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The Solar Orbiter Mission and its Polarimetric and Helioseismic Imager (SO/PHI)

Achim Gandorfer[1], Sami K Solanki[1], Joachim Woch[1], Valentin Martínez Pillet[2,3], Alberto Álvarez Herrero[3] and Thierry Appourchaux[4]

[1] Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Straße 2, D-37191 Katlenburg-Lindau, Germany
[2] Instituto de Astrofísica de Canarias, C/ Vía Láctea, s/n, E38205 - La Laguna (Tenerife), Spain
[3] Instituto Nacional de Técnica Aeroespacial, E-28850, Torrejón de Ardoz, Madrid, Spain
[4] Institut d'Astrophysique Spatiale, CNRS-Université Paris XI UMR8617, 91405 Orsay Cedex, France.

E-mail: `gandorfer@mps.mpg.de`

Abstract. We briefly outline the scientific and instrumental aspects of ESA's *Solar Orbiter* mission. Special emphasis is given to the Polarimetric and Helioseismic Imager, the instrument with the highest relevance for helioseismology applications, which will observe gas motions and the vector magnetic field in the photosphere at high spatial and temporal resolution.

1. Introduction

Solar Orbiter will be hopefully selected in 2011 and finally launched in 2017. Then the mission will be Europe's follow-up of the successfull SoHO observatory of ESA and NASA. Like SoHO, *Solar Orbiter* will not be particularly focussed on Helioseismology, but the mission will offer unique opportunities to study surface flows and to probe the solar dynamo. *Solar Orbiter* is more than a pure helioseismology mission: it is an integrated and complete approach to heliophysics in all senses: As an encounter mission it takes unique advantage of its orbit design. Approaching the Sun as close as 0.28 AU, and reaching heliographic latitudes of up to 34°, its suite of instruments will combine remote sensing techniques (typical for observatory like missions) with in-situ analysis of the inner heliosphere.

2. Science Goals

The fundamental science questions, around which *Solar Orbiter* is designed, can be listed as follows:

- How and where do the solar wind plasma and magnetic field originate in the corona?
- How do solar transients drive heliospheric variability?
- How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive the connections between the Sun and heliosphere?

In order to be able to answer these scientific goals *Solar Orbiter* needs to address the following science targets, namely

- to determine in-situ the properties and dynamics of plasma, fields and particles in the near-Sun heliosphere
- to investigate the detailed structure of the Sun's magnetised atmosphere
- to identify the links between activity on the Sun's surface and the resulting evolution of the corona and inner heliosphere, especially during solar co-rotation passes
- to observe and characterise the Sun's polar regions and equatorial corona from high latitudes.

3. Mission Profile

Solar Orbiter draws its unique capabilities by taking particular advantage of its special orbit characteristics.

3.1. Orbit Design

After separation from the launch vehicle, *Solar Orbiter* will start its three-and-a-half year transfer orbit. Subject to a first Gravity-Assist-Manouvre (GAM) at Venus, and two subsequent GAMs at Earth, the spacecraft will lose orbital energy, which allows *Solar Orbiter* to come close to the Sun. After a second GAM at Venus, *Solar Orbiter* begins its operational phase. From then on its orbit is in a three-to-two resonance with Venus, such that after each third orbit the inclination of the orbital plane with respect to the ecliptical plane can be increased by Venus gravity assists. This particular and unique feature gives *Solar Orbiter* access to the high latitude regions of the Sun.

While the in-situ instrument suite will be operational over the full orbit, the remote sensing instruments will be used in three distinct science phases per orbit, the perihelion passage, and the phases of maximum and minimum solar latitude.

The perihelion passage harbours the unique potential of a corotating vantage point, from which *Solar Orbiter* can follow the evolution of surface structures and solar features not only from close-by, but in addition under practically unchanged geometrical viewing conditions for several days.

This will allow the orbiter to fullfill its prime science goal, to study the magnetic coupling of the different layers of the solar atmosphere from below the surface, through the photosphere, the chromosphere, into the corona and to the inner heliosphere, where the consequences of the remotely observed magnetic surface phenomena will be sensed directly by the in-situ instrumentation package.

