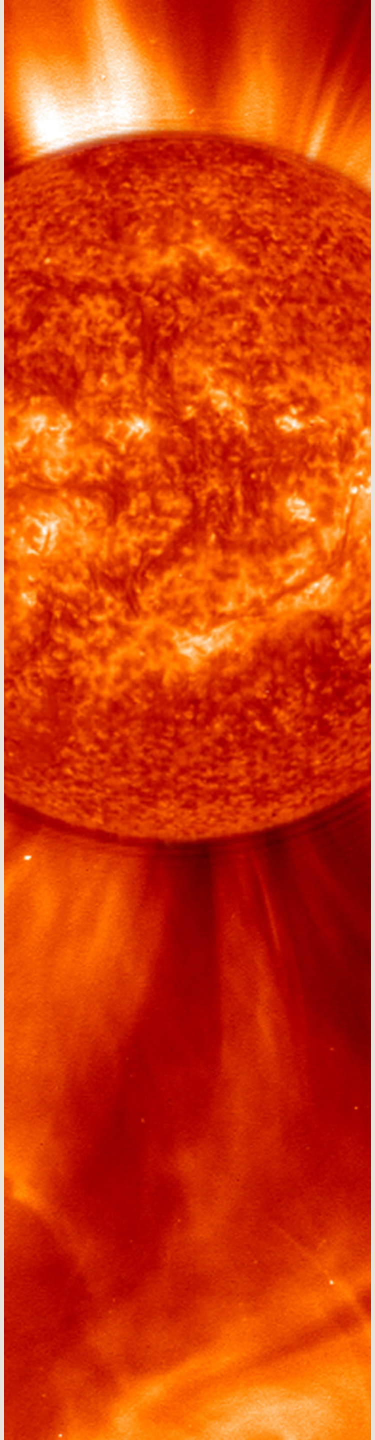
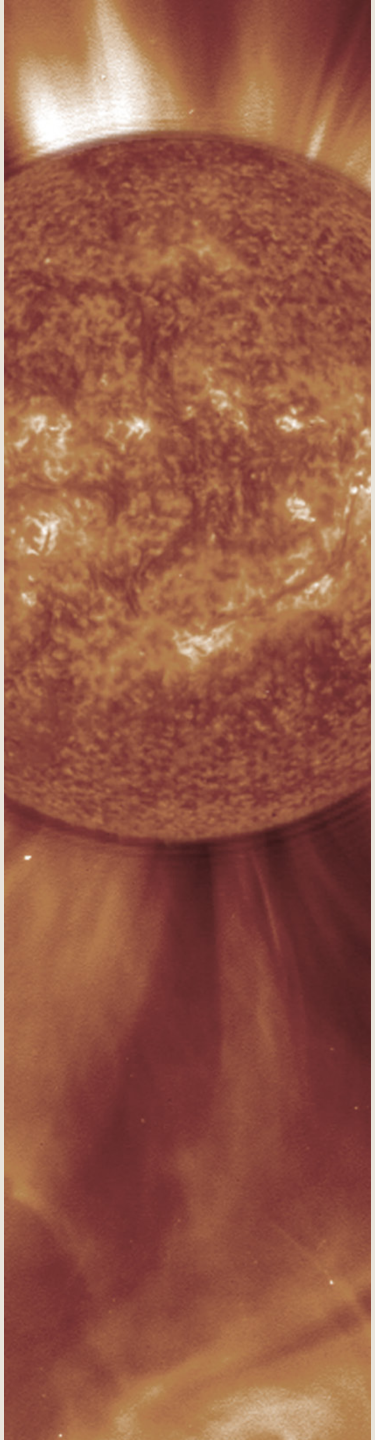


Coronal and heliospheric imaging instrumentation development at RAL Space

JA Davies, CJ Eyles, DK Griffin, RA Harrison, KF Middleton, AG Richards, JK Rogers, SJ Tappin, IAJ Tosh, NR Waltham

RAL Space



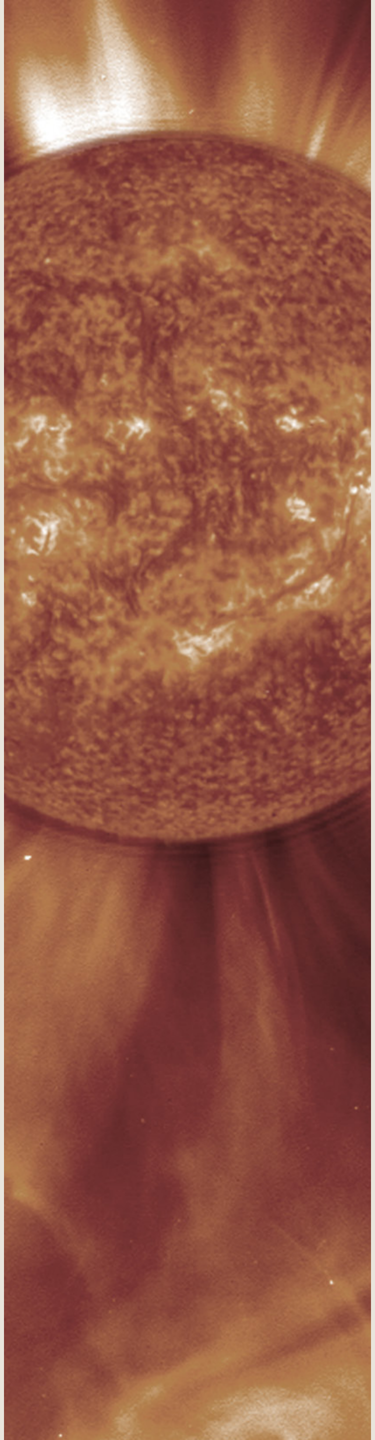
Heritage (1)

- RAL Space has been involved in the construction of over 200 space-based instruments*

- …for example on AMPTE, Chase, Cluster, ERS-1, ERS-2, GOES-R, Herschel, Hinode, IRAS, ISO, Polar, SDO, SMM, SOHO, STEREO, Yokoh…

- …and we wish to continue in that vein!

