Solar Orbiter: A Challenging Mission Design for Near-Sun Observations

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The Sun's atmosphere and 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 duplicate on Earth, and at a level of detail that it is not possible to achieve at astronomical distances. A Solar Orbiter Mission designed to take the next step in our exploration of these domains was the topic of a technical pre-assessment study performed in 1999 within the framework of ESA's Solar Physics Planning Group. A Solar Orbiter-type mission was also proposed to ESA by an international team of scientists in response to the recent call for mission proposals for two Flexi-missions (F2 and F3).

A key feature of the mission is a spacecraft orbit that not only provides multiple, near-Sun passes, but which also carries the Orbiter to moderately high solar latitudes. This, together with the cost constraints associated with Flexi-type missions, represented a significant challenge in terms of mission and system design.

Introduction

The results from missions such as Helios, Ulysses, Yohkoh, SOHO and TRACE (Transition Region and Coronal Explorer) have advanced enormously our understanding of the solar corona and the associated solar wind and three-dimensional heliosphere. We have now reached the point, however, where in-situ measurements 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 acquisition of these measurements is the primary scientific objective of the Solar Orbiter Mission that has been studied in the framework of ESA's Solar Physics Planning Group, and which was proposed as a possible Flexi-mission (F2/F3) candidate.

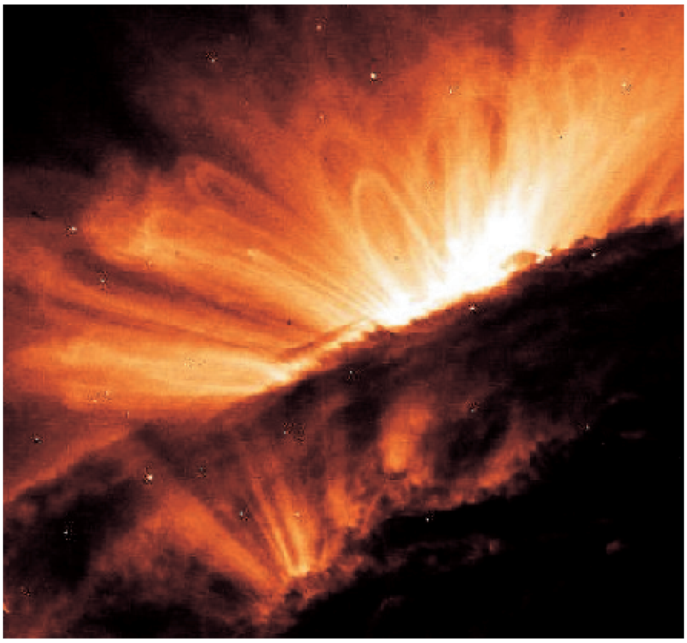
The Solar Orbiter Mission as studied embodies several totally novel aspects that would allow unique science investigations to be performed. For example:

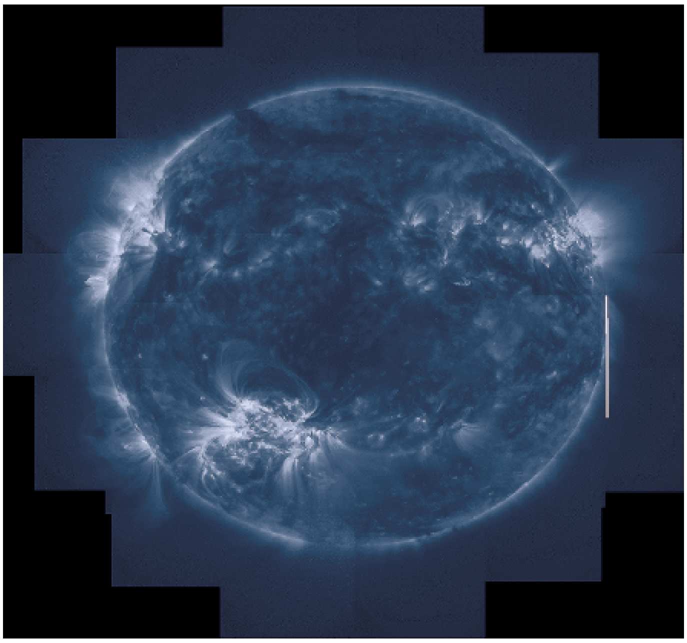
– By approaching the Sun to within 45 solar radii, or 0.21 Astronomical Units (AU), Solar Orbiter would enable close-up remote-sensing observations of the magnetised solar atmosphere, providing: (a) unprecedented high-resolution, and (b) in-situ measurements of the unexplored innermost region of the heliosphere.
– By matching the speed of the Orbiter near perihelion to the Sun's rotation rate, unique helio-synchronous observations could be acquired, enabling a better understanding of the links between solar and heliospheric processes.
– By increasing the inclination of the orbital plane with respect to the solar equator, the first-ever out-of-ecliptic imaging and spectroscopic observations of the solar poles and equatorial corona from latitudes as high as 38° could be acquired.

Scientific goals

Close-up observations of the solar atmosphere: the Sun's magnetised plasma

High-resolution imaging of the solar atmosphere from Solar Orbiter would represent a major step forward, providing an order-of-





magnitude improvement in spatial resolution over past missions. When operated in concert, the scientific instruments envisaged for Solar Orbiter would enable:

- a thorough analysis of the time-variability, evolution and fine-scale structure of the dynamic chromosphere, transition region and corona
- the study of the Sun's magnetic activity on multiple scales
- the investigation of energetic-particle acceleration, confinement and release
- the plasma and radiation processes underlying the heating of the chromosphere and corona to be revealed.

The Sun is the only star that can be imaged at a level of detail such that the physical processes responsible for magnetic activity can be resolved.

Helio-synchronous observations: linking the photosphere and corona to the heliosphere
Studies of the evolution of solar features such as active regions, loops, prominences or sunspots are greatly complicated by the fact that their evolution time scales are comparable to the solar rotation period. As a result, the evolution is entangled with other effects such as centre-to-limb variations, foreshortening and projection effects. In order to disentangle these effects, it is necessary to have an instrument platform that co-rotates with the Sun. The Solar Orbiter would, for the first time, provide such an opportunity and would thus help to resolve old and otherwise intractable problems related to the solar dynamo and the diffusion of the magnetic field across the solar surface. It would also allow, again for the first time, the evolution of sunspots and active regions to be followed, as well as the influence of the observed changes on the corona above.

