Solar Orbiter: A mission update

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Abstract. ESA's Solar Orbiter mission will determine *in situ* the properties of fields and particles in the unexplored near-Sun heliosphere in three dimensions, investigate remotely the fine-scale structures and events in the magnetically coupled layers of the Sun's atmosphere, identify through near-corotation the links between activity on the solar surface and the resulting evolution of the inner heliosphere, and observe the polar regions and equatorial corona from relatively high latitudes. In this paper, we review the current status of the preparations for the mission, including the key findings from the recent industrial and ESA internal assessment studies.

Index Terms. Heliosphere, solar wind, space weather, Sun.

1. Introduction

The Solar Orbiter mission will provide the next major step forward in the exploration of the Sun and the heliosphere and will address many of the fundamental problems remaining in solar and heliospheric science. It incorporates both a near-Sun and a high-latitude phase. The near-Sun phase of the mission enables the Orbiter spacecraft to approach the Sun as close as 48 solar radii (~0.22 AU) during part of its orbit, thereby permitting observations from a quasi-helio-synchronous vantage point (so-called co-rotation.). At these distances, the angular speed of a spacecraft near its perihelion approximately matches the rotation rate of the Sun, enabling instruments to track a given point on the Sun surface for several days. During the out-of-ecliptic phase of the mission (extended mission), the Orbiter will reach intermediate solar latitudes (up to 35° in the extended phase), making possible detailed studies of the Sun's polar caps by the remote-sensing instruments.

In 2000, the Solar Orbiter mission was submitted to ESA and selected by ESA's Science Programme Committee (SPC) to be implemented as a flexi-mission, with a launch envisaged in the 2008-2013 timeframe (after the BepiColombo mission to Mercury). In November 2003, the SPC agreed to begin an assessment study of Solar Orbiter. ESA subsequently confirmed the place of Solar Orbiter in the Cosmic Vision programme with the objective of a launch no later than May 2015.

The Solar Orbiter mission has now completed the assessment phase in which the technical feasibility of the mission has been demonstrated. This paves the way for the release of the Announcement of Opportunity for provision of the scientific payload and the start of the definition phase once approval is given by the SPC.

2. Science goals

The Sun's atmosphere and the heliosphere represent uniquely accessible domains of space, where fundamental physical processes common to solar, astrophysical and laboratory plasmas can be studied under conditions impossible to reproduce on Earth or to study from astronomical distances. The results from missions such as Helios, Ulysses, Yohkoh, SOHO, TRACE and RHESSI have advanced significantly our understanding of the solar corona, the associated solar wind and the three-dimensional heliosphere. Further progress is to be expected with the launch of STEREO, Solar-B, and the first of NASA's Living With a Star (LWS) missions, the Solar Dynamics Observatory (SDO). Each of these missions has a specific focus, being part of an overall strategy of coordinated solar and heliospheric research. An important element of this strategy, however, has yet to be implemented. We have reached the point where further *in-situ* measurements, now much closer to the Sun, together with high-resolution imaging and spectroscopy from a near-Sun and out-of-ecliptic perspective, promise to bring about major breakthroughs in solar and heliospheric physics. The Solar Orbiter will, through a novel orbital design and an advanced suite of scientific instruments, provide the required observations. The unique mission profile of Solar Orbiter will, for the first time, make it possible to:

- Explore the uncharted innermost regions of our solar system;
- Study the Sun from close-up;

- Fly by the Sun tuned to its rotation, examine solar surface and space above from a co-rotating vantage point;
- Provide images and spectral observations of the Sun polar regions from out of the ecliptic

Within the framework of the global strategy outlined above, the top-level scientific goals of the Solar Orbiter mission are to:

- Determine the properties, dynamics and interactions of plasma, fields and particles in the near-Sun heliosphere;
- Investigate the links between the solar surface, corona and inner heliosphere;
- Explore, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun's magnetized atmosphere;
- Probe the solar dynamo by observing the Sun's high-latitude field, flows and seismic waves.