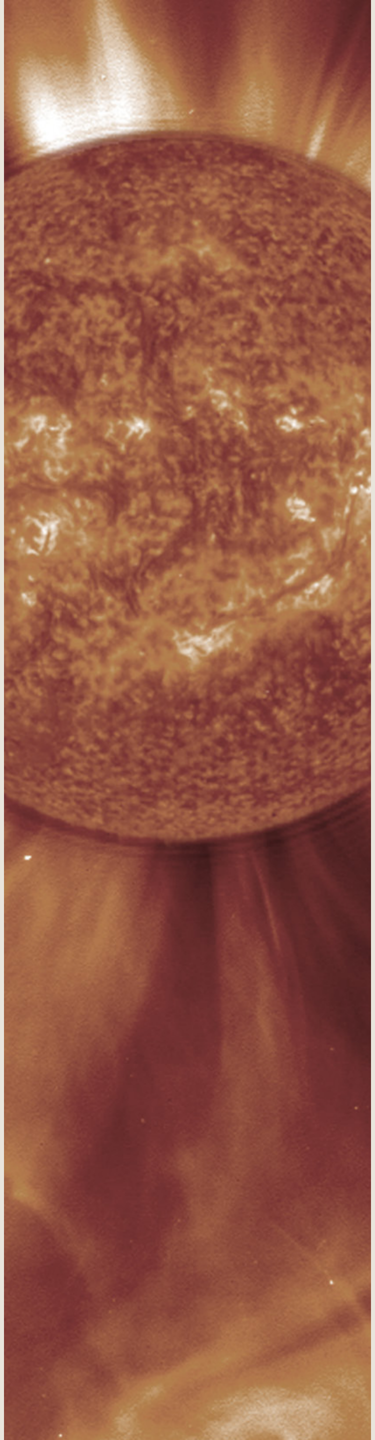
*as well as some ground-based instrumentation



Heritage (2)

- RAL Space staff have significant heritage in building white-light coronal and heliospheric imagers (SOHO/LASCO, Coriolis/SMEI, STEREO/HI).

- Over the last 6 months, in response to a variety of opportunities (and the re-emerging realization within RAL Space that scientists are actually a potential source rather than a sink of money), we have been rekindling our white-light endeavours!



Heliospheric Imaging

- RAL Space led the European consortium that designed and built STEREO/HI (HI PI: Richard Harrison).

- SO/SoloHI and SPP/WHISPR lend heavily from the STEREO/HI instrument design.

- PHELIX is the RAL Space polarizing heliospheric imager that was part of the payload of the recently-proposed (and sadly unsuccessful) INSTANT ESA/CAS S2 science mission (PHELIX PI: Jackie Davies).

PHELIX: Polarizing Heliospheric Imaging eXplorer

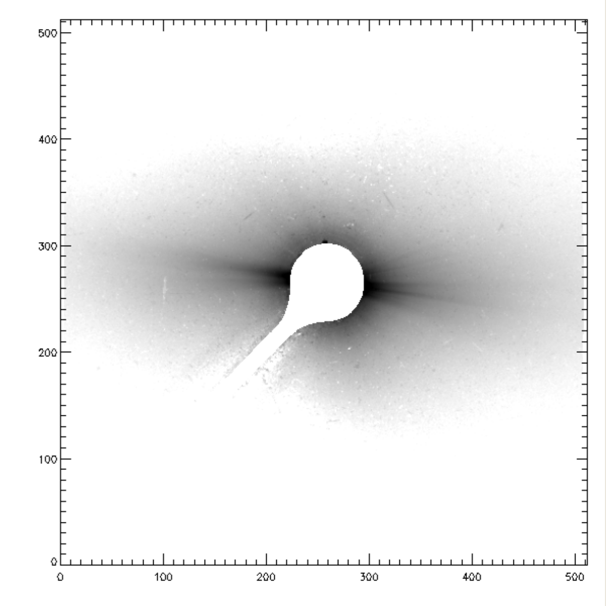
PHELIX budgets and resources.

Parameter	PHELIX-1	PHELIX-2
Field-of-view diameter	30°	50°
Elongation range (FOV)	3.75° – 33.75°	20° – 70°
Spectral bandpass	630 – 730 nm	400 – 1000 nm
Image bin size (1k x 1k binning)	1.75′	2.9′
Summed image cadence	Phase 1/2: 15/30 min	Phase 1/2: 20/60 min
Polarimetry capability	N/A	Polarized images at -60°, 0° and +60°
Brightness sensitivity	3 x 10^{-15} B_O	3 x 10^{-16} B_O
	Total Resource Requirements	
Mass (PHELIX / DPU)	16 kg / 4 kg (10% / 20% margins)	
Size (PHELIX / DPU)	840 x 550 x 260 mm / 250 x 150 x 60 mm	
Power	14.2 W / 6 W (10% / 20% margins)	
Pointing accuracy (3σ)	± 6′ for PHELIX pitch axis; ± 1° for yaw & roll axes	
Pointing stability (3σ / 30 min)	21″ for PHELIX pitch & yaw axes; 37″ for roll axis	
Accommodation	Minimize other spacecraft units above plane of baffles	
Data product	Polarized brightness images of K coronal activity	
Telemetry rate	Phase 1: 26 kbps (1024 x 1024 images) Phase 2: 4 kbps for 512 x 512 (15.5 kbps for 1024 x 1024: burst) Beacon: 330 bps for 256 x 256, 1 hr, total brightness only	
TRL	> 6 (9 for most sub-systems)	

