The Coronagraph and Heliospheric Imager for the Lagrange L5 Mission

J. Davies[1*], S. Kraft[2] and the Lagrange COR and HI teams

1. STFC-Rutherford Appleton Laboratory, UK (Jackie.Davies@stfc.ac.uk)

2. ESA/ESOC

The Space Weather (SWE) element of ESA's Space Situational Awareness (SSA) programme (now Space Safety) was established to address the increasing risks of solar effects on human technological systems and health. Within its Period 3, the SSA programme was extended to include an additional element (LGR), targeted towards the development of a space weather monitoring mission to the L5 point; it is envisaged that this mission, entitled Lagrange, will operate in coordination with a US-led mission to L1. Under the auspices of LGR, a number of Phase A/B1 studies have taken place; these studies, recently completed, covered the remote-sensing payload, the in-situ payload, and overall Lagrange system. The remote-sensing instrument package includes a Photospheric Magnetic Field Imager (PMI), EUV Imager (EUVI), Coronagraph (COR) and Heliospheric Imager (HI). In this presentation, we will, firstly, provide an overview of the consolidated observational requirements for the visible-light coronal and heliospheric imaging instruments, COR and HI. We will then present the optical, mechanical, thermal and electrical design - as well as the operations concept - of these two instruments that have been developed to meet the instrument requirements and those of the mission.

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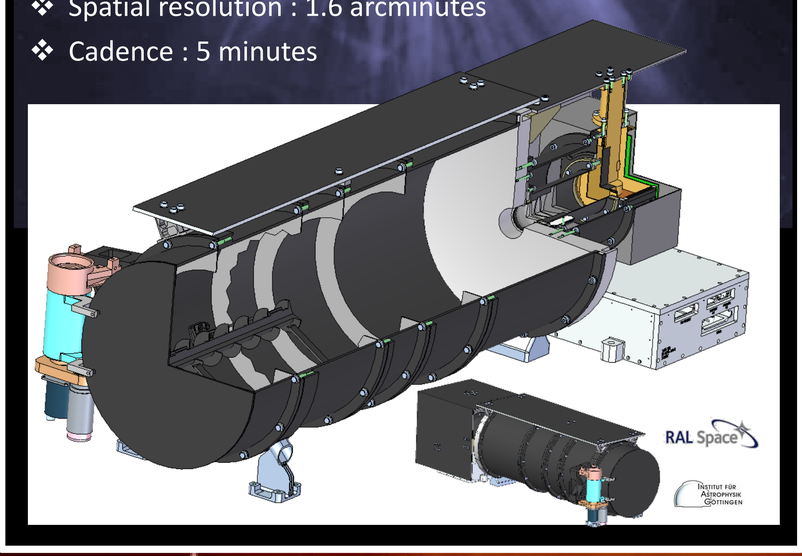
COR : Coronagraph

Early CME detection and tracking; provides the basis of CME parameterization for most operational CME arrival forecasts.

L5 provides clear side-on view of Earth-directed CMEs for more accurate arrival speed/time determination, especially when combined with corresponding near-Earth imagery.

- COR lead : RAL; COR partner : UGOE
- Concept : SCOPE study undertaken under ESA's GSTP programme
- Product : visible-light imagery of the outer corona
- FoV (radial) : 2.7 to 25 Rsun
- FoV (azimuthal) : 360°
- Spatial resolution : 1.6 arcminutes
- Cadence : 5 minutes

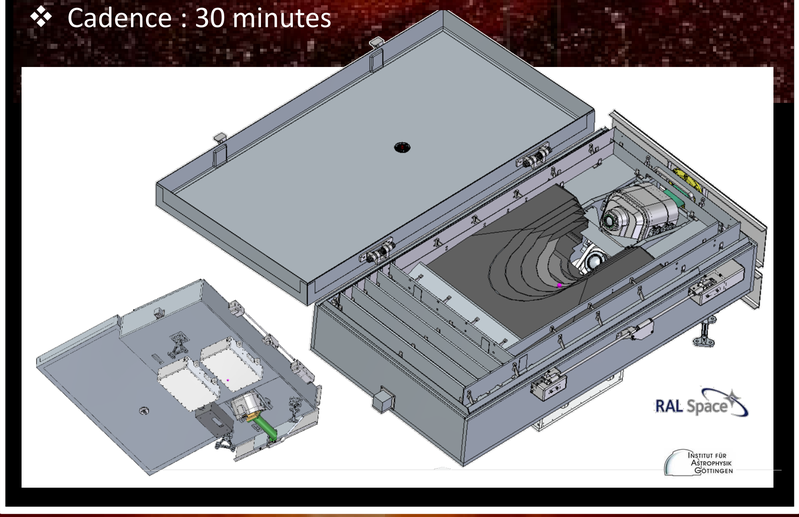


HI : Heliospheric Imager

Monitors CME propagation through vast under-sampled region between outer corona and 1 AU; also gives information on the background solar wind .

