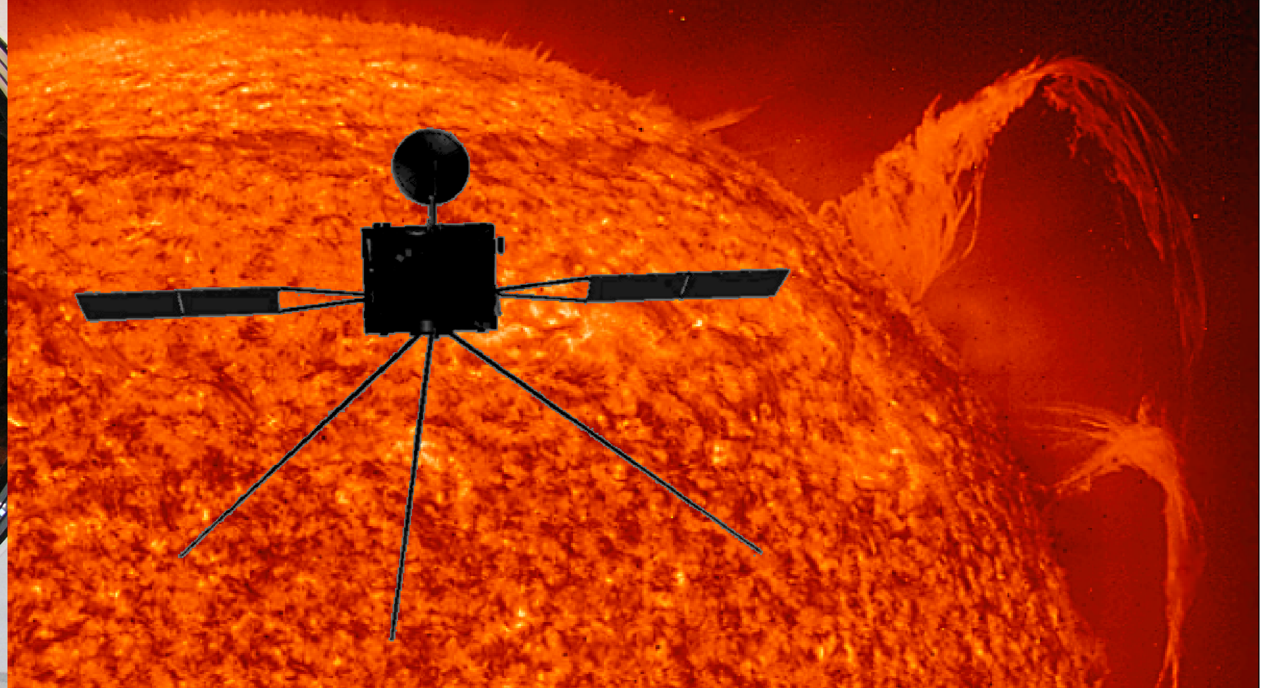
SOLAR ORBITER

Heat Shield / System Technology

FINAL PRESENTATION

Noordwijk, October 4th 2007



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Agenda

- 09:00 - 09:15 Welcome
- 09:15 - 09:30 Introduction by ESA
- 09:30 - 12:00 Thales Alenia Space achievements
  - 09:30 Introduction, Team, Study logic
  - 09:35-09:55 System design and Payload Accommodation
  - 09:55-10:05 System justification: budgets, trade-offs, system analyses
  - 10:05-10:45 Heat Shield: definition, trade-offs, justification, sample-testing

------------------------------(10:45 - 11:00 Coffee break) ---

  - 11:00-11:20 Heat shield breadboard design, manufacturing and testing
  - 11:20-11:40 Spacecraft thermal, mechanical and Subsystems design and analyses
  - 11:40-11:50 Spacecraft AIV and schedule
  - 11:50-12:00 Impacts of joint mission with Solar Sentinels
  - 12:00 Conclusion
- 12:00 - 13:00 Questions & discussions

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INTRODUCTION

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Introduction

- Thales Alenia Space is proud to present the achievements of this Heat Shield System Technology contract

- Our integrated team has combined the experience and resources of:

  - Cannes (lead, system, AOCS, data handling...)