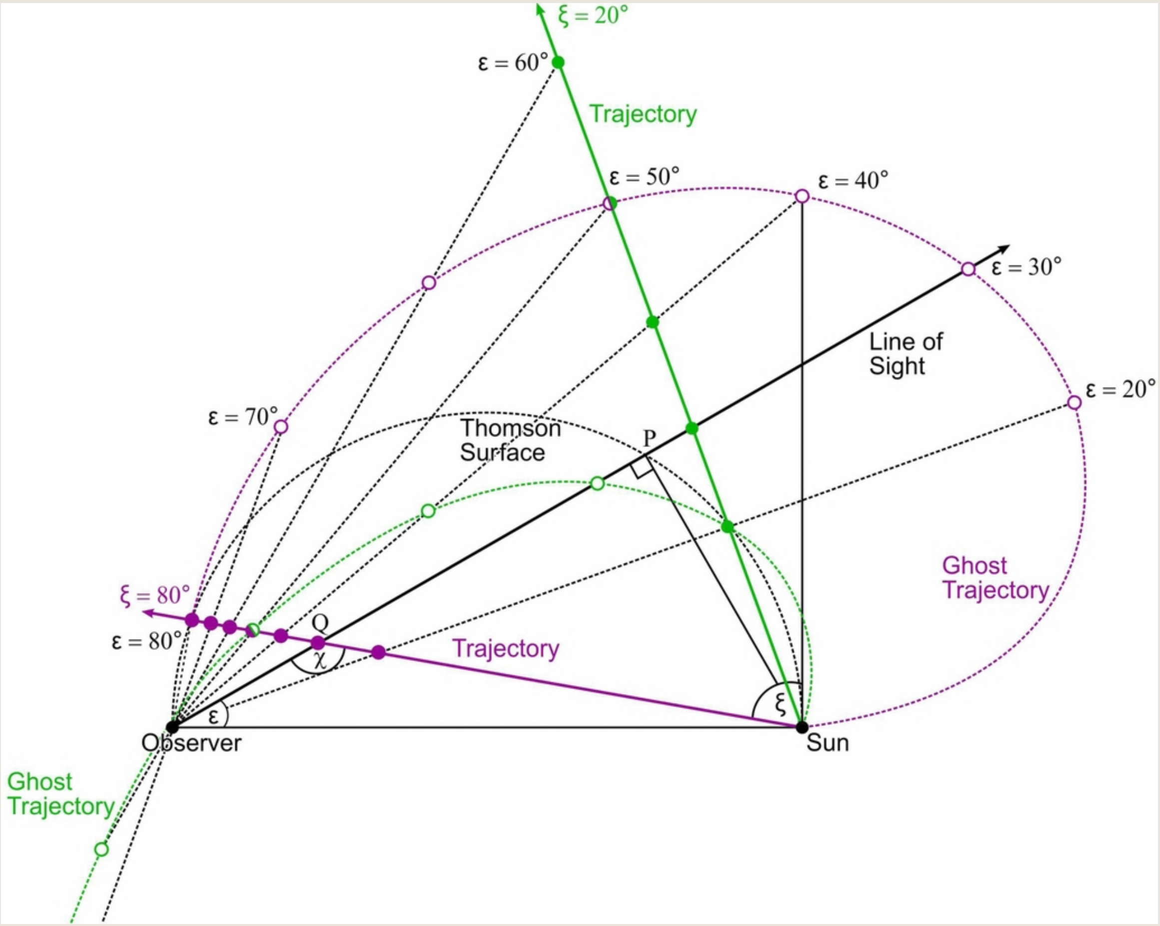
Why/where/how Polarize?

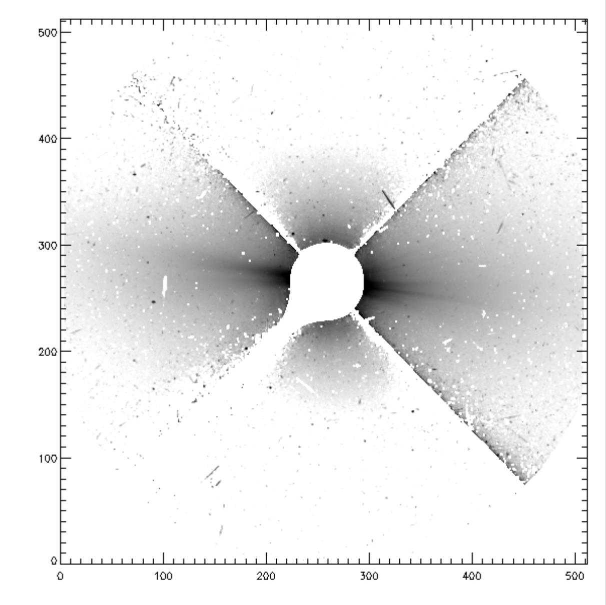
- Degree of polarization of Thomson-scattered light is high (over 50%) to beyond 100° elongation.
- The scattering function for the polarized component is more strongly peaked at the Thomson surface than for unpolarized.
- So we can use the pB/B ratio to estimate the location of a disturbance along the line of sight.
- pB/B is symmetrical about the Thomson surface. A single coronagraph can't distinguish "front" and "back-sided" CMEs.
- **However**, for a wide-angle imager we can exploit non-linearity to make that distinction as one side will lead to an unphysical trajectory.
- Because the non-linearity is greater at larger elongations, the distinction becomes greater (proposed polarization of PHELIX-2 only).
- Baselined use of 3 components (2 leaves 45^o line undefined) and no clear (mass considerations – with a clear, you can't rotate a single polarizer).

Use of 2-component versus 3-component.

