# Solar Orbiter assessment study and model payload

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**ABSTRACT**

The Solar Orbiter mission is presently in assessment phase by the Science Payload and Advanced Concepts Office of the European Space Agency. The mission is confirmed in the Cosmic Vision programme, with the objective of a launch in October 2013 and no later than May 2015. The Solar Orbiter mission incorporates both a near-Sun (~0.22 AU) and a high-latitude (~ 35 deg) phase, posing new challenges in terms of protection from the intense solar radiation and related spacecraft thermal control, to remain compatible with the programmatic constraints of a medium class mission.

This paper provides an overview of the assessment study activities, with specific emphasis on the definition of the model payload and its accommodation in the spacecraft. The main results of the industrial activities conducted with Alcatel Space and EADS-Astrium are summarized.

**Keywords:** Solar physics, space weather, instrumentation, mission assessment, Solar Orbiter

## 1. INTRODUCTION

The Solar Orbiter mission was first discussed at the Tenerife "Crossroads" workshop in 1998, in the framework of the ESA Solar Physics Planning Group. The mission was submitted to ESA in 2000 and then selected by ESA's Science Programme Committee in October 2000 to be implemented as a flexi-mission, with a launch envisaged in the 2008-2013 timeframe (after the BepiColombo mission to Mercury) [1]. The mission was subsequently re-confirmed in May 2002 on the basis of implementation as a mission group together with BepiColombo. A re-assessment of BepiColombo was conducted in 2003, leading to an SPC decision in November 2003 to maintain Solar Orbiter in the Cosmic Vision programme, and to begin an assessment study [2]. In June 2004, ESA confirmed the place of Solar Orbiter in the Cosmic Vision programme, with the objective of a launch in October 2013 and no later than May 2015.

The Solar Orbiter mission will provide the next major step forward in the exploration of the Sun and the heliosphere to solve 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 modest solar latitudes (up to 35º in the extended phase), making possible detailed studies of the Sun's polar caps by the remote-sensing instruments.

## 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 & 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 [3] 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.

## 3. THE MODEL 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 model payload described in this paper is used as to progress with the mission definition before selection of actual instruments and comprises units (in-situ and remote-sensing measurements) defined on the basis of input received from the scientific community. As to maintain compatibility with the boundary conditions of a medium size mission, a resource effective payload is required (max total allocated mass of 180 kg, including maturity margins). A summary of the Solar Orbiter reference payload [4] is provided in the table 3.1. In order to optimize the use of resources, several of the smaller in-situ sensors have been grouped into so-called *suites*. In this way, four categories are identified: a) In-Situ sensor units (sharing common DPU); b) In-Situ suite common elements (providing the common resources required by each suite); c) '*1 arcsec, 1m class'* Remote Sensing instruments (representing the maximum allowed envelope for the biggest units; d) Payload Support Elements (e.g. boom, rotating platform, etc.). The table refers to the *core payload complement*, reflecting the science prioritization given in [3]. All figures reported in the table include design maturity margins (depending on heritage).

