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SOLAR ORBITER

TECHNICAL & PROGRAMMATIC REPORT

COSMIC VISION DOWN-SELECTION REVIEW

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European Space Agency
Agence spatiale européenne

ESTEC
European Space Research and Technology Centre - Keplerlaan 1 - 2201 AZ Noordwijk - The Netherlands
Tel. (31) 71 5656565 - Fax (31) 71 5656040 www.esa.int

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1 INTRODUCTION

1.1 Procedure and Board composition

The Solar Orbiter Cosmic Vision down-selection review was run in accordance with procedure SRE-PA/2009/013 issue 1 revision 1 dated 15 April 2009 "Cosmic Vision 2015/25 M-class internal reviews.

In accordance with nominations by SRE-PA (Excel table circulated June 2009), the Board composition was originally as follows:

Mission candidate (Review cycle)	Solar Orbiter 1
Chair	T. Passvogel
Chair Deputy	M. Novara
Secretary	P. Kletzkine
Observers	F. Safa, T.Passvogel, R. Fontaine, external (+)
Mission Analysis (^)	R. Biesbroek (*)
Thermal	O. Piersanti
Structure	O. Piersanti
Mechanisms	O. Piersanti
Propulsion	----
Optics	----
AOCS	----
EPS	L. Gerlach (*)
TT&C / DHS	A. Polegre (*)
Payload #1 & AIV-T	O. Piersanti
Payload #2	B. Johlander
Payload #3	L. Duvet
Programmatics	T. Siwitza

However, in view of the nature of the mission, thermal engineer H. Frueholz was added to the board composition and took over the thermal engineering responsibility from O. Piersanti.

1.2 Meeting dates and participants

In accordance with the meeting schedule specified by the review procedure, the following meetings were held:

1. Kick-off meeting 01/09/2009 Minutes SRE-PS/01454 "Cosmic Vision Solar Orbiter Down-selection Review Kick-off meeting"
2. 2nd meeting 08/09/2009 Minutes SRE-PS/01457 "Cosmic Vision Solar Orbiter Down-selection Review 2nd meeting"
3. 3rd meeting 15/09/2009 Minutes SRE-PS/01467 "Cosmic Vision Solar Orbiter Down-selection Review 3rd meeting"
4. 4th meeting 22/09/2009 Minutes SRE-PS/01471 "Cosmic Vision Solar Orbiter Down-selection Review 4th meeting"

The minutes list the participants to the respective meetings.

1.3 List of documents

1 Presentations and Minutes, Solar Orbiter Design Status Review, 15-16 June 2009
2 Solar Orbiter Mission Requirements Document
3 Solar Orbiter Mission Analysis Report
4 Solar Orbiter Mission Assumptions Document
5 Solar Orbiter Experiment Interface Document Part A (EID-A)
6 Solar Orbiter Science Requirements Document i1r2 31-03-2005
7 Solar Orbiter Environmental Specification TEC-EES-03-034/JS, issue 2.0, rev.0 14/11/2008
8 Science Operations Assumptions Document (SOAD) for Solar Orbiter, July 2009
9 Solar Orbiter Experiment Interface Documents Part B (EID-Bs) for 10 Instruments
10 Solar Orbiter Technology Development Plan
11 Solar Orbiter DSR closure data package documents register
12 SOL-S-ASTR-RS-0007 - Solar Orbiter System Requirements Specification - Issue 1.1
13 SOL-S-ASTR-TN-0014 - Solar Orbiter System Design Report
14 SOL-S-ASTR-TN-0012 - Solar Orbiter System Trade Offs
15 SOL-S-ASTR-TN-0010 - Solar Orbiter System Budgets
16 SOL-S-ASTR-PL-0021 - Solar Orbiter DD&V Plan
17 SOL-S-ASTR-PL-0009 - Solar Orbiter AIV Plan
18 SOL-S-ASTR-CH-0001 - Solar Orbiter Master Schedule
19 SOL-S-ASTR-TN-0011 - Solar Orbiter Mission Operations
20 SOL-S-ASTR-ICD-0004 - Solar Orbiter Launcher IRD
21 SOL-S-ASTR-IRD-0001 - Solar Orbiter Heatshield Interface Requirement Document
22 SOL-S-ASTR-RS-0002 - Solar Orbiter Feedthrough Door and Mechanism Requirements Specification
23 SOL-S-ASTR-RS-0003 - Solar Orbiter Structure Requirements Specification
24 SOL-S-ASTR-TN-0005 - Solar Orbiter PHI Filter Accommodation and Interface
25 SOL-S-ASTR-TN-0015 - Feedthroughs Doors and Mechanisms Design Report
27 SOL-S-ASTR-TN-0028 - Solar Orbiter Thermal Analysis Report

