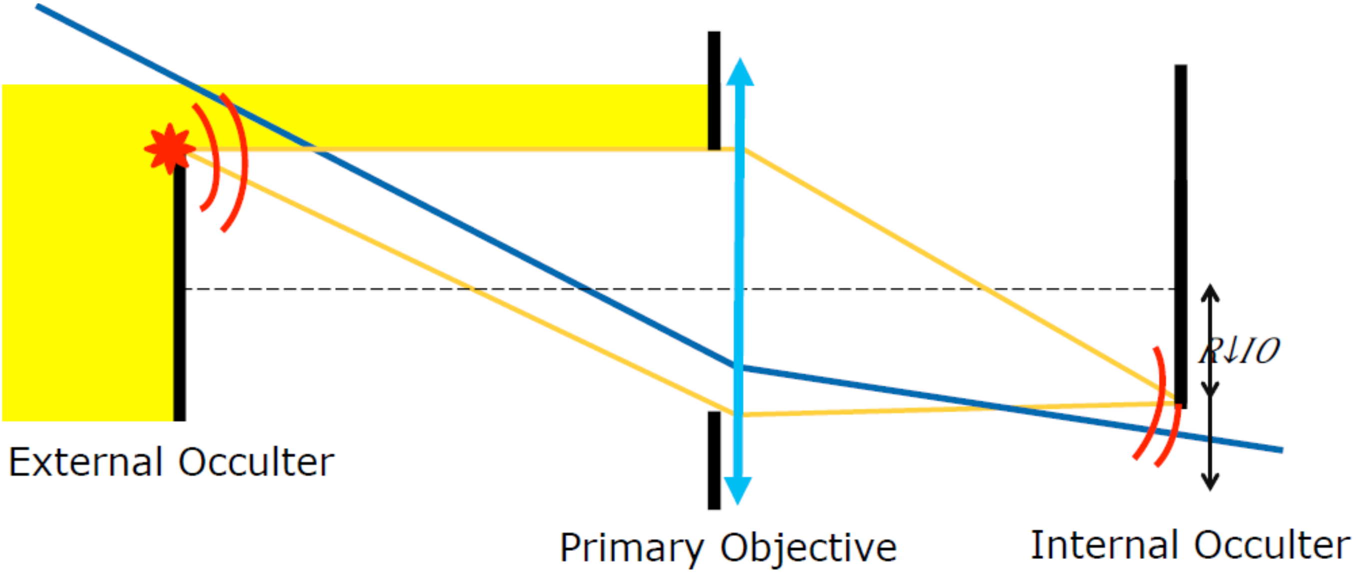
Lyot stop and internal occulter



Howard et al. (2000)

- The light diffracted at the external occulter edge is further diffracted by the entrance pupil and isfocused at the internal occulter.
- The internal occulter should block the image of the external occulter and several diffraction fringes,
- The size of the internal occulter determines the lower edge of the field of view and is therefore critical.
- Note that we cannot extend the ASPIICS field of view to lower heights by moving the external occulter further away from the telescope!

Diffraction and over-occultation



The internal occulter must be made larger. But then vignettes the Corona light!
Over-occultation: compromise between vignetting and stray light rejection

Example on LASCO C2

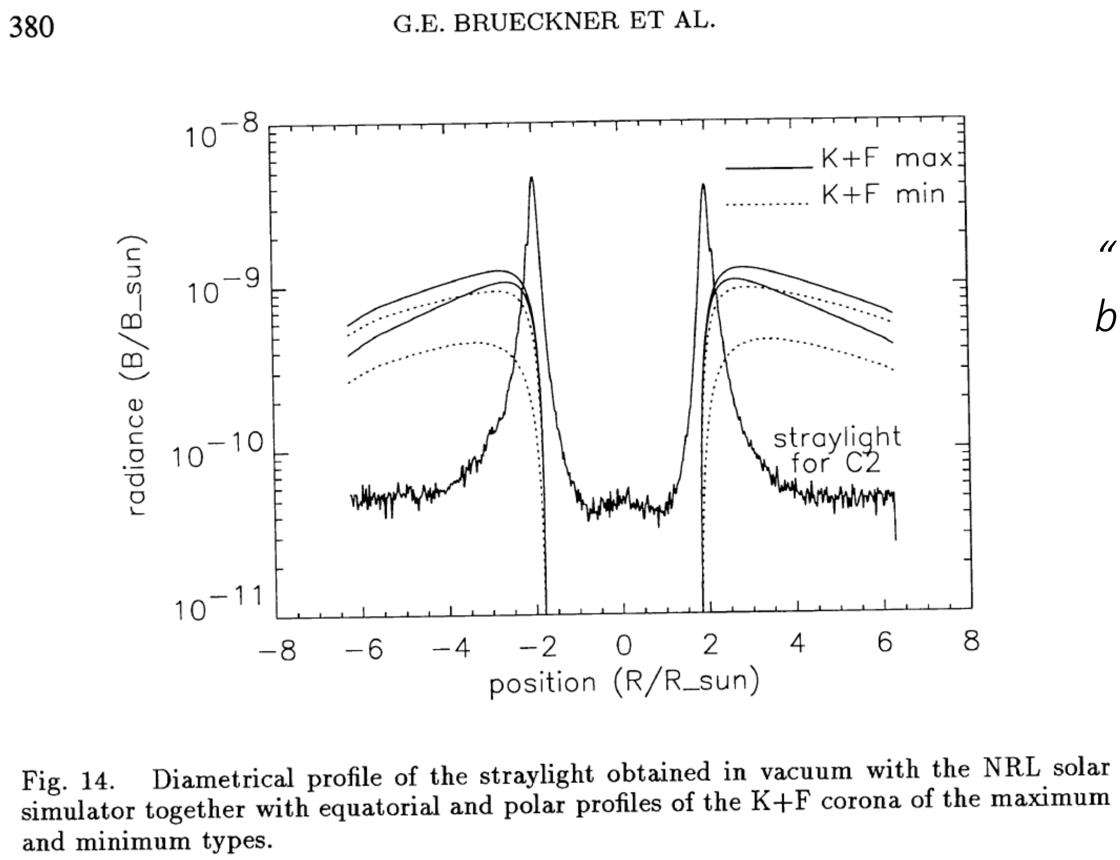


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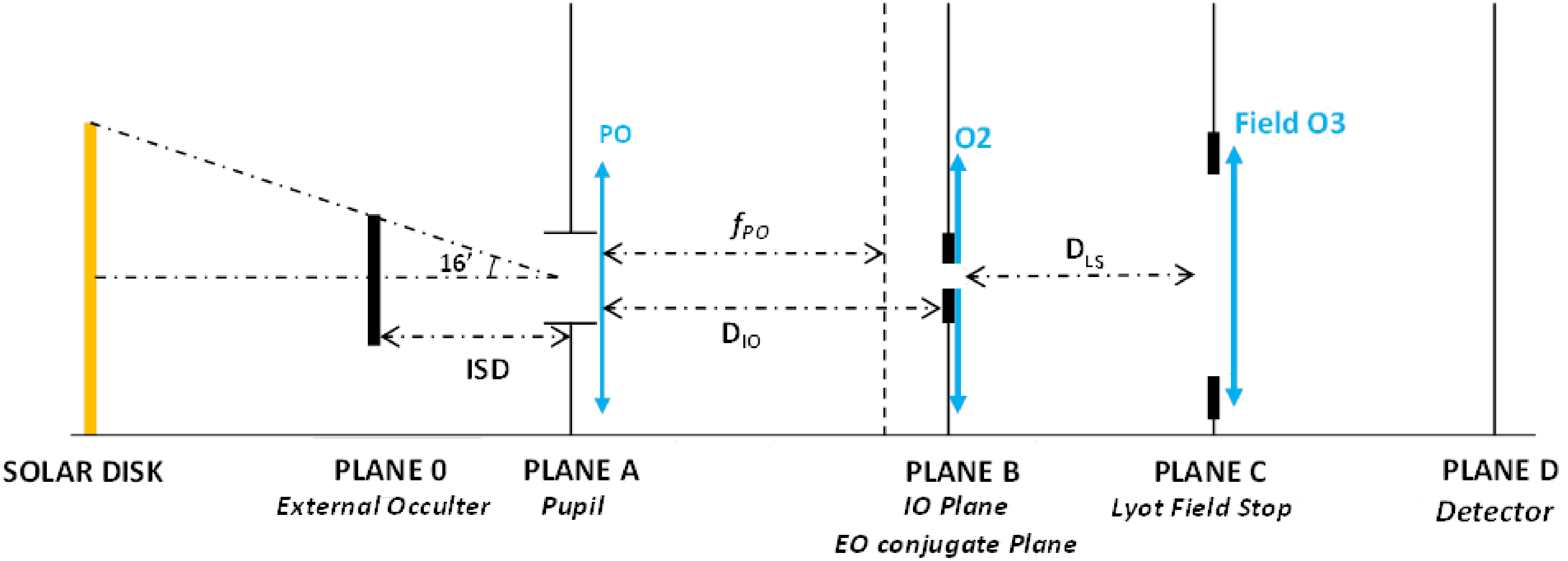
Fig. 14. Diametrical profile of the straylight obtained in vacuum with the NRL solar simulator together with equatorial and polar profiles of the K+F corona of the maximum and minimum types.