In-situ measurements in the inner heliosphere: particles and fields
According to recent SOHO findings, coronal expansion arises because of the high temperature of the coronal ions. The temperature of the minor species can reach as much as 10^8 K at a few solar radii. In contrast, coronal electrons are comparatively cool. In fact, they hardly reach the canonical coronal temperature of 10^6 K, and consequently the electric field has a minor role in accelerating the ions. The high pressure of the coronal ions and the low pressure of the local interstellar medium

Figure 1. High-resolution image of the Sun recorded by the NASA Transition Region and Coronal Explorer (TRACE) mission

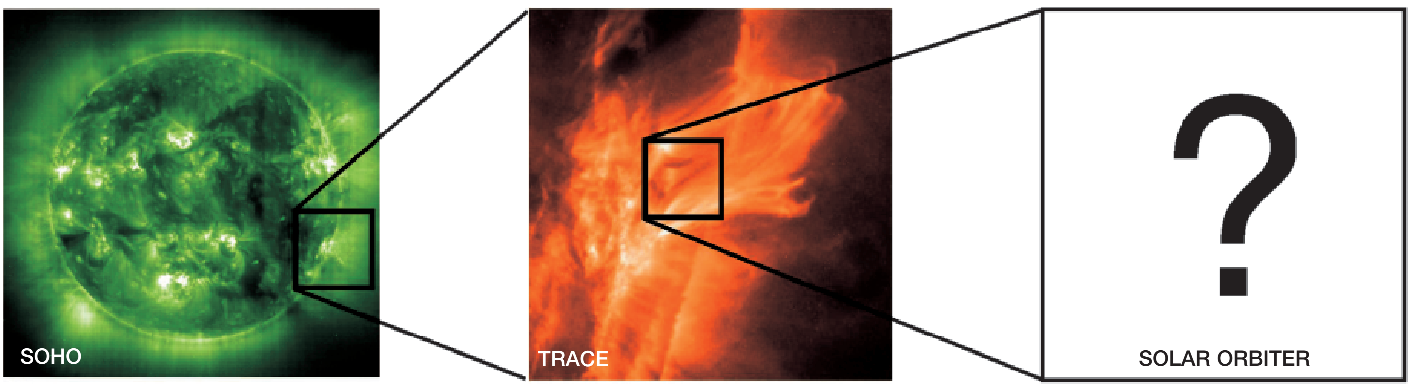


Figure 2. The Sun as seen by the Extreme-ultraviolet Imaging Telescope (EIT) on SOHO (left) and TRACE (centre). Pixel sizes on the Sun of EIT and TRACE are 1850 and 350 km, respectively. The Extreme Ultra-Violet (EUV) imager envisaged for the Solar Orbiter will have a pixel size of 35 km on the Sun

lead to a supersonic solar wind extending to large distances from the Sun (typically 100 AU). Yet, even given the insights resulting from SOHO, the detailed physical mechanisms that heat the corona and accelerate the plasma to supersonic speed remain poorly understood. This is largely because the resolution of the SOHO imagers and spectrometers was still not sufficient. Furthermore, the solar-wind plasma has never been sampled directly closer to the Sun than 0.3 AU (the perihelion distance of Helios).

The Solar Orbiter would provide the first opportunity of going closer to the Sun than the Helios space probes. Furthermore, it would carry powerful, high-resolution optical instruments in addition to the in-situ experiments. In particular, the envisaged plasma and field instruments would have high temporal resolution, ranging between 0.01 s and 1 s, offering unique possibilities to resolve physical processes at their intrinsic scales. This would in turn provide new insights into the plasma kinetic processes that structure the Sun's atmosphere, heat the extended corona, and accelerate both the solar wind and energetic particles.

The excursion out of the ecliptic: the Sun's polar regions and equatorial corona

Despite the great achievements of Ulysses and SOHO, significant scientific questions concerning the nature of the Sun, its corona and the solar wind remain unanswered. A Solar Orbiter mission combining high-latitude vantage points and a suite of remote-sensing instruments is the next logical step. For example, progress in understanding the solar dynamo will depend on how well we understand differential rotation and the circumpolar and meridional flows near the poles of the Sun. The poles appear to rotate comparatively slowly, but the polar vortex is still not well characterised due to the serious limitations of in-ecliptic observations. The Solar Orbiter would provide the first opportunity to measure directly the magnetic field at the poles, as well as the surface and subsurface flows there.

The large-scale unipolar character of the magnetic field in coronal holes gives rise to the fast solar wind that expands super-radially into the heliosphere. The Solar Orbiter offers the opportunity to sample the fast wind at distances where the plasma still retains some memory of the acceleration processes. With regard to the sites of acceleration, SOHO spectroscopic measurements suggest that the supergranulation network plays a special role. High-latitude observations would provide a definite answer.

Even with new, dedicated missions such as STEREO, it is impossible to determine the mass distribution of large-scale structures such as streamers, and the true longitudinal extent of Coronal Mass Ejections (CMEs). The Solar Orbiter would provide the first observations of the complete equatorial corona and its expansion in the equatorial plane. Furthermore, it would provide crucial information on the three-dimensional form of CMEs.

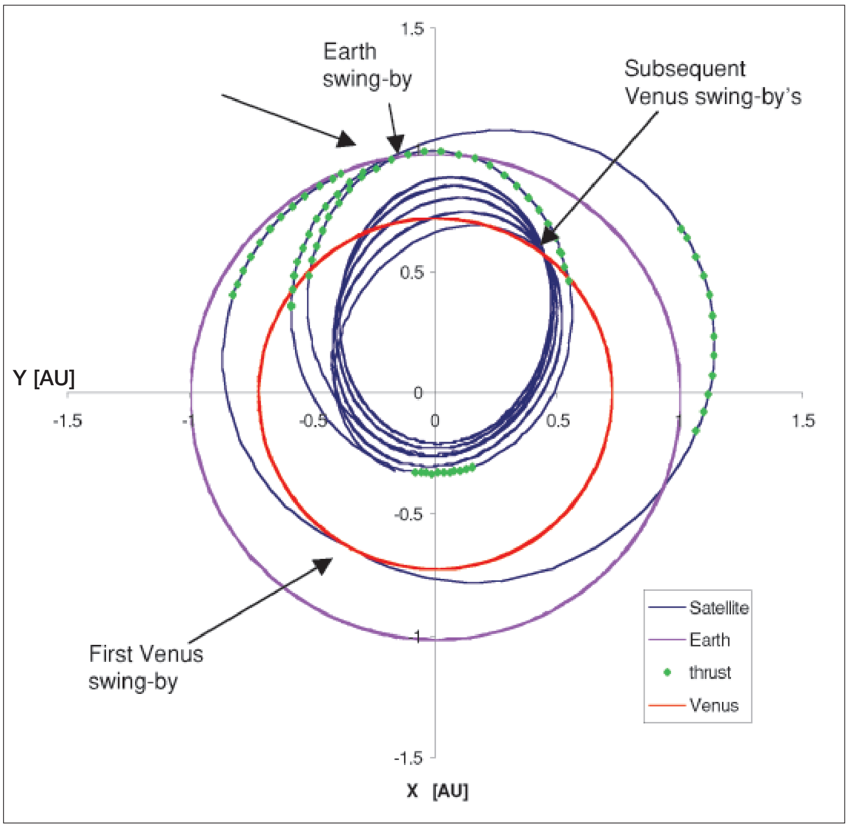


Figure 3. Ecliptic projection of the Solar Orbiter's trajectory

Scientific payload

In order to achieve the wide-ranging aims described above, the Solar Orbiter must carry a suite of sophisticated instruments. Owing to the Orbiter's proximity to the Sun, the instruments could be smaller than comparable instrumentation located at the Earth's orbit. The payload envisaged includes two instrument packages, optimised to meet the specific solar and heliospheric science objectives:

- Heliospheric in-situ instruments: solar-wind analyser, radio- and plasma-wave analyser, magnetometer, energetic-particle detectors, interplanetary dust detector, neutral-particle detector, solar-neutron detector.
- Solar remote-sensing instruments: extreme-ultraviolet (EUV) full-Sun and high-resolution imager, high-resolution EUV spectrometer, high-resolution visible-light telescope, and magnetograph, EUV and visible-light coronagraph, radiometer.