3.2. Instrument Suite

The *Solar Orbiter* Instrumentation can be grouped in three major packages, each consisting of several instruments:

- Field Package: Radio and Plasma Wave Analyser and Magnetometer.
- Particle Package: Energetic Particle Detector and Solar Wind Plasma Analyser
- Solar remote sensing instrumentation: Visible-light Imager and Magnetograph, Extreme Ultraviolet Spectrometer, EUV Imager, Coronagraph, and Spectrometer/Telescope for Imaging X-rays, Heliospheric Imager.

The most important mission aspect is the combination of remote observing with in-situ measurements.

The suite of instruments is listed on the official ESA project webpage (http://sci.esa.int/solarorbiter). For the sake of completeness we will repeat it here.

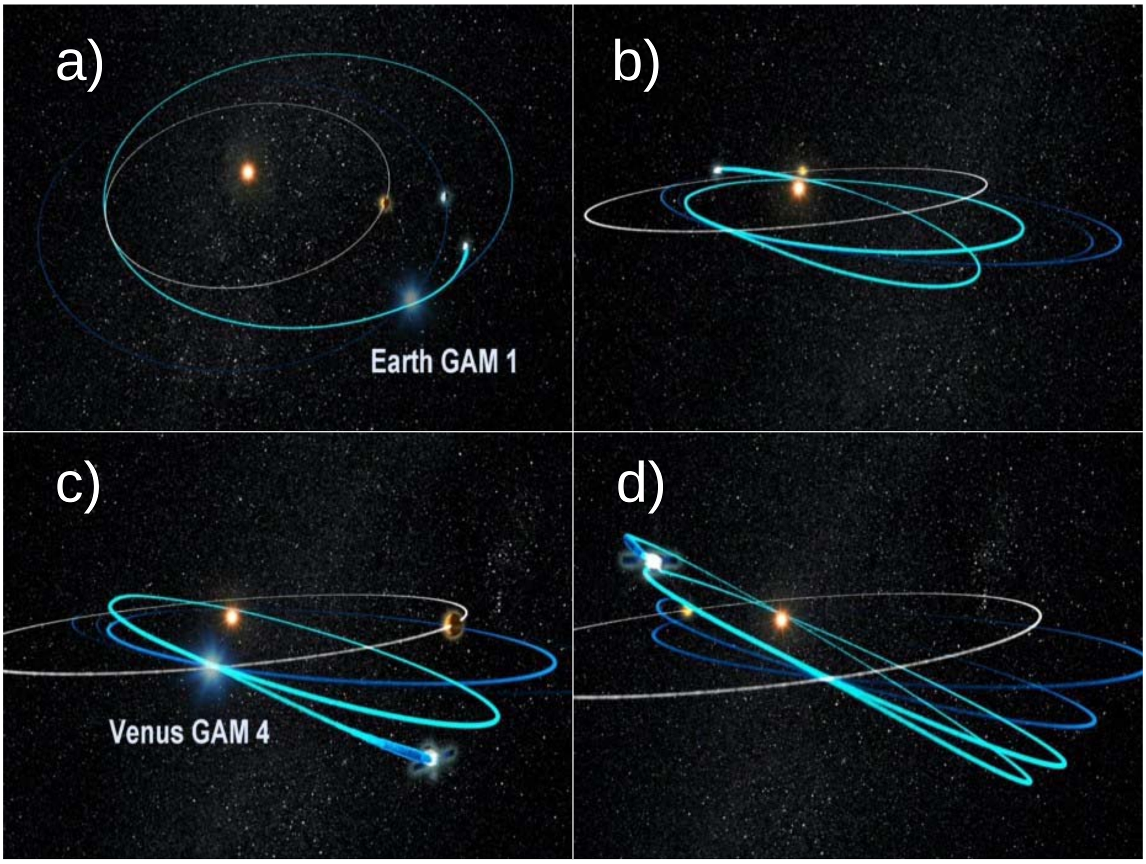

Figure 1. Sketch of different snapshots of Solar Orbiters journey: a) Thanks to a first Gravity Assist Manouvre (GAM) at Earth the spacecraft loses orbital energy and comes closer to the Sun. b) With the third GAM at Venus the operational orbit begins. The orbit is already inclined with respect to the ecliptic plane. c) The spacecraft is in a three-to-two resonance with Venus; every third orbit the inclination can be increased by Venus gravity assist. d) At the end of the operational orbit the inclination will be 34°. The material for these sketches is taken from the Solar Orbiter mission video by EADS/Astrium, which can be found at the ESA mission homepage: http://sci.esa.int/solarorbiter