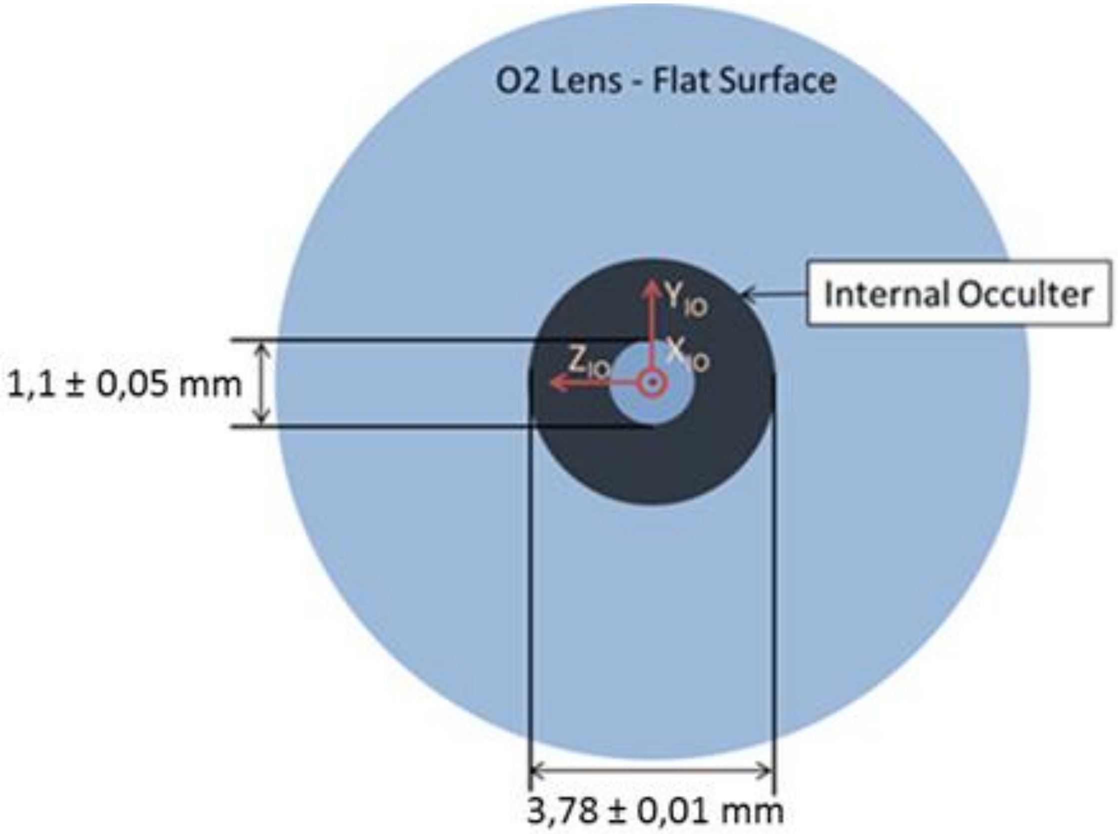
“ The over-occultation of 10% results from a compromise between stray light rejection […] and vignetting […] “

Brueckner et al. (1995)

Model design for ASPIICS

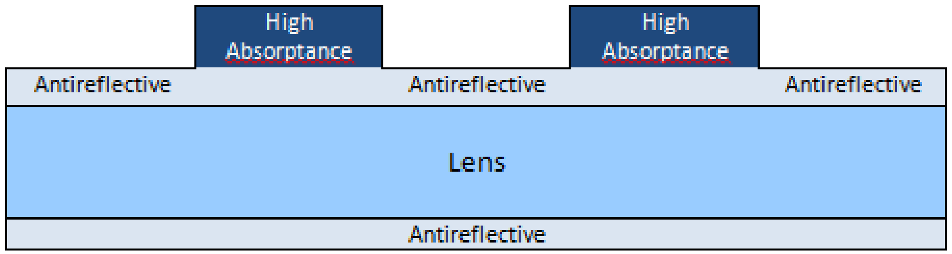


Optical Design - IO

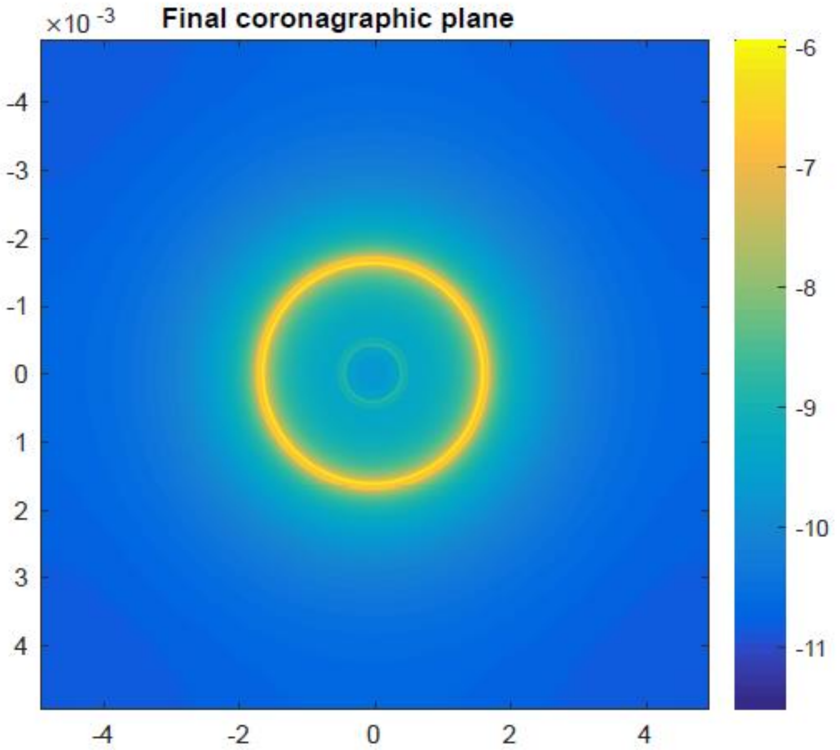


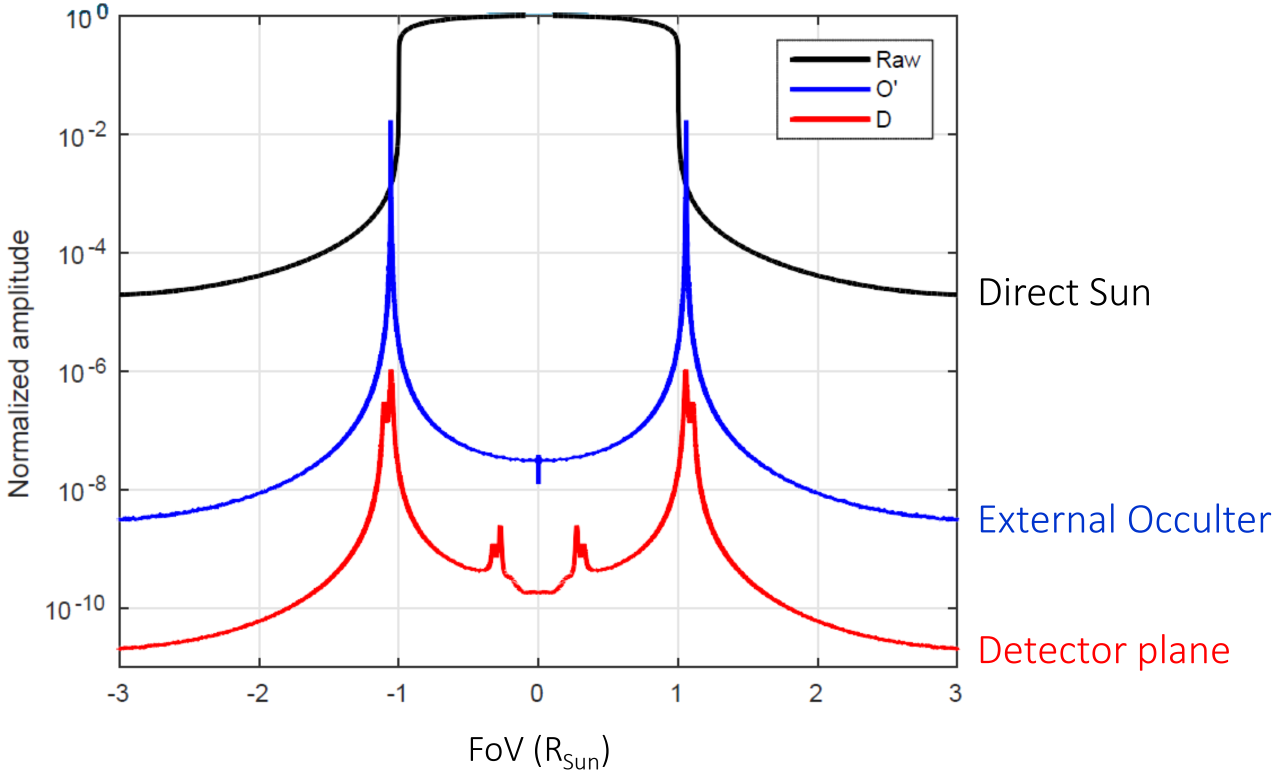
The IO is designed to block the diffraction produced by the edge of the EO.

Coating on the O2 Lens, with a central hole so that images of the OPSE CI can acquired.