30 SOL-S-ASTR-TN-0025 - Solar Orbiter Finite Element Model Description
31 SOL-S-ASTR-TN-0027 - Solar Orbiter Instrument Boom Design Description
32 SOL-S-ASTR-TN-0017 - Solar Orbiter Structure Design Description
33 SOL-S-ASTR-TN-0022 - Solar Orbiter Thermo-elastic Distortion Analysis PHI Feedthrough
34 SOL-U-ASTR-TN-0010 - Solar Orbiter Heat Shield Feedthrough Vane Design
35 SOL-U-ASTR-TN-0011 - Solar Orbiter CPS Trade-off
36 SOL-S-ASTR-TN-0021 - Solar Orbiter Chemical Propulsion System Design Report
37 Solar Orbiter Non Compliances and Suggested MRD Changes
38 SOL.F.ASTR.PL.00022_I1.1_EMC Control Plan
39 SOL.F.ASTR.RP.00001_I1.1_AOCS_Subsystem_Design_Description
40 SOL.F.ASTR.RP.00002_I1.1_Data_Handling_Subsystem_Design_Description
41 SOL.F.ASTR.RP.00003_I1.2_BepiColombo Equipment_Reuse_for Solar Orbiter
42 SOL.F.ASTR.RP.00004_I2_Solar Orbiter Link Budget
43 SOL.F.ASTR.RP.00008_I1.1_AOCS_Performance Simulation Report
44 SOL.F.ASTR.SP.00010_I1.2_Solar Orbiter AOCS Specification
45 SOL.F.ASTR.SP.00033_I1.1_EMC Requirements Specification
46 SOL.F.ASTR.SP.00090_I1_Failure Control Electronics (FCE) Requirements Specification
47 SOL.F.ASTR.TN.00001_I2.2_Compilation_of_Astrium GmbH_Engineering_Work
48 Input for a Solar_Array_TDA (Technology Development Activity)
49 High Gain Antenna (HGA) Specification, SOL-T-TAS-RS-00008
50 Medium Gain Antenna (MGA) Specification, SOL-T-TAS-RS-00010
51 Low Gain Antenna (LGA) Specification, SOL-T-TAS-RS-00007
52 Solar Array Specification, SOL-T-TAS-RS-00014
53 Heat Shield Thermal Analysis, SOL-T-TAS-AN-00001
54 SOL-S-ASTR-TN-0035 - Solar Orbiter Alternative Configuration Trade-Off (document listed but actually outside of review purview)
55 Solar Orbiter Assessment Study Report ("Yellow Book")

1.4 Overview of activities (main facts)

The review meetings were held as scheduled. The activities are described in the respective minutes of meetings. The main findings were discussed during the 2nd and 3rd meetings. The 4th meeting (22/09/2009) was held in the presence of SPC observers and summarized the findings and conclusions. Immediate actions were carried out, largely by the Board technical experts themselves, to complement the findings of the Board, in particular in the areas of Solar Generator development (revision of the corresponding Technology Development Activity definitions) and Mission Analysis (rapid investigation of sizing of an additional propulsion stage in the case of the back-up launch vehicle).

The technical and programmatic findings are described in the following sections of the present report.

2 TECHNICAL REVIEW

The technical review was performed across the documents provided in the data package. The following paragraphs concentrate on the major issues identified throughout the review.

2.1 Spacecraft design

- The Board has not identified any missing issues with the already well established baseline science requirements and hence mission **requirements** (with a small exception of a spacecraft and payload autonomy duration requirement, which is to be corrected).
- The Board is of the opinion that the translation of **mission requirements to system requirements** is complete and adequate. Generally, the status of requirement definition is already in an advanced state and in a number of cases extends down to sub-system and unit levels.
- Accordingly, the **spacecraft design** is quite elaborate and a detailed design is available is many areas. The design is supported by adequate analyses and was found to be generally **robust**, **except for the solar generator**, the low technological readiness of which may still dictate design changes at spacecraft level (e.g. single-sided, instead of double-sided array). Of less concern, but in need of improvement, are, not surprisingly for such a mission, the heat rejection capability provided by the thermal control and the thermal design verification.
- The Board notes that the solidification of responsibilities and interfaces with **NASA** for what concerns the **(nominal) Launch Vehicle** is not formalized and later could affect the spacecraft design activities. However, it concurs that the lack of formalization of the agreement on the launch vehicle provision is normal, pending the formal down-selection and confirmation of the Solar Orbiter project. The temporary lack of a formal inter-Agency agreement does not affect the technical definition at present. The programmatic risk is discussed further in this report.

