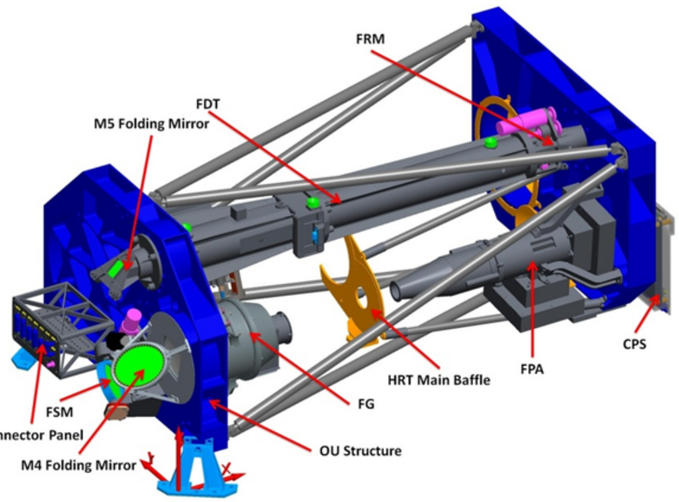
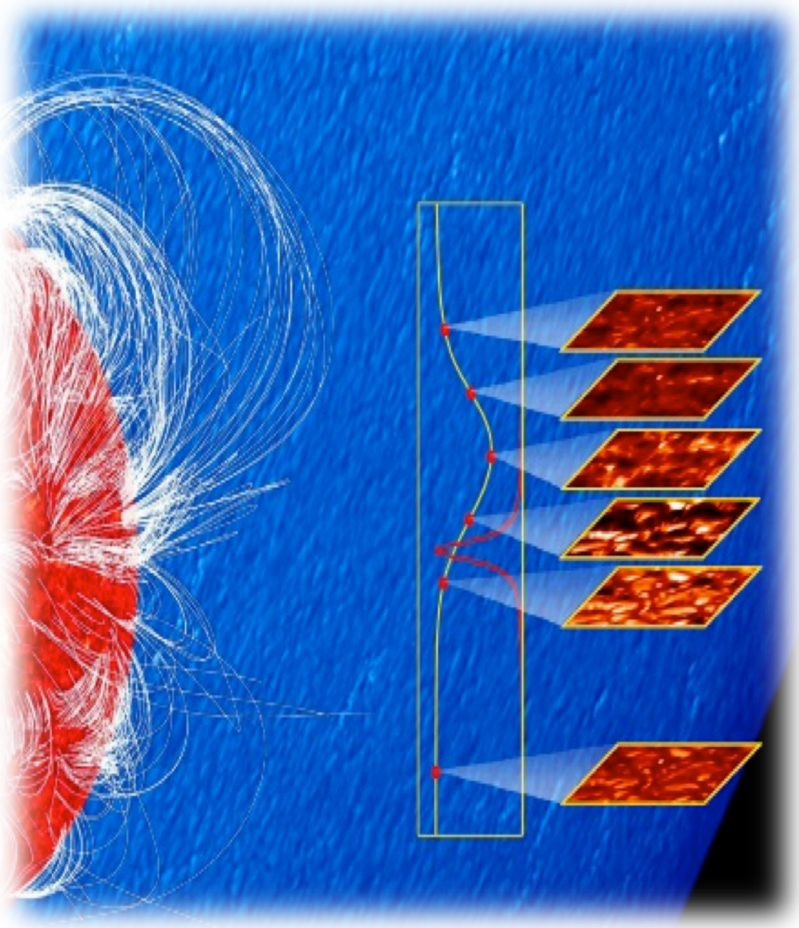
SO/PHI

The Polarimetric & Helioseismic Imager for Solar Orbiter





SO/PHI Science

- SO/PHI probes the solar interior and provides the magnetic field at the solar surface that drives transient and energetic phenomena in the solar atmosphere and the heliosphere

- Polarimetry and local helioseismology provided by SO/PHI will be central to reach 3 of the 4 top-level science goals of Solar Orbiter

- SO/PHI will be the main instrument needed to answer the top-level science question: How does the solar dynamo work and drive connections between the Sun and the heliosphere?

- SO/PHI has the capability of doing a lot of unique science that goes well beyond the official science goals of Solar Orbiter

Relevance for Science Goals of Solar Orbiter

Polarimetry and local helioseismology will be central to reach 3 of the 4 science goals of Solar Orbiter.

- *Investigate Links Between Solar Surface, Corona, and Inner Heliosphere* → measure field in photosphere, extrapolate to corona and heliosphere (partly high resolution, partly full disk; in combination with other instruments)

- *Explore, at all Latitudes, the Energetics, Dynamics, and Fine-scale Structure of the Sun's Magnetized Atmosphere* → measure field in photosphere, extrapolate to corona (high resolution; in combination)

- *Probe the Solar Dynamo by Observing Sun's High-Latitude Field, Flows, and Seismic Waves* → uninterrupted time series of velocity and B-field (partly high resolution, partly low resolution; stand alone)