The in-situ instrumentation package consists of the following instruments:

- *Energetic Particle Detector* (EPD) EPD will measure the properties of suprathermal and energetic particles. Scientific topics to be addressed include the sources, acceleration mechanisms, and transport processes of these particles. Principal Investigator of EPD is Dr. Javier Rodrguez-Pacheco, University of Alcala, Spain.
- *Magnetometer* (MAG) The magnetometer will provide in-situ measurements of the heliospheric magnetic field. This will facilitate detailed studies into the way the Sun's magnetic field links into space and evolves over the solar cycle; how particles are accelerated and propagate around the solar system, including to the Earth; how the corona and solar wind are heated and accelerated. Principal Investigator of MAG is Dr. Tim Horbury, Imperial College London, United Kingdom.
- *Radio and Plasma Waves* (RPW) The RPW experiment is unique amongst the *Solar Orbiter* instruments in that it makes both in-situ and remote sensing measurements. RPW will measure magnetic and electric fields at high time resolution using a number

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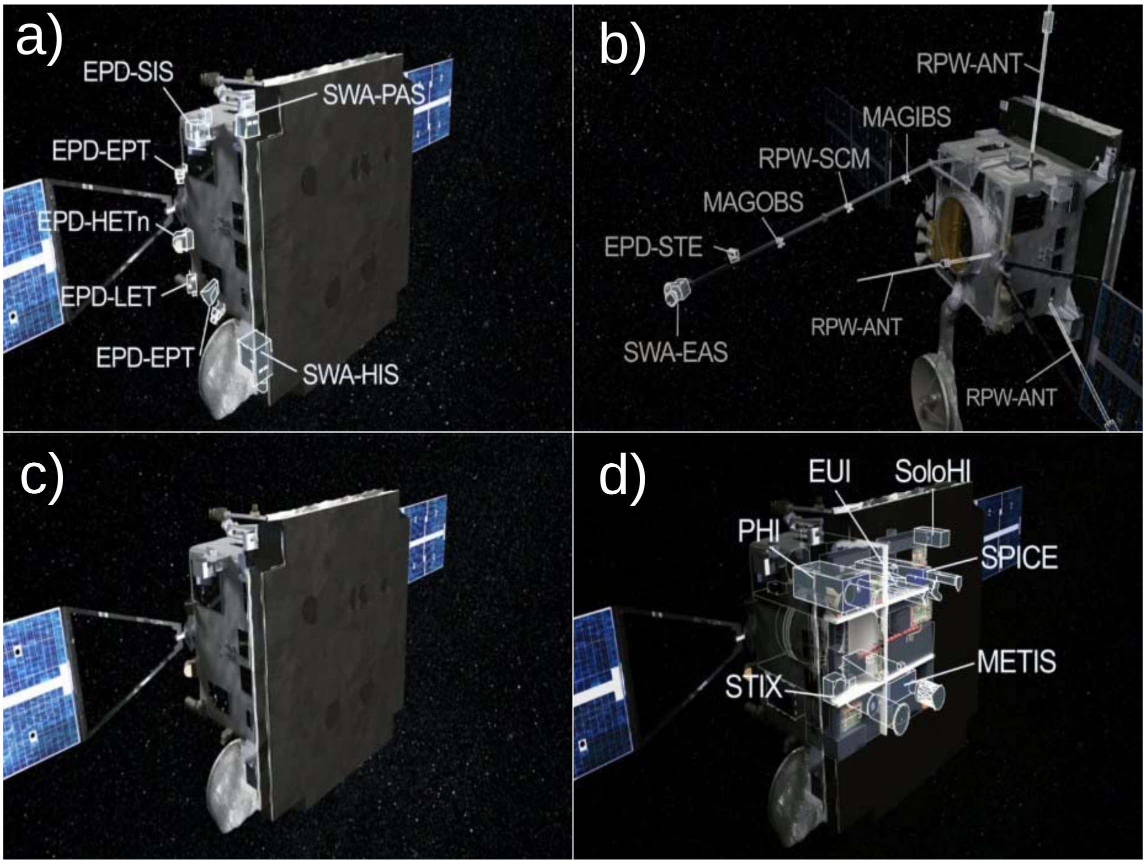