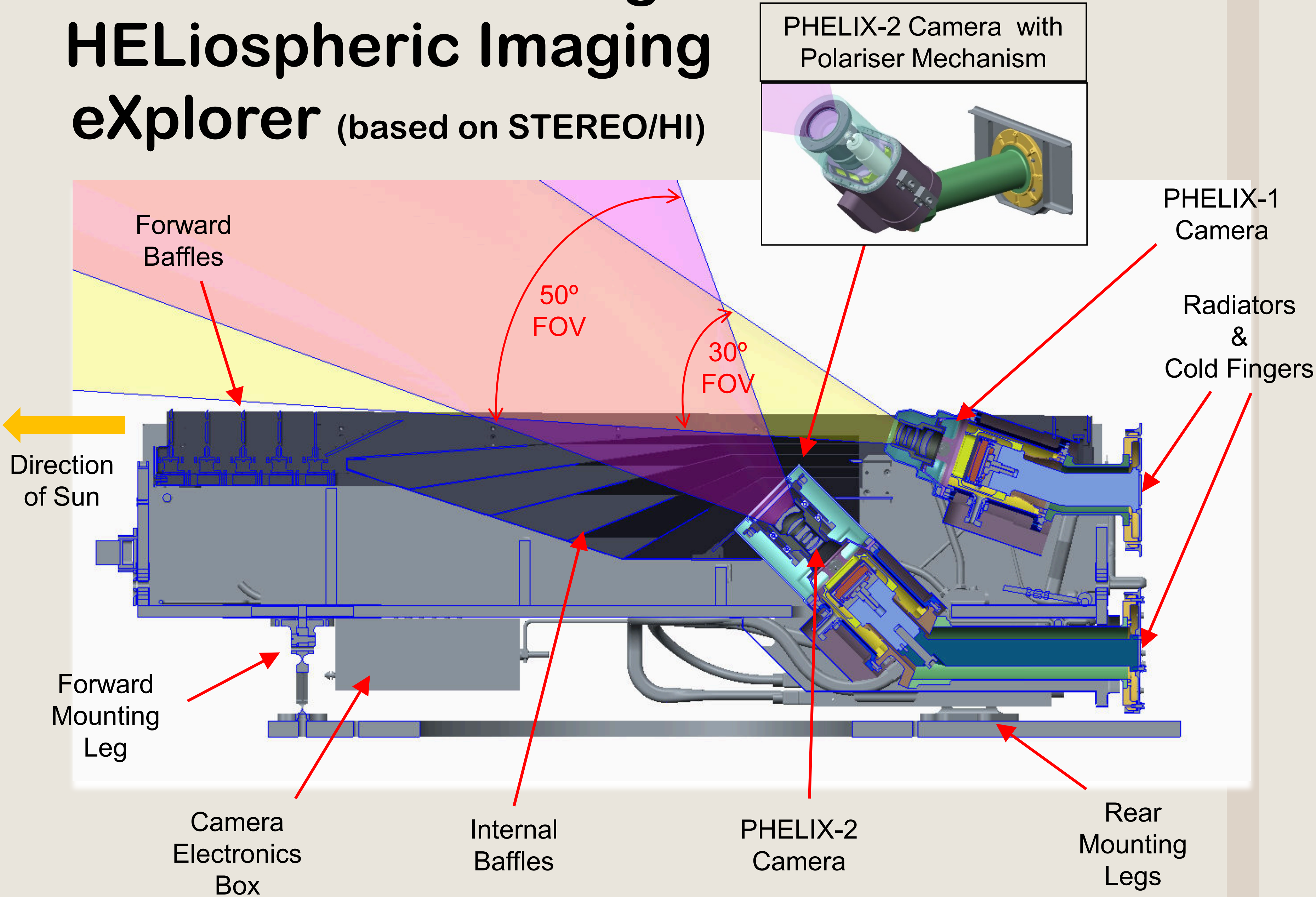


Depth perception.





PHELIX: Polarizing HELiospheric Imaging eXplorer (based on STEREO/HI)



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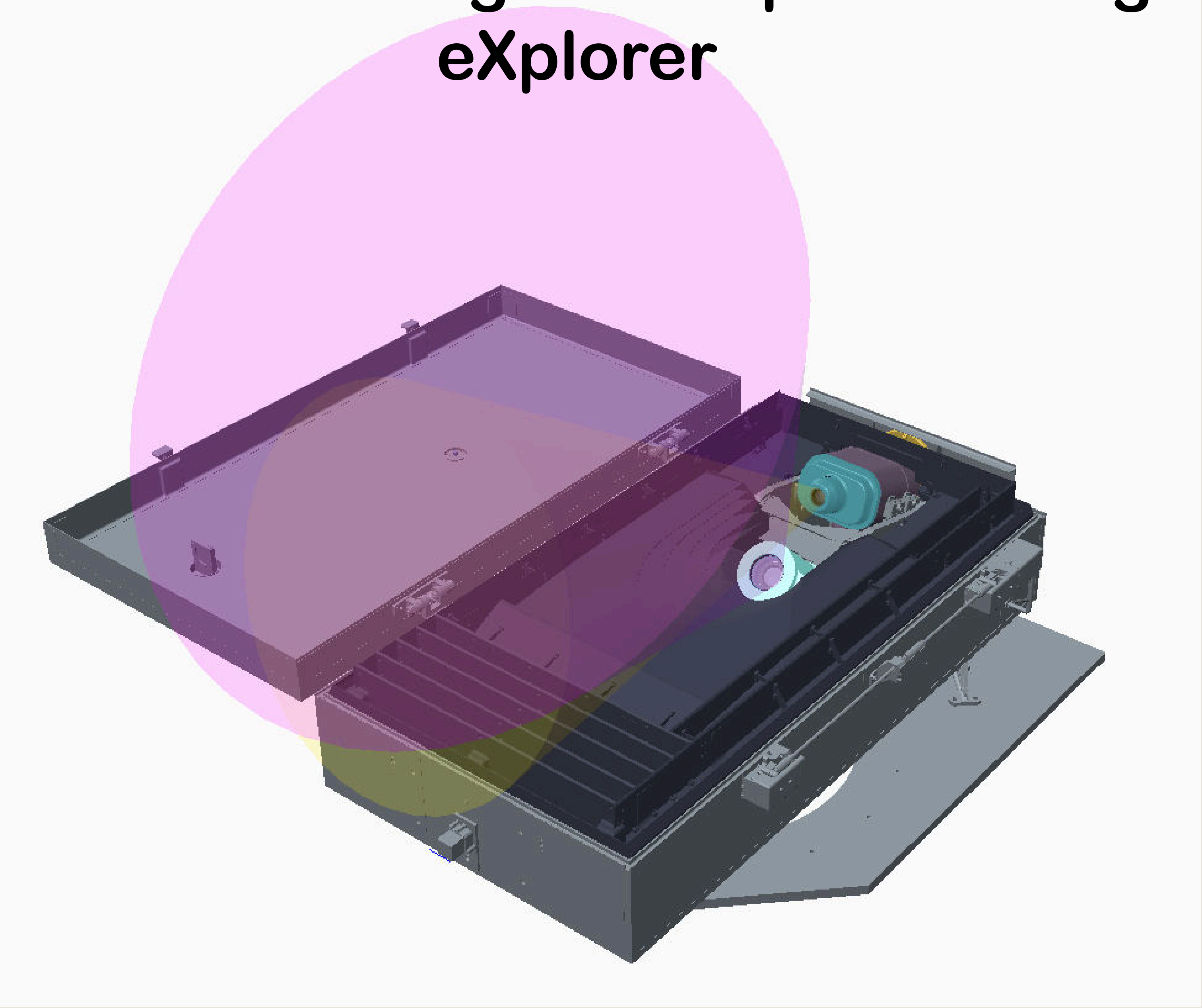