The scientific objectives of the mission are discussed in detail in Marsch et al. (2001, 2005) and Marsden and Fleck (2003).

3. The reference payload

The actual scientific payload for the Solar Orbiter mission will be selected on a competitive basis, following an Announcement of Opportunity that will be open to the international scientific community. The reference payload described in this paper has been used in order to progress with the mission definition before selection of actual instruments and comprises instruments (in-situ and remote-sensing measurements) defined on the basis of input received from the scientific community. In order to maintain compatibility with the boundary conditions of a medium-size mission, a resource-effective payload is required (e.g., a maximum total allocated mass of 180 kg, including maturity margins).

A summary of the Solar Orbiter reference payload is provided in Table 1. The reference payload can be grouped into three main categories: a) In-Situ instruments; b) Remote-Sensing instruments, constrained to follow a *'1 arcsec, 1 meter'* philosophy (representing the spatial resolution and maximum allowed envelope for the largest units; c) Payload Support Elements (e.g. boom, doors and windows, etc.). The table refers to the *core payload complement*, reflecting the science prioritization given by the Science Definition Team. All figures reported in the table include design maturity margins (depending on heritage). Detailed descriptions of the reference instruments are given in the Payload Definition Document (ESA-ESTEC, SCI-A/2004/175/AO). The scientific requirements for the payload are given in the Science Requirements Document (Marsden and Marsch, 2005).

Table 1. The Solar Orbiter Reference Payload

Instrument	Mass [kg]	Power [W]
a) In-Situ instruments		
Solar Wind Plasma Analyzer (SWA)	16.5	15.5
Radio and Plasma Wave Analyzer (RPW)	13.0	7.0
Magnetometer (MAG)	2.1	1.5
Energetic Particle Detector (EPD)	9.0	8.5
Dust Particle Detector (DPD)	1.8	6
Neutron Gamma ray Detector (NGD)	5.5	5.5
b) Remote-Sensing instruments		
Visible Imager & Magnetograph (VIM)	30.4	35
EUV Spectrometer (EUS)	18.0	25
EUV Imager (EUI)	20.4	28
Coronagraph (COR)	18.3	30
Spectrometer Telescope Imaging X-rays (STIX)	4.4	4
c) Payload Support Elements (PSE)	**28.4**	**4**
TOTAL	**167.8**	**170.0**

4. Mission profile

Obtaining an orbit that reaches both high solar latitude and low perihelion distance requires high-energy transfers. This can only be done with conventional propulsion systems by making use of gravity assist manoeuvres (GAM). The Solar Orbiter will therefore use Venus GAMs to obtain orbital inclinations allowing the spacecraft to reach latitudes of 35º with respect to the Sun's equator at the end of the mission.

Solar Orbiter will be in a resonant orbit with respect to Venus, making it possible to perform regular GAMs to raise the inclination. A trade-off between the time needed to achieve the required inclination (which ideally should be as short as possible) and the maximum tolerable thermal load on the spacecraft resulted in a decision that the science orbits should be in 3:2 resonance with Venus (three 150-day spacecraft orbits for every two Venus orbits), giving a minimum perihelion distance of about 0.22 AU.

Several mission design approaches were investigated during the assessment phase. A common constraint for all investigated alternatives was that that they would need to be compatible with a launch on a Soyuz-Fregat 2-1B launch vehicle from Centre Spatial Guyanais (CSG). The alternatives included the use of Solar Electric Propulsion (SEP), chemical propulsion or hybrid solutions. As a hybrid solution utilizing both chemical and electric propulsion would add both complexity and cost it was decided to discard this option. The chemical option and the SEP option were therefore studied in detail.

Although attractive from the point of view of offering a shorter cruise time than the chemical option, the SEP option is considered to be a higher risk and higher cost solution, and is presently not considered as the baseline. That being the case, we focus here on the chemical option.

Using chemical propulsion, the minimum cruise time to reach the nominal science orbit is about 3.4 years for launches in 2013 or 2015. In this scenario, the spacecraft would execute a Venus-Earth-Earth-Venus gravity assist trajectory before insertion. The current baseline is for a launch in 2015, with a back-up in 2017. The 2015 orbit is shown in Fig. 1.