SO/PHI Unique Science

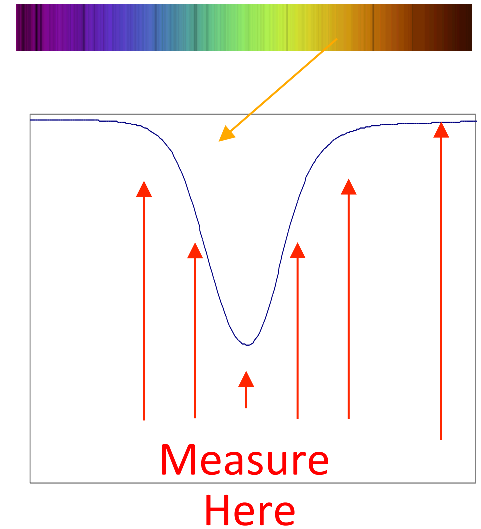
- Provide ***B*** to EUV imager and spectrometer, all observing at high spatial resolution (up to 180 km): linkage science
- First *decent* view of magnetic and velocity field at poles: trace flows and field at the surface and probe the sub-surface
- Follow surface and subsurface evolution of solar features (e.g. active regions) without changing viewing angle
- Stereoscopic helioseismology to better probe interior
- Stereoscopy of the photosphere
- Measure complete field of the Sun (360^o view)
- Provide magnetic context for Solar Probe Plus

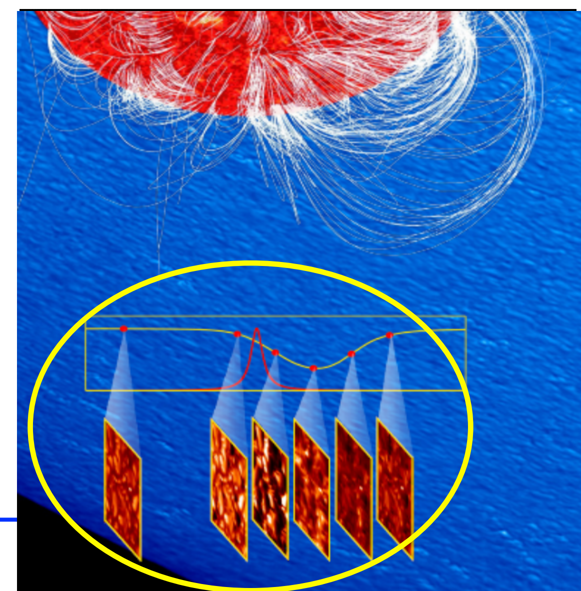
Needs instruments in Earth orbit or on the ground

Measurement Principle

- SO/PHI uses Doppler & Zeeman effects in one spectral line to achieve science goals
- It will measure 2D intensity maps at
  - 6 wavelength points within the line
  - 4 polarisation states at each λ point
- From these difference images are created
  - between opposite polarizations
  - between wavelength points

➔ PHI is a (differential) imager:
  - diffraction limited,
  - wavelength tunable,
  - quasi-monochromatic,
  - polarisation sensitive





Data Products

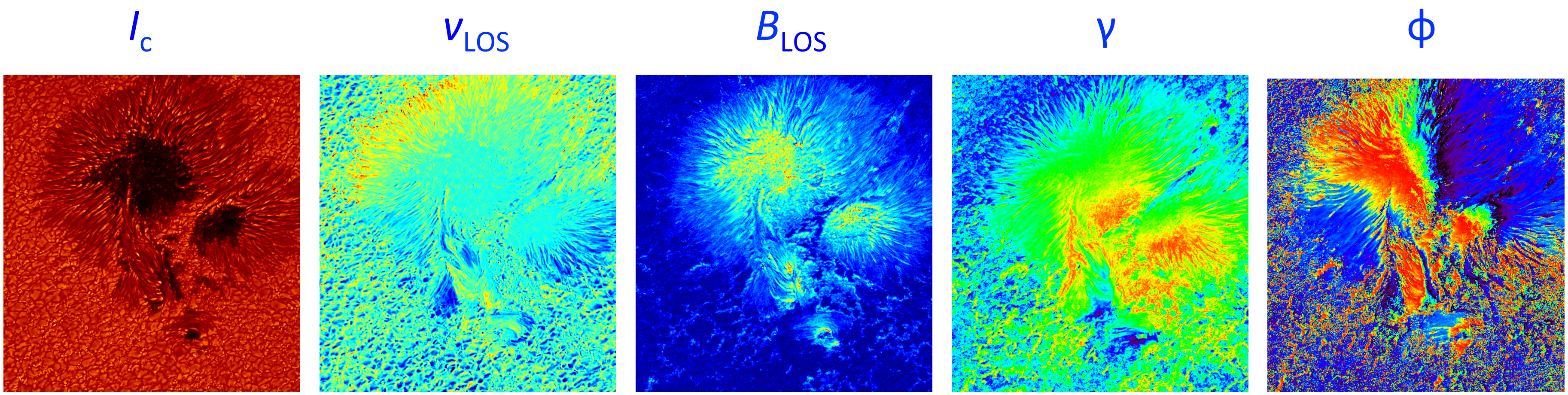
PHI data products:

- continuum intensity, I_c
- LOS velocity, v_{LOS}
- LOS magnetic field strength, B_{LOS}
- magnetic field inclination, γ
- magnetic field azimuth, ϕ

PHI requirements:

- high-resolution data (~150 km)
- full-disk data
- 2k x 2k FOV
- 1 data set per minute
- 4...5 bits (compressed) digital depth