Mission profile

The mission profile needed to fulfil the scientific requirements is in many respects the fundamental design driver in the Solar Orbiter mission. In order to achieve the desired operational orbit within a reasonable transfer time, having a perihelion as close as possible to the Sun and with a high orbital inclination with respect to the solar equator, a strategy based on low-thrust Solar Electric Propulsion (SEP) and planetary gravity-assist manoeuvres was adopted. In the context of the study, the baseline orbit is achieved using a standard Soyuz-Fregat launcher from Baikonur, together with interleaved Earth/Venus gravity assists and SEP firings. Operations are assumed to be conducted from the European Space Operations Centre (ESOC) using the 35-m ground station near Perth, in Australia.

The baseline orbit provides a satisfactory scientific mission, reaching a heliographic latitude of about 40° (end of extended phase), with a minimum Sun–spacecraft distance of 0.21 AU (beginning of nominal mission). Equally importantly, the design of the spacecraft is still thermally feasible (Figs. 4 & 5). The celestial constellation of Sun, Venus and Earth lead to a launch window of 3 weeks every 19 months.

The spacecraft trajectory consists of three phases (Fig. 3, facing page):

– Cruise phase (0 – 1.86 y): this starts with the spacecraft's separation from the launcher, and ends at the start of scientific operations (some science may be performed during the cruise phase); there are thrust phases, Venus swing-bys (for semi-major-axis changes), and an inclination increase.
– Nominal mission phase (1.86 – 4.74 y, duration: 2.88 y): the prime scientific mission is performed; there are two Venus swing-bys for inclination increase during seven orbits (orbit period is 150 days on average).
– Extended mission phase (4.74 - 7.01 y, duration: 2.28 y): contingent on additional funding, the mission is extended; further gravity-assist manoeuvres enable the high-inclination requirement to be more closely met; there are two Venus swing-bys for inclination increase during six orbits (orbit period is 150 days on average).

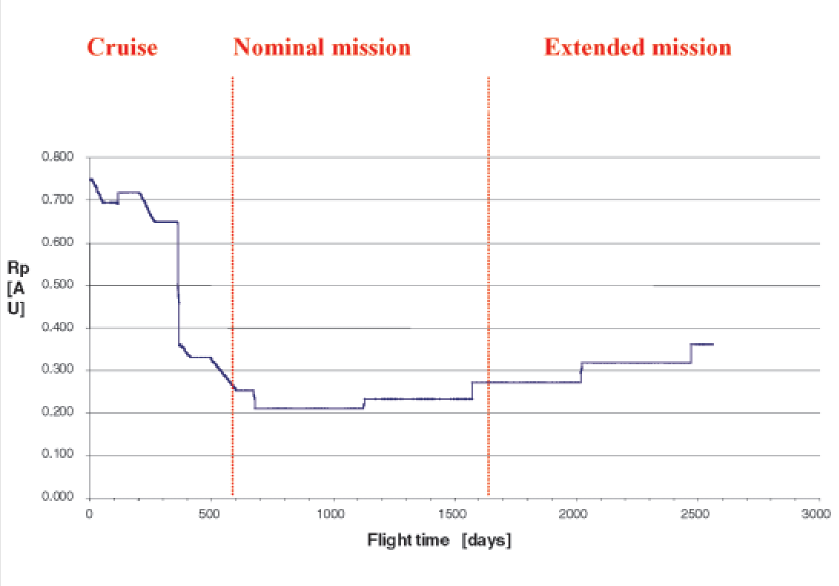


Figure 4. Perihelion distance as a function of time

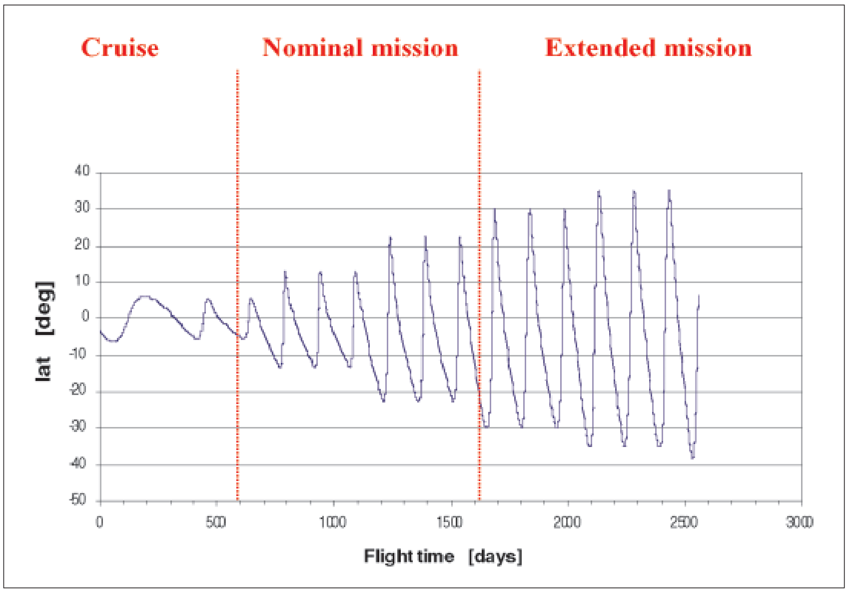


Figure 5. Solar latitude as function of flight time

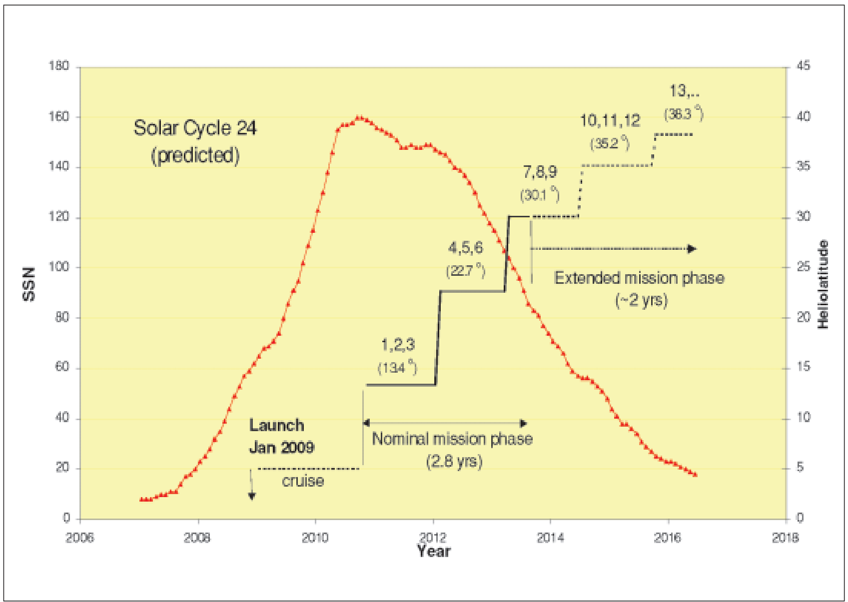


Figure 6. The various mission phases plotted together with the predicted solar activity cycle (represented by Smoothed Sunspot Number, SSN - red triangles). For a launch in January 2009, the near-Sun phase of the Solar Orbiter mission (orbits 1, 2 and 3) would take place under conditions of high solar activity, whereas the higher-latitude orbits would occur during the declining phase of the solar cycle