**Figure 3.1** – Model design for the Visible Imager Magnetograph (VIM)

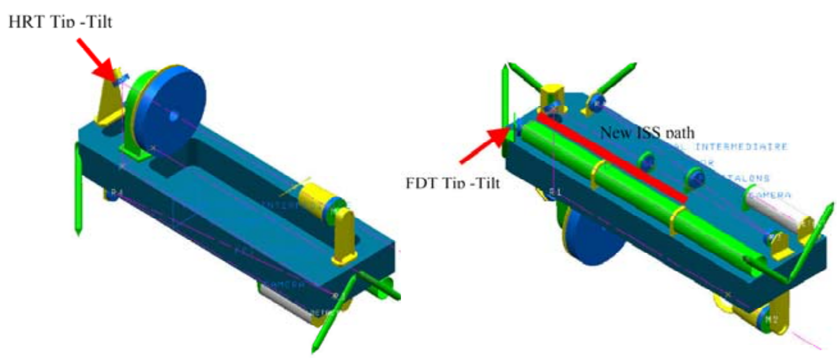


**Figure 3.2** – Model design for the High Resolution Telescope of the EUV Imager (EUI)

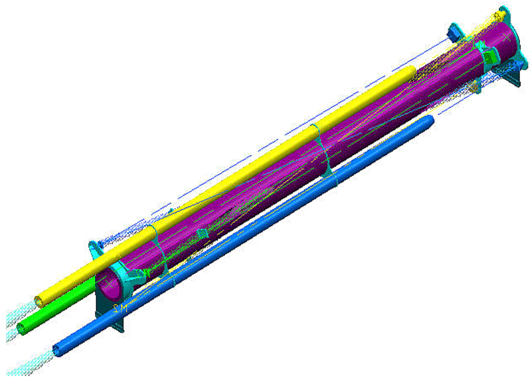


**Table 3.1** – Summary of the Solar Orbiter reference payload.

| Instrument | Acronym | Mass [kg] | Power [W] | Accommodation / remarks |
|---|---|---|---|---|
| **a) In-Situ instruments** | | | | |
| Solar Wind Plasma Analyzer | SWA | 14.0 | 13 | PAS and HIS are S/C body mounted with aperture through the heat shield, EAS1 on the boom, EAS2 is behind the shield |
| Radio and Plasma Wave Analyzer | RPW | 9.6 | 6.4 | 3 × antenna on S/C, magnetometer loop and 3x search coils on the boom |
| Magnetometer | MAG | 1.5 | 1.5 | 2× sensors located on boom (in the shadow) |
| Energetic Particle Detector | EPD | 5.7 | 8.5 | 5× sensors on scanning platform located behind the heat shield. |
| Dust Particle Detector | DPD | 1.8 | 6 | 2 sensors mounted on the S/C body in velocity and orthogonal to velocity direction |
| Neutron Gamma ray Detector | NGD | 4.2 | 4 | Located behind shield, no optical aperture is required (but low Z materials) |
| b) IS suites items | --- | 11.3 | 8 | Elements ensuring full suite functionality |
| **c) Remote-Sensing instruments** | | | | |
| Visible Imager & Magnetograph | VIM | 30 | 35 | Located behind shield, 2 apertures with covers and heat rejection filters |
| EUV Spectrometer | EUS | 18.0 | 25 | Located behind shield, 1 aperture (6 cm diameter) with cover, thin Al filter is TBC |
| EUV Imager | EUI | 20.4 | 25 | Located behind shield, up to 4 apertures with covers, baffles – thin Al filters |
| VIS Coronagraph | COR | 18.0 | 25 | Located behind shield, 1 aperture with cover and occulter – optional EUV channel |
| Spectrometer Telescope Imaging X-ray | STIX | 4.4 | 4 | Located behind shield, 1 apertures with cover and filters |
| d) Payload Support Elements | PSE | 27.6 | 20 | Scanning platform, boom, doors/windows and specific P/L thermal HW |
| **TOTAL** | **---** | **167.2** | **175.9** | **Compliant with MRD requirement** |

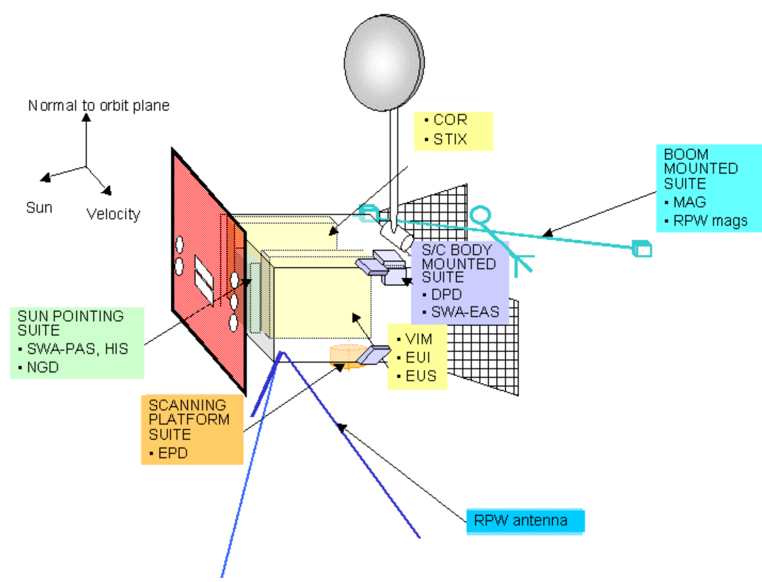
## 4. PAYLOAD ACCOMMODATION

Payload accommodation in the Orbiter Module (baseline), or in the Cruise/Orbiter Module (back-up profile, see chapter 6) has been analyzed during the industrial studies. The Solar Orbiter will be a three-axis stabilised spacecraft, with the main body permanently maintained in the shade by a dedicated heat shield. The main characteristics of the proposed accommodation (see figures 4.1) are:

- The overall philosophy to minimize / intercept heat loads at the instruments apertures by reducing the size of the apertures and through externally mounted, heat rejecting elements and baffles.
- The installation of all Remote Sensing instruments inside the S/C body and behind the heat shield, on lateral or shear panels as to guarantee: a) a controlled thermal environment; b) easy access to the S/C radiators; c) stiff mechanical support to meet the co-alignment requirement.
- The installation of the In-Situ payload elements depending on actual FOV requirements: a) sun-pointing through the heat shield; b) boom mounted; c) rotating platform mounted; d) S/C body mounted.

Key issues to emerge from the accommodation studies are: a) the interface between instrument apertures and heat shield (e.g. instrument covers/doors/baffles); b) the potential interference to pointing stability performance caused by the rotating platform (subject to a further trade-off); c) standard interfaces between the instruments and the platform DHS.