➢ 92 Mbits per minute

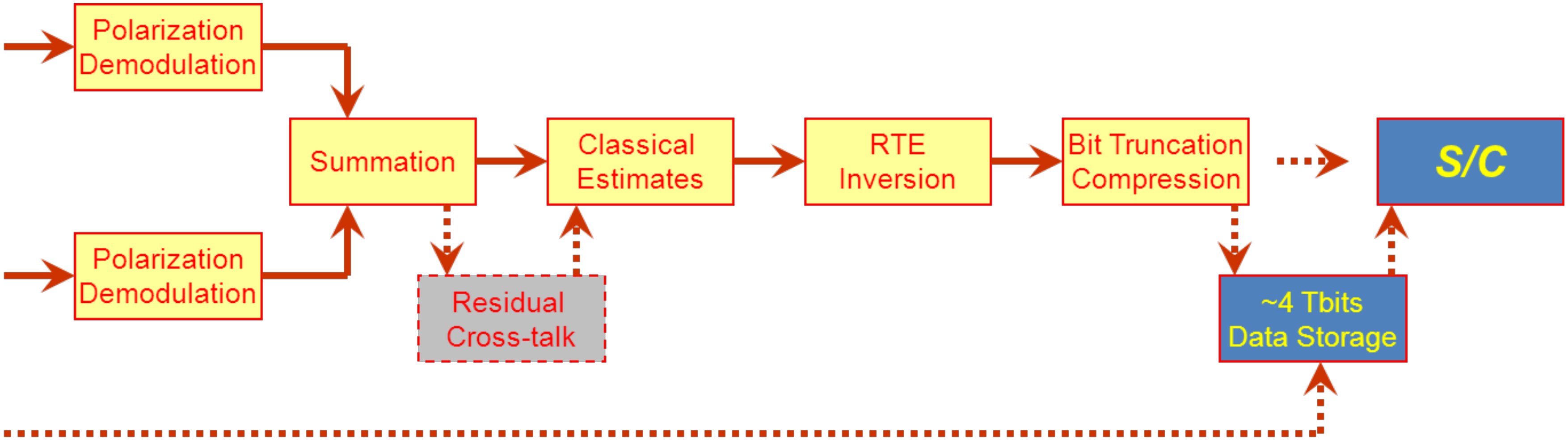


Data Products, Analysis and Compression

- SO/PHI will obtain (either at high resolution or over the full solar disk at lower resolution)
  - one set of images in all 4 Stokes parameters (differences between the polarization images) at 6 wavelengths every minute
- Produce maps of magnetic vector, velocity and continuum images (with noise level ≈ 10^{-3})
  - SO/PHI heavily constrained by telemetry
  - The tricky data reduction and processing will take place on-board (full Milne-Eddington inversion of Stokes profiles → non-linear fitting with solutions of a set of coupled differential equations)
  - This and other measures will reduce data volume by factor of 60