System design

Design requirements and drivers

As noted above, the system design for the Solar Orbiter was driven by requirements imposed by the mission profile, as well as the cost objectives that were set in the context of the study. The spacecraft is designed to get as close as possible to the Sun as the available materials and engineering will allow (0.21 AU), and the increase in solar radiation while approaching the Sun is, of course, the most challenging aspect of the mission. The solar constant at a distance r in astronomical units (AU) is given by $C_s(r)=C_{so}/r^2$, where C_{so} is the solar constant measured at 1 AU, i.e. 1367 W/m^2. Figure 7 illustrates the maximum heat load that the Solar Obiter will be subjected to during its mission. The locations of two other spacecraft (Cassini and Mercury Orbiter) are shown for comparison. The orbit is as highly inclined to the Sun's equator as the launcher and propulsion capability will allow. The power demand is higher during cruise, the majority being needed for electric propulsion. The solar array must be sized to provide adequate power at the furthest distance from the Sun. The solar array is also a thermal burden on the system: when electric propulsion is no longer needed, the surplus area must be protected by thermal louvers. The spacecraft size and shape is directly linked to the envelope of the largest instruments and the service-module performance.

The major design-driving features for the spacecraft were:

- Instrument requirements (mainly field of view, pointing stability, operations and size).
- Launcher mass envelope and interfaces.
- Earth communication, mainly accommodation of the High Gain Antenna (HGA), and HGA pointing for data transmission.
- Use of existing hardware to minimise both risk and cost.

Main system-design features

The three-axis-stabilised 1308 kg spacecraft (at launch, incl. adapter; see Fig. 8) is box-like in shape, about 3.0 m long, 1.6 m wide and 1.2 m deep. It has internally mounted instruments, a two-axis steerable High Gain Antenna (HGA), two sets of one-degree-of-freedom steerable solar arrays, and a Solar Electric Propulsion (SEP) system.

The spacecraft comprises two modules, a Service Module (SVM) and a Payload Module (PLM). The benefits of this approach include flexibility during the Assembly, Integration and Verification (AIV) programme – the two modules can be integrated and tested concurrently – as well as allowing easy access to the propulsion system. Carbon-Fibre Reinforced Plastic (CFRP) is used for the structure to achieve the required thermo-elastic stability, while the PLM includes a central cylinder to ensure the required stiffness.

The ±Y sides of the PLM accommodate the cruise solar array (two wings, three panels per wing) and the top shield radiators. The optical instruments are located directly beneath the top shield (Fig. 9), pointing along the +X axis. They are attached to the central cylinder isostatically and are open to cold space on the ± Z sides. The instruments' electronic boxes are mainly mounted on the PLM's bottom panel.

The SVM accommodates the second solar array and the SEP/equipment radiators on the ±Y panels. The thrusters are attached to the +Z panel. The propellant tank is mounted on a dedicated ring inside the central SVM cylinder, at the spacecraft's Centre-of-Gravity (COG). This design allows for possible changes in COG height during spacecraft development. The equipment boxes are mounted internally on the SVM panels.