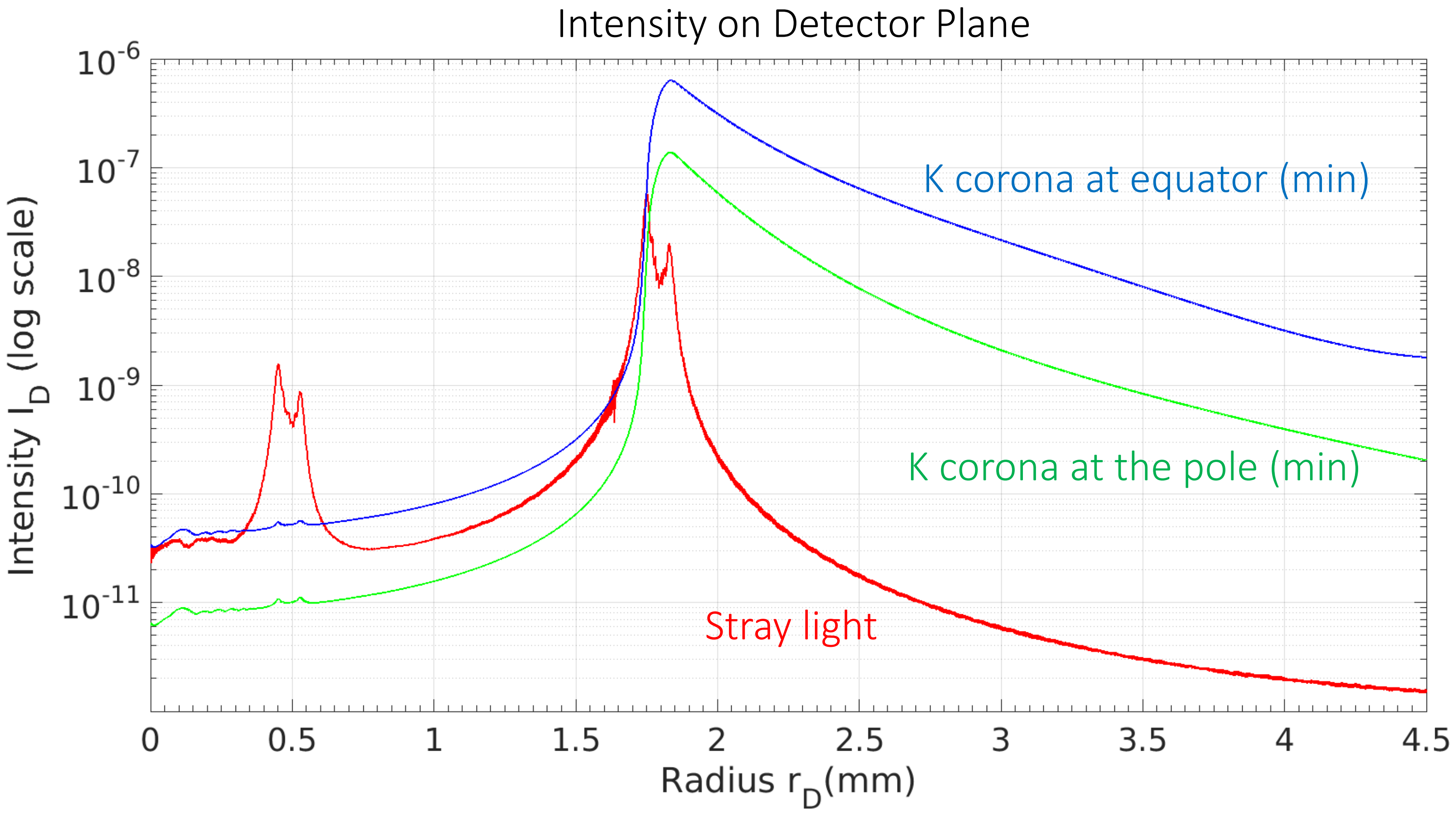


ASPIICS performance

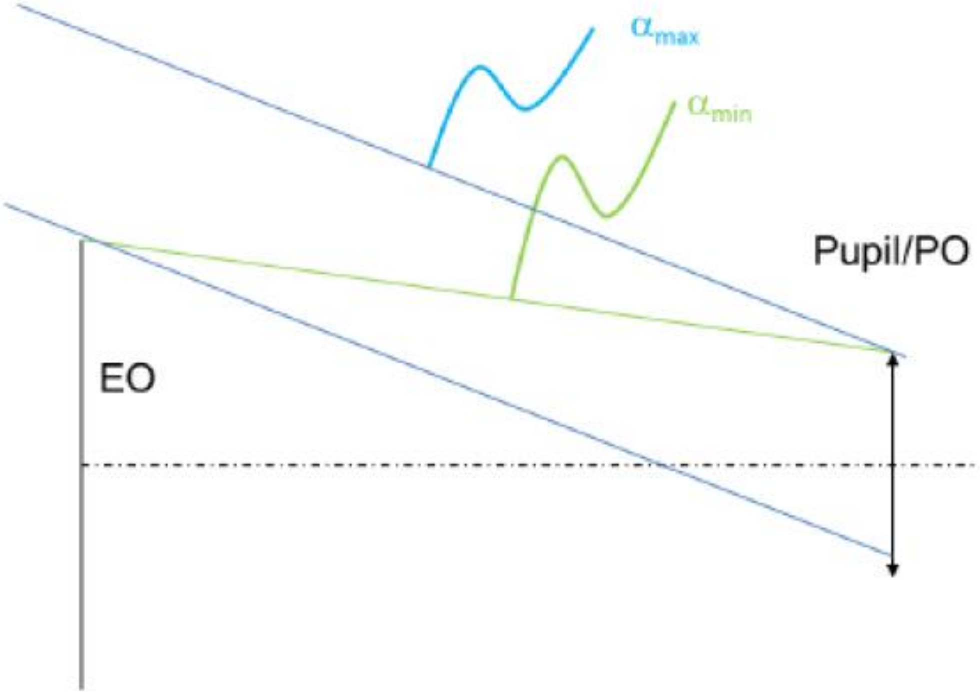




ASPIICS performance



Vignetting



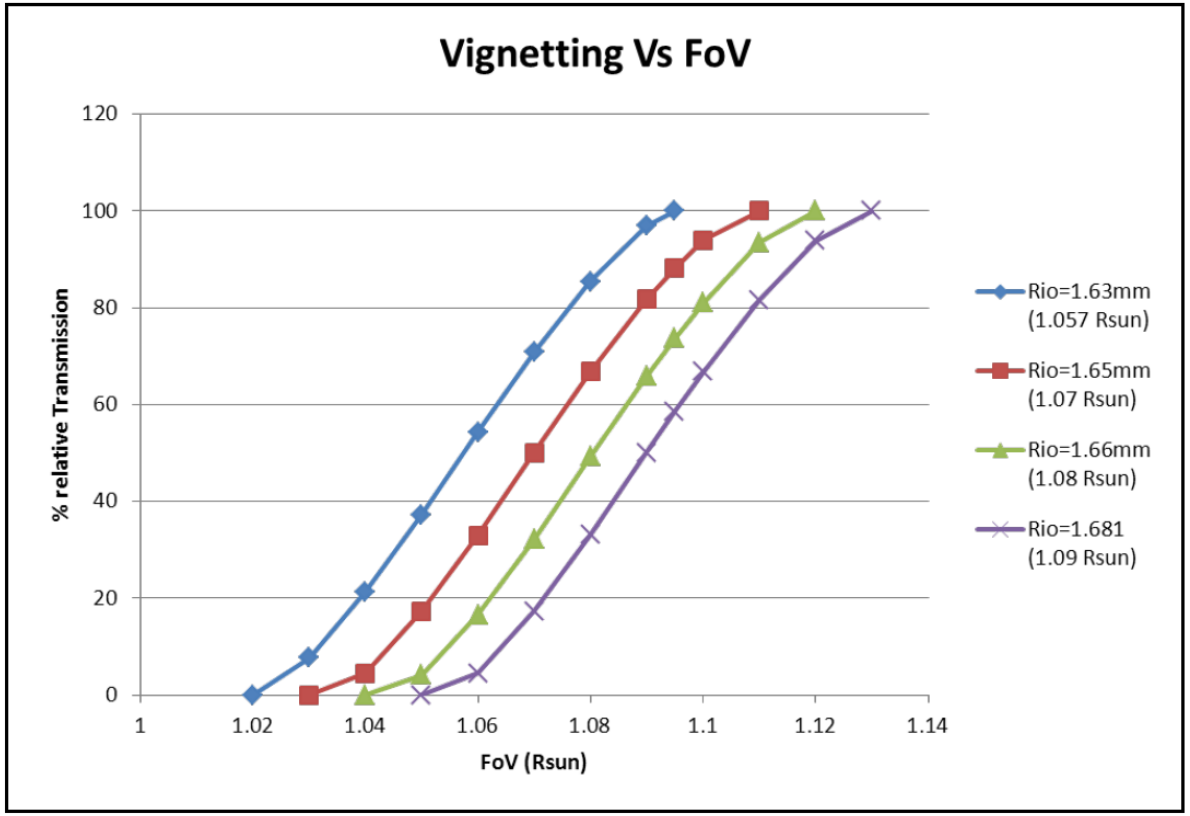
- The external occulter vignettes the pupil between 1.02 R_s and 1.095 R_s.
- The minimum dimension of the internal occulter is when its size equals to the size of the conjugate image of the external occulter. In this configuration, the internal occulter radius shall be R_{io} = 1.631 mm, corresponding to an angular dimension of 1014.6 arcsec (equivalent to 1.057 Rs).

Vignetting

Table 4-4 - Evaluation of the minimal observable FoV and minimum FoV without vignetting given different IO sizes

RIo (~RSun)	1.057	1.07	1.08	1.09	1.10
Minimum Observable FoV (100% vignetting)	1.020	1.033	1.043	1.053	1.063
Minimum FoV without vignetting (0%)	1.095	1.107	1.117	1.127	1.137

Vignetting is also produced by the internal occulter.