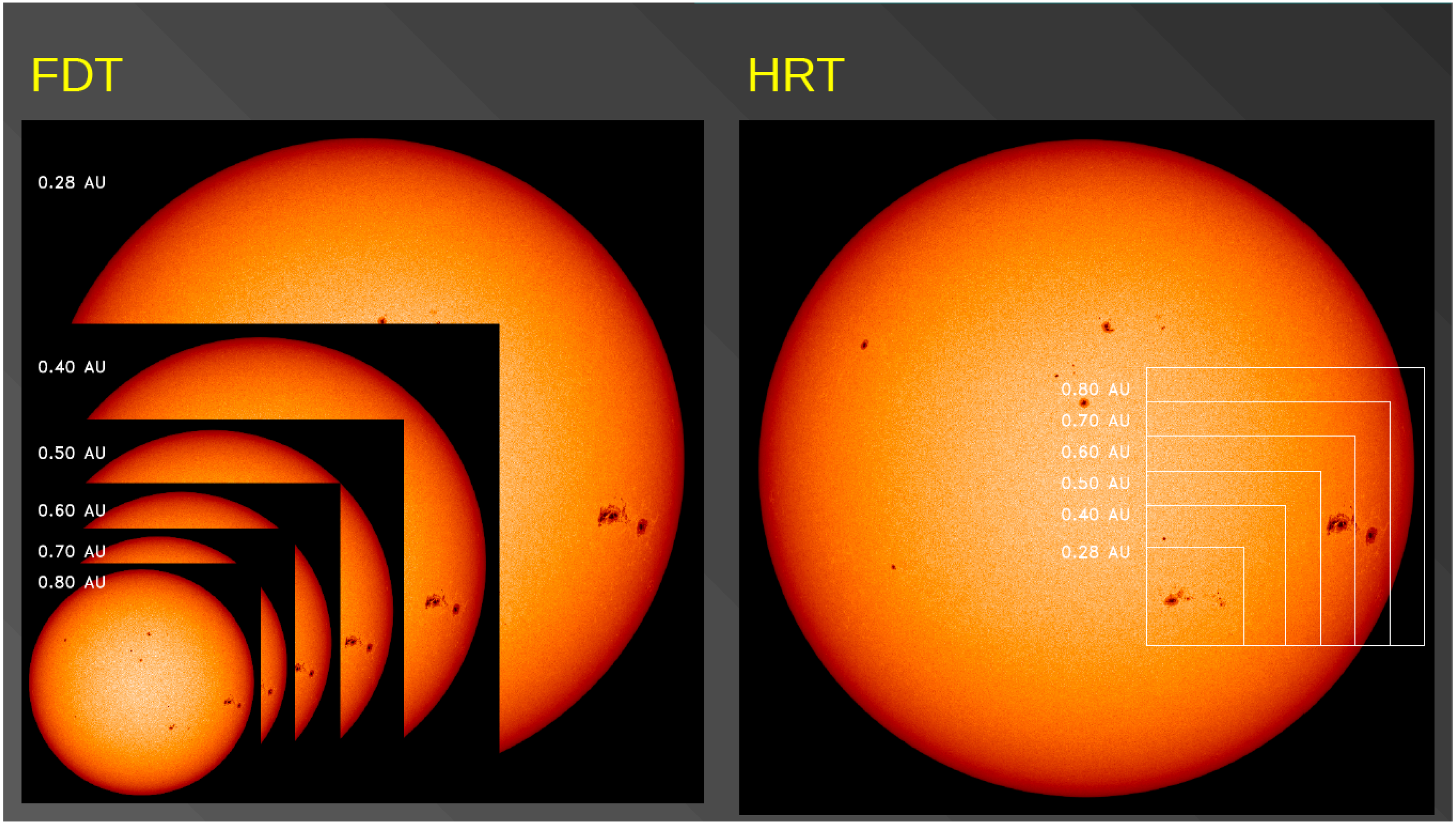
On-board Data Processing

RTE inversion Standard compression



Raw/partially processed data have to be buffered in data storage

PHI FOVs

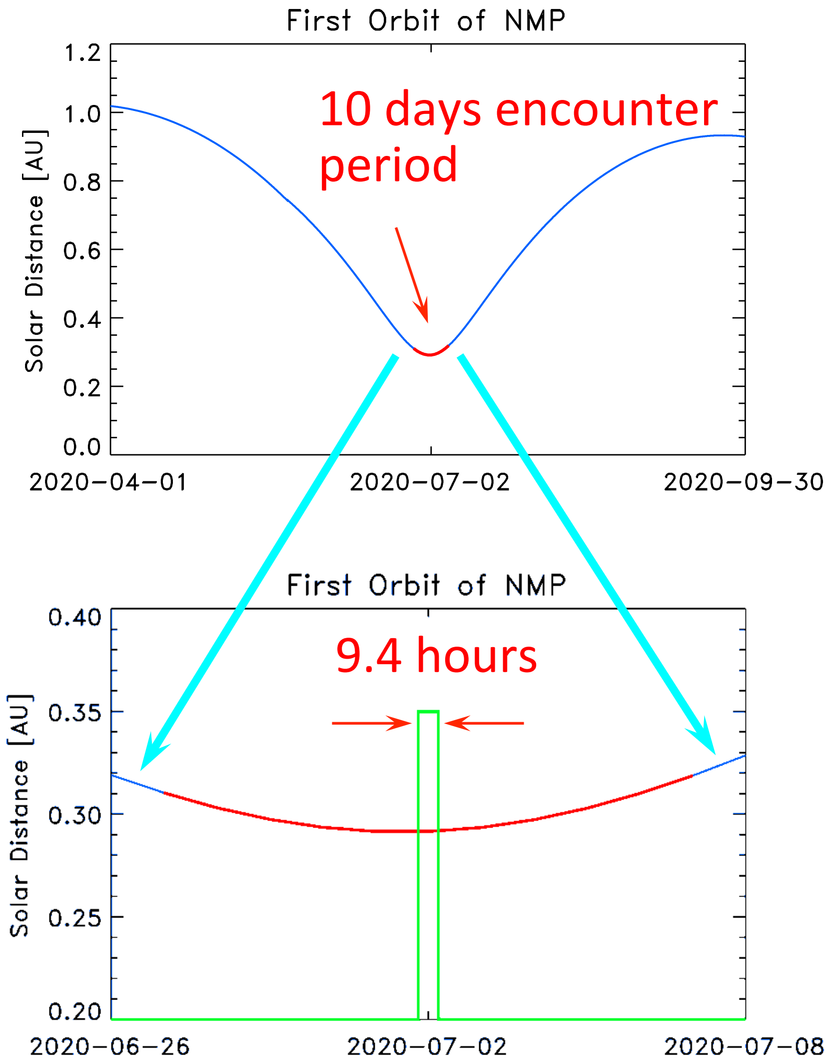

FDT
0.28 AU
0.40 AU
0.50 AU
0.60 AU
0.70 AU
0.80 AU
HRT
0.80 AU
0.70 AU
0.60 AU
0.50 AU
0.40 AU
0.28 AU

Telemetry Allocation

- PHI telemetry: 20.5 kbits/s (for 3 x 10 days)
  - ➔ 52 Gbits per orbit
  - ➔ No more than 564 data sets per orbit (92 Mbits each)

➔ Maximum of 9.4 hours operation per orbit in nominal science mode

- In order to test the procedure we will need to download a few raw data sets in each orbit



Telemetry Allocation

- PHI telemetry: 20.5 kbits/s (3 x 10 days)

Raw data :	6.14 Gbits per set
Processed data :	92 Mbits per set
Compression factor :	60...70

- 52 Gbits per orbit
- no more than 564 data sets (92 Mbits each)
- max. 9.4 hours operation per orbit when operated in the nominal science mode