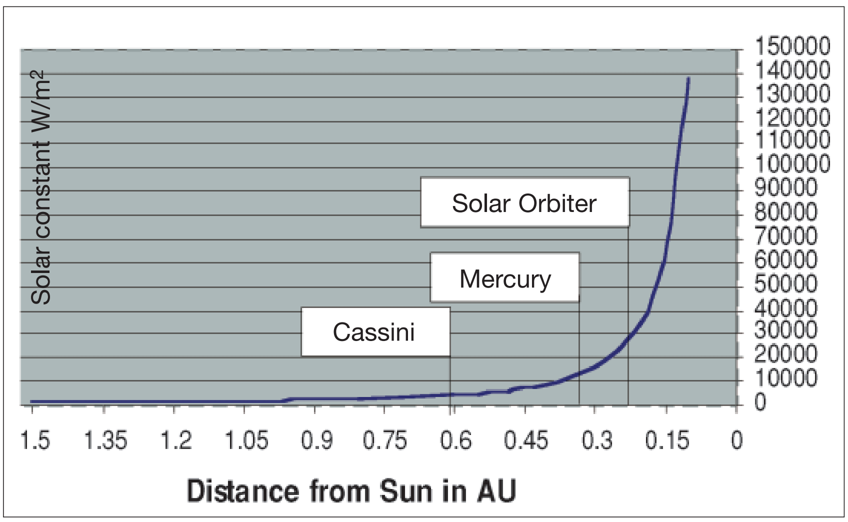


Figure 7. Solar Constant behaviour as a function of distance from Sun

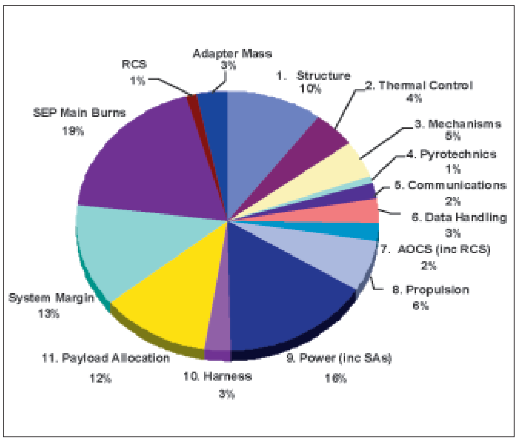


Figure 8. Satellite mass breakdown

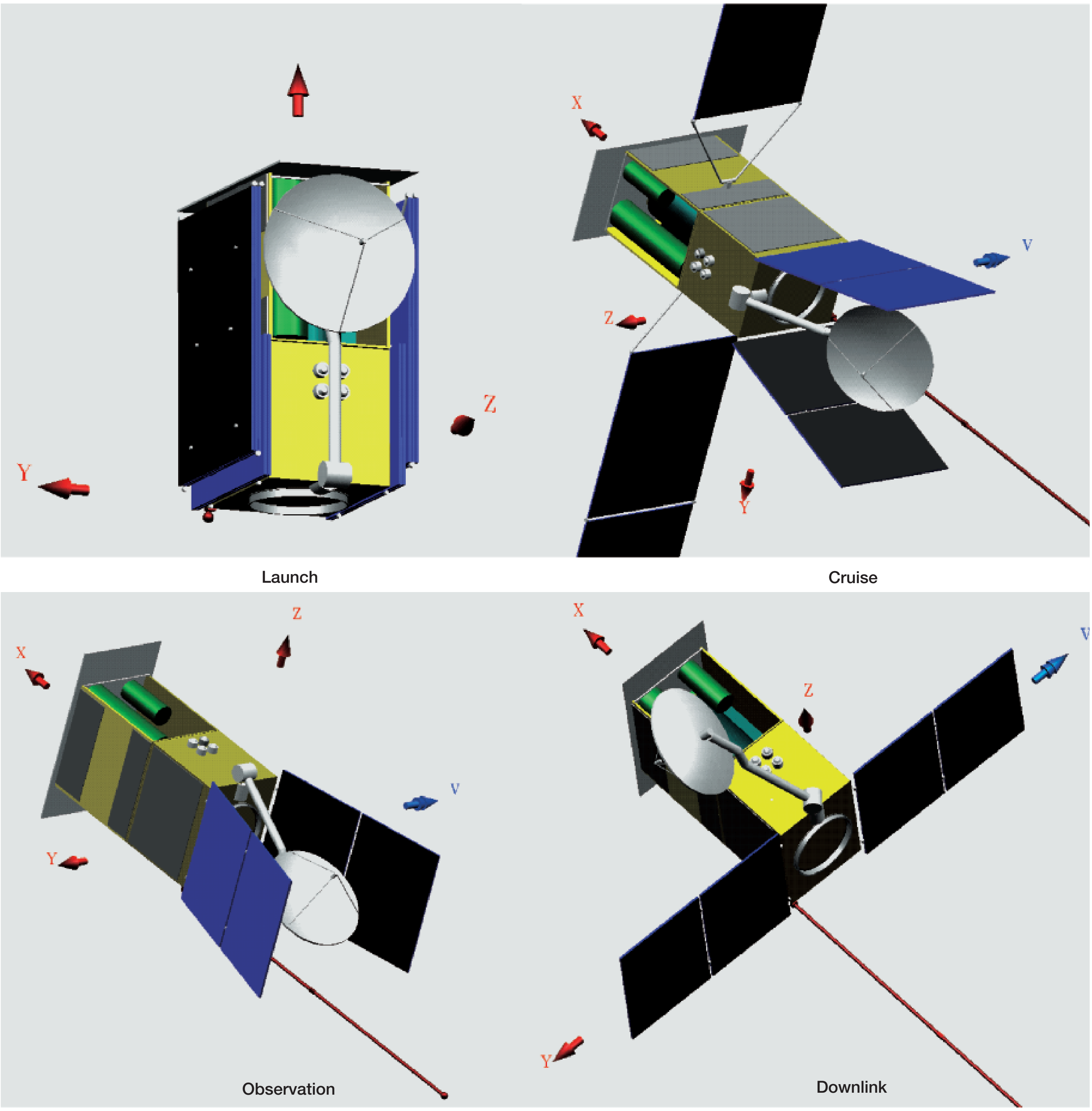


Figure 9. Solar Orbiter configurations

The difficulties encountered during the study associated with the implementation of this mission were many and varied.

Thermal control
The extreme environments to be encountered by the Solar Orbiter throughout the mission require a sophisticated thermal design that can accommodate a wide range of heat loads. At one end of the scale, the spacecraft approaches the Sun to within 0.21 AU, whilst at the other it travels as far away as 1.21 AU. This represents a change in solar-energy input by a factor of more than 30. Another important, albeit intermittent, source of heat is the SEP system when thrusting.

The proximity to the Sun is particularly demanding for appendages that cannot be protected by thermal shielding. Figure 12 shows the temperature profile (a surface perpendicular to the Sun is considered) with distance from the Sun using different technologies for external coating.

Special attention needs to be given to the selection of a suitable coating that has an α/ε ratio below 0.25, even after ageing effects have been taken into account. Furthermore, the selected external coating needs to be electrostatic-discharge (ESD) and spall resistant. This is a considerable technological challenge.