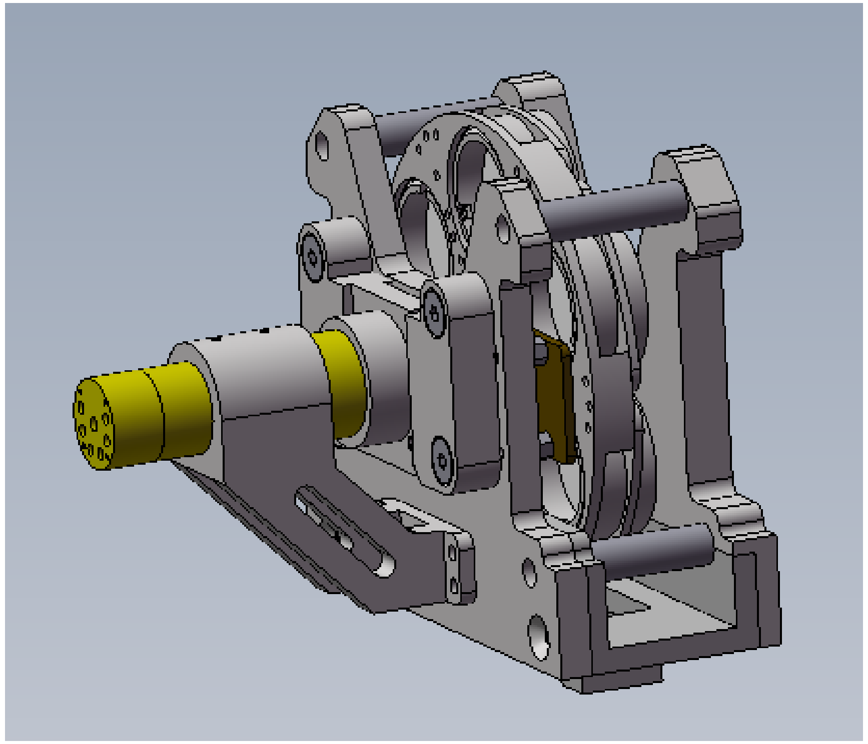


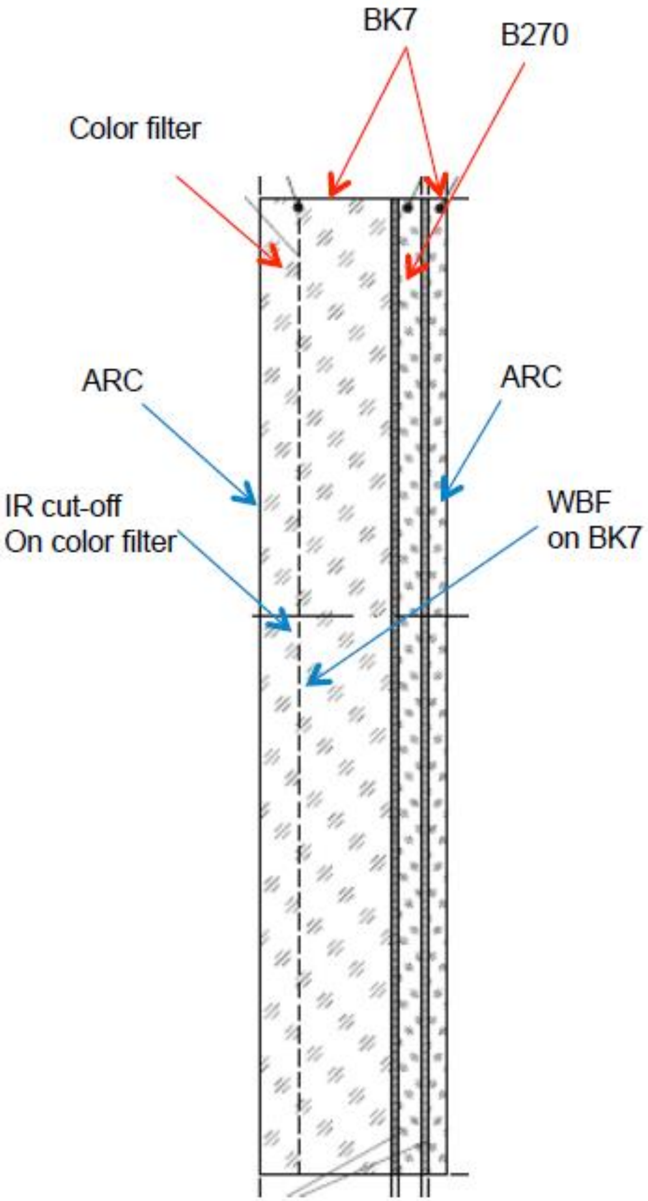
(ASPIICS optical design, Galy et al. 2014)

Filters

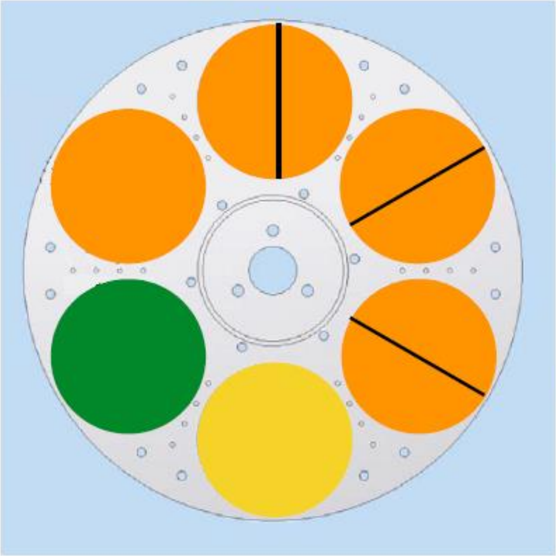
Filters in the FWA:

- WBF [540-570 nm]
- 3 WBF + pola
- NBF Fe XIV at 530.3 nm
- NBF He I D3 at 587.6 nm