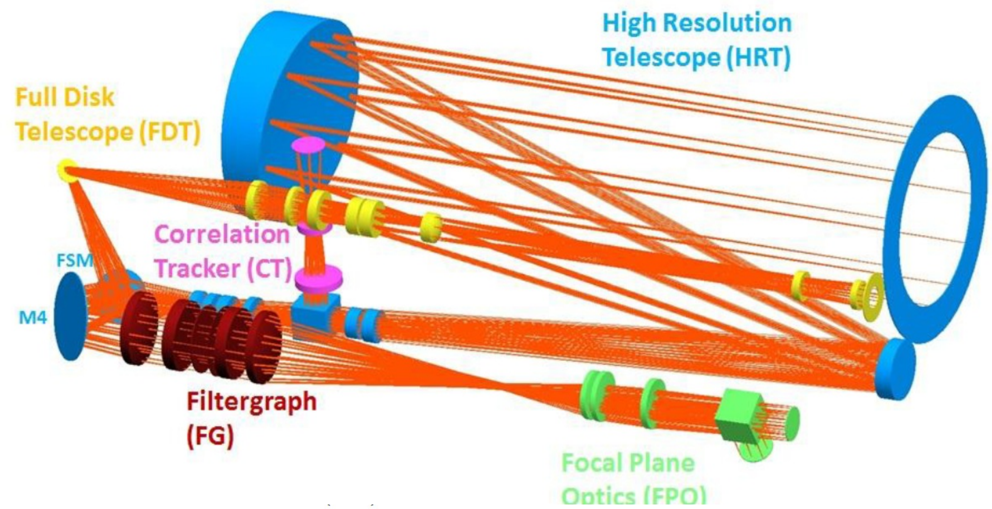
➢ Science Operation Modes with lower data rate have been defined

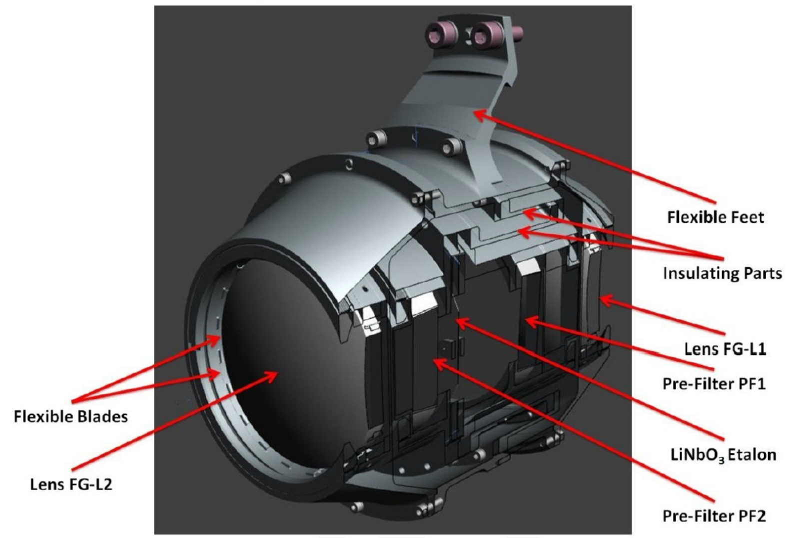
Operations – Science Modes

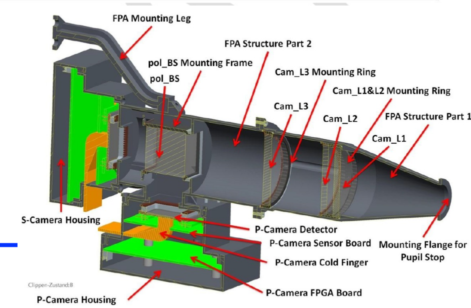
Science Mode	Description	Data Rate [kbits/s]
PHI Mode 0	Nominal Mode Full FOV (2048 x 2048 pixels), no binning, 5 quantities; cadence: 1 min^{-1}	1607
PHI Mode 1	Low resolution high cadence binning to 512 x 512 pixels; 1 physical magnitude (v_{LOS}); cadence: 1 min^{-1}	21
PHI Mode 2	Medium resolution medium cadence binning to 1024 x 1024; 3 physical magnitudes; (I_c, B_{LOS}, v_{LOS}) or (B_{LOS}, γ, φ) ; cadence 5 - 60 min^{-1}	52
PHI Mode 3	High resolution medium cadence as PHI Mode 2 but selecting a subframe (512 x 512 or 1024 x 1024) instead of binning; cadence 1 - 60 min^{-1}	261
PHI Mode 4	Context full frame (2048 x 2048); 3 magnitudes (B_{LOS}, γ, φ) or (I_c, B_{LOS}, v_{LOS}); cadence: 5 min^{-1}	181
PHI Mode 5	Global helioseismology/synoptic observations 128x128 pixels or 256 x 256 pixels; v_{LOS} and I_c; cadence: 1 min^{-1}	<5
PHI Mode 6	Daily context one full set of parameters per day (4 bits per quantity); <1024 x 1024 pixels depending on orbital position	<0.25
PHI Mode 7	PHI burst mode Triggered by STIX; most likely fast continuum images	TBD

Instrument Concept

- FDT as refractor
- HRT as oblique reflector
- Feed selection mechanism
- Fabry Perot narrow-band filter with $LiNbO_3$ etalon
- Polarisation modulation with liquid crystal variable retarders
- one 2k x 2k APS detector
- Image stabilization system (Correlation Tracker)