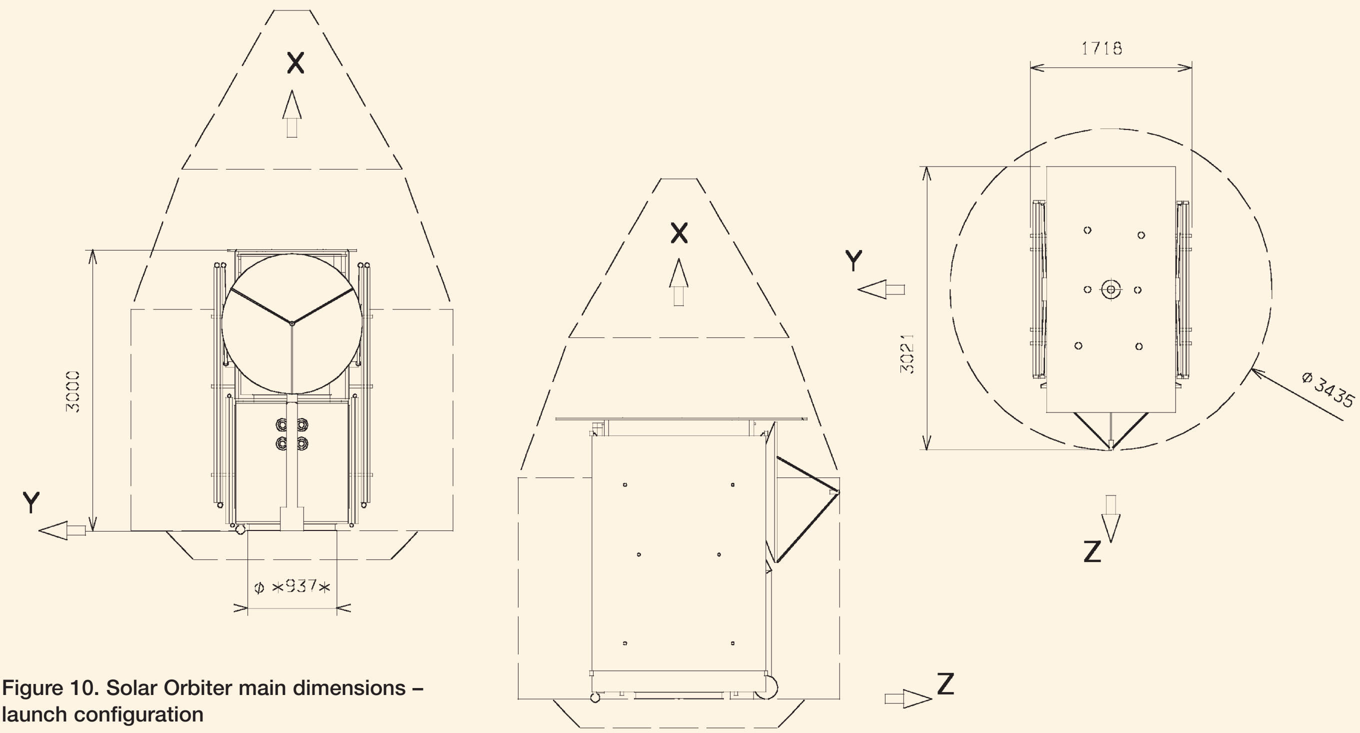


Figure 10. Solar Orbiter main dimensions – launch configuration

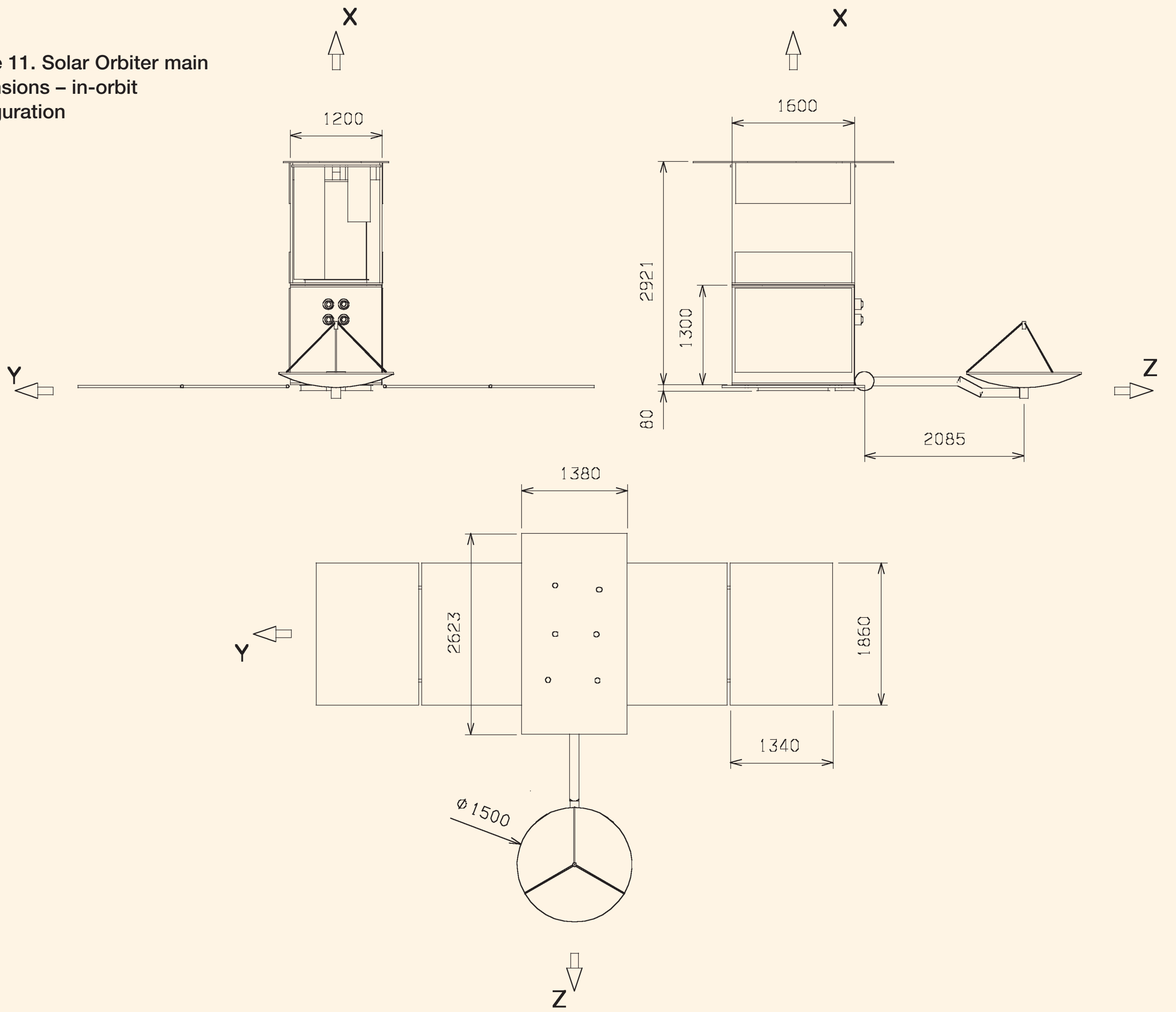


Figure 11. Solar Orbiter main dimensions – in-orbit configuration

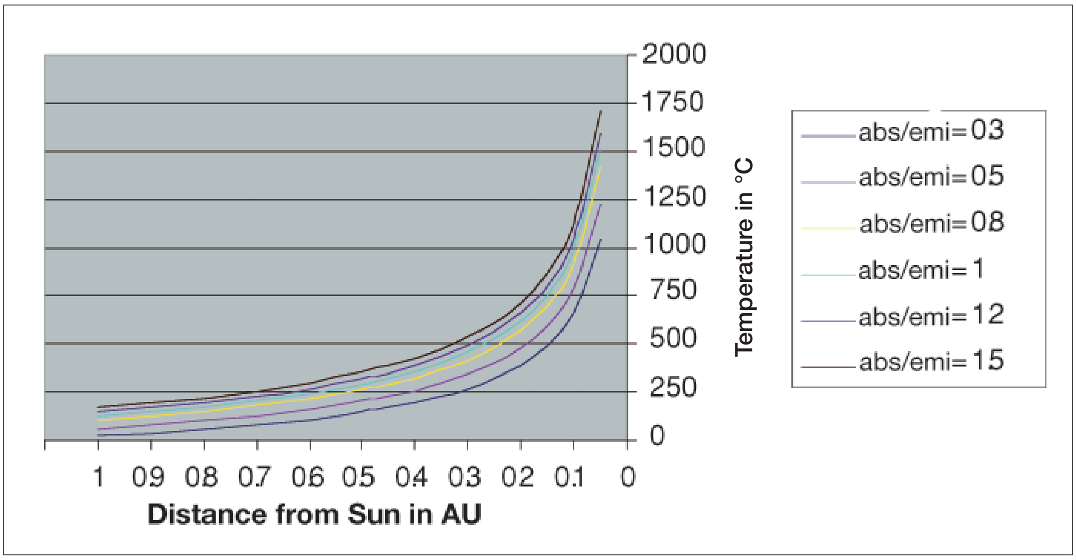


Figure 12. Temperature of a generic satellite surface as a function of absorptivity/ emissivity (abs/emi) ratio and as a function of solar constant (theta = 0°).

To ease the thermal control and to meet instrument requirements, the spacecraft is three-axis-stabilised and always Sun-pointed (X-axis), except during SEP firing. The Sun-pointing face is made as small as possible to minimise solar heat input, and the remaining satellite walls are used as radiators. With that assumption, only one thermal shield made of three titanium foils plus 15 layers of Kapton/Mylar/Dracon net Multi-Layer Insulation (MLI) is needed to protect the spacecraft bus and Z-faces during the most demanding mission phases (design cases). The external surface is painted so as to have a very low α/ε (see above). In addition, behind the structure, another 15 layers of MLI are used to insulate the spacecraft further from any remaining solar flux leaking through the MLI and to avoid heat leaks during the coldest phases.

The thermal shield has been tailored to shadow spacecraft walls during thruster firing (Sun depointing) at minimum Sun–spacecraft distance. Furthermore, it has also been designed to keep the HGA and solar-array mechanisms in shadow such that the temperatures they experience will always remain within standard Earth-orbit limits (i.e. temperatures experienced at 1 AU) to increase reliability.

To cool down the sunshield and avoid heat leaks inside the spacecraft, dedicated radiators are accommodated on the spacecraft's walls (± Y). Heat pipes are used to increase thermal conductance between the sunshield structure and its radiators.

Power supply

Electrical power for the Solar Orbiter is provided by solar arrays. Photovoltaic solar cells convert light directly into electricity, but the efficiency of this process decreases with increasing temperature. Since the Solar Orbiter will experience a wide range of thermal environments during its mission, including exposure to extremely high temperatures at perihelion, the design of the solar arrays constituted quite a challenge.