2.2 Technology readiness

The Board concurs that the following elements, which all play a critical role in the overall design, constitute moderate to high technical risks where technology development is required.

- Solar array – <u>High Technical Risk</u>
- Heat shield – Technical Risk
- AOCS Sensor – Technical Risk (critical)
- Thermal Design and Verification – Technical Risk.

Besides, the Board finds that the current program of Technology Development Activities (TDAs) can in itself be considered as a Programmatic Risk

2.2.1 SOLAR ARRAY

The Solar Orbiter solar array has to function at a high temperature with a very high energy density and UV radiation. The feasibility of the original assumption – direct heritage from BepiColombo (BC) is doubtful, in the face of the difficulties encountered by BepiColombo itself while Solar Orbiter faces up to twice the sun intensity (20 Solar Constants) and requires a double sided array for the phase of the mission far away from the sun.
The Board considers that the design presented as part of the data package, based on recurring BepiColombo technology, is not a viable solution for Solar Orbiter, and that mission feasibility is therefore fully dependent on the success of upcoming dedicated technology developments. The dedicated developments have not started yet. They are planned to start in 2010, with expected qualification obtained only in 2014, assuming nominal progress.

In that context the Board notes that:

- Spacecraft-size testing capabilities will be limited to 10 Solar Constants (existing high-temperature high-UV chambers, plus LSS adaptations done for BC)
- Full testing to 20 Solar Constants will only be possible with smaller, unit-size testing capabilities. Update of test facilities are planned under a Solar Orbiter TDA.
- A TDA for test methodology (acceleration and higher flux) is planned, and this will be of particular criticality for the verification of solar array life.
- A TDA for a 20 Solar Constants small (unit level) solar facility is pending initiation and is regarded by the Board as an urgently needed investment.\
- The identification of TDAs is not a guarantee of their technical success or implementation schedule.

As part of the review process, two alternatives were discussed and highlighted:

- A low risk approach fully based on BepiColombo heritage but entailing a modified orbit, coming no closer to the sun than about 0.28 AU (therefore with an impact on the science case to be evaluated) with Solar Cell Assemblies <u>inherited from BepiColombo</u>. The review Board recommends an early decision on this. It considers that this would remove a major development risk for the mission and would allow for starting the Definition Phase on a solid, low risk, technical ground. This solution is to be assessed by revisiting the mission scenario (ESOC) and evaluating the impacts on the science case. It relies on designing a Solar Obiter-specific double-sided array, which is considered technically a low risk at this increased distance to the sun, and schedule-wise a medium risk. A dedicated TDA is proposed to further reduce the risk.

- A new design, with inherent technology and schedule risks, compatible with the nominal orbit (perihelion at 0.23 AU, nominal science). This requires a new development with a challenging schedule, i.e. the completion of the development cycle of single junction cells with infra-red filtering by cover glass. This approach will significantly lower the temperature. It carries a mass penalty. It needs a double-sided solar array design as above.

Further backups have been discussed for the case that the considered double sided array would show unexpectedly significant technological risks. However, at the present stage they are not considered in need of further follow up:

- A single sided Solar Array design capable of covering the complete range of sun distances (0.23 AU to 1.5 AU) and of providing the same global power output, i.e. an array of significantly increased area. This is rated as a high technology risk. The large area requires special attention to wing flatness (risk of wing warping) and carries a higher overall mass. Some science impact is to be expected e.g. via reduced pointing stability.

- Introduction of a separate, additional solar array to cover “deep space” power demand. This leads to a higher overall mass and possible accommodation problem (wing to be stowed behind the spacecraft below a certain distance to sun), as well as an expected reduced science due to significantly reduced Fields-of-View available for instruments.

In all cases, mechanical and thermal design improvements are needed to cope with the 20 Solar Constants environment (panel edges, cable duct, hinges/hold-downs, deployment mechanism). This is addressed in the TDAs for the alternatives mentioned above.

2.2.2 HEAT SHIELD

The Heat Shield and its feedthroughs and doors are critical items for both spacecraft and payload designs. Heat Shield TDAs have been run with good results; a feedthrough TDA is planned to start in 2010.

The Board concurs that, while activities have to be completed and need attention and continuation through TDAs, this area can be considered as under control.