**Figure 4.1** – Solar Orbiter payload accommodation.




## 5. MISSION DESIGN

The Solar Orbiter mission design is based on a *cruise phase* and a *science phase.* The cruise phase comprises the Earth escape and a trajectory that remains close to the ecliptic in order to bring the Orbiter into a Venus resonant orbit. The mission design for the science phase, which begins with a Venus Gravity Assist Manouvre – GAM V, aims to reduce the perihelion distance (permitting the Orbiter to move in near-synchronism with the solar surface for periods of a few days), and to gradually increase the orbital inclination to more than 30 degree with respect to the solar equator through repeated Venus gravity assists.

Alternative mission profiles have been examined for the cruise phase in the context of the Solar Orbiter assessment, without affecting the science phase. Given the strong link to BepiColombo and the benefits of a shorter cruise phase, more emphasis was initially given to the so-called '*baseline profile'*, assuming Solar Electric Propulsion (SEP). All profiles assume launch from CSG-Kourou on a Soyuz Fregat type 2-1B and a 3-week launch window. Launch dates are governed by the Venus synodic period (~19 months). The nominal launch date is October 2013, with May 2015 as back up (next Venus window). The alternatives that have been investigated are: a) *Baseline* (direct injection, SEP); b) *Hybrid* (injection into HEO, CP + SEP); c) *LSB* (Lunar Swing By, SEP); d) *Chemical* (direct injection, CP). The table below summarizes the key parameters for each profile.

| **Mission duration (yr)** | **a) Baseline (Direct, SEP)** | **b) Hybrid (HEO+CP/SEP)** | **c) Lunar SB (HEO+SEP)** | **d) Chemical (Direct, CP)** |
|---|---|---|---|---|
| Launch date | 19 Oct 2013 | 28 Sep 2013 | 3 Mar 2014 | 11 Nov 2013 |
| Cruise | 1.82 | 1.82 | ~2.50 | 3.32 |
| Science nom. | 2.80 | 2.80 | 2.80 | 4.00 |
| Science ext. | 2.43 | 2.43 | 2.43 | 2.51 |
| Total | 7.05 | 7.05 | ~7.73 | 9.83 |
| S/C config. | SEPM+OM | SEP/CPM+OM | SEPM+OM | C/OM |

Options b) and c) aim to provide additional mass margins compared with the baseline profile a), while retaining a large S/C design commonality (but higher risk and cost). Option d) is a lower risk / cost option (longer cruise, and weaker coupling to BepiColombo).

The spacecraft configuration envisaged for option a) and c) is identical (composite based on a Solar Electric Propulsion Module – SEPM and Orbiter Module – OM). The configuration for option b) consists of a composite with a combined Solar Electric and Chemical Propulsion Module – SE/CPM and Orbiter Module). The configuration for option d) consists of a single spacecraft (combined Cruise/Orbiter Module – C/OM).

The Hybrid scenario assumes launch into an Earth HEO orbit via the Soyuz-Fregat, apogee raising manouvres to Earth escape via a chemical engine integrated into the Propulsion Module and subsequent cruise by SEP. The anticipated net mass gain is of order 150/200 kg compared with the baseline, but at the price of additional cost, risk and complexity.

The Lunar Swing-By scenario is similar to the one baselined for BepiColombo and allows a considerable increase in the useful mass (up to +400 kg), at the price of a longer cruise (typ. 7-8 months), larger total delta-V, additional risks and operations complexity. This scenario implies a further 14 month of cruise (Earth-Moon-Earth transfer).

Based on the assessment activities, options a) (*baseline*) and d) (*chemical*) have been identified as most interesting (and are described further in section 6.1), while options b) and c) are found to be sub-optimal from a cost-benefit point of view (longer cruise – additional complexity and cost) and are not described further.

The science phase orbit (starting with the second Venus GAM, V2) remains basically unchanged for all different profiles: in all cases the trajectory is based on a 3:2 Venus resonant orbit (i.e. 3 S/C orbits around the Sun in 450 days, corresponding to 2 Venus orbital periods) and its key parameters (minimum perihelion distance and maximum heliospheric latitude) are determined by the entry velocity vector (amplitude and angle) at GAM V2. Finally, the co-rotation parameter (relative angular speed between Sun and S/C) is determined once the perihelion distance is fixed. It is also useful to recall that the solar cycle will be close to its peak in 2021, while from a science point of view, it would be preferable to view the Sun's polar regions from an out of ecliptic perspective near solar minimum.