In order to be compliant with these mission and spacecraft requirements, it was necessary to implement two sets of solar arrays. The first one is used during the cruise phase and is designed mainly to provide sufficient power for the solar electric propulsion module. It is not possible to retain this array during the observation phase because of difficulties in maintaining the required instrument pointing stability, so it will be jettisoned after the last firing. The cruise solar array takes advantage of a standard design used for geostationary-orbit missions (for which the maximum allowed temperature is 130°C). It comprises two symmetric wings of three panels each, and is able to provide 6.2 kW at 1 AU. The second solar array will only be used during the observation phase. Its design is different from that of the cruise array, since there is a need to increase the upper temperature limit (max. allowed temperature 150°C). In order to meet this requirement, it is envisaged to use panels made of a honeycomb core with aluminium face sheets on which Optical Surface Reflectors (OSRs) are installed. The use of aluminium for the face sheets is necessary to reduce the thermal gradient within the panels when exposed to the Sun.

The definition of the solar-array pointing strategy during both the cruise and observation phases of the mission such that the maximum allowed temperatures are never exceeded was a challenge. Figure 13 shows the effect of the Sun's incidence angle on the temperature of the solar arrays.

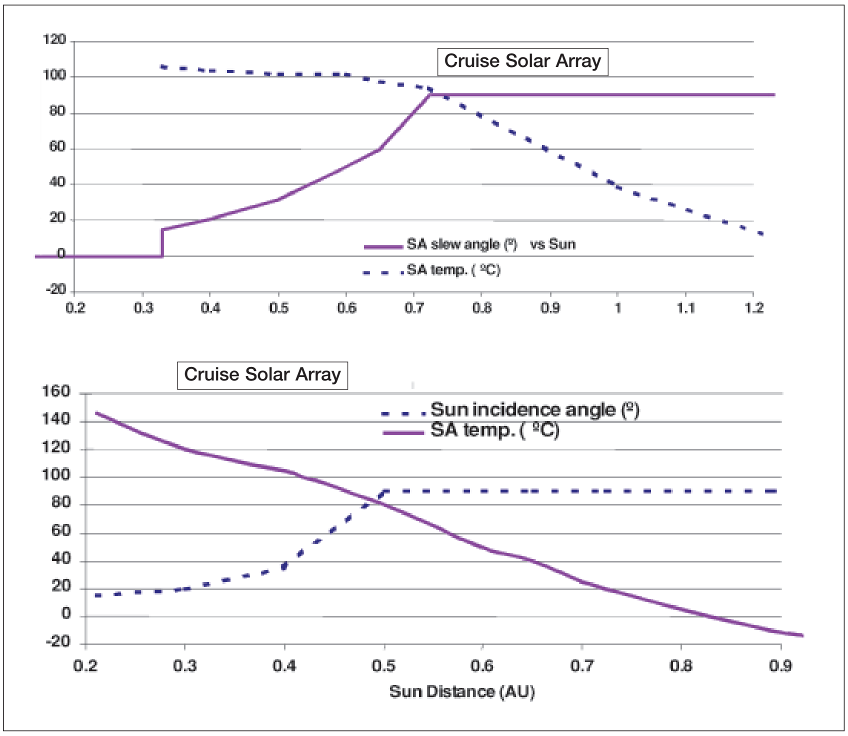


Figure 13. Cruise/Orbiter solar-array temperature as a function of distance from the Sun and solar incidence angle

Data collection/dumping

During the cruise phase, the downlink data consist mainly of housekeeping information (up to 1 kbps). Communication via wide-beam Low-Gain Antennas (LGAs) at X-band is the baseline for both up- and down-linking. During the observation phases, the spacecraft–Earth distance will change from orbit to orbit (from 0.3 up to 1.8 AU), and consequently the downlink data rate that can be supported will vary. The orbital period is 150 days on average, and the scientific data acquired during each orbit must be transmitted to the ground before commencing the next set of observations. Because of these limitations, three sets of high-data-rate scientific observation periods of ten days each are considered as a baseline, with the observation strategy then tailored for each orbit. These periods are (Fig.14):

– 5 days before to 5 days after maximum southern solar latitude
– 5 days before to 5 days after maximum northern solar latitude
– 5 days before to 5 days after perihelion.

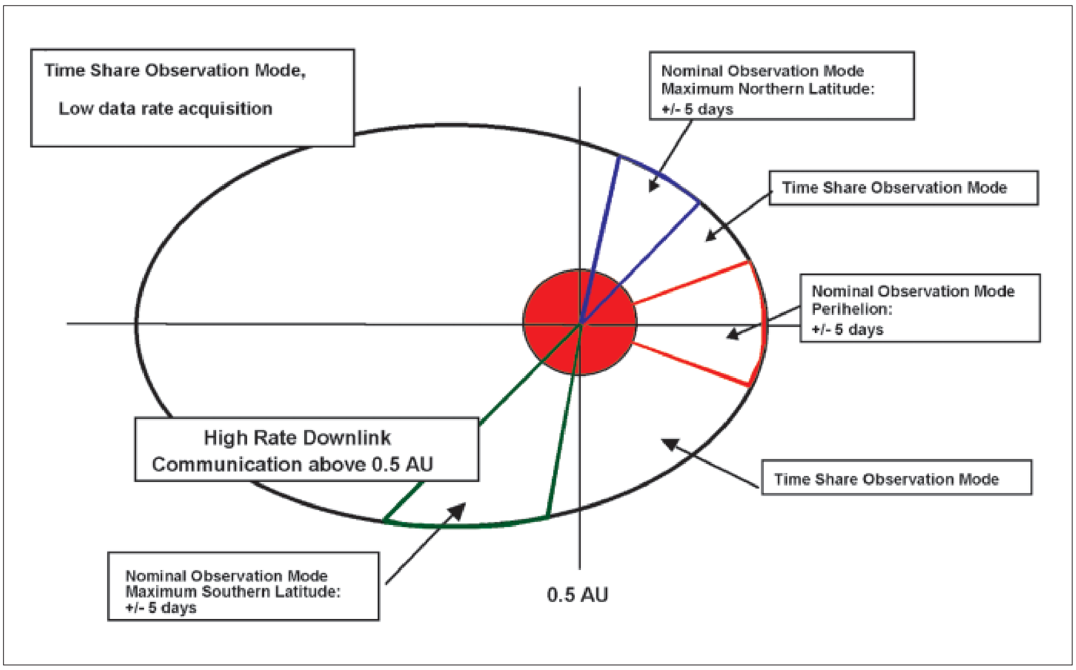
During such periods of high-data-rate acquisition (mainly the remote-sensing instruments operating at 74.5 kbps; see Fig. 14), on-board data storage in a 240 Gbyte memory is foreseen. Low-rate data acquisition at 11.5 kbps (mainly the particles and fields instruments) is possible throughout the majority of the orbit.

The severe thermal environment when approaching the Sun does not allow the use of the HGA to downlink data to Earth. Therefore, in order to avoid antenna pattern distorsion as well as technological problems, a minimum Sun–spacecraft distance of 0.5 AU for HGA operation was adopted. This limits the downlink via the HGA to approximately 110 days per orbit. Whenever possible, the low-rate data will be downlinked in real time, otherwise it will also be stored onboard and dumped later.