Passband choice



Orange filter
linear polarizer at 0°

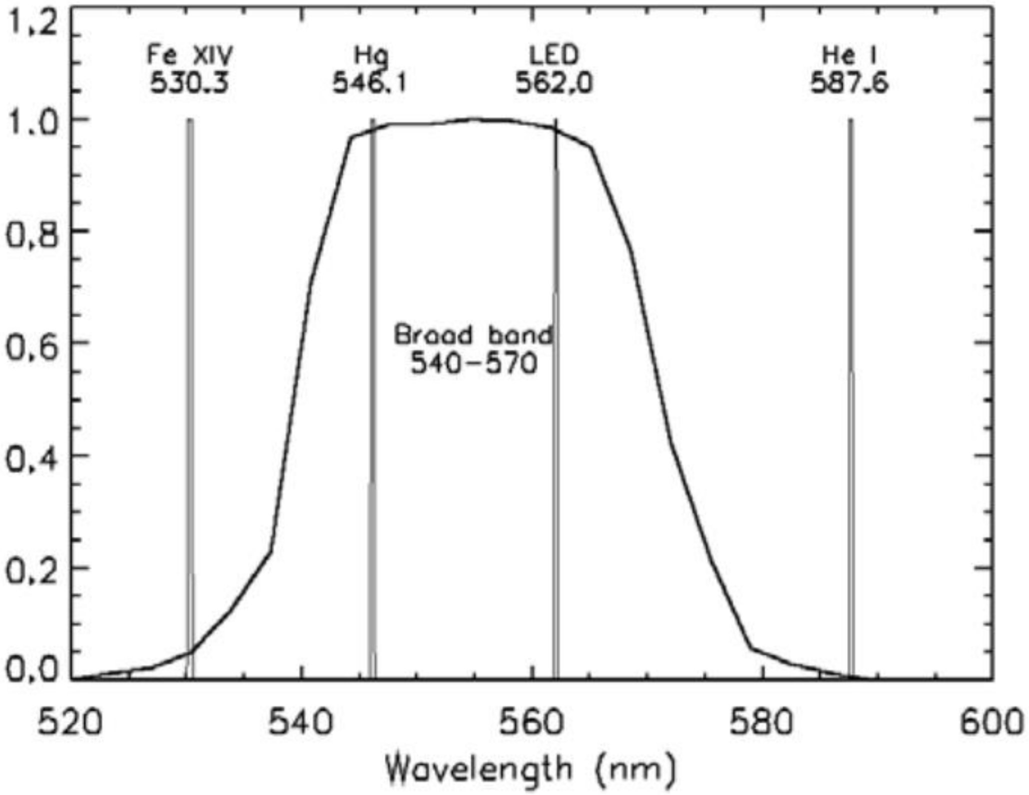
Orange filter
5400 - 5700 Å

Orange filter
linear polarizer at +60°

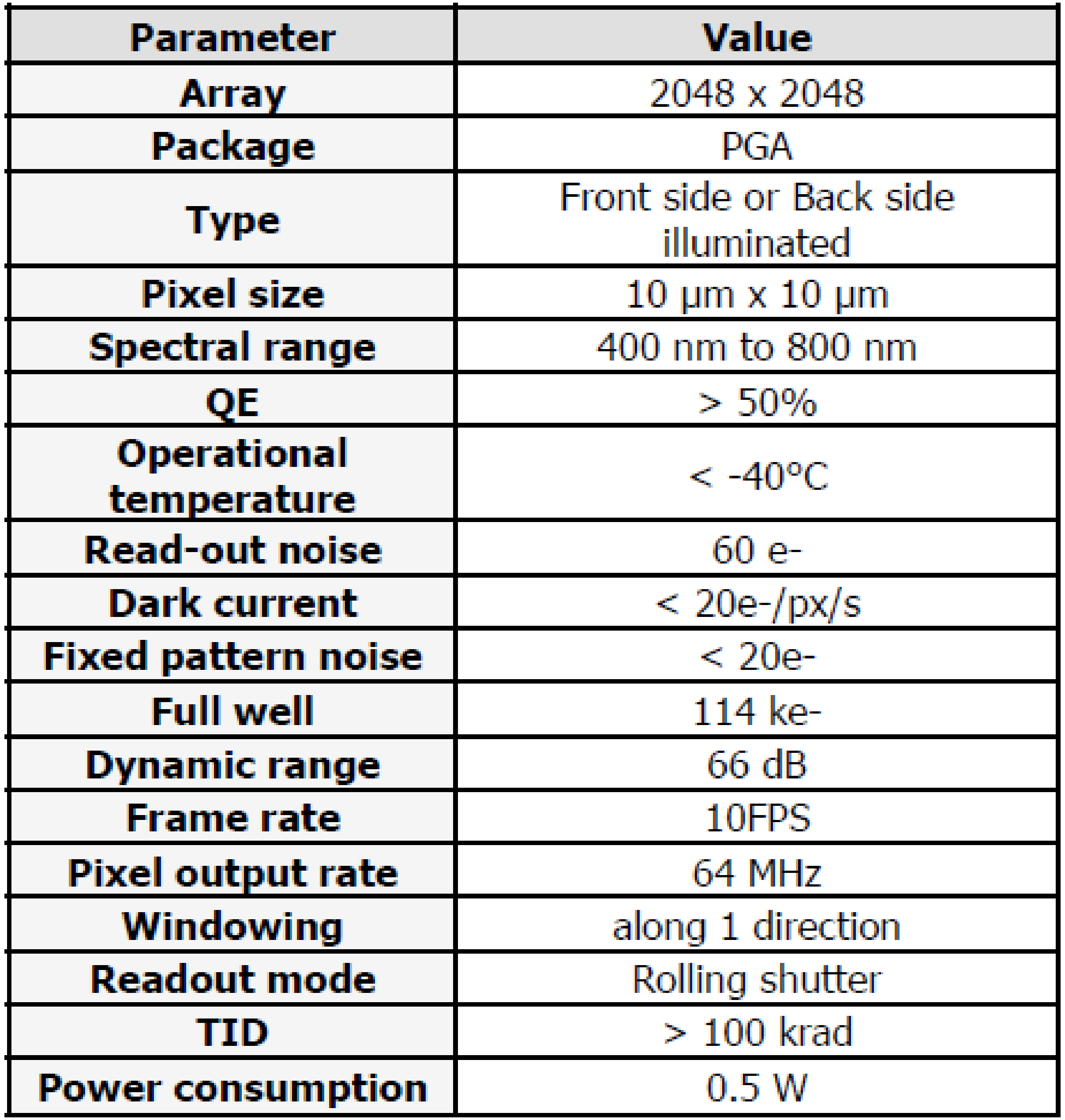
Fe XIV
“green line”
5304.5 Å

Orange filter
linear polarizer at -60°

He I D3 line
5876 Å

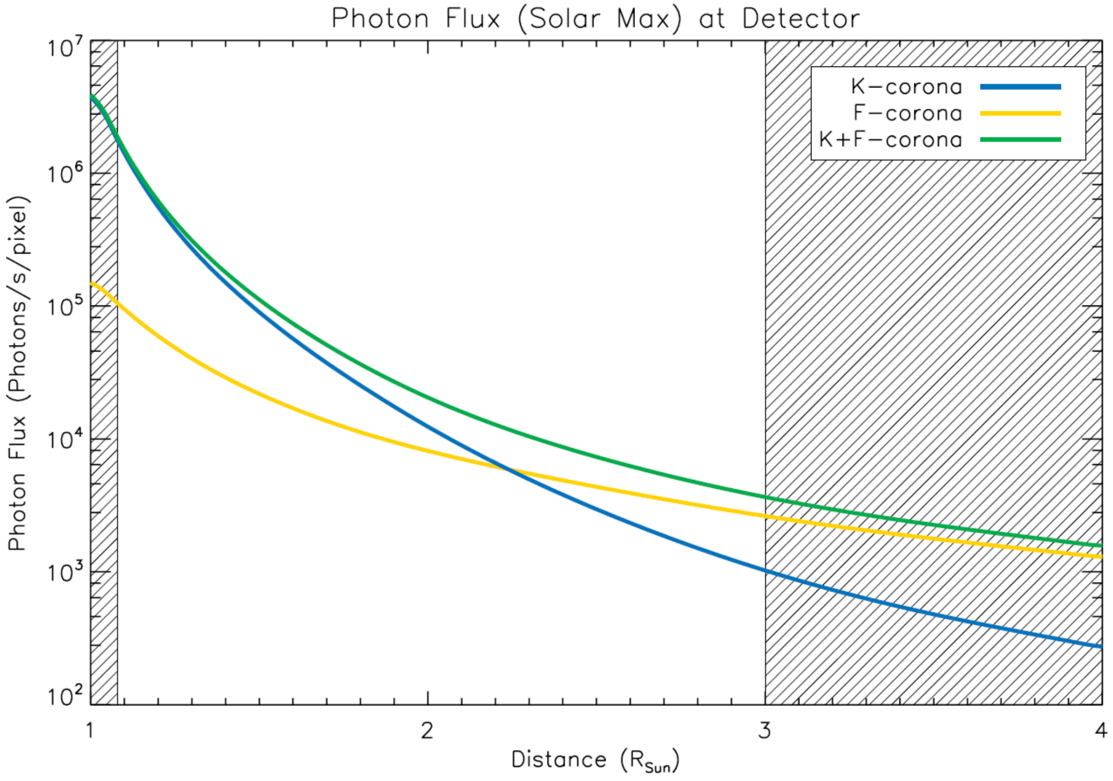


CMOS Detector



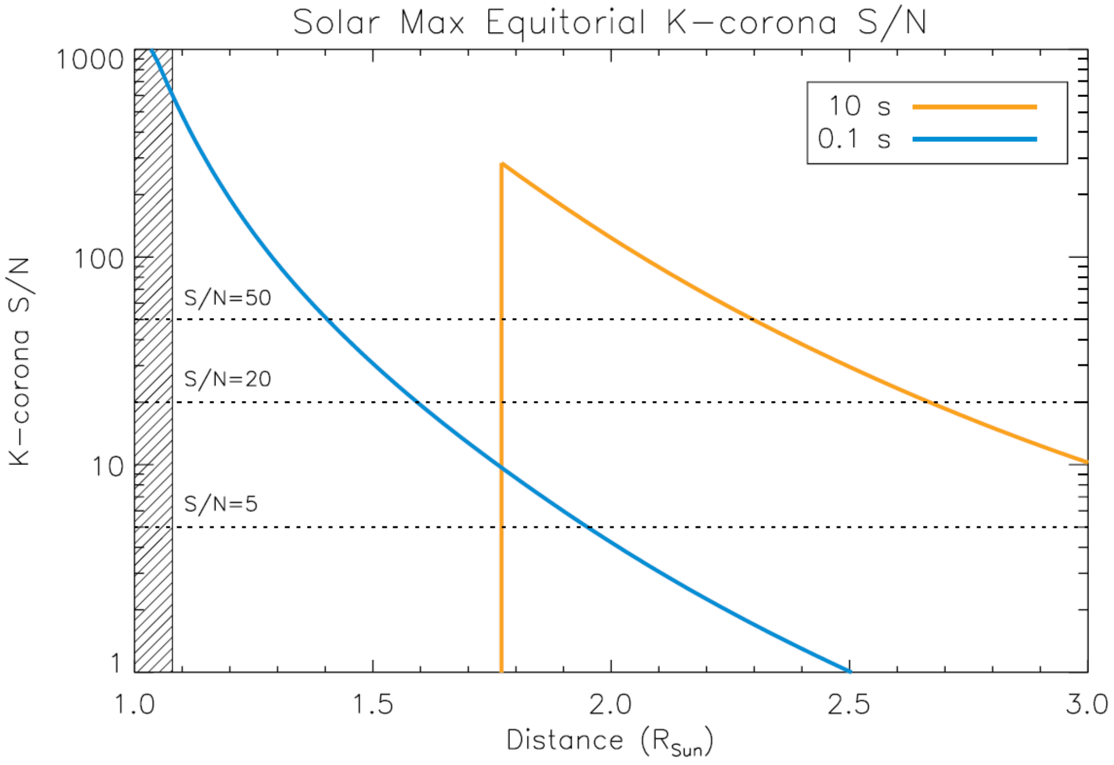
Parameter	Value
Array	2048 x 2048
Package	PGA
Type	Front side or Back side illuminated
Pixel size	10 µm x 10 µm
Spectral range	400 nm to 800 nm
QE	> 50%
Operational temperature	< -40°C
Read-out noise	60 e-
Dark current	< 20e-/px/s
Fixed pattern noise	< 20e-
Full well	114 ke-
Dynamic range	66 dB
Frame rate	10FPS
Pixel output rate	64 MHz
Windowing	along 1 direction
Readout mode	Rolling shutter
TID	> 100 krad
Power consumption	0.5 W