### 5.1 The Solar Electric Propulsion (SEP) scenario

The so-called baseline scenario has been initially favored because of the faster science return (SEPM jettisoned after ~1.8 yr), the stronger link to BepiColombo. The key events of the scenario are provided in Table 6.1. The actual low thrust trajectory to be followed by the spacecraft is represented in figures 5.1.1 (projection on the ecliptic plane) and 5.1.2 (projection on the perpendicular plane). The ecliptic view shows the S/C trajectory in the inner Solar system during the cruise phase, from launch to the second Venus GAM. The SEP thrust arcs are indicated in different colours. The Earth orbit is shown in blue. Venus' orbit is in yellow. The trajectory followed during the science phase is indicated in red. Actual thrust arc trajectory and duration depends on the maximum SEP thrust level and different options exist within the capabilities of the BepiColombo/Alpha-bus T6 thrusters. The X-Z projection shows the evolution of the trajectory in a plane perpendicular to the ecliptic as to highlight the progressive inclination increase at each Venus GAM. A corresponding scenario for a launch in May 2015 has been investigated, showing slightly more favorable delta-V conditions than the nominal trajectory.

The baseline profile consists of a composite spacecraft comprising a Solar Electric Propulsion Module (SEPM) and an Orbiter Module (OM). Both elements are protected by a dedicated heat shield, representing a main mission element. The SEPM is jettisoned at the end of the *cruise phase* (~1.8 yr), with the following start of the *science phase* (3+2.4 yr). Figures 5.1.3 and 5.1.4 show the composite configurations identified by the industrial contractors. Typical total (composite) dry separated mass (without margin) is about 1050 kg. SEP propellant (Xe gas mass) is of about 150 kg, while chemical propellant mass is about 50 kg. Sizing power is of order 750 W.

**Table 5.1:** Summary of baseline (SEP) profile (October 2013).

| | Date | Flight time | | Event | Inclination [°] | | Aphelion | Perihelion | |
|---|---|---|---|---|---|---|---|---|---|
| | | Days | Years | | Ecliptic | Sol. equ. | [AU] | [AU] | [Sol. rad.] |
| Cruise Phase | 2013-10-19 | 0 | 0 | Launch | 3.2 | 5.7 | 0.997 | 0.718 | 154 |
| | 2013-10-23 | 4 | 0.01 | T1 BEG | 3.2 | 5.7 | 0.997 | 0.718 | 154 |
| | 2014-01-10 | 83 | 0.23 | T1 END | 3.9 | 4.9 | 0.991 | 0.680 | 146 |
| | 2014-02-09 | 113 | 0.31 | GAM V1 | 3.9 | 4.9 | 0.990 | 0.680 | 146 |
| | 2014-03-20 | 152 | 0.42 | T2 BEG | 5.2 | 6.3 | 1.241 | 0.716 | 154 |
| | 2014-09-08 | 324 | 0.89 | T2 END | 5.4 | 6.6 | 1.214 | 0.619 | 133 |
| | 2014-10-08 | 354 | 0.97 | GAM E | 5.4 | 6.6 | 1.214 | 0.619 | 133 |
| | 2014-10-11 | 357 | 0.98 | T3 BEG | 3.3 | 6.3 | 1.017 | 0.340 | 73 |
| | 2014-12-31 | 439 | 1.20 | T3 END | 3.5 | 6.3 | 0.984 | 0.320 | 69 |
| | 2015-02-04 | 474 | 1.30 | T4 BEG | 3.5 | 6.3 | 0.984 | 0.320 | 69 |
| | 2015-05-07 | 565 | 1.55 | T4 END | 3.7 | 6.3 | 0.976 | 0.289 | 62 |
| | 2015-07-01 | 620 | 1.70 | T5 BEG | 3.7 | 6.3 | 0.976 | 0.289 | 62 |
| | 2015-07-15 | 634 | 1.74 | T5 END | 3.7 | 6.3 | 0.993 | 0.289 | 62 |
| Science Phase | 2015-08-14 | 664 | 1.82 | GAM V2 | 9.3 | 12.4 | 0.879 | 0.225 | 48 |
| | 2016-11-05 | 1114 | 3.05 | GAM V3 | 18.4 | 21.6 | 0.849 | 0.255 | 55 |
| | 2018-01-29 | 1563 | 4.28 | GAM V4 | 25.4 | 28.6 | 0.806 | 0.298 | 64 |
| Extended Phase | 2019-04-23 | 2012 | 5.51 | GAM V5 | 29.8 | 32.9 | 0.759 | 0.345 | 74 |
| | 2020-07-16 | 2462 | 6.74 | GAM V6 | 31.7 | 34.9 | 0.730 | 0.374 | 80 |
| | 2020-10-29 | 2567 | 7.03 | EOM | 31.7 | 34.9 | 0.730 | 0.374 | 80 |