Figure 2. Payload suite of the *Solar Orbiter* spacecraft: a) The in-situ instruments are arranged at the periphery of the spacecraft body. b) Instruments needing clean electromagnetic environment are mounted on dedicated booms on the backside of the spacecraft. c): View of the heat-shield assembly, which protects the spacecraft from the intense solar radiation at perihelion passages. d) Sketch of the remote sensing instrument package, which is arranged behind dedicated feedthroughs in the heat-shield. Optical instrument like PHI are protected by heat-rejecting entrance windows. The material for these sketches is taken from the Solar Orbiter mission video by EADS/Astrium, which can be found at the ESA mission homepage: http://sci.esa.int/solarorbiter

of sensors/antennas, to determine the characteristics of electromagnetic and electrostatic waves in the solar wind. Principal Investigator of RPW is Dr. Milan Maksimovic, LESIA, Observatoire de Paris, France.

- *Solar Wind Plasma Analyser* (SWA) The Solar Wind Plasma Analyser, SWA, consists of a suite of sensors that will measure the density, velocity, and temperature of solar wind ions and electrons, thereby characterising the solar wind between 0.28 and 1.4 AU from the Sun. In addition to determining the bulk properties of the wind, SWA will provide measurements of solar wind ion composition for key elements (e.g. the C, N, O group and Fe, Si or Mg). Principal Investigator of SWA is Dr. Christopher Owen, Mullard Space Science Laboratory, United Kingdom.
- *Suprathermal Ion Spectrograph* (part of EPD) This experiment will measure energetic particles ejected from the Sun. Data will be compared to other solar and interplanetary processes to understand solar system space weather. Understanding the connections

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between the Sun and its planets will allow better prediction of the impacts of solar activity on humans, technological systems and even the presence of life itself in the universe. Principal investigator of the Suprathermal Ion Spectrograph, which is funded by NASA, is Dr. Glenn Mason, Applied Physics Laboratory in Columbia, Maryland, USA.

In addition to the in-situ instruments the *Solar Orbiter* instrumentation comprises a suite of remote sensing instruments:

- *Extreme Ultraviolet Imager* (EUI) EUI will provide image sequences of the solar atmospheric layers above the photosphere, thereby providing an indispensable link between the solar surface and outer corona that ultimately shapes the characteristics of the interplanetary medium. EUI will also provide the first-ever images of the Sun from an out-of-ecliptic viewpoint (up to 34° of solar latitude during the extended mission phase). Principal Investigator of EUI is Dr. Pierre Rochus, CSL, Belgium.
- *Coronagraph* (METIS/COR) METIS/COR will simultaneously image the visible and ultraviolet emission of the solar corona and diagnose, with unprecedented temporal coverage and spatial resolution, the structure and dynamics of the full corona in the range from 1.2 to 3.0 (from 1.6 to 4.1) solar radii from Sun centre, at minimum (maximum) perihelion during the nominal mission. This is a region that is crucial in linking the solar atmospheric phenomena to their evolution in the inner heliosphere. Principal Investigator of METIS/COR is Dr. Ester Antonucci, INAF- Astronomical Observatory of Turin, Italy.
- *Polarimetric and Helioseismic Imager* (PHI) The Polarimetric and Helioseismic Imager, PHI, will provide high-resolution and full-disk measurements of the photospheric vector magnetic field and line-of-sight (LOS) velocity as well as the continuum intensity in the visible wavelength range. The LOS velocity maps will have the accuracy and stability to allow detailed helioseismic investigations of the solar interior, in particular of the solar convection zone. Principal Investigator of PHI is Dr. Sami Solanki, Max-Planck-Institut für Sonnensystemforschung, Germany.
- *Heliospheric Imager* (SoloHI) This instrument will provide revolutionary measurements to pinpoint coronal mass ejections or CMEs. To this end the instrument is designed as a low stray light, wide angle, visible camera. Principal Investigator of SoloHI (funded by NASA) is Dr. Russell A. Howard, US Naval Research Laboratory, USA.
- *EUV Spectrometer* (SPICE) This instrument will provide an extreme ultraviolet spectrometer or optical instrument that will measure different wavelengths of light emitted from the sun. Data will advance our understanding of the various dynamics of the sun to better understand the affects on Earth and the solar system. Principal Investigator of SPICE (funded by NASA) is Dr. Don Hassler, Southwest Research Institute, Boulder, USA.
- *X-ray Imager* (STIX) STIX provides imaging spectroscopy of solar thermal and non-thermal X-ray emission. STIX will provide quantitative information on the timing, location, intensity, and spectra of accelerated electrons as well as of high temperature thermal plasmas, mostly associated with flares and/or microflares. Principal Investigator of STIX is Dr. Arnold O. Benz, Institute of Astronomy, ETH Zurich, Switzerland.