FOV implications for baffling

- There were initial suggestion to move the inner edge of the PHELIX field-of-view (FOV) inwards from its nominal STEREO/HI value (note also the FOV size of PHELIX-1 was increased from the HI-1 value).

Instrument	FOV Diameter	FOV edge Closest to Sun Centre	Offset from Sun Centre
PHELIX	30 degrees	2.65	17.65 degrees
STEREO HI-1	20 Degrees	3.65	13.65 degrees

- Whilst retaining a 5 vane forward baffle, we studied how this could be achieved with original scattered light performance.

Model number	STEREO 1	PHELIX 1	PHELIX 2	PHELIX 3	PHELIX 4	PHELIX 5	PHELIX 6
Pupil Radius,mm	8	8	7	6	6	6	6
Length,mm	550	550	550	550	600	650	700
Diffraction Angle	1.322	0.363	0.615	0.867	1.022	1.149	1.254
Integrated Scatter	5.9e-11	2.8e-7	1.75e-8	1.58e-9	4e-10	1.4e-10	6.2e-11

- Based on the same general design, the STEREO/HI scattered light performance could only be achieved by reducing the size of the entrance aperture (reduces signal to noise ratio) AND increasing the instrument length by 150mm.

Model number	STEREO 1	PHELIX 1	PHELIX 2	PHELIX 3	PHELIX 4	PHELIX 5	PHELIX 6
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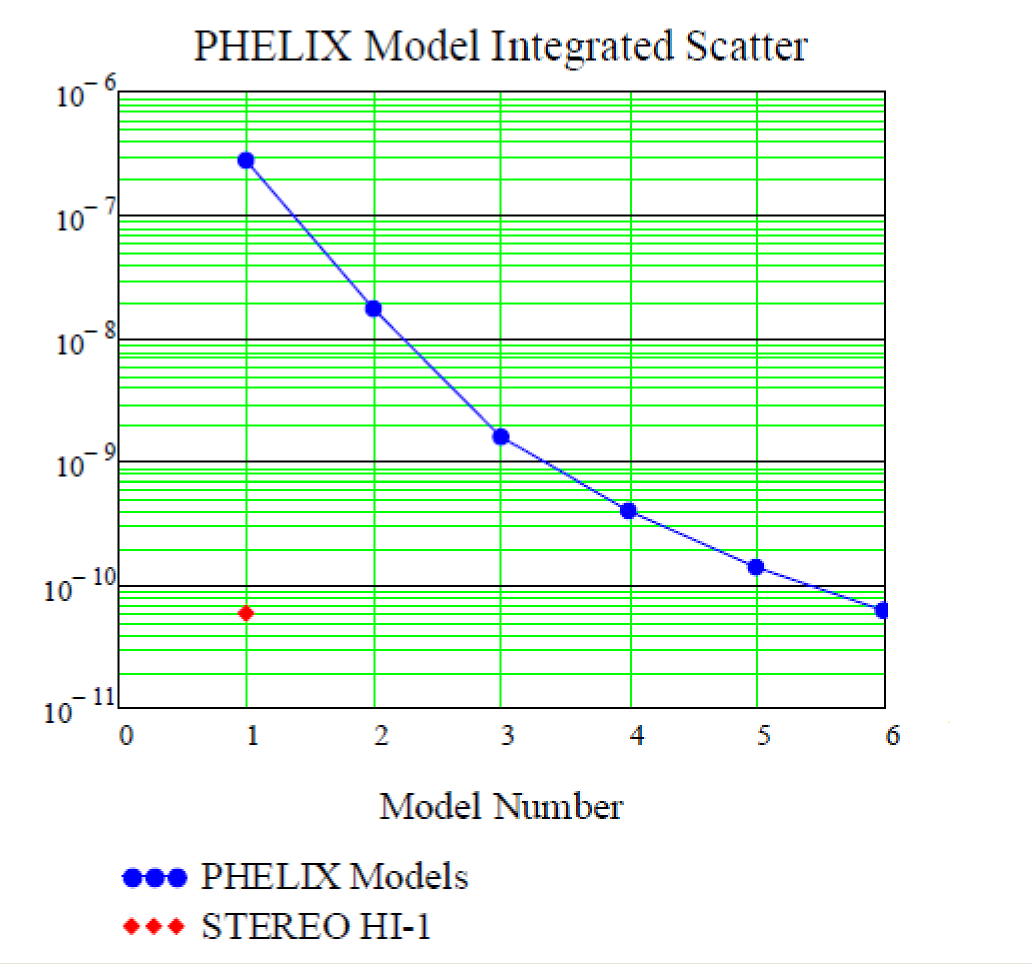
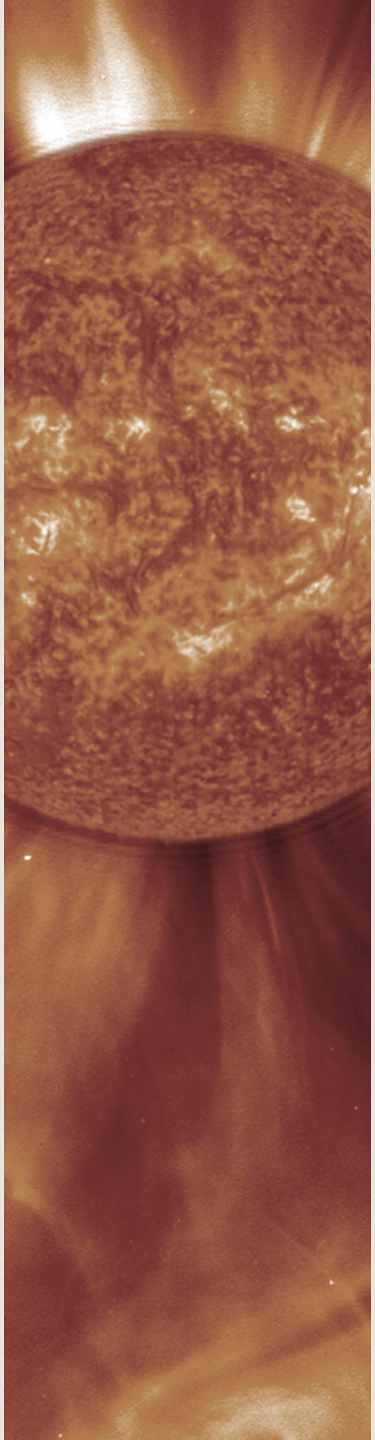
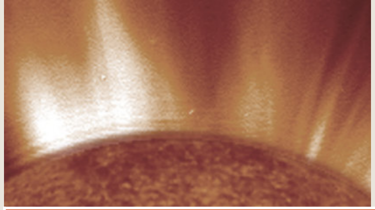