However, the Board emphasizes the need for additional design and analysis work to create an escape route in case the heat leak from the heat shield and/or feedthroughs turns out higher than expected (even as late as a Thermal Balance Test at STM level). This can take the form of e.g. a larger radiator area, shorter thermal path from units to radiator, with likely impact on configuration and mass. *It is recommended to make sure that the spacecraft configuration is optimized for thermal control, e.g. ensure sufficient margins on radiator areas.*

2.2.3 AOCS SENSORS

Several AOCS sensors – mainly sun sensor and star tracker need new developments and/or adaptation. A high solar intensity sun sensor TDA was started in 2009. In view of the similarity of the sun sensor with the solar array (sensor is a solar cell) and the difficulties with the qualification of the solar cells (in particular the risk area at the sensor edges) it is considered that the sensor is an open issue. The validity of the technical approach of the TDA should be re-visited with priority and if needed the effort should be re-directed.
A high radiation environment star tracker TDA is still to be initiated. This area is considered of low criticality if started early.

2.2.4 THERMAL DESIGN AND VERIFICATION

Thermal design, testing and verification is of course critical for Solar Orbiter due to the very nature of the mission. The thermal tests are expected to be difficult, due to the extreme environment, partial illumination capability of existing and planned spacecraft-level facilities, and entail unusually long system-level test durations.

Spacecraft-level testing will be limited to the 9 or 10 Solar Constants (LSS facility limits inherited from BepiColombo) requiring additional test heaters and infra-red lamps, and a supplementary extrapolation analysis effort. The spacecraft thermal design and testing also imposes severe constraints (e.g. heat pipe orientations).

The Board considers that it is necessary to ensure testing of all external materials, Solar Array, heatshield and antennae at least on representative sample level with flight representative solar heat loads. ***This implies that facilities capable of providing a flux of 20 Solar Constants, including the UV content, are critical and should be given high priority within the TDAs.***

The Board concludes that this area does not raise issues of feasibility but is essential for the development of the spacecraft. It does need early attention to include all constraints in the design phase and ensure development and availability of the necessary facilities.

3 PROGRAMMATIC REVIEW

3.1 Development plan and schedule risk

The Board considers that the development schedule provided is complete, with adequate level of detail and generally realistic durations.
Four major programmatic risks have been identified and are discussed below:

- Launch Vehicle
- Technology Development Activities (TDAs)
- Schedule
- Instrument Development

3.2 Launch Vehicle

3.2.1 LAUNCH VEHICLE AVAILABILITY (INTERNATIONAL COOPERATION)

The nominal launch vehicle (Atlas V or Delta IV) will be provided by NASA. The temporary lack of a formal inter-Agency agreement does not hamper the technical definition but does constitute a programmatic risk. However, in view of the NASA commitment to the project as demonstrated by the funding of a significant part of the payload, no particular concerns are raised on this point.
The mass margin available on either vehicle, even if the smallest version is chosen, is sufficient.

3.2.2 LAUNCH VEHICLE BACK-UP

To cover the programmatic risk further and comply with ESA policy, the Project maintains a back-up launch vehicle scenario based on Soyuz-Fregat from Kourou. However, its mass margins as studied until now are clearly insufficient (close to 0%). The Board identified a further back-up scenario based on the use of an additional transfer stage (a dedicated additional element of Solar Orbiter) derived from e.g. the LISA Pathfinder Propulsion Module, which restores adequate mass margins and will likely entail limited spacecraft design consequences, but has not been studied yet.
The Board concurs that spacecraft specifications should include compatibility with Soyuz and interfaces with this transfer stage, and that the definition phase should include basic design work on the stack configuration to secure its feasibility.

3.3 Technology Development Activities (TDAs)

The Board found the status of the TDAs to be of serious concern:

- 3 TDAs have run for spacecraft development since 2008 or earlier
- Out of 6 TDAs planned and agreed for 2009, only 1 is running, 3 are pending
- Out of 7 TDAs planned for 2010, none is ready to start yet, readiness is expected by mid-2010 at the earliest
- The average duration of a TDA is 18 months, which entails that not all TDAs will be completed by the start of phase B2 in 2012.

The solar array TDA is the most prominent and the most urgent. Its target and scope are to be updated as a result of the present review. Coordination with BepiColombo running development and upcoming qualification activities is required for the potentially conflicting uses of limited available test facilities.

Pre-development activities in 2010 are necessary in order to meet the 2017 launch opportunity.

Generally, the Board concludes that execution of TDAs is not progressing in accordance with the project development needs. This needs to change. ***Further it is considered essential that the responsibility for the management (technical and programmatic responsibility) of the TDAs is given to the project.***

3.4 Schedule

The Board considers that a complete development schedule is available with adequate level of detail and generally realistic durations, for design phase, procurement phase and spacecraft AIT and taking into account the ESA-mandated 6-month margin.