**Figure 5.1.1/2:** Baseline trajectory (ecliptic view and X-Z projection)

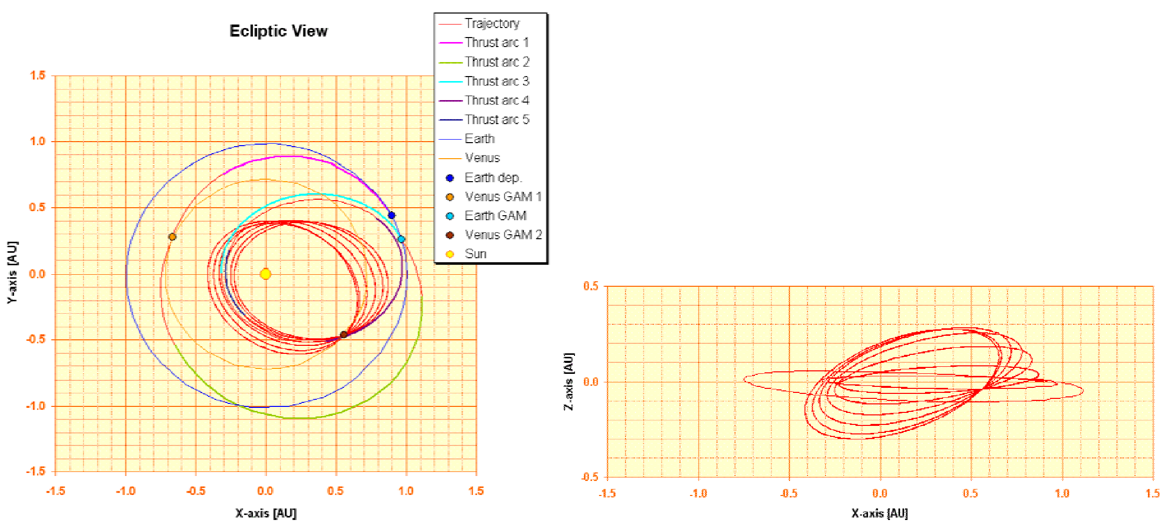


**Figure 5.1.3** – Baseline profile: spacecraft configuration from EADS-Astrium.

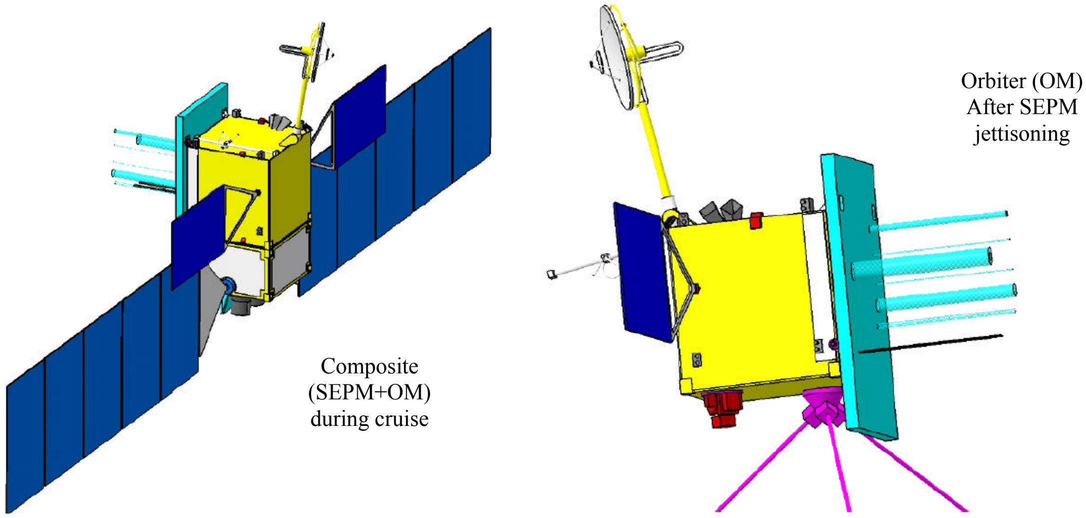
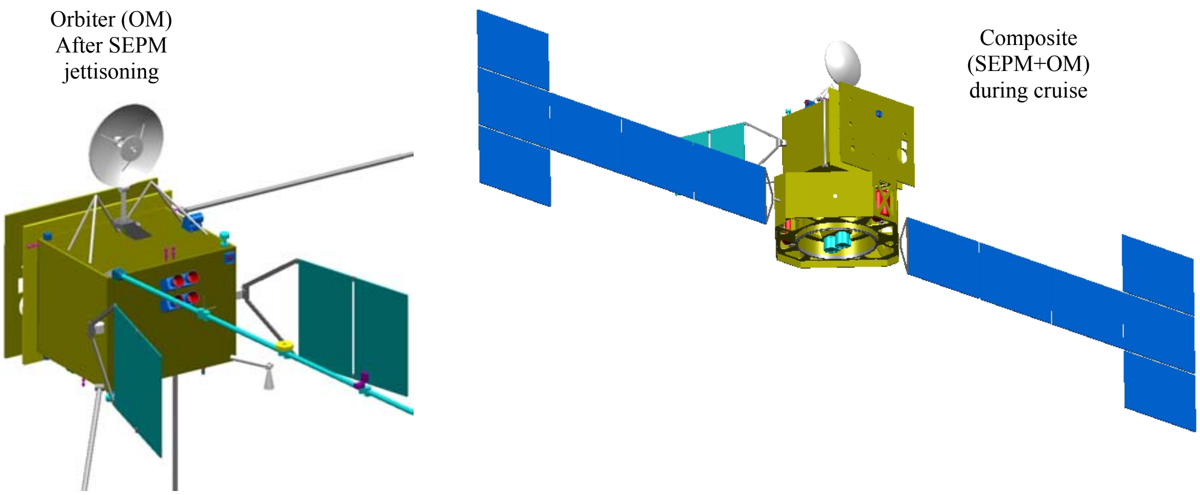