L5 provides clear side on view of Earth-directed CMEs to mitigate deficiencies in modelling arrival based on near-Sun data.

- HI lead : RAL; HI partner : UGOE
- Concept : optically-modified version of twin-camera HI instrument on STEREO mission
- FoV (ecliptic extent) : 4 – 70° elongation
  HI1 : 30° FoV; boresite 19°
  HI2 : 50° FoV; boresite 45°
- Spatial resolution :
  HI1 : 3.5 arcminutes; HI2 : 6 arcminutes
- Cadence : 30 minutes



COR and HI Activities

- Performance analysis
- Optical and stray light design/analysis
- Mechanical design/analysis
- Thermal design/analysis
- Electrical design
- Reliability/availability analyses
- Started critical pre-developments [COR/HI FEE; particle-scrubbing algorithm development]
- Developed plans for future mission phases, including:
  - model philosophy
  - MAIT plans
  - on-board/on-ground processing and calibration plans
  - PA and management plans
  - contamination control plan
  - schedule (compatible with current mission scenario)
  - RFI campaign for critical elements/reviewing responses
- Supported E2ES prototyping (HI in particular)

COR and HI Performance Modelling

Parameter	COR	HI1	HI2	Units
EPD	25	15	8.5	mm
CCD array	2k x 2k	2k x 2k	2k x 2k	
Pixel angle	0.4	0.88	1.48	arcmin
Binning factor	2	2	2	
Spatial resolution	1.6	3.5	5.9	arcmin
Texp	3.2	22.0	47.0	sec
Nexp	3	64	36	
Texp total	9.6	1408	1692	sec
FWC	300000	300000	300000	e-
Lambda min	500	600	500	nm
Lambda max	700	750	900	nm
Optics trans	0.8	0.75	0.83	
CCD QE	0.90	0.90	0.77	
Stray-light budget	20*	20	20	% F+K

*plus modelled diffraction around occulter

Parameter	COR	HI1	HI2	Units
FWC used*	<70	<70	<20	%
SNR per bin	4 - 60	4 - 60	2 - 20	

*per exposure

COR : Hardware overview

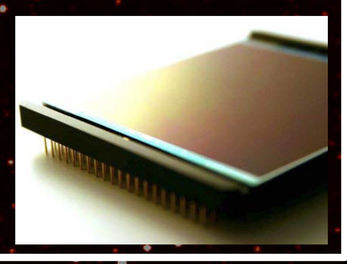
- CFRP tube with aluminium 7-disc occulter/baffles;
- Heat rejection mirror at back of baffle tube;
- Radiatively-cooled CCD-based camera system attached via short harness to separate CEB (ideally mounted on spacecraft);
- SpaceWire interface from CEB to the IPCU (for ICPU control of CEB / data for ICPU processing);
- Single-shot door opened near start of transfer;
- Shutter in front of camera (off-point protection/some contamination control);
- Three (thermally-isolated) feet on imaging unit, acting as semi-kinetic mount;
- Survival/operational/decontamination heaters/ monitors, powered by spacecraft or via IPCU as appropriate;
- As much redundancy as practical.
  - **Mass: 15.6 kg inc 20% margin**
  - **Req: <15 kg inc margin**
  - **Power: 18.4 W (av) inc 20% margin**
  - **Req: <30 W inc margin**
  - **Dimensions: ~310 x 280 x 860 mm (door shut, inc CEB)**
  - **Req: <340 x 340 x 880 mm (door shut, inc CEB)**
  - **Data rate: 35 kbps**
  - **Req: <35 kbps excluding margin**
  - **Latency: 3 min (start acqu. to s/c)**