However, taking into account the Cosmic Vision implementation schedule guidelines, the project schedule will not meet the January 2017 launch opportunity, even under optimistic present development assumptions. The present development schedule assumes that the definition phase is actually a “pre B2” phase, and that phase B2 can start already in January 2012, leading to a PDR in October 2012. This schedules shows readiness for launch in July 2017 (including the 6-month ESA margin that is specified at this early stage), assuming all the above mentioned technical problems are solved and all necessary TDAs are successfully implemented and delivering their output on time.

The Board notes that the next launch opportunity is in July 2018 and that according to the mission analysis, this would result in ending the nominal mission in orbit with a delay of two months only.

The Board considers the July 2018 launch date as realistic (exhibits 12 months contingency with start of the development in Q3 2012), in particular if the re-use of Bepi-Colombo solar cell technology is retained.

3.5 Instrument development

The responsibilities and **interfaces with NASA and NASA-funded institutes** are clearly defined for what concerns provision of the **payload complement** (which has already been selected as a result of an Announcement of Opportunity), with the minor exception of one part of one sensor of one in-situ instrument suite. All other instruments are covered by Letters of Endorsement from their respective Lead Funding Agencies. However, the Board notes that they date back to the situation where Solar Orbiter was not within the Cosmic Vision competition and recommends that a re-confirmation be sought at the present stage and up-to-date Letters of Endorsement be provided to consolidate and confirm the payload funding support.

Instruments forming the full payload complement have already been selected and will all be nationally provided. The necessary resources and performance of instruments appear compliant (as stated today). The payload development schedule is found to be globally in line with spacecraft schedule needs. This can be considered realistic, provided instrument consortia are given funding as committed at the time of instrument proposals in response to AO.

The development of detectors is an area of concern and is schedule critical. A TDA has been run on the topic, further development is now entirely with the respective instrument teams.

Instrument reviews are defined and compatible with spacecraft reviews:

- Instrument Design Status Review (IDSR) : running now – completed by Jan 2010
- Instrument Preliminary Design Review (IPDR): Autumn 2011
- Instrument Critical Design Review (ICDR): January 2013
- Instrument Delivery: January 2015.

Critical interfaces need to (and can, given sufficient funding) be frozen in 2010. Resources at ESA and Industry for instrument follow-up will be critical.
The Board recommends to ensure that resources for instrument follow-up are made adequate to the purpose.

4 RECOMMENDATIONS

4.1 Summary of key findings

- The Board has found no significant issues with the baseline science and mission **requirements** and finds the translation of **mission requirements to system requirements** complete and adequate. The status of requirement definition is already in an advanced state and in a number of cases extends down to sub-system and unit levels.
- The **spacecraft design** is quite elaborate and detailed design is available is many areas. The design is supported by adequate analyses and was found to be generally **robust**, **except for the solar generator and to a lesser extent** the sun sensor and availability of radiator area.
- The payload responsibilities and **interfaces with NASA and NASA-funded institutes** are clearly defined.
- The Board lists the following technical risks:
  - **Solar array** – <u>Highest risk</u> – several scenarios have to be considered, including a low risk approach relying on Bepi-Colombo solar cells which entail an evaluation of the science impacts.
  - Heat shield, Sun Sensor, Thermal Design and Verification including facilities.
- A development schedule is available that is complete, with an adequate level of detail and generally realistic durations and margins and leads to a spacecraft readiness in early 2018 for a launch in July 2018.

4.2 Specific recommendations

- Obtain **up-to-date Letters of Endorsement** from Lead Funding Agencies to reconfirm the timely availability of payload funding.
- Perform Mission Analysis and **study science return consequences of raising the minimum perihelion** distance to that provided by BepiColombo solar array technology. Initiate as soon as possible and fully resource the **solar array design and Technology Development Activities**.
- Optimize the **spacecraft configuration for thermal control**, e.g. ensure sufficient margins on radiator areas.
- Initiate and pursue without delay the identified **Technology Development Activities** on AOCS sensors, test facilities, test methodology; and keep them under control of Project.
- Re-visit the validity of the **Sun Sensor TDA** technical baseline.
- Ensure early availability of the **test facilities** in coordination with the BepiColombo project.
- Study and include compatibility with **back-up Soyuz-Fregat plus transfer stage** in spacecraft specifications.
- Make sure that resources for instrument follow-up are made adequate at ESA and Industry.