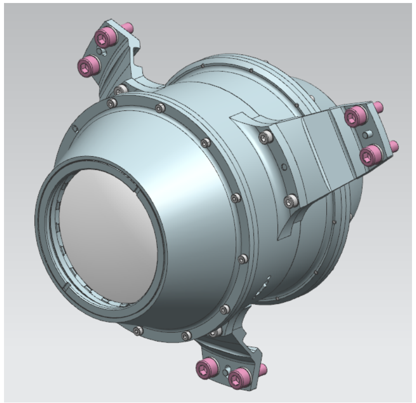


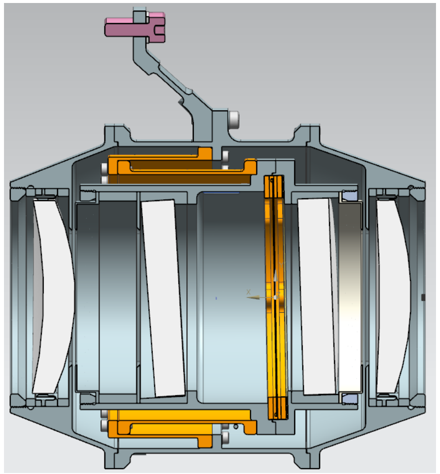




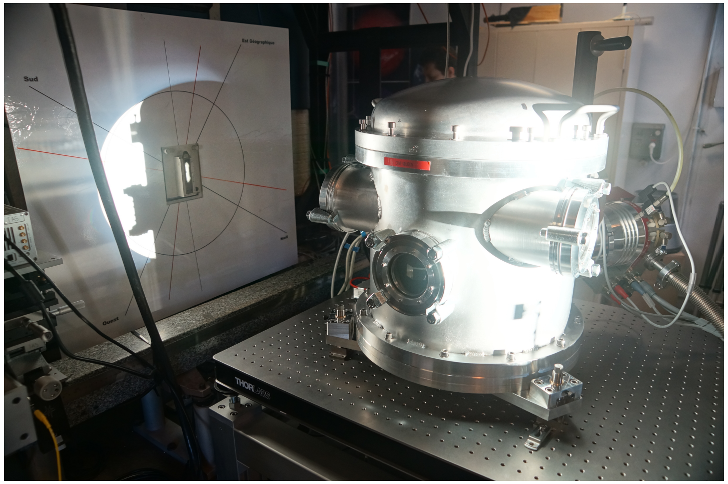
Role of IAS: Filtergraph

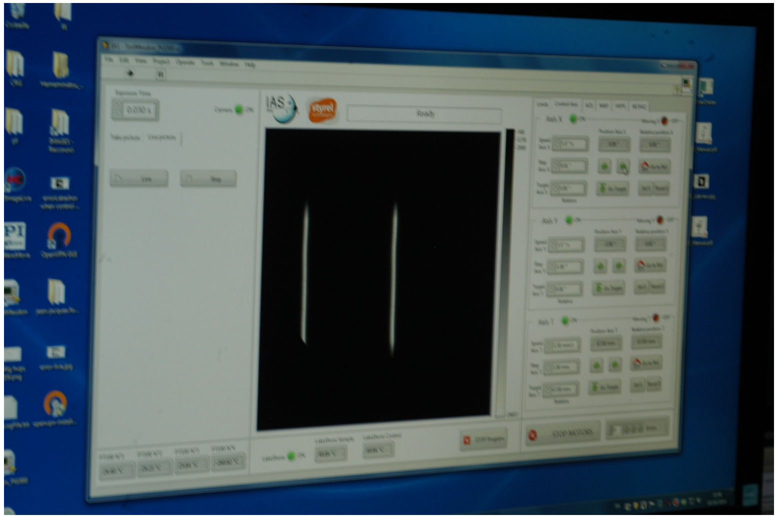
- Composed of five optical components
  - 2 lenses, and one etalon (MPS procurement)
  - 2 prefilters (IAS procurement)
- Design goals
  - Thermal gradients
    - lower than 1°C on the narrow band prefilter
    - lower than 0.1°C on the Lithium Niobate etalon
  - Thermal stabilization
    - 1°C on the narrow band prefilter
    - 30 mK rms over 30 minutes for the etalon
- Integration, qualification and calibration by IAS





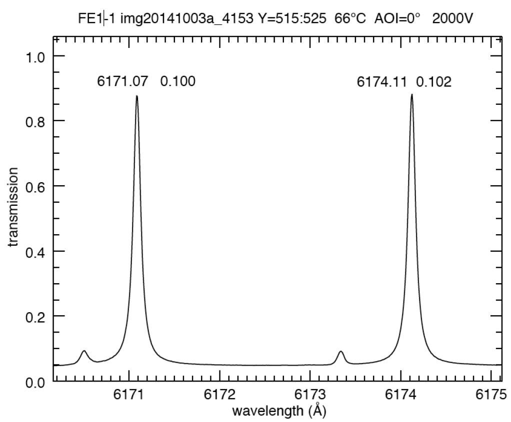
Calibration at the Meudon *Tour Solaire*

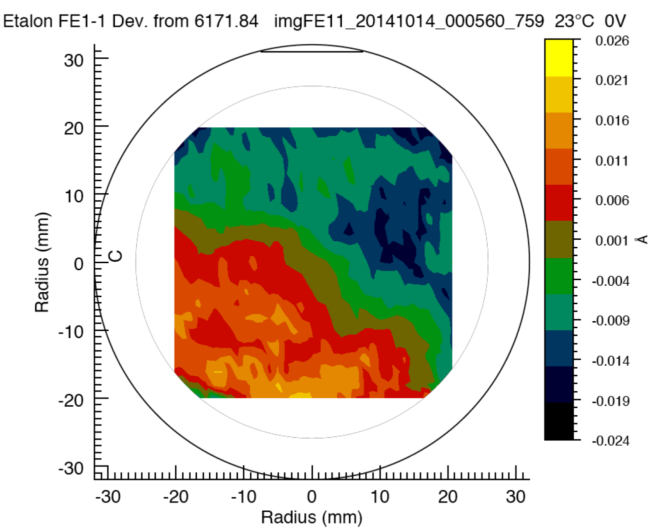




Filtergraph: On ground Optical Testing

- Optical calibrations of the FG to be done at IAS under air and/or vacuum.
- Transmission and tilt measurements of each optical component separately
- Etalon thickness map measured between 50°C and 70°C
- Etalon H/V Sensitivity Calibration : λ as a function of high voltage
- FG angular sensitivity calibration : λ as a function of tilt angle
- FG wavelength temperature stability