Conclusion

Clearly, the Solar Orbiter is a very exciting and ambitious mission for the solar-physics community. As has been shown in this article, it also represents a formidable challenge from the point of view of system design, the more so because the project must be executed within the stringent cost cap of an F-class mission. An important element in achieving this goal is the use of hardware and new technologies that are

Figure 14. Modes of operation during nominal and extended mission phases



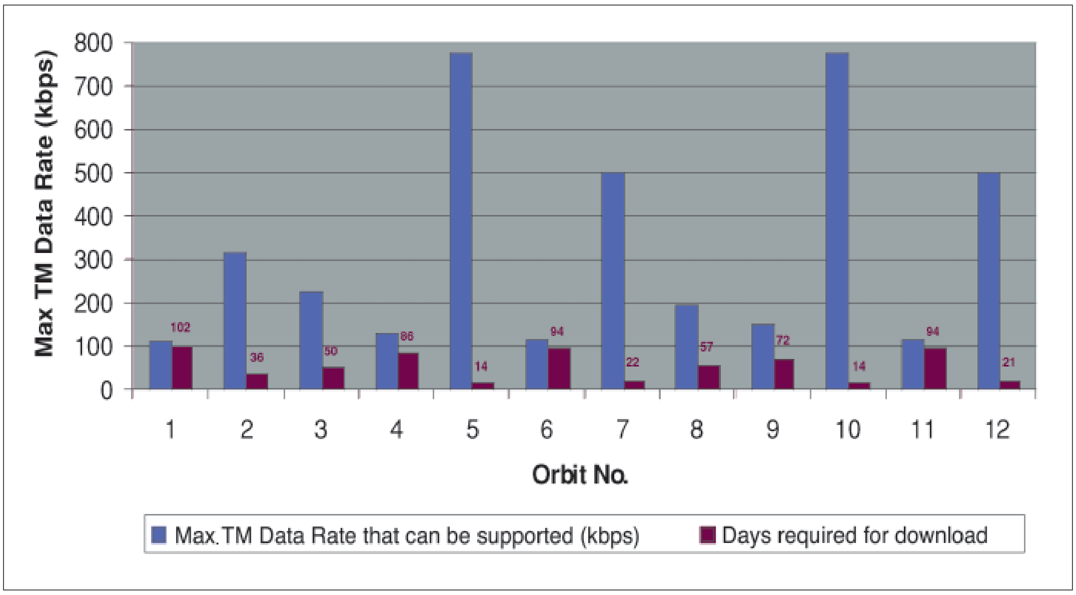


Figure 15. Downlink capabilities for the different orbits. The distance between the spacecraft and the Earth varies considerably from one orbit to the next, and the time taken to downlink the data acquired during each high-data-rate observation period varies proportionately

already being developed (or will be developed) in the framework of the ESA Cornerstone project Bepi-Colombo. This strategy is necessary in order to arrive at an acceptable mission cost coupled with low risk.

The study has shown that, in general, the mission is technically feasible, given the assumed programmatic and technical requirements. A few areas still need to be refined/optimised, including the detailed accommodation of the scientific payload.

Acknowledgements

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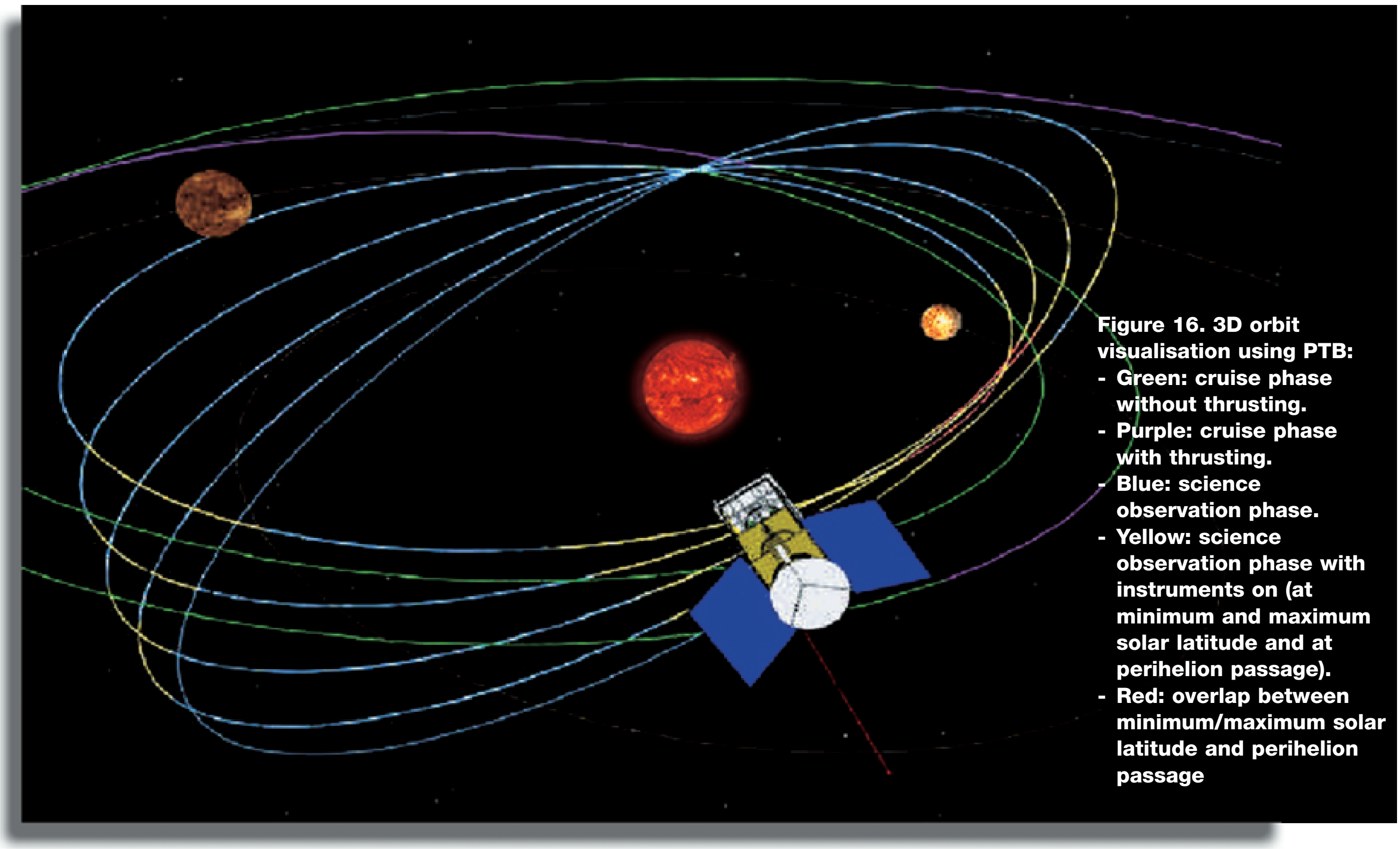

Figure 16. 3D orbit visualisation using PTB:
- **Green: cruise phase without thrusting.**
- **Purple: cruise phase with thrusting.**
- **Blue: science observation phase.**
- **Yellow: science observation phase with instruments on (at minimum and maximum solar latitude and at perihelion passage).**
- **Red: overlap between minimum/maximum solar latitude and perihelion passage**