SO/PHI

The Solar Orbiter
Polarimetric and Helioseismic Imager

and the SO/PHI Team
The Solar Orbiter Mission

**min. perihelion:** 0.28 AU
**max. solar latitude:** ~34°
**baseline launch:** July 2017
**backup launch:** October 2018

**Cruise Phase:** ~ 35 months [38 months for October 2018 launch]
**Nominal Mission Phase:** 10 orbits (~7 years) [ 8 orbits for October 2018 launch]
**Extended Mission Phase:** 6 orbits (~2.5 years) [ 8 orbits for October 2018 launch]
The Solar Orbiter Payload

Heat shield (max >10 Solar constants)
Instrument boom
5 in-situ instruments
5 remote sensing instruments
| Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, D |
| Kiepenheuer-Institut für Sonnenphysik, Freiburg, D |
| Institute of Computer and Communication Engineering, Braunschweig, D |
| Instituto Nacional de Técnicas Aeroespacial, Madrid, E |
| Instituto de Astrofísica de Canarias, La Laguna, E |
| Instituto de Astrofísica de Andalucía, Granada, E |
| ETSI Aeronáuticos, Madrid, E |
| Dep. d’Electrònica Facultat de Física, Uni. de Barcelona, E |
| Grupo de Astronomía y Ciencias del Espacio, Valencia, E |
| Institut d’Astrophysique Spatiale, Paris, F |
SO/PHI science

SO/PHI will probe the solar interior and provide 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 Solar Orbiter top-level science question: How does the solar dynamo work and drive connections between the Sun and the heliosphere?
SO/PHI Science

Q1: How and where does the solar wind plasma and magnetic field originate in the corona?

Q2: How do solar transients drive heliospheric variability?

Q3: How do solar eruptions produce energetic particle radiation that fills the heliosphere?

Q4: How does the solar dynamo work and drive connections between the Sun and the heliosphere?

Q5: PHI stand-alone science goals:
- What is the nature of magnetoconvection?
- How do active regions and sunspots evolve?
- What is the global structure of the solar magnetic field?
- How strongly does the solar luminosity vary and what is the source of these variations?
Atmospheric Coupling

SO is designed to probe the Sun from its interior up to the heliosphere.

SO with both remote sensing and in-situ measurements aims to address the largely unsolved problems of the origin of the solar wind as well as transport phenomena in the heliosphere.

SO/PHI will provide the photospheric magnetic field structure, i.e. an essential boundary condition needed to achieve these goals.

Marsch et al., 2004
Stereoscopy and Global Sun

SO’s trajectory will allow doing Stokes stereoscopy, i.e. determining Stokes profiles of a feature from two different directions. Allows resolving the 180° ambiguity of Zeeman effect.

Vantage points far from Earth allow for near instantaneous 4π magnetic maps.

Tadesse et al., 2014

HMI movie: 4.-17.9.2014
Near Co-rotation and Global Sun

SO’s close perihelion transits enables to follow surface structures for more than half of a rotation period, i.e. up to 23 days.

Vantage points far from Earth allow for near instantaneous $4\pi$ magnetic maps.
Polar Science

Polarimetric and dynamic studies of the solar polar regions from the ecliptic plane suffer from geometric foreshortening. SO/PHI will be the first polarimeter looking at the poles from a heliographic latitude > 7°

Tsuneta et al., 2008
Operations (I)

Science Phases (NMP, EMP):
3 Remote Sensing Windows (10 days each) per orbit: perihelion, min. and max. latitude (tbd)

Cruise Phase:
2 instrument check-outs per year

NECP:
Instrument commissioning

LEOP:
SO/PHI is off
Outside RSW SO PHI will carry out onboard data analysis:
⇒ Raw data have to be kept in memory (4 Tbits internal memory size)
⇒ Post-facto data selection for an efficient use of limited Telemetry
⇒ Baseline concept, however, disallows long-term observations
SO/PHI Measurement Principle

PHI is a tunable imaging filtergraph:

- Scans over a magnetic sensitive photospheric absorption line (Fe I 617.3nm)
- Narrow-band filtergrams at 6 spectral positions
- Full polarimetric information
- On-board data processing & inversion
SO/PHI Measurement Principle (II)
**SO/PHI Primary Observables**

Full Stokes maps at 6 wavelength positions:

<table>
<thead>
<tr>
<th></th>
<th>-400</th>
<th>-160</th>
<th>-80</th>
<th>0</th>
<th>80</th>
<th>160</th>
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<tr>
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<td><img src="image1.png" alt="Image" /></td>
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<td><img src="image21.png" alt="Image" /></td>
<td><img src="image22.png" alt="Image" /></td>
<td><img src="image23.png" alt="Image" /></td>
<td><img src="image24.png" alt="Image" /></td>
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</table>

after onboard data calibration and polarimetric demodulation!
SO/PHI Data Products