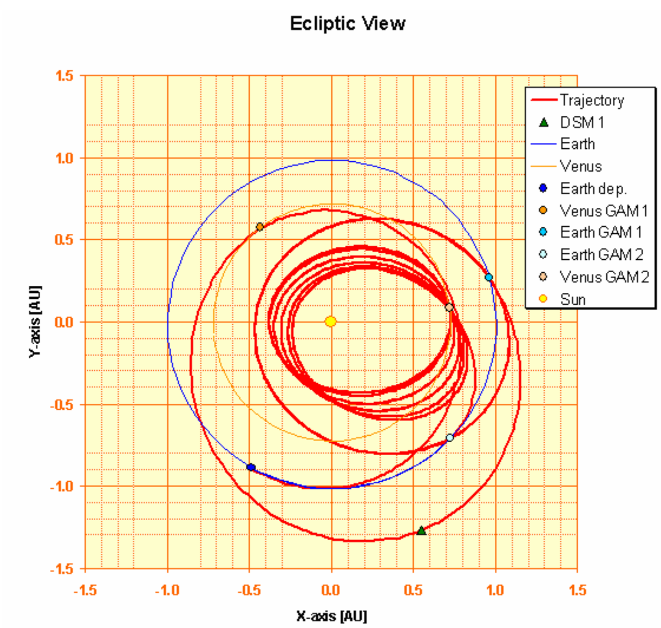

Fig. 1. Chemical trajectory (2015 launch opportunity, ecliptic plane projection).

5. Science operations

From the point of view of science planning, the Solar Orbiter will be operated as a multiple encounter mission rather than as an observatory. This is particularly true for the remote-sensing instruments. During each 150-day science orbit, the prime data-taking periods for these instruments will be three 10-day intervals centred on maximum southern heliographic latitude, perihelion and maximum northern latitude. Data downlink will generally occur outside these prime science windows, depending on the constraints on the use of the High Gain Antenna (HGA). The *in-situ* payload will operate continuously throughout the orbit, albeit with varying data rates depending on heliocentric distance. The entire payload will operate largely according to pre-planned sequences during the perihelion passes.

6. Orbiter design

The main challenge for the Solar Orbiter, which will be a three-axis stabilized spacecraft, is the widely varying thermal environment. The Sun flux experienced at 0.22 AU will be about 28000 W/m^2 and this thermal environment largely drives the orbiter design. In addition to the high solar flux, the radiation will be higher at perihelion, resulting in possible degradation of the components used. In the following, we describe some of the key features of the orbiter design as currently envisaged.

A. Thermal design

The thermal control of the orbiter is based on using a Sun shield to obtain a benign environment for the spacecraft bus. This approach is complicated by the fact that the remote-sensing instruments in many cases require a direct view of the Sun and hence openings in the shield. These interfaces will require further study once the payload has been selected. As the Sun shield is such a mission-critical component, two alternatives of the shield design are presently considered; one employing a white or gray front layer, the other a black front cover.

B. Power system

The main challenge for the power system is the solar array, as this has to withstand the high solar flux at perihelion. The current concept is based on a carbon-carbon substrate with triple junction GaAs solar cells. Even with this substrate, the maximum allowable temperature is ~230 degrees. In order to meet this constraint, the orbiter will tilt its solar arrays. To contend with issues like edge effects, internal reflection in the solar array, and uncertainties in the degradation of the cells, the tilt will be limited to not more than 70 degrees. A mixture of solar cells and optical solar reflectors (OSR) is required, with a typical cell to OSR ratio of about 40-50 %.

C. Communication and data handling

The communication subsystem of the Solar Orbiter is based on the use of X-band and Ka-band in simultaneous downlink, with X-band uplink. The ground station is assumed to be New Norcia. The HGA will be based on the BepiColombo design, possibly with additional developments to allow for its use closer to the Sun than 0.3 AU.