Summary

- Provide ***B*** to EUV imager and spectrometer, all observing at high spatial resolution (up to 180 km): linkage science
- First *decent* view of magnetic and velocity field at poles: trace flows and field at the surface and probe the sub-surface
- Follow surface and subsurface evolution of solar features (e.g. active regions) without changing viewing angle
- Stereoscopy: helioseismology and photosphere
- IAS involved in integration, qualification and calibration of the main subsystem: the Filtergraph
- IAS involved in on-board calibration and data reduction

Operations – Calibration

Dark field calibration	
FDT calibration	- exposure time - focus position - flat field - polarimetry (LCVRs) - spectral tuning (FG)
ISS calibration	- exposure time - focus position - flat field - actuator gains
HRT calibration	- exposure time - focus position - flat field - polarimetry (LCVRs) - spectral tuning (FG)
Data processing pipeline calibration	

Operations – Commissioning

LEOP: No Operations, No decontamination heaters

NECP: Basic functionality check

Phase	Operation	Duration	Power	Telemetry
LEOP	▪ Instrument is off			
NECP	▪ Switch on engineering mode ▪ Basic housekeeping telemetry and commanding check ▪ Take images of all detectors and download ▪ Check mechanisms ▪ Check FDT & HRT LCVR voltages ▪ Check tip-tilt actuator voltages ▪ Check etalon HVPS ▪ Re-write FPGA firmwares (tbc)	2 days	nominal	Up/downlink

No S/C operations required !

Operations – Commissioning (cont.)

CP: Instrument commissioning at two solar distances (0.8 AU and 0.5 AU) in order to re-adjust thermal behaviour

Phase	Operation	Duration	Power	Telemetry
CP	▪ Switch on engineering mode, housekeeping ▪ Heaters on, thermal re-adjustment. ▪ Dark field calibration, check thumbnails ▪ FDT full commissioning/calibration ▪ HRT full commissioning/calibration ▪ ISS full commissioning/calibration ▪ Test observations, commissioning of data processing pipeline	7 days each	nominal	Up/downlink

S/C operations: - Instrument doors

- S/C off-pointing manoeuvres (FDT flat field, calibration)

Operations – Pre-encounter Calibration

NMP, EMP: Instrument re-calibration prior to each encounter period

Phase	Operation	Duration	Power	Telemetry
NMP EMP	▪ Switch on engineering mode, housekeeping ▪ Heaters on, thermal re-adjustment. ▪ Dark field re-calibration ▪ FDT re-calibration ▪ HRT re-calibration ▪ ISS re-calibration ▪ Test observations, check data processing pipeline	1 day each	nominal	Up/downlink

S/C operations: - Instrument doors

- S/C off-pointing manoeuvres (FDT flat field, calibration)

Overview - Team

Institutes with prime HW and/or SW contribution
Max-Planck-Institut für Sonnensystemforschung (MPS) Katlenburg-Lindau, Germany
Kiepenheuer Institut für Sonnenphysik (KIS), Freiburg, Germany
Institut für Datentechnik und Kommunikationsnetze (IDA), Braunschweig, Germany
Instituto de Astrofísica de Andalucía, (IAA), Granada, Spain
Instituto Nacional de Técnica Aeroespacial (INTA), Madrid, Spain
Instituto de Astrofísica de Canarias (IAC), La Laguna, Tenerife, Spain
Instituto Universitario de Microgravedad "Ignacio Da Riva", Universidad Politécnica de Madrid (IDR), Madrid, Spain
Grupo de Astronomía y Ciencias del Espacio, Universidad de Valencia, (GACE), Valencia, Spain
Universidad de Barcelona (UB), Barcelona, Spain
Institute D'Astrophysique Spatiales (IAS), Paris, France