**Figure 5.1.4** – Baseline profile: spacecraft configuration from Alcatel-Alenia.




### 5.2 The Chemical Propulsion (CP) scenario

At the end of 2004, additional mission analysis work indicated the existence of low delta-V trajectories (i.e. compatible with a chemical propulsion scheme) with a cruise time shorter than initially envisaged (~3.3 yr against 4.9 yr). Table 5.2.1 below summarizes the key events of the chemical scenario with launch date in Nov 2013.
The total delta-V is limited to about 720 m/s (840 m/s including margins), fully compatible with chemical propulsion.

**Table 5.2.1** – Summary of chemical profile (launch in November 2013).

| Phase | Date | Flight time Days | Flight time Years | Event | Inclination [°] Ecliptic | Inclination [°] Sol. equ. | Aphelion [AU] | Perihelion [AU] | Perihelion [Sol. rad.] |
|---|---|---|---|---|---|---|---|---|---|
| Cruise Phase | 2013-11-08 | 0 | 0 | Launch | 1.0 | 6.4 | 0.991 | 0.684 | 147 |
| | 2014-03-06 | 118 | 0.32 | DSM 1 | 1.1 | 6.3 | 1.024 | 0.685 | 147 |
| | 2014-04-20 | 163 | 0.45 | GAM V1 | 0.8 | 7.0 | 1.379 | 0.727 | 156 |
| | 2014-10-24 | 350 | 0.96 | DSM 2 | 0.8 | 7.3 | 1.379 | 0.699 | 150 |
| | 2015-03-06 | 483 | 1.32 | GAM E1 | 0.0 | 7.3 | 1.104 | 0.463 | 100 |
| | 2016-12-29 | 1147 | 3.14 | GAM E2 | 4.1 | 3.8 | 0.990 | 0.294 | 63 |
| Science Phase | 2017-03-04 | 1212 | 3.32 | GAM V2 | 5.2 | 7.0 | 0.879 | 0.225 | 48 |
| | 2018-05-30 | 1663 | 4.55 | GAM V3 | 14.5 | 16.4 | 0.859 | 0.245 | 53 |
| | 2019-08-20 | 2111 | 5.78 | GAM V4 | 22.5 | 24.4 | 0.822 | 0.282 | 61 |
| | 2020-11-11 | 2560 | 7.01 | GAM V5 | 28.1 | 30.0 | 0.775 | 0.329 | 71 |
| Extended Phase | 2022-02-04 | 3010 | 8.24 | GAM V6 | 31.2 | 33.1 | 0.733 | 0.371 | 80 |
| | 2023-04-29 | 3459 | 9.47 | GAM V7 | 32.1 | 33.9 | 0.719 | 0.397 | 85 |

The actual ballistic trajectory to be followed by the spacecraft is represented in figures 5.2.1 (projection on the ecliptic plane) and 5.2.2 (projection on the perpendicular plane). The ecliptic view shows the S/C trajectory in the inner Solar system during the cruise phase, from launch to the second Venus GAM. The impulsive Deep Space Manouvres (DSM's) are indicated with triangles. The Earth orbit is shown in blue. Venus' orbit is in yellow. The trajectory followed during the science phase is indicated in red. The X-Z projection shows the evolution of the trajectory in a plane perpendicular to the ecliptic as to highlight the progressive inclination increase at each Venus GAM. Note that a corresponding scenario for a launch in May 2015 has been investigated, showing more favorable delta-V conditions than the nominal trajectory.

The chemical profile calls for a single spacecraft, the Cruise/Orbiter Module(C/OM), with an estimated total dry mass of about 800 kg. The C/OM is protected by a dedicated heat shield, as in the baseline profile. The C/OM retains an extremely large degree of commonality with the OM of profile a), with an increased size (due to larger propellant tank/s) and a factor 2 larger solar arrays (due to larger distance from Sun during cruise). A dedicated trade off (mono/bi-propellant) is required on the propulsion system. The figure 5.2.3 below shows the C/OM configuration identified by Astrium. It is clear that, albeit at the cost of a longer cruise and of a modest loss in terms of maximum orbit inclination, the chemical profile provides a lower complexity, risk and cost configuration, with the benefit of science operations during parts of the cruise for a subset of the instruments.