Note that the high resolution instruments are all designed to observe the same target region on the solar surface with an identical angular sampling of 0.5 arcsec per pixel. This is of fundamental importance to address the magnetic coupling between the different atmospheric layers, which will be seen using the different instruments.

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4. Solar Orbiter Polarimetric and Helioseismic Imager SO/PHI

The instrument, which harbors the greatest potential for helioseismology and the studies of magnetic fields and (sub-)surface flows in the photopheric layers, is the visible light imager and magnetograph, called *Polarimetric and Helioseismic Imager*.

4.1. Science Goals

The *Polarimetric and Helioseismic Imager* PHI onboard *Solar Orbiter* obtains information on gas flows/motions and vector magnetic fields in a two-dimensional field-of-view on the visible solar surface. It will thus probe the deepest layers of the Sun (including the solar interior by helioseismology) of all the instruments on *Solar Orbiter*. Since the magnetic field anchored at the solar surface produces most of the structures and energetic events in the upper solar atmosphere and significantly influences the heliosphere, PHI plays a key role in reaching the science goals of *Solar Orbiter*. Extrapolations of the magnetic field observed by PHI into the Sun's upper atmosphere and heliosphere will provide the information needed for other optical and in-situ instruments to analyse and understand the data recorded by them in a proper physical context.

4.2. Measurement principle

PHI makes use of the Doppler- and Zeeman-effects in a single selected spectral line of neutral iron at 617.3 nm. To retrieve the encoded physical information it must measure two-dimensional intensity maps at six wavelength points within this line, while measuring four polarisation states at each wavelength point.

4.3. Instrument Concept

PHI is a diffraction limited, wavelength tunable, quasi-monochromatic, polarisation sensitive imager.

4.4. Instrument Implementation

PHI consists of two telescopes, which feed one filtergraph and one focal plane array: The High Resolution Telescope (HRT) will provide a restricted FOV of 16.8 arcmin squared and achieve a spatial resolution that, near the closest perihelion pass, will be about 200 km on the Sun.

It is designed as an off-axis Ritchey-Chrétien telescope with a decentered pupil of 140 mm diameter.

The Full Disk Telescope (FDT), with a FOV of 2.1° squared and a pixel size of 730 km (at 0.28 AU), will provide a complete view of the full solar disk during all orbital phases.

The FDT is designed as a refractive telescope. The two telescopes are used sequentially and their selection is made by a feed selection mechanism.

Both telescope apertures are protected from intense solar flux by special heat-rejecting entrance windows, which are part of the heat-shield assembly of the spacecraft. They are purely dielectric broad-band reflectors with a narrow notch in the reflectivity curve around the science wavelength of the instruments. With more than 80% transmittance at the science wavelength, in combination with almost perfect blocking from 200 nm to the far infrared, the heat load into the instruments can be effectively decreased, while preserving the high photometric and polarimetric accuracy of PHI.