HI : Hardware overview

- Five-sided box: Al honey-comb/CFRP sandwich panels, with internal stiffeners; 5 CFRP front baffles;
- Two-radiatively-cooled CCD-based camera systems each attached via short harness to separate CEB (mounted on the underside of the instrument);
- SpaceWire interface from CEB to the IPCU (for ICPU control of CEB / data for ICPU processing);
- Single-shot door (opened near start of transfer);
- Shutter inside camera assembly (off-point protection/some contamination control);
- Three (thermally-isolated) feet on imaging unit, acting as semi-kinetic mount;
- Survival/operational/decontamination heaters/ monitors, powered by spacecraft or via IPCU as appropriate;
- As much redundancy as practical.
  - **Mass: 23.8 kg inc 20% margin**
  - **Req: <24 kg inc margin**
  - **Power: 32.4 W (av) inc 20% margin**
  - **Req: <35 W inc margin**
  - **Dimensions: ~820 x 500 x 265 mm (door shut)**
  - **Req: <840 x 550 x 270 mm (door shut, inc CEB)**
  - **Data rate: 14 kbps**
  - **Req: <14 kbps excluding margin**
  - **Latency: 35 min (start acqu. to s/c)**

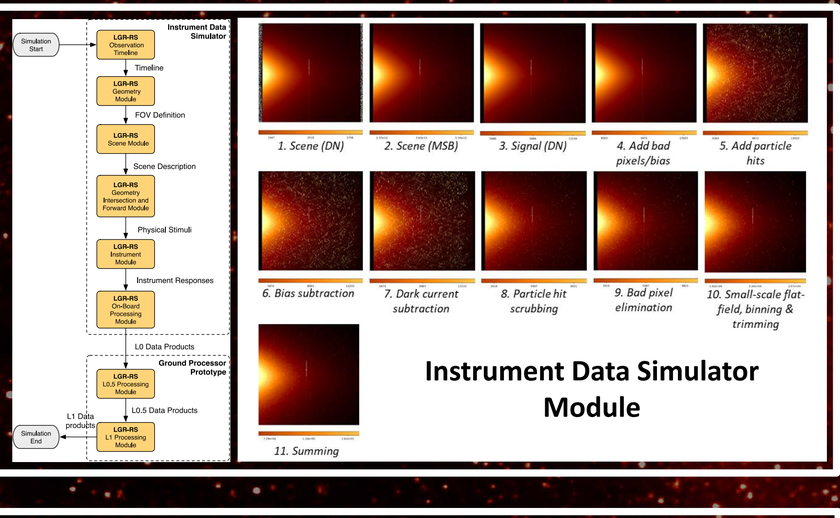
COR and HI CCD

- CCD detector selected in preference to CMOS
- Baselined 2k x 2k imaging-area CCD from e2v CCD230 family:
  - 2k x 2k full frame, FF, device
  - 2k x 4k pseudo frame-transfer, PFT, device
  - 2k x 4k true frame-transfer, TFT, device
- FF, PFT and TFT trade-off:
  - Smearing considerations less important for HI than COR
  - 2k x 4k PFT and TFT formats require enlarged detector housing
- PFT baselined, due to commonality with COR (and PUNCH)



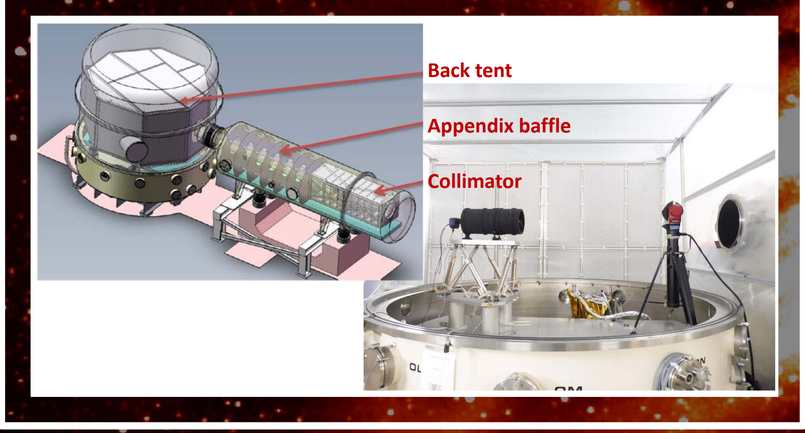
End-to-End Simulator (E2ES)

- E2ES supports definition of instrument/IPCU, flight operations and ground segment. Built on the standard Space Science E2ES Reference Architecture, tailored to required high-level architecture, and modules defined.
  - Instrument Data Simulator
  - Ground Processor Prototype
  - Performance Assessment Tool
- Prototyped for HI; being extended to the other instruments