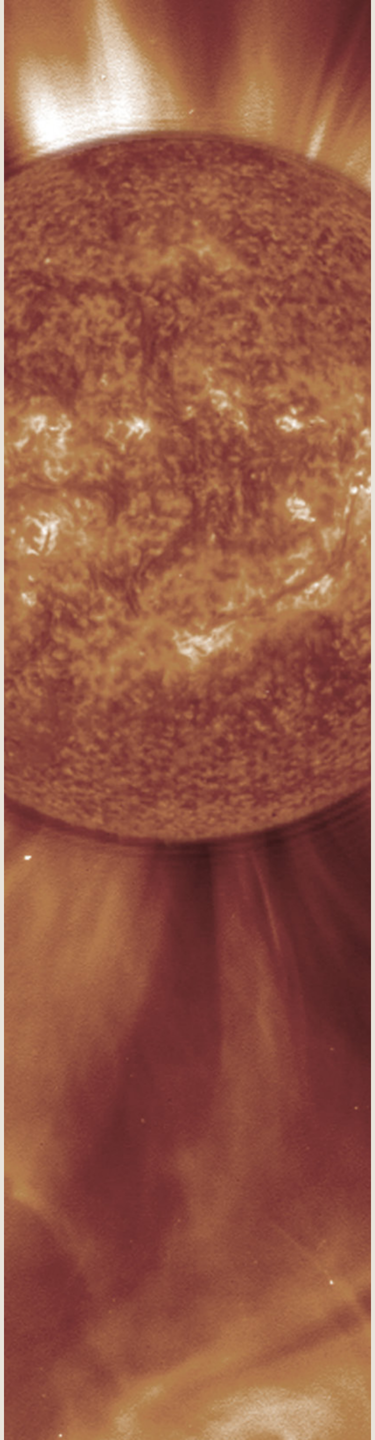
Coronagraphic Imaging

In order to respond to emerging coronal imaging opportunities (e.g. ESA SSA), RAL Space (in collaboration with other institutes) are also base-lining a design for a compact space weather coronagraph.



Compliance with ESA's stated goals

Parameter	Requirement (with goal in brackets)	Proposed Baseline Design
Power	7 W (5 W)	11 W + heaters and mechanisms
Mass	12 kg (10 kg)	< 12 kg
Volume	0.015 m^3 (0.01 m^3)	0.04 m^3
Lifetime	10 years	TBC
Field of View	1.5 – 20 R (1.2 – 20 R)	3 – 30 R
CME Velocity Detection Range	400 – 3000 km/s (300 – 3500 km/s)	300 – 3500 km/s
Resolution	<10"	53"
SNR	>10 in corona at 20 R	>2 for at R ≤ 20 for 10 s exposure