The filtergraph unit FG is based on heritage from the Imaging Magnetograph eXperiment (IMaX, Martínez Pillet et al. 2010) onboard the successful Sunrise balloon-borne observatory (Barthol et al. 2010): A $LiNbO_3$ etalon in a telecentric configuration selects a passband of 100mÅ width. Applying a voltage across the crystal allows changing the refractive index of the material, and thus tuning the passband in wavelength across the spectral line. A 3 Å wide prefilter acts as an order sorter for the Fabry-Pérot channel spectrum. The polarimetric analysis

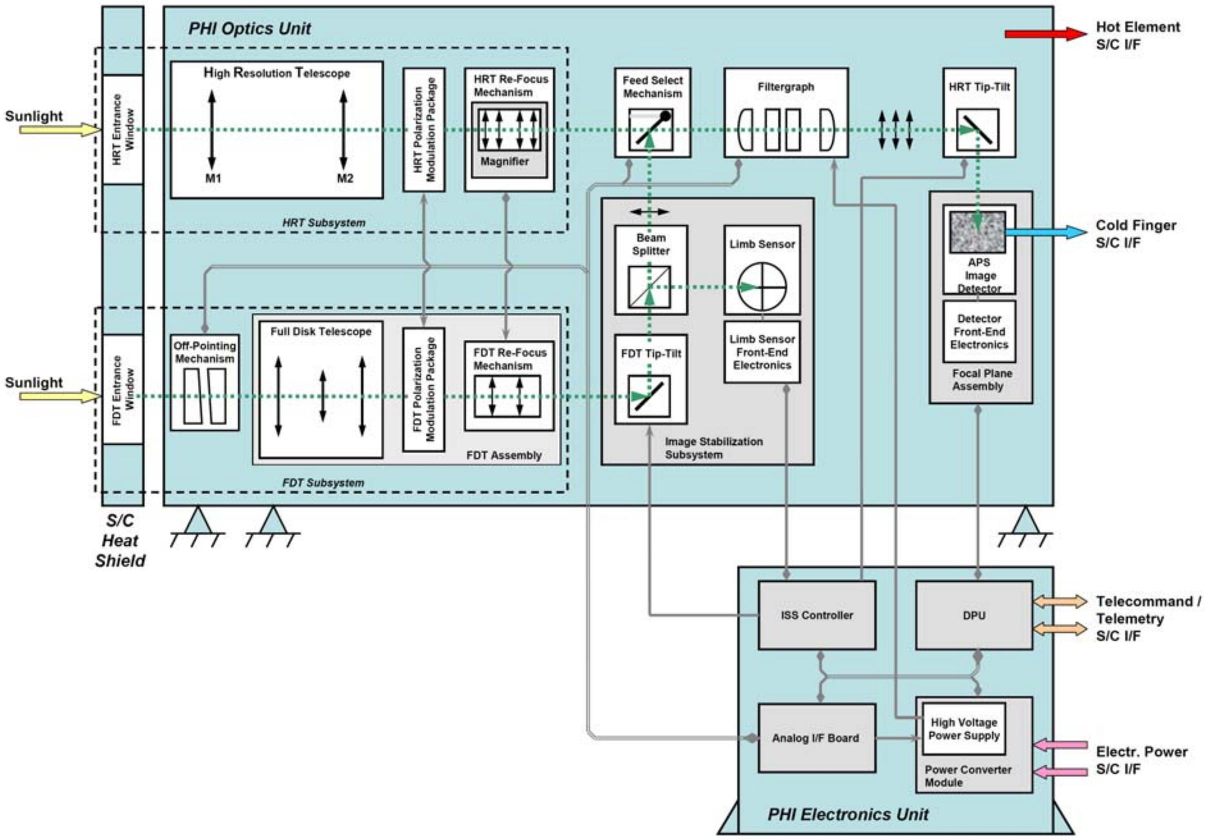

Figure 3. Functional diagram of the PHI instrument (prepared by R. Meller, MPS).

is perfomed by two Polarisation Modulation Packages (PMP) in each of the telescopes. Each PMP consists of two nematic liquid crystal retarders, followed by a linear polariser as analyser. The modulation scheme is the same as the one used in IMaX (Martínez Pillet et al. 2010).