Coronal brightness in the FOV



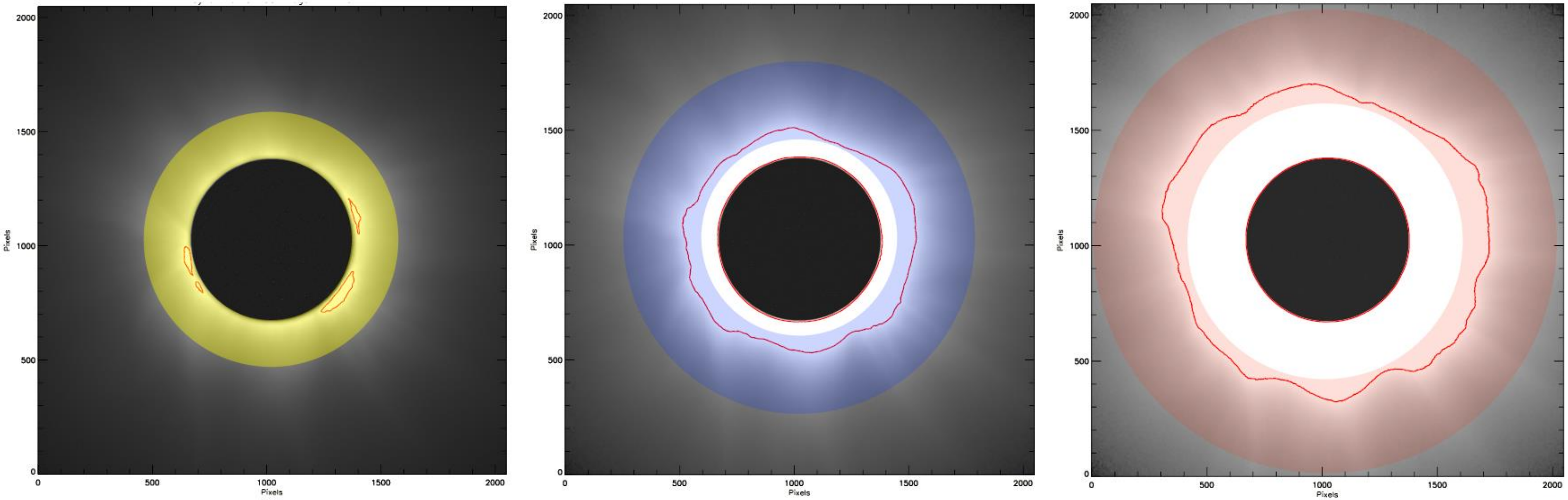
3+ orders of magnitude of total (K+F) brightness

Multiple exposures



Need several exposures for sufficient S/N over the FOV

Multiple exposures



Short exposure

Medium exposure

Long exposure

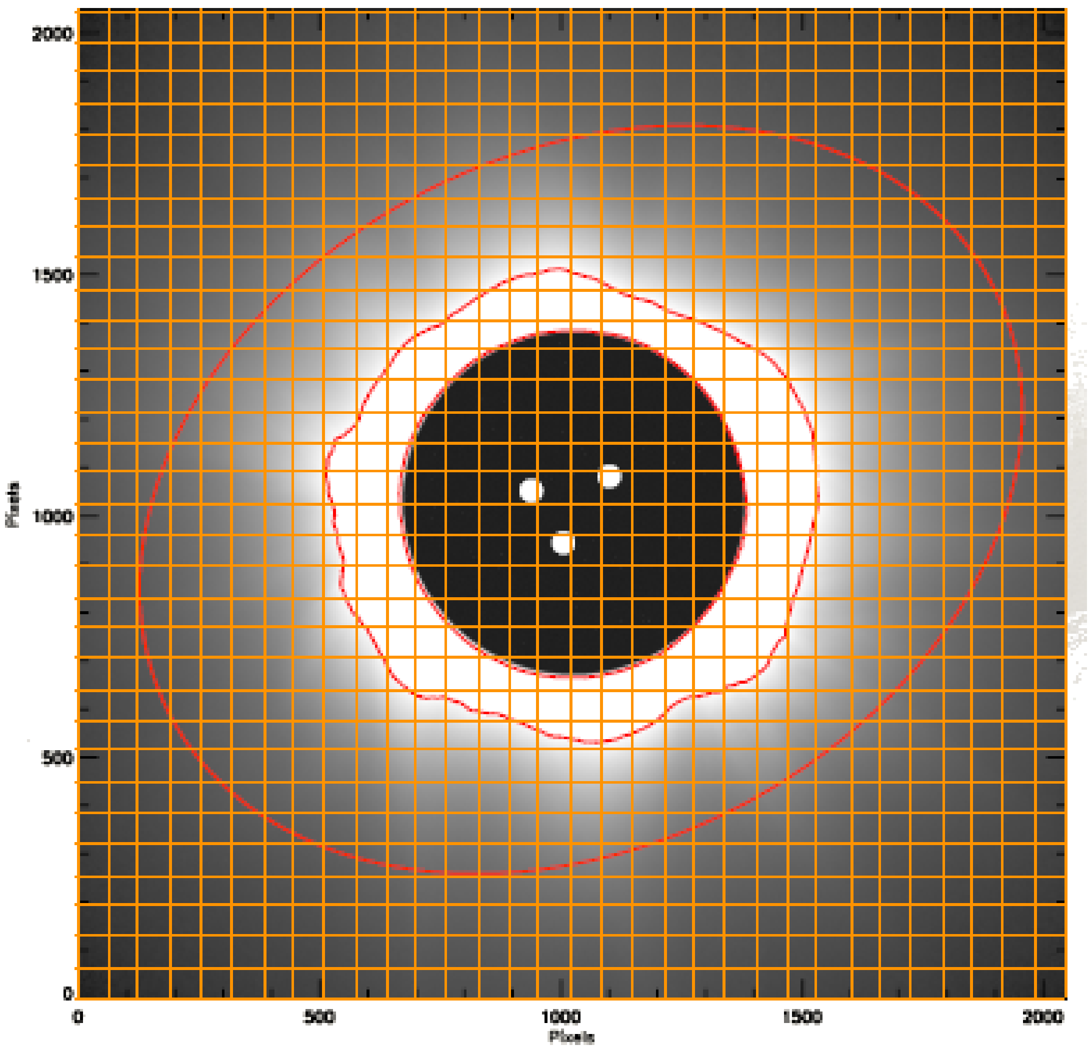
Three exposures reconstructed into one unpolarized WL image

Image tiling

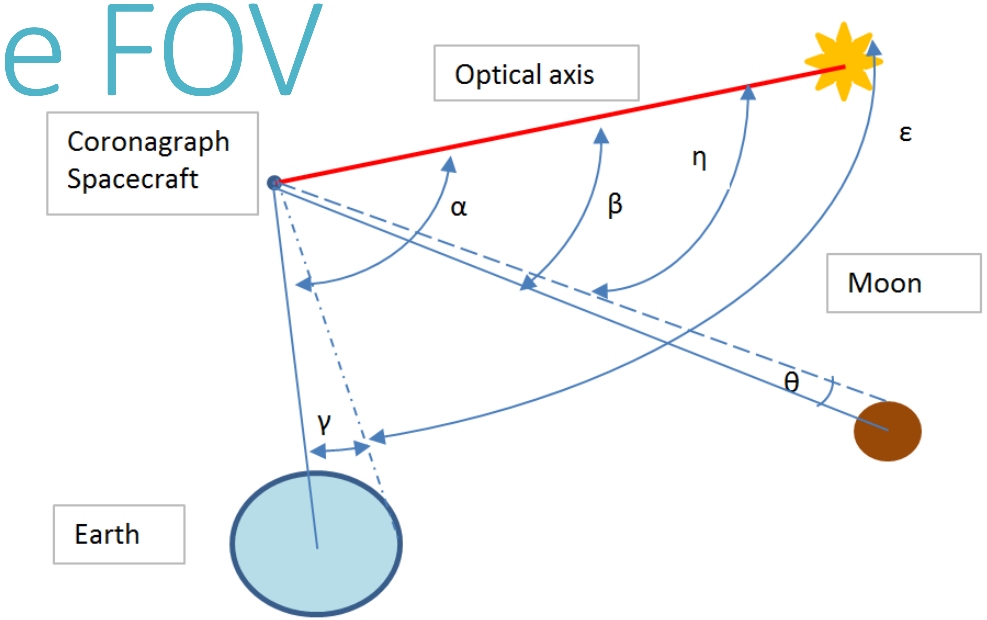
Tile each image into blocks of 64×64 pixels

Compress and store each tile individually

Send down a subset of the tiles in each image (based on ”quality”)