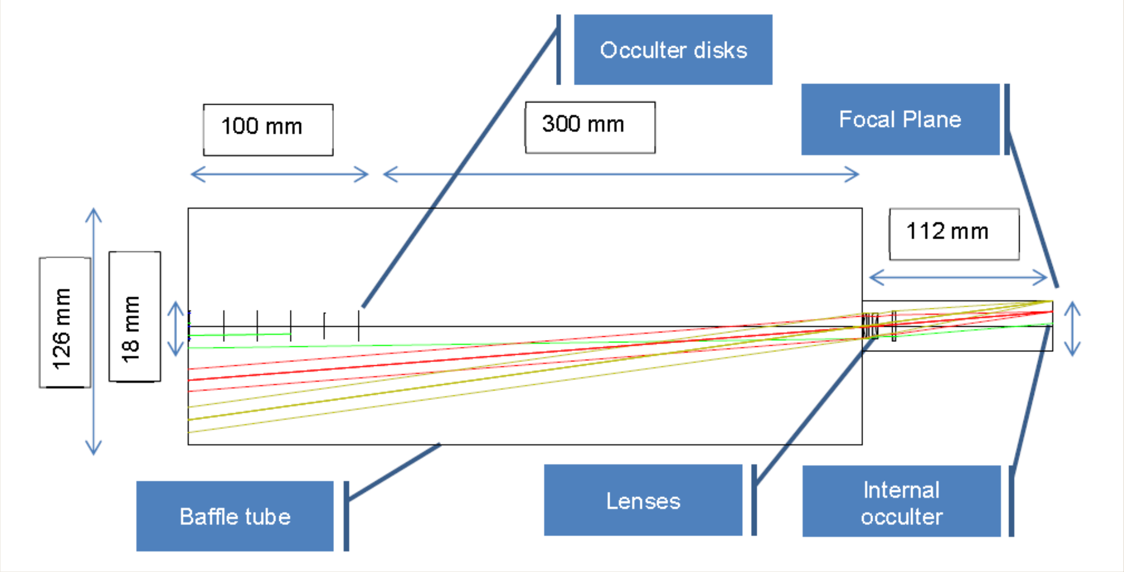


Design Trade-Offs

- Field of view versus size and complexity
  - Especially lower limit on FoV (influences complexity of baffle design)
- Detector technology
  - CCD vs CMOS
- Aperture, waveband and exposure time
  - Aim to maximise throughput without over-complicating optical design
  - Exposure time constrained by CME velocity and pointing stability
- On-orbit versus on-ground processing
  - Limited telemetry budget
  - Prefer to process on-ground where possible
- Orbit
  - Options are L1, L4/L5, GEO or LEO
  - L1 or L4/L5 are most credible
  - Different orbits place different constraints on instrument thermal design

Preliminary optical Design

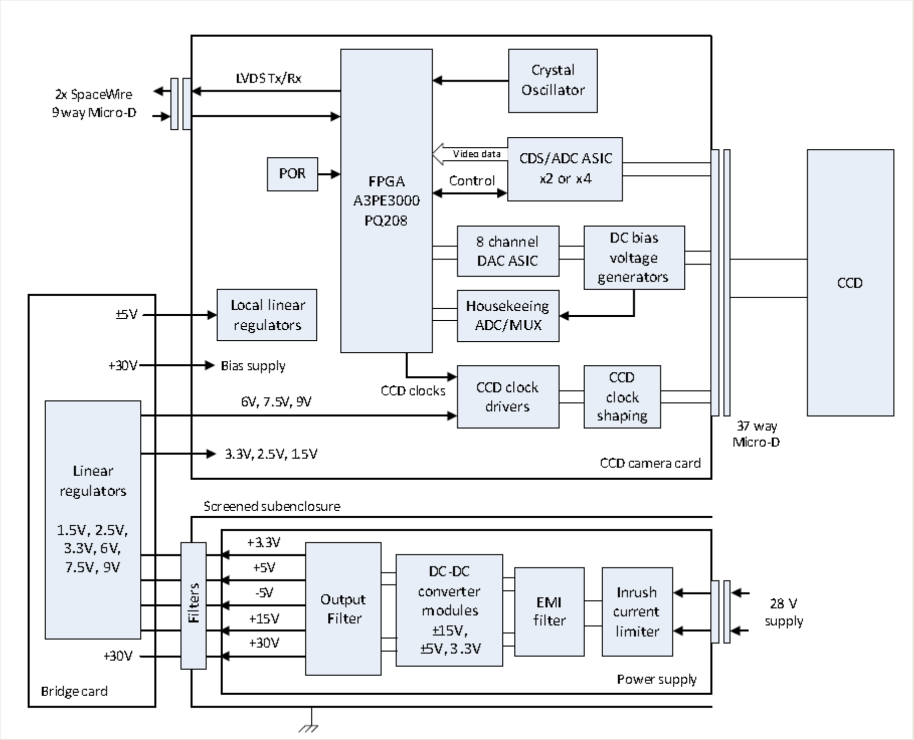
- Compact design with external occulter, objective lens and internal occulter in front of detector – no Lyot stop and relay lens
- Follows approach proposed by NRL[1]
- Allows compact design without too much compromise to stray light rejection (TBC – see later)
- 1k x 1k detector – gives 53” / pixel at 30 R FoV



[1]Theoretical study of the occulted solar coronagraph, Qian Gong et al, Proceedings of SPIE Vol. 5526, pp 208 – 219 (2004)

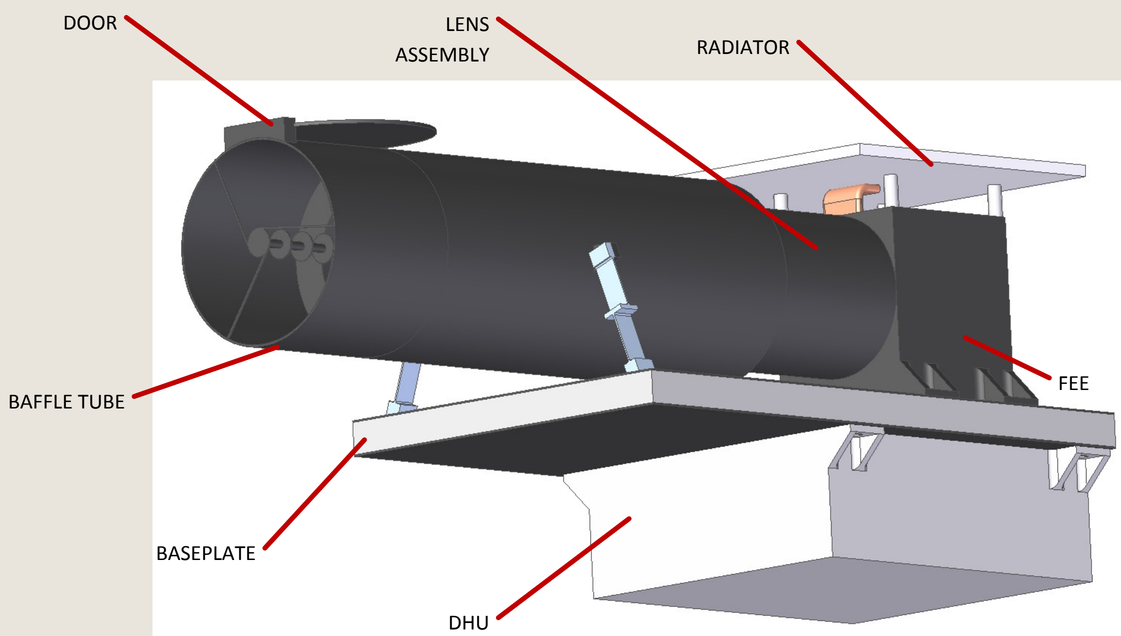
Detector & Front End Electronics

- ITAR-free version of the electronics developed by RAL Space for SDO and GOES
- e2v CCD-230
  - 2k x 2k 15 um pixel with on-chip binning to 1k x 1k
- CCD preferred to CMOS
  - On-chip binning; greater dynamic range; better linearity