NSO

LMSAL

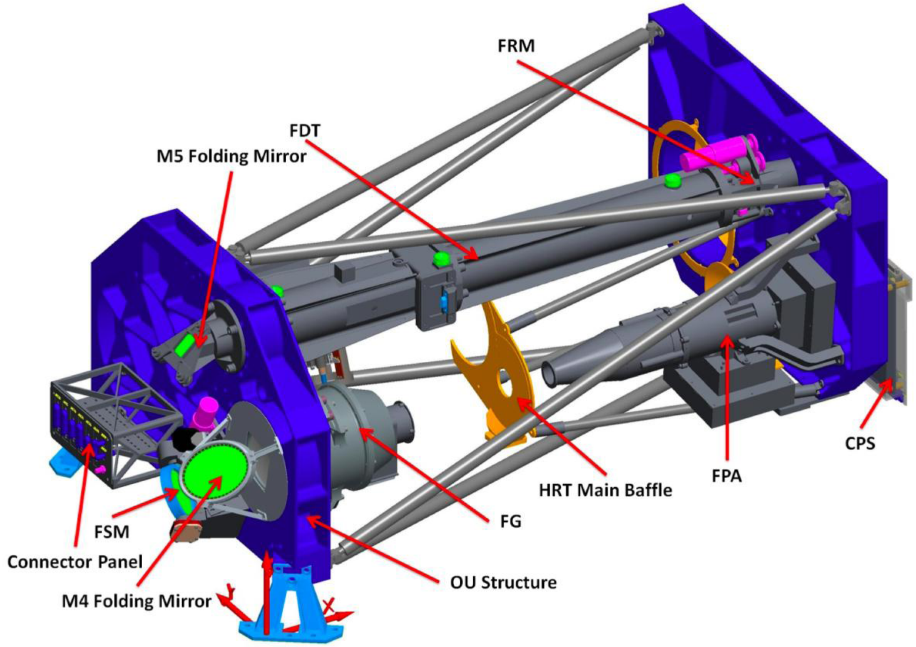
HEPL

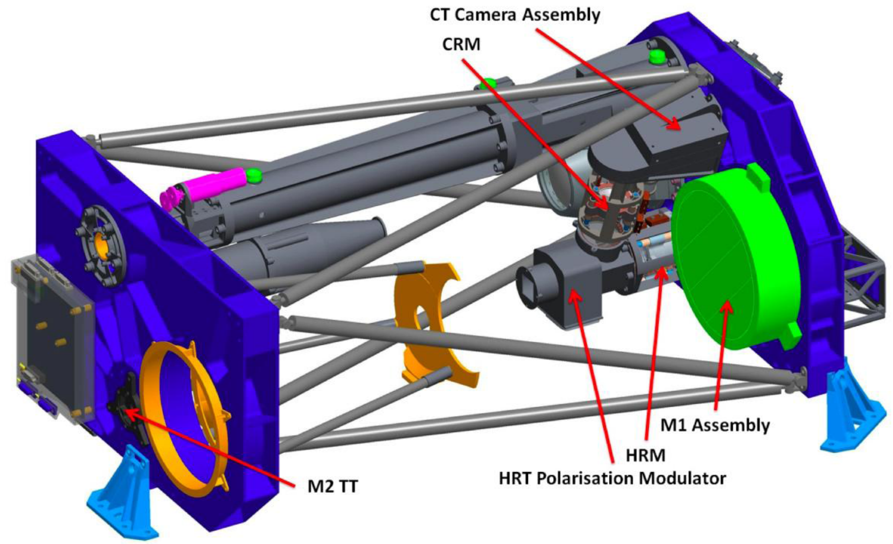
CSPA

Model Philosophy and AIT

PHI Optics Unit Assembly & Integration

(shown w/o MLI)

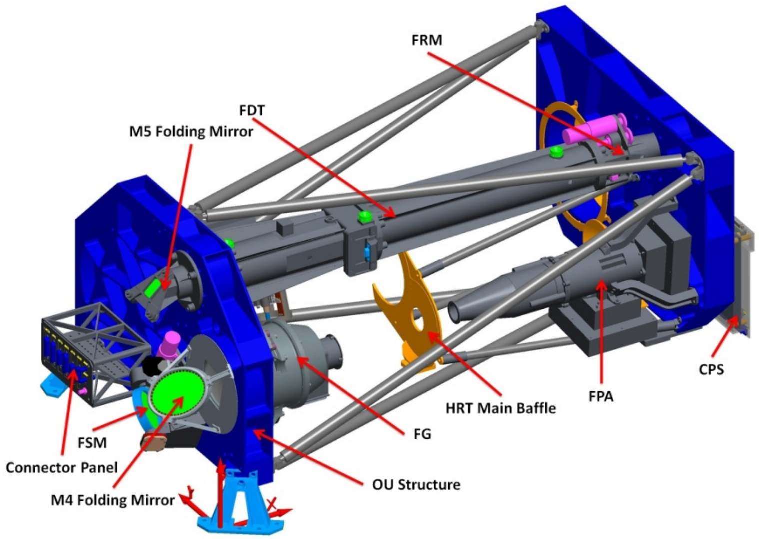


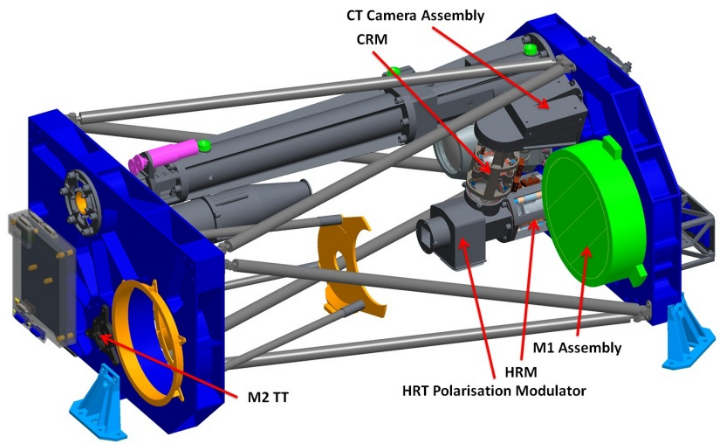


Design Description – Optics Unit Structure

Design Principles

- High stiffness @ low mass
- Reduced sensitivity to thermal environment especially in length direction
- Concentration of subsystems/ subassemblies and thus mass at both unit ends to simplify structural concept





Filtergraph: Breadboard Assembly