### PHI data products:

<table>
<thead>
<tr>
<th></th>
<th>Dynamic range</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>continuum intensity, $I_c$</td>
<td>-</td>
<td>$\leq 10^{-3}$</td>
</tr>
<tr>
<td>LOS velocity, $v_{\text{LOS}}$</td>
<td>$\pm 5 \text{km/s}$</td>
<td>$\leq 40 \text{m/s}$</td>
</tr>
<tr>
<td>LOS magnetic field strength, $B_{\text{LOS}}$</td>
<td>$\pm 3.5 \text{kG}$</td>
<td>15 G</td>
</tr>
<tr>
<td>magnetic field inclination, $\gamma$</td>
<td>180°</td>
<td>1°</td>
</tr>
<tr>
<td>magnetic field azimuth, $\varphi$</td>
<td>$\pm 180°$</td>
<td>2°</td>
</tr>
</tbody>
</table>

### PHI requirements:
- high-resolution data
- full-disk data
- 2k x 2k FOV
- 1 data set per minute
SO/PHI Field of Views

Two Telescopes:

Full Disk Telescope:
- FoV ~ 2°
- Resolution ~3.5 arcsec per pixel
- Full disk at all orbit positions
- 17 mm aperture diameter

High Resolution Telescope:
- FoV ~ 16 arcmin
- Resolution: 0.5 arcsec per pixel
- Resolution: ~200 km at closest perihelion
- 140 mm aperture diameter
SO/PHI Functional Diagram (simplified)

2 Entrance windows
2 Telescopes
4 Mechanisms
1 Active mirror
2x2 Tunable LCVRs
1 Tunable etalon
2 APS cameras
SO/PHI – Some pictures

PHI optics unit

PHI Filtergraph

PHI electronics

PHI entrance window
SO/PHI Design – Optics Unit

- 2 AlBeMet main blocks
- 6 low CTE CFRP struts
- Al honeycomb baseplate
- Total volume: 30 x 40 x 80 cm
- Total mass: 35 kg

- HRT: off-axis Ritchey-Chrétien telescope
- FDT: off-axis refractor
- Polarization Packages: based on Liquid-Crystal Variable Retarders (LCVRs)
- Filtergraph: transfer-optics with LiNbO$_3$ solid state etalon and interference filters
- Image stabilization: 30 Hz Correlation Tracker
- Focal Plane: 2k / >10fps APS detector
SO/PHI Design – Electronics Unit

High Voltage Power Supply
Analog Motor and Heater Drivers
Tip-Tilt Controller & Memory Board
Digital Processing Unit
Power Converter Modules (redundant & main)

PCM top-view
New and Critical Technologies

- Line scanning: first ever solid-state etalon in space (LiNbO$_3$)
- Polarization modulation: space-qualification of LCVRs for SO
- Science detector: custom made APS sensor development
- Heat rejection windows: optical/polarimetric performance between 0.28 and 0.9 AU
- Data processing:
  - use of powerful reconfigurable FPGAs
  - autonomous onboard calibration and data processing (including inversion)

Most critical issue:
Low Telemetry: 6.4 GBytes per orbit ≈ 100 GBytes over entire mission lifetime
Conclusions

• SO/PHI is an extremely complex instrument on a highly ambitious space mission.

• SO/PHI has incorporated a series of new technologies which have to be functionally proven

• SO/PHI is an essential instrument to achieve the SO science goals - the SO/PHI instrument concept and design allows addressing a number of fundamental problems in solar physics

• The current status of SO/PHI is solid, however, schedule issues have to be tackled

• The entire SO mission suffers from the extremely limited telemetry. SO/PHI is one of the most telemetry starved instrument of the scientific payload. Additional telemetry has been requested
23 - 10 = 13 SLIDES

REDUCE TO 10-12!!!!
BUT FIRST CHECK AVAILABLE TIME
The Solar Orbiter Spacecraft

Spacecraft:
- Spacecraft bus with power supply (solar panels) and telemetry system (retractable high-gain antenna)
- Heat shield (>9 solar constants per m²)
- Instrument boom

Payload:
- 5 in-situ instruments
- 5 remote sensing instruments
Observations from a vantage point in the ecliptic does not allow probing solar latitudes higher than ~70°. SO/PHI observations from out of the ecliptic will help to accomplish the unsolved problems of, e.g., the solar dynamo.