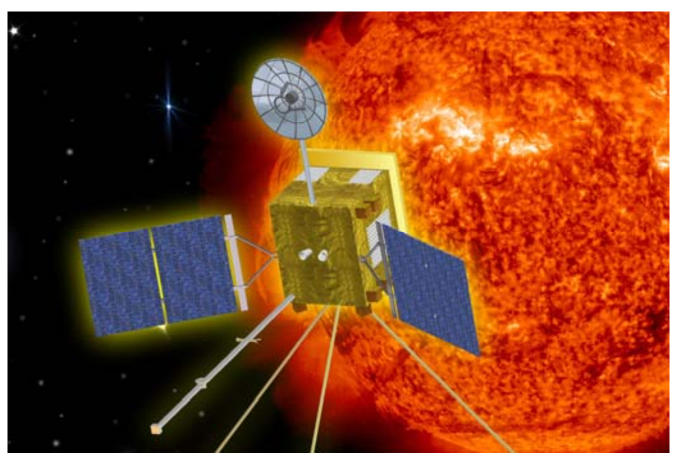

Fig. 2. Artist's impression of the Solar Orbiter at perihelion. Note that the actual spacecraft configuration may differ from the one shown.

The 10-day science windows drive the sizing of the mass memory, as the data acquisition rate will then be at its peak. A mass memory of at least 24 Gbytes is foreseen.

7. Programmatic issues

The present working assumption is the release of the instrument Announcement of Opportunity (AO) in the first quarter of 2007 and a launch date in May 2015. In this case, the ~5-yr implementation phase would start in 2010.

When discussing the Solar Orbiter development schedule and selecting the launch date, two main issues are to be considered (in addition to any programmatic constraints):

1) The Venus launch window driving the mission delta-V requirement and the cruise duration, with a synodic period of about 19 months;
2) The solar cycle (predicted maxima in 2010 and 2021).

From a scientific point of view, an ideal phasing of the mission with respect to the solar cycle would be such that the polar regions of the Sun are viewed from the highest achievable latitudes when well-developed coronal holes are present, i.e. near solar minimum. Similarly, many of the near-Sun studies would benefit from a relatively active Sun. On this basis the 2015 launch opportunity is better than the 2013 (ballistic transfer). Nevertheless, it should be stressed that first-class science will be achieved by the Solar Orbiter independent of the exact point in the solar activity cycle at which these mission phases occur.

8. Conclusions

The assessment study of the Solar Orbiter has addressed all mission areas, from the scientific requirements to the payload complement, the space and ground segments, technology readiness and all corresponding programmatic aspects.

Special attention has been paid to the reference payload, in the form of a dedicated industrial study as well as internal activities, in order to prepare adequately for the future AO and maintain the required degree of control over the relevant spacecraft resources. The system level study has indicated that two mission profiles are viable and compatible with the science requirements: Solar Electric propulsion and a 1.8-year cruise phase (higher development risk/cost); chemical propulsion, with a 3.4-year cruise phase (lower development risk/cost). In both cases, all critical design drivers have been analysed and, while design challenges certainly exist, no show-stoppers have been identified, showing the mission to be feasible.

Based on the work performed in the context of the assessment study, the following recommendations have been made:

- To select the chemical profile for the forthcoming definition phase on the basis of its full compliance with the science requirements, the additional possibility to perform science during transfer, and the lower development risks and cost.
- To consider Solar Orbiter as a mature mission, ready for entering the Definition Phase.
- To enable the approval process leading to the release of the payload AO as soon as possible, so as to maintain adequate schedule margins.
- Although the mission is technically compatible with a launch date in November 2013, the May 2015 launch opportunity has a more attractive trajectory and provides margins to further reduce the development risk of both S/C and payload.
- To make planning provisions so as to ensure a launch in 2015, thus minimising the probability of using the 2017 back-up launch date, with its longer transfer phase.
- To start the highest priority technical developments as early as possible, especially those focusing on payload issues.
- To start the development of a heat shield breadboard as soon as possible.

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