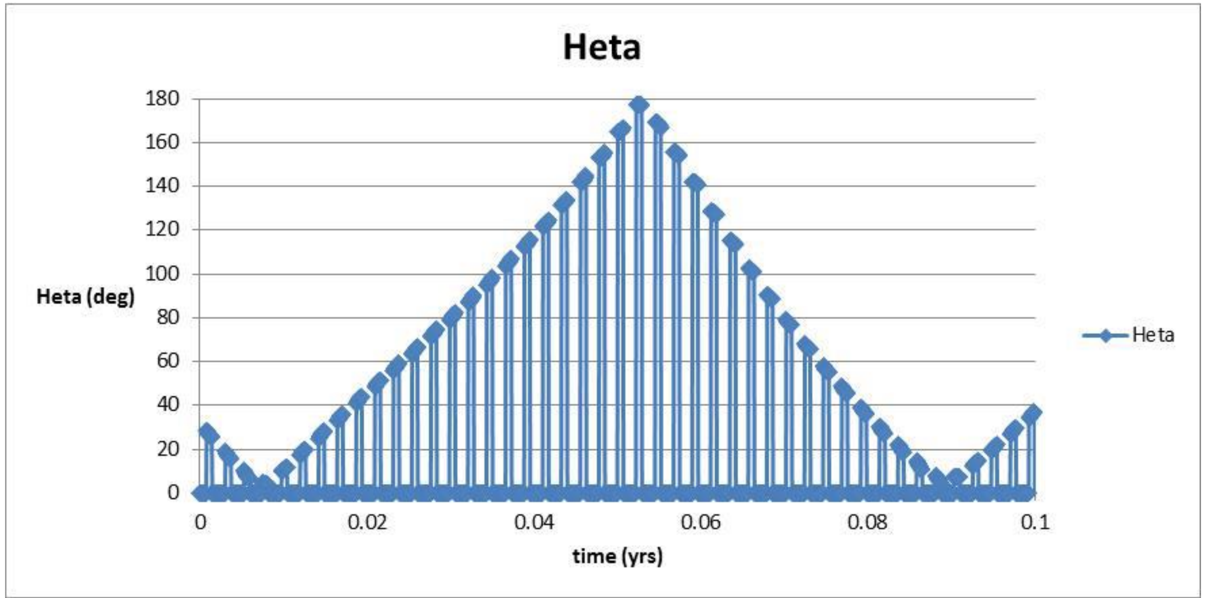


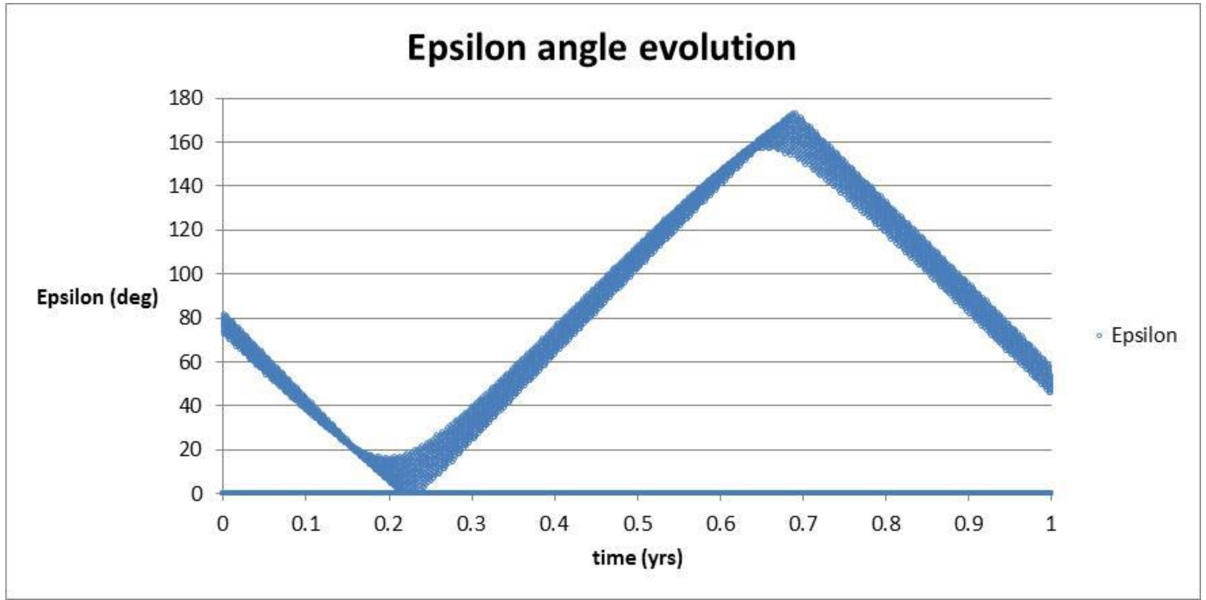
Proba-3 orbit: Earth in the FOV



Moon in or close to the FOV: not an issue as radiometrically equivalent to the Corona

Earth: there are ~27 consecutive days when, during the Coronagraphy period, the Earth can have an view angle ε < 5 deg

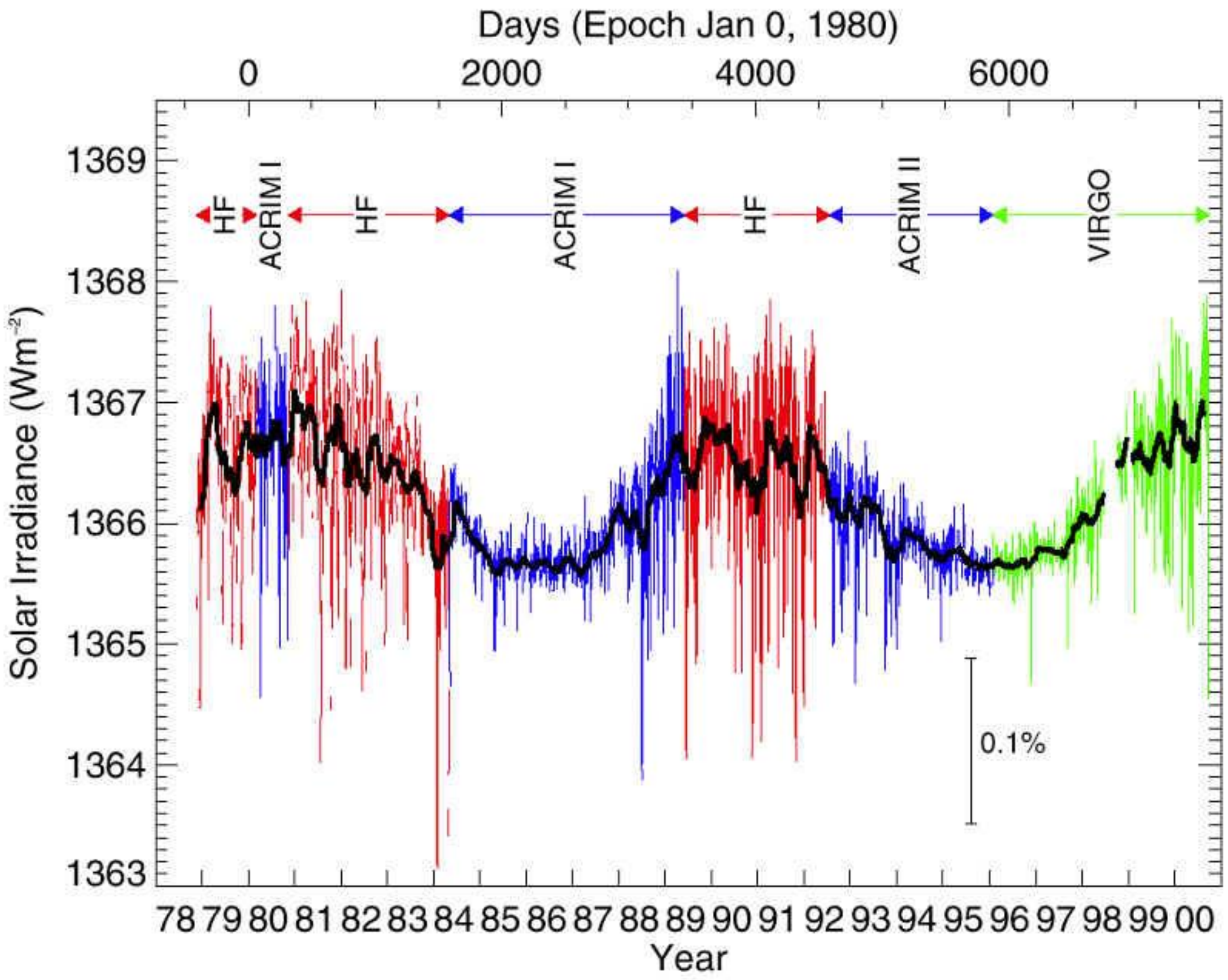




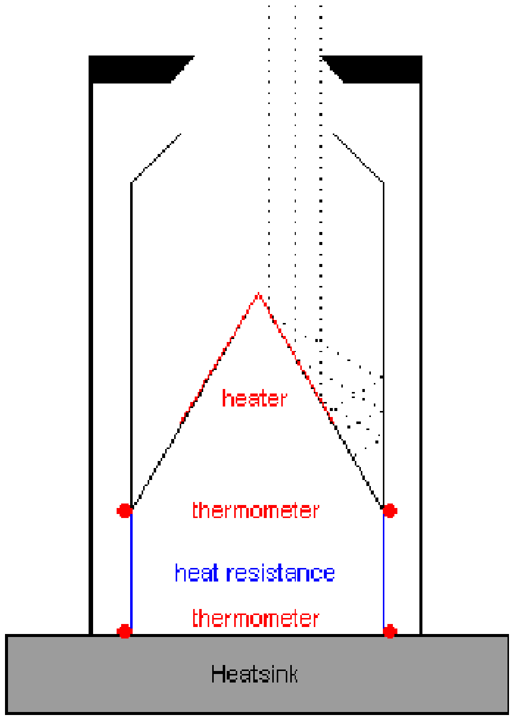
DARA

- Total Solar Irradiance (TSI) and Solar Spectral Irradiance (SSI) are „Essential Climate Variables“ (WMO)
    - TSI (SSI) is a most fundamental parameter in climate research [Haigh J., (2001), Science 294 Ermolli et al., 2013]
    - Operational TSI monitoring from space is curicial for climate reconstruction and forecast
- Dedicated space missions are rare, expensive, and TSI radiometers used to be quite heavy – changed with DARA