Stereoscopic Helioseismology

Probing the Sun from different vantage points may allow for probing deeper layers than what is possible with only one instrument.
### SO/PHI Nominal Observations Mode

<table>
<thead>
<tr>
<th>Telescope</th>
<th>FDT</th>
<th>HRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image size</td>
<td>2048 x 2048</td>
<td>2048 x 2048</td>
</tr>
<tr>
<td>Resolution</td>
<td>3.5”/pixel</td>
<td>0.5”/pixel</td>
</tr>
<tr>
<td>Cadence</td>
<td>60s</td>
<td>60 s</td>
</tr>
<tr>
<td>Parameters</td>
<td>$I_c, B_{\text{LOS}}, \gamma, \phi, v_{\text{LOS}}$</td>
<td>$I_c, B_{\text{LOS}}, \gamma, \phi, v_{\text{LOS}}$</td>
</tr>
</tbody>
</table>
| Digital depths | 10 bits ($I_c, B_{\text{LOS}}, v_{\text{LOS}}$), 8 bits ($\gamma, \phi$) |}

- Each data set requires $2048^2 \times 46 = 184$ Mbits
- Compression by a factor of 2 gives 92Mbits per data set
- Telemetry allocation allows only for ~500 data sets per orbit!

In addition SO/PHI requires:
- Calibration data
- Raw data (sporadic)
- Overhead (file headers, housekeeping, etc.)
Science Prospects

Owing to the low telemetry and the baseline operation concept (only 3 Remote Sensing Windows per orbit) the achievement of the SO science goals will be highly insecure:

- Progress on the dynamo requires long-term/high-cadence observations (feature tracking, helioseismology)
- Solar wind/heliospheric science requires long term synoptic observations

The variable environment along the orbit will require additional effort and resources for instrument calibration, which will stress the limited telemetry allocation:

- Re-calibration intervals will be short (at least prior to each RSW)
- Onboard data processing requires ground checks of calibration results
- Sporadic downlink of raw data will secure smoothness onboard data processing and will allow for advanced processing procedures
SO/PHI Synoptic Mode - proposed

- Full-disk data sets:
  - Continuum intensity
  - Magnetic field vector
  - Dopplergram (tbc)
- 1-4 data sets per day or longitude interval
- 1k x 1k maximum size (rebinning for d < 0.5 AU)
SO/PHI Helioseismology - proposed

High-cadence (~1 min)
Dopplergrams interlaced by synoptic observations

Time series: 1 - 100 days (and more) 80-90% duty cycle

Image sizes between 128 x128 and 2048 x 2048 pixels

Global (full-disk) and local (high-resolution) helioseismology observations intended

Most efficient data compression strategy is under investigation

(e.g. Löptien et al. 2014)
Heat Rejection Entrance Windows

Sun

PHI

IR shield

617nm lo-pass

617nm hi-pass

UV mirror

HRT-HREW STM2

space-side temperature model at perihelion
Filtergraph

Line scanning device based on a solid state Fabry-Pérot etalon

FWHM = 90mÅ
Free spectral range = 3.0Å
~1nm surface roughness
~10nm absolute thickness tolerance

T-stability: <0.1K on etalon
66°C operating temperature
1.5 W heater power

• 2 optical windows (lenses, ITO coated)
• 2 interference filters (order sorter, IR blocker)
• 1 LiNbO₃ etalon
• Oven (active thermal control)
• HV connection
Focal Plane Assembly

- 2k x 2k read-out at > 10fps
- FWC: 100ke⁻ (<1% linearity)
- Actively cooled sensor (cold element) => dark noise: ~100 e⁻/s per pixel
- Automatic Single Event Upset (SEU) recovery
- Automatic sensor Single Event Latch-up (SEL) detection and recovery (sensor power cycle)
Digital Processing Unit

Tasks:
- Instrument control
- Science data Acquisition with >10 fps
- Correlation Tracker control
- Onboard data calibration
- Onboard data inversion
- 4 Tbits flash memory control
- Commanding/Telemetry

Most critical items:
2 reconfigurable FPGAs for onboard data analysis, image acquisition and CT control
On-board Data Processing

Data Pre-Processing:

- **FPA**
  - Image Accumulation
  - Flat & Dark Correction
    - Pixel Binning
    - PSF Deconvolution
    - Additional Correction
  - Polarization Demodulation
    - Cross-talk Correction

- **Standard data pipeline**
- **Optional processing steps**
- **Additional paths (calibration, commissioning, etc.)**
On-board Data Processing (contd.)

Inversion and Compression:

1. Classical Processing
2. RTE
3. Bit truncation Compression
4. Telemetry Packetting
5. S/C
6. 4 Tbit Flash memory

Flowchart:
- Classical Processing → RTE → Bit truncation Compression → Telemetry Packetting → S/C
- 4 Tbit Flash memory → RTE → Classical Processing

Diagram notes:
- "Inversion and Compression" as a title
- "On-board Data Processing (contd.)" as a subtitle
Solar Orbiter Science Cases

Q1: How and where does the solar wind plasma and magnetic field originate in the corona?

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