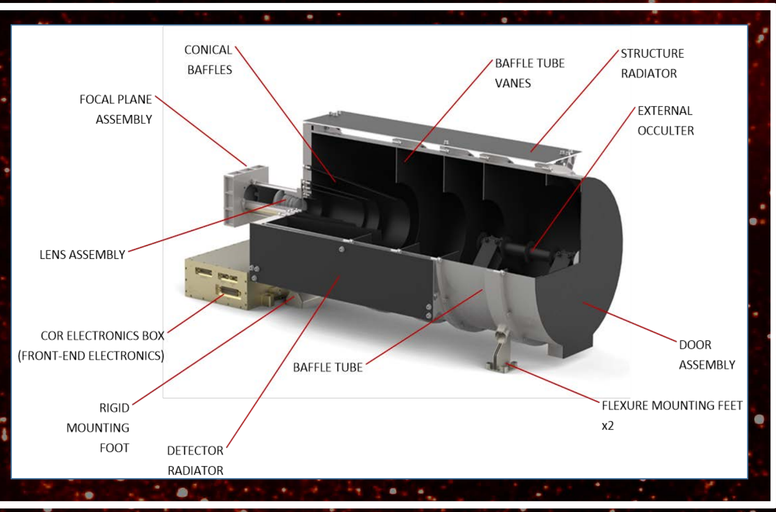
SCOPE OBB Testing at CSL

- Tested in air in Focal 3 chamber
- CSL ground-test CCD camera:
  - QS1516 (Kodak KAF-1603ME CCD)
  - 1536 x 1024 pixels (9 μm)
  - 13.8 mm x 9.2 mm
- Collimator:
  - Laser source, fold mirror and off-axis parabola
  - Produces ~380 mm diameter collimated beam (stopped down to prevent illumination of collimator front vane)
  - Source: fiber-fed 20W red (805 nm) laser diode



SCOPE: Solar Coronagraph for OPErations

- Compact coronagraph developed under ESA's GSTP programme
- Included design, manufacture and test of Optical Bread Board (OBB)
  - OBB design: RAL
  - OBB manufacture: UGOE
  - OBB testing: CSL
- No specific orbit (LEO, MEO, GEO, 1 AU)
- FOV (radial): 2.5 to 30 Rs
- 5 occulter discs
- Larger λ range
- Different baffle design



SCOPE: CSL Results

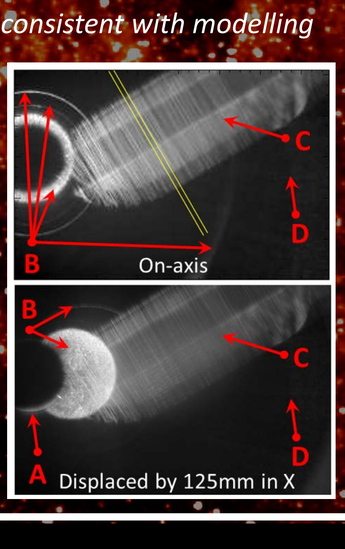
A : diffraction around occulter → *consistent with modelling*

B : facility features; large disc mirror visible to the aperture → *consistent with modelling*

C : diffraction from rough spider → *consistent with modelling*

D : diffraction from illuminated edges of conical and field-defining vanes → *consistent with modelling*

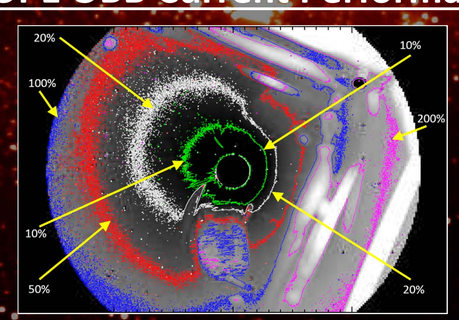
- Mitigation:
  - Smooth spider
  - Remove conical baffles (replace with heat rejection mirror for flight)
  - Replace field-defining vane with petal shape baffle
  - And retest...



SCOPE OBB Testing at RAL

- Underway in black-painted clean room
- Ex-MIRI (JWST) ground-test CCD camera:
  - Atik11000 4007 x 2671 pixels (9 μm)
  - 36 mm x 24 mm
- Anodized Bosch frame (6m long) with Thorlabs blacking sheets
- Ex-BBR calibration collimator:
  - Collimated laser, feeding a simple lens & off-axis parabola
  - Produces 100mm diameter collimated beam
  - Source: 5 mW green (532 nm) laser diode

SCOPE OBB Current Performance



- Testing shows SCOPE is performant with stray-light requirement (<20% of F+K-corona) out to ~15Rs in the region away from the spiders (there are clear limitations imposed by the facility).
- Caveats:
  - Collimator doesn't fill instrument aperture;
  - On-axis test only (Sun is ~16 arcmin in radius from 1 AU).
- Alongside other facility improvements, currently cleaning/aligning new collimator with 30 cm mirror that, when stopped down, will illuminate inner edge of petal baffle without the mirror being visible to the aperture.