TSI composed from normalized observations of radiometers on different satellites

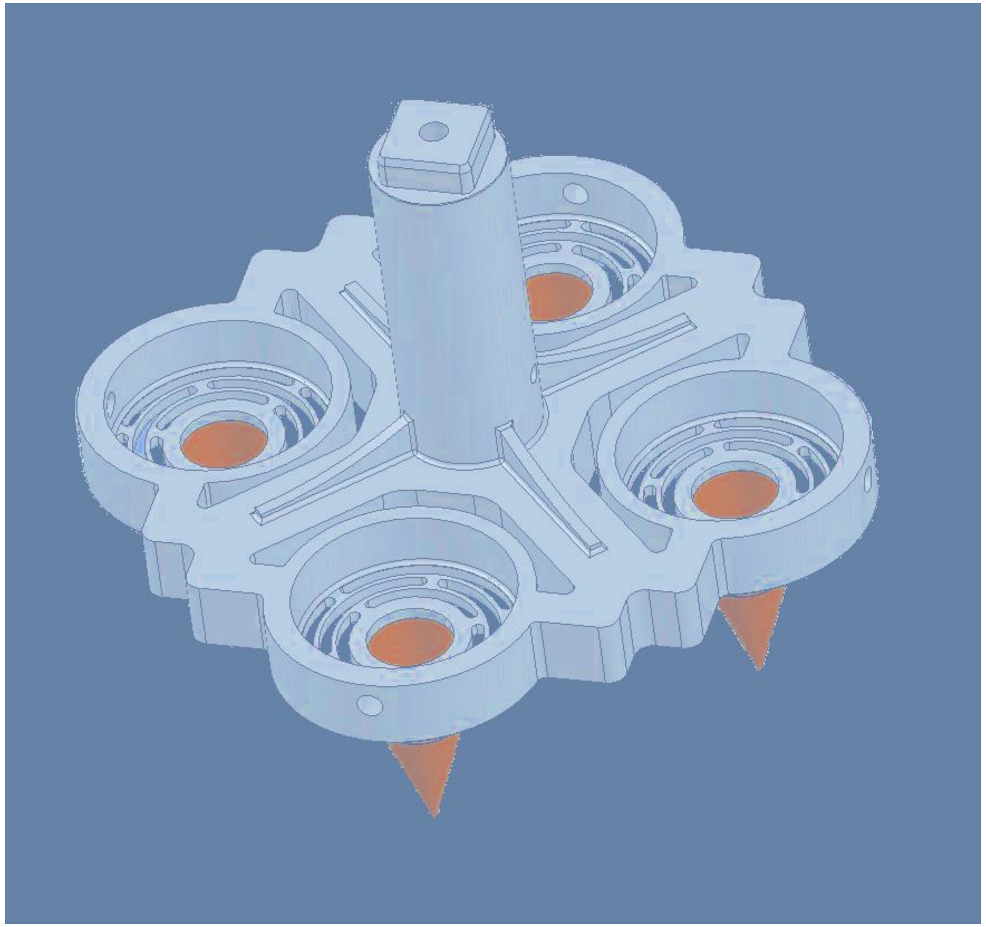


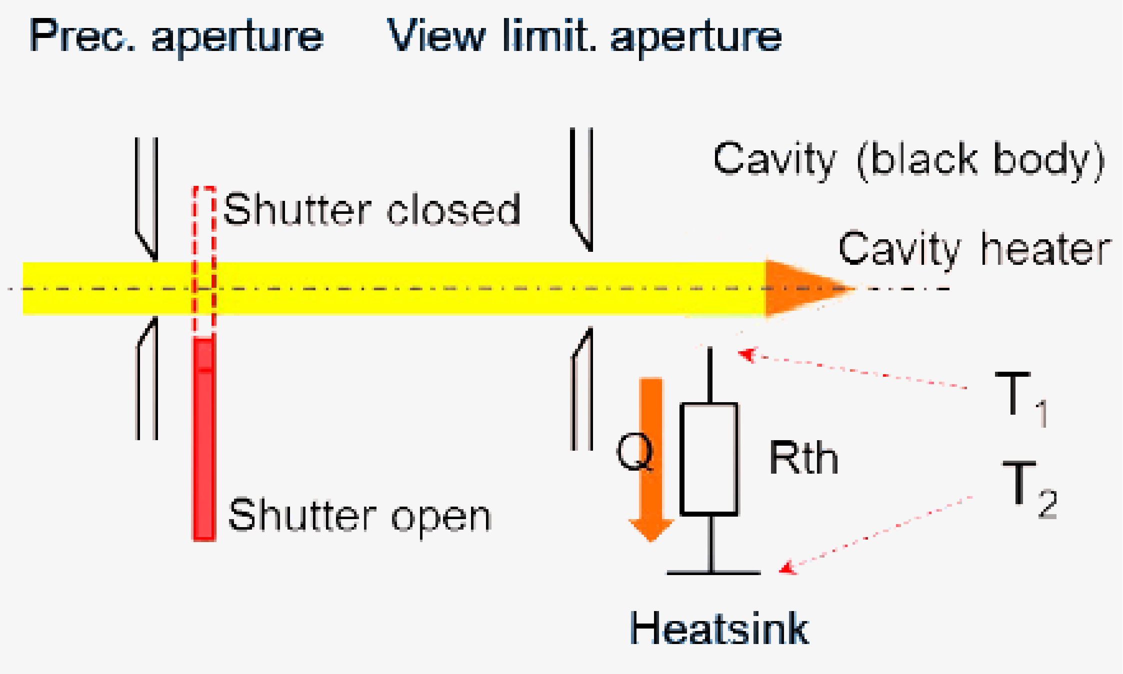
DARA thermal design



- Thermally decoupled from s/c
- Control unit thermally decoupled from sensor unit (titanium struts, MLI)
- Front shield
- – Thermal reference
- – Low absorptance, high emittance
- Heatsink
- – Connects to front shield
- – Provides symmetrical heat flow from all four cavities to the thermal reference
- Sensor box housing
- – Part of thermal mass to minimize temperature drifts

Principle of Electrical Substitution



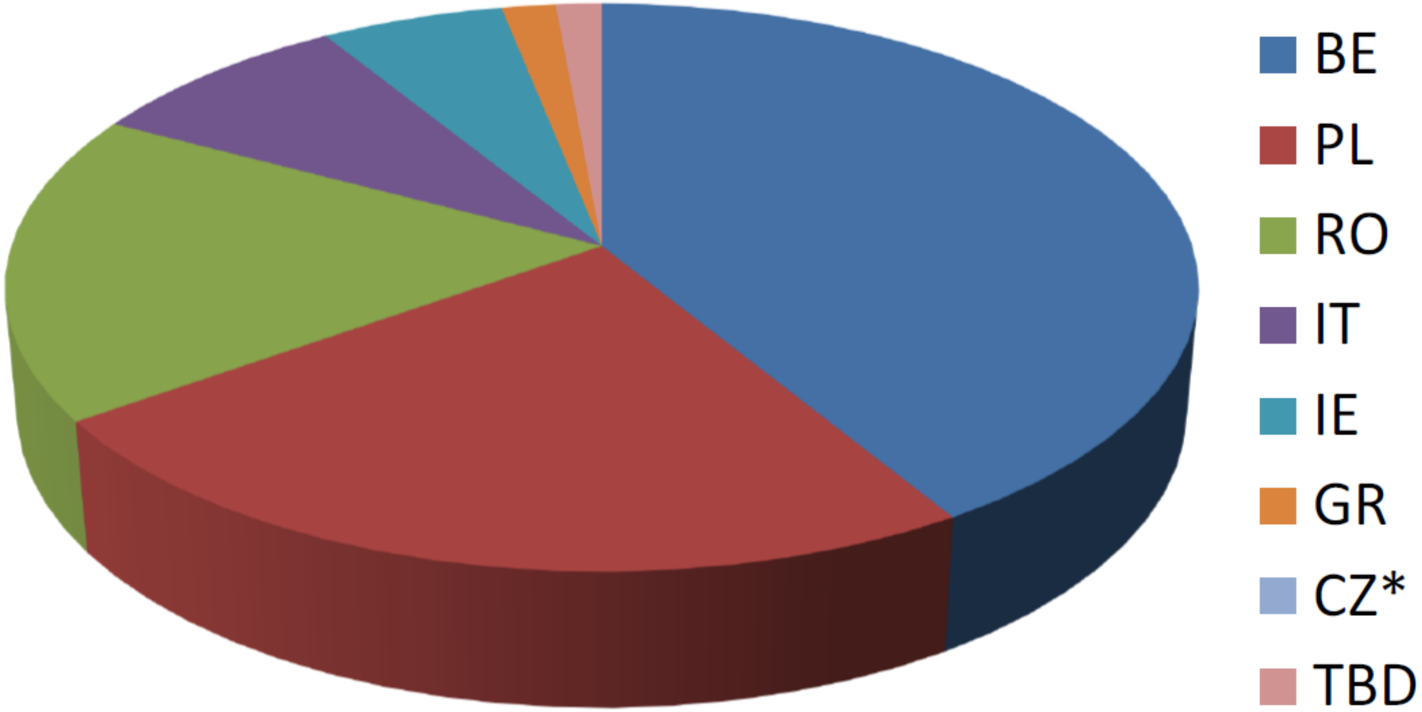


Summary

- ASPIICS is a unique solar coronagraph project.
- It will cover The Gap between the low corona (typically observed by EUV imagers) and the high corona (typically observed by externally occulted coronagraphs).
- ASPIICS observations will be crucial for solving several outstanding problems in solar physics:
  - structure of the magnetized solar corona,
  - sources of the slow solar wind,
  - onset and early acceleration of CMEs,
  - origin of coronal shocks waves.
- ASPIICS data will serve as an example of will test formation flying technologies that can be used by future ESA missions. Several formation flying missions were proposed to ESA in the past:
  - DynaMICCS (a comprehensive solar observatory),
  - XEUS (X-ray observations of galaxies and their supermassive black holes),
  - SolmeX (measurements of the magnetic field in the solar corona),
  - FLIP3 (high-energy solar physics).

ASPIICS
Formation Flying Coronagraph

Thank you!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