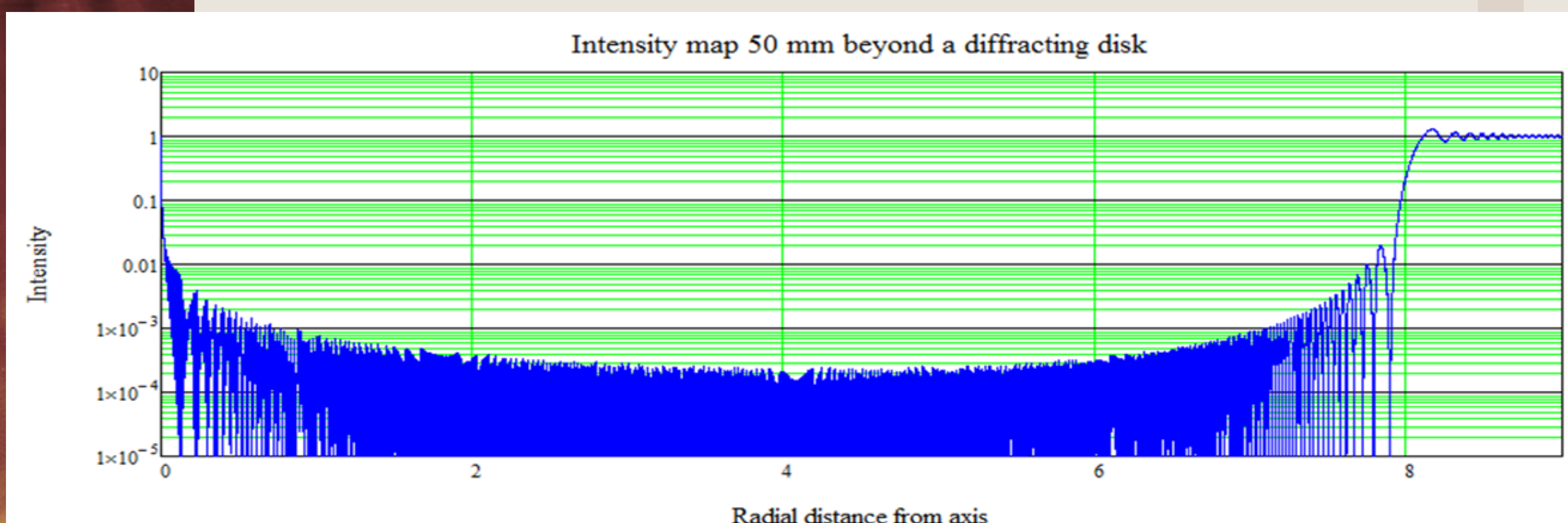
Baseline design

- 600 x 250 x 250 mm
- Basic CAD model worked up
- Includes data handling unit and thermal control
- Aim to minimise required spacecraft resources
- Re-use mechanical design heritage from similar sized RAL camera systems



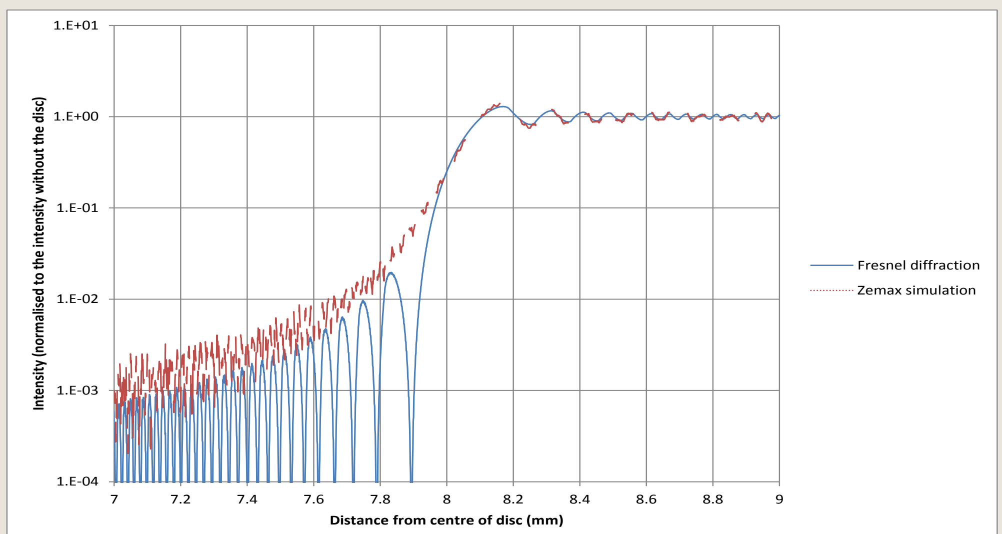
Occulter design

- Preliminary work started at RAL on occulter design
- Modelling of efficiency of multiple-disc external occulter
- Predict diffracted intensity in the shadow of the occulter from first principles (Fresnel diffraction) for simple geometry
- Code checked by calculating in Fortran and Mathcad with comparison of results – good agreement



Occulter design

- Build model in optical design code (e.g. Zemax, ASAP) and check against prediction from first principles for the simple case – good agreement
- Gives confidence that the model is correct
- Next steps:
  - Build optical model and explore optimisation of baffles
  - Compare efficiency of the proposed design against traditional 3 stage coronagraph



Summary

- **RAL Space scientists  designing and building space instruments (and so do our engineers).**
- **We are seeing a resurgence in opportunities for doing so!**
- **Many are space weather related; scientists will do science with “space weather” instruments!**