**Figure 5.2.1/2** Chemical trajectory (ecliptic view and X-Z projection)

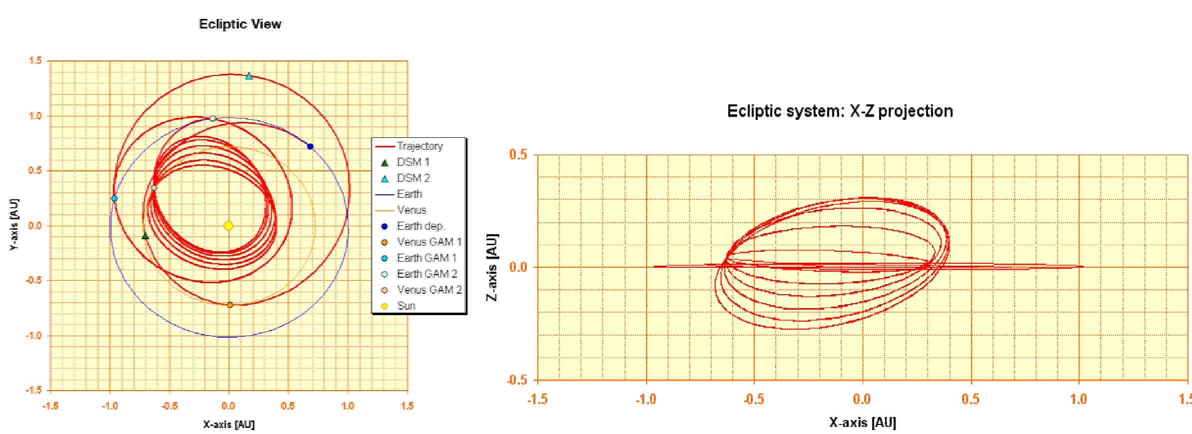
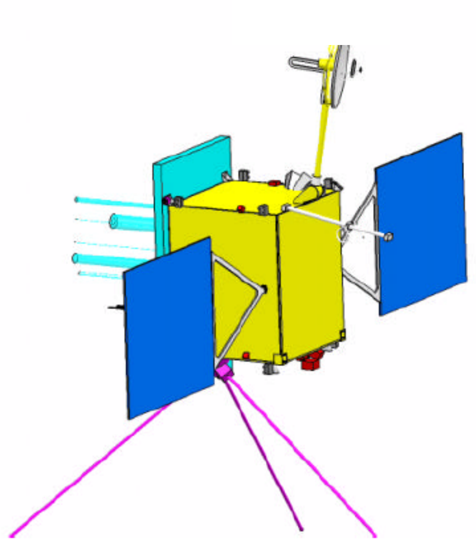
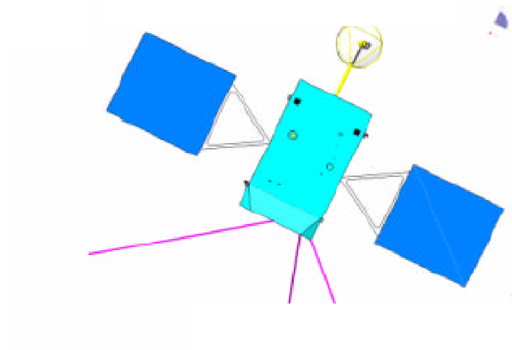


**Figure 5.2.3** – Back-up (chemical) profile: preliminary spacecraft configuration from EADS-Astrium.



Cruise/Orbiter Module with all appendages deployed



## 6. DESIGN DRIVERS & TECHNOLOGY DEVELOPMENT

A key aspect of the industrial studies has been the re-use of functional elements from other ESA missions. The commonality with BepiColombo has been promoted throughout all activities. The industrial activities have indeed confirmed the possibility to re-use a large number of units, as to minimize the development costs. This effort has allowed shortening drastically the list of the Solar Orbiter Technology Development Activities (TDA). The key technical challenges are summarized in the table below for both mission profiles.

| Baseline profile (SEP) | Back-up profile (CP) |
|---|---|
| SEP elements as from BepiColombo development | Longer cruise duration – mission lifetime |
| SEPM arrays (thermal qualification) | ---- |
| Tighter resource margins (mass) | ---- |
| Development and qualification of the heat shield, including instrument doors / baffles | |
| Orbiter solar arrays – design tailoring and thermal qualification | |
| Autonomous, fail-proof Sun Pointing Keeping Mode, including SEU recovery under intense $p^+$ fluence | |
| Development of the HTHGA (BepiColombo) and optimization of the TM link budget | |
| Overall thermal qualification at system level, in absence of a full scale, 22 Solar Constant test facility | |
| Cleanliness approach at both design level and during AIV/T activities | |

The main development drivers for the space segment are:

- Overall qualification PA and approach, with particular regard to thermal testing.
- Challenging thermal design induced by large variations of the solar flux (heat shield).
- High Single Event Upset (SEU) rate expected during the perihelion passes.
- Demanding pointing stability required by the Remote Sensing instruments.
- In the case of the baseline scenario, the synchronization of the development of the 2 modules (SEPM and OM) and specific needs related to SEP performance.
- Need to meet launch date dictated by celestial mechanics (October 2013, May 2015).