In addition to these instrument units there are a number of other functional systems: An internal image stabilisation system based on a fast steerable mirror greatly reduces residual pointing error by the spacecraft to levels compatible with high resolution polarimetry. The error signal is derived from intensity differences within a full solar image on a quadrant diode. This image is provided also by the FDT via a beam splitter. An off-pointing mechanism in front of the FDT ensures that the full disk image is always centered on the quadrant cell, even when the other instruments, and thus the spacecraft, point to the limb of the Sun.

The focal plane assembly is built around a 2048 by 2048 pixel Active Pixel Sensor (APS), which is especially designed and manufactured for the instrument. It will deliver 10 frames per second which are read out in synchronism with the switching of the polarisation modulators.

The limited telemetry rate and the large amount of scientific information retrieved from the PHI instrument demand a sophisticated on-board data reduction. The measurement technique of PHI, i.e. the determination of the full Stokes vector at several wavelengths, is ideally suited to apply a robust and reliable technique to obtain maps of the physical quantities magnetic field strength and direction, filling factor, line-of-sight velocity and, continuum brightness. A non-linear, least-square, inversion technique is used, numerically solving the radiative transfer equation on board.

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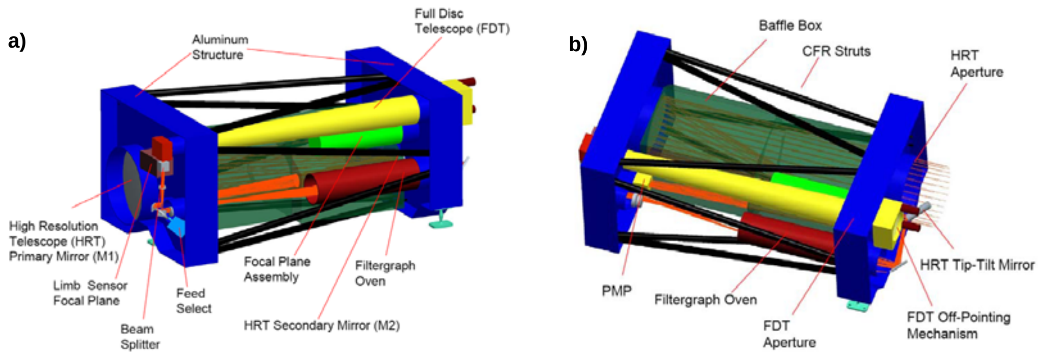

Figure 4. CAD model sketch of the PHI instrument: a) as seen from the backside, b) as seen from the front side of the instrument.

5. Outlook

Solar Orbiter will provide unique opportunities to study the Sun, from its interior to the inner heliosphere. A core instrument is the Polarimetric and Helioseismic Imager PHI, which will allow the vector magnetic field and gas flows/motions to be observed at high spatial resolution, thanks to the close-by observing conditions during the perihelion passages. PHI will for the first time ever provide measurements of the polar magnetic fields, that can not be studied from within the ecliptic plane: Although the polar regions are sometimes visible also from Earth (thanks to the inclination of the solar rotation axis of 7°), a quantitative measurement of the polar field is hindered by the strong angle dependence of the Zeeman effect, which reduces the polarised signal from polar fields to values below the noise level. Only thanks to the unique polar view from an orbit inclined by as much as 34° a reliable estimate on the polar flux and the flux transport to the poles during late phases of the activity cycle, a crucial observation for understanding the solar dynamo, can be obtained.

By co-observations with other instruments on the ground and in space, PHI also promises to probe, for the first time ever, the concept of *stereoscopic helioseismology*, by combining Dopplergrams of the same target region on the solar surface as seen from two different viewing directions. Although this has to be further studied and simulated in detail, *Solar Orbiter* and its Polarimetric and Helioseismic Imager have the potential to establish this new diagnostic technique.

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