- Management of the system resources (especially for the baseline scenario) aiming to identify adequate margins and to avoid uncontrolled growth of P/L demands.
- Requirements deriving from operations, due to the large number of Gravity Assist Manouvres and different space environment conditions (aspect more relevant in the case of low thrust propulsion – SEP, due to long propulsive arcs).

The TDAs deemed necessary for the P/L development are summarized below. Considering their critical role for a timely delivery of the instruments it is recommended to begin activities as a matter of priority.

| Activity | Remarks |
|---|---|
| Active Pixel Sensor for EUV applications | Important to all Remote Sensing units |
| Heat rejecting entrance window – VIM | Critical element due to close I/F to heat shield |
| Polarization Modulation Package - VIM | Testing on radiation damage / qualification issues |
| Fabry-Perot filter - VIM instrument | Engineering model required to validate design |
| RPW antenna's (high temperature – stacer) | Heritage exists in US – cooperation with EU |
| Charge sensitive preamplifier – TOF ASIC | Required by a number of In-Situ sensor heads |

A preliminary, top-level list of the TDA's deemed necessary for the platform development is provided in the table below. Specific attention is to be paid to the solar arrays of the Orbiter module and to the availability of test facilities capable of re-creating Solar Orbiter representative conditions.

| Activity | Remarks |
|---|---|
| Orbiter Solar Array | Critical – customization of BepiColombo design to survive the 22 SC flux |
| High Temperature HGA | Delta development to extend operations below 0.3 AU from the Sun |
| SAS-AAD glasses | Protective glasses to be applied to existing SAS and AAD |
| High Temperature MLI | Delta development activities on BepiColombo HTMLI to match environment |
| Heat Shield Material Testing | Qualification of heat shield material in representative environment |
| Dedicated test facility | '1 $m^3$ class' test facility to create representative test environment |

## 7. GROUND SEGMENT

A summary of the assumptions related to Mission Operations Centre (MOC) infrastructure and activities is reported below.

- MOC based at ESOC. Large commonalities with BepiColombo mission as to reduce costs.
- Science Operations Centre at ESTEC, using planning tools developed for planetary & solar-terrestrial missions.
- The Principal Investigator teams will be responsible for the calibration of their instrument data, and the provision of fully calibrated, archival data sets, in line with the Science Management Plan.
- Operations will be pre-planned and tele-commands loaded to the spacecraft into a time tag buffer (e.g. autonomous operations and data storage during perihelion passes, when the High Gain Antenna cannot be deployed due to thermal constraints).
- New Norcia is the baseline ground station. It requires upgrading for Ka band downlink (already planned by ESOC) and will operate in parallel to X band downlink to achieve a greater telemetry return.
- Cebreros to be considered for post BepiColombo operations, especially when visibility from New Norcia is poor, due to the increasing orbit inclination, to the benefit of a larger science return.

## 8. PROGRAMMATIC ISSUES

The present working assumptions include the release of the instruments AO in Q2/2006. In the case of the baseline profile (SEP) and assuming a launch date in October 2013 (nominal), the following milestones have been identified:

- Technical assistance phase (1 yr, Q2/06 – Q2/07)
- Definition phase (~1.5 yr, Q3/07 – Q4/08)
- Implementation phase (~5 yr, Q2/09 – Q4/13, including 6 month contingency)

A detailed cost assessment has been performed in order to estimate the Cost at Completion of the Solar Orbiter mission, based on the documentation provided by both the industrial teams. A cost-risk analysis has also been applied. The assessment shows a lower cost for the chemical profile.

## 9. 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, including all corresponding programmatic aspects. Specific attention has been given to the reference payload, in order to prepare adequately for the future AO and maintain control over the corresponding spacecraft resources. These activities have indicated that, given the number and complexity of the instruments on board, such an attention should be also given in the following mission phases. The system level study has indicated that two mission profiles are viable:

- Baseline profile (Solar Electric Propulsion - 1.8 year cruise), with higher development risk;
- Back-up profile (chemical propulsion - 3.3 year cruise), with lower development risk.

In both cases, all critical design drivers have been analyzed and, while design challenges do exist, no major feasibility questions have been raised, showing a feasible mission, compatible with the nominal launch date of October 2013. The industrial study has also confirmed the relevance of the BepiColombo link and of the related TDAs, showing that a very limited number of Solar Orbiter specific technology development activities is to be considered. The programmatic analysis has indicated that, under the assumption of a tight resource management and a '*no-nice-to-have'* approach, the Solar Orbiter mission is compatible with the original budget allocation.

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