  - and Turin (thermal control, Heat Shield, TTC RF subsystem)

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Achievements

- Thales Alenia Space has completed the activities along the five axes of the Statement Of Work:
  - Payload accommodation
  - System design update
  - Heat Shield development, with manufacturing and testing a full-scale model
  - Solar Array and HGA technology
  - Cost and schedule drivers analysis

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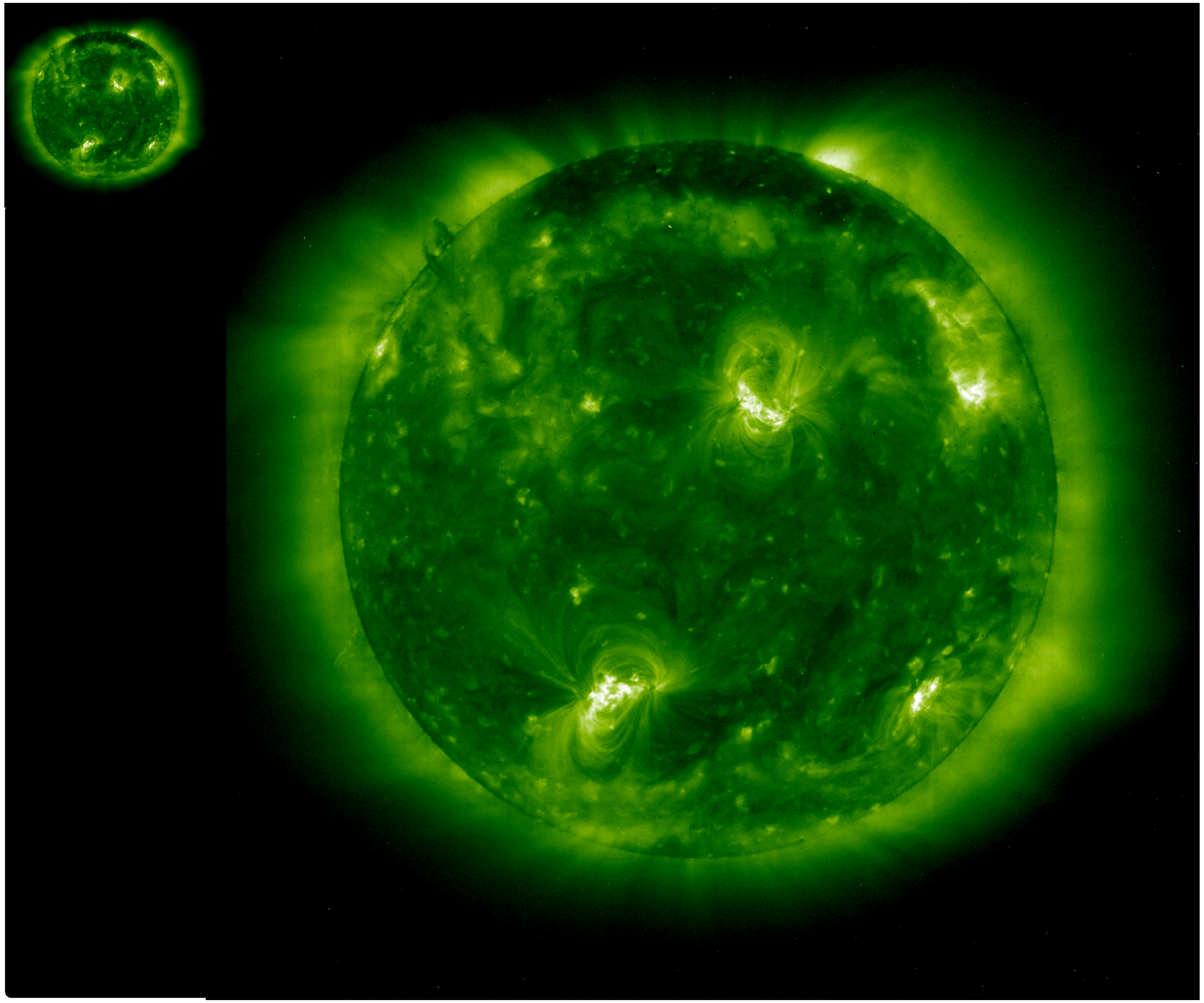
A factor of 4.5 on distance to Sun:

Solar Orbiter will enhance our knowledge of the Sun by measuring its properties and observing the star as close as 0.22 AU (as opposed to current data at 1 AU –picture above from SOHO EIT-).



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SYSTEM DESIGN

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Design drivers (1/2)

- Cost and schedule => privilege recurring units and reuse the specific developments of BepiColombo, especially on Solar Array and High Gain Antenna

- Close perihelion (0.22 AU in baseline mission scenario) => thermal fluxes up to 28500 W/m², high radiations, UV ageing and solar disturbance torques

- Large variation in Solar Array illumination, from 0.5 to 20 solar constants, with the cruise phase at 1.5 AU => sizing the power generation

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Design drivers (2/2)

- Very large data transmission capability required, due to variable distance between Earth and Spacecraft

  => powerful RF system and large mass memory

- Numerous instruments requiring reliable thermal rejection, crossing of the Heat Shield, high pointing accuracy, many appendages or fields of view and very stringent cleanliness levels

- Launcher compatibility, limiting the mass and volume of the spacecraft: Soyuz launch, with Atlas as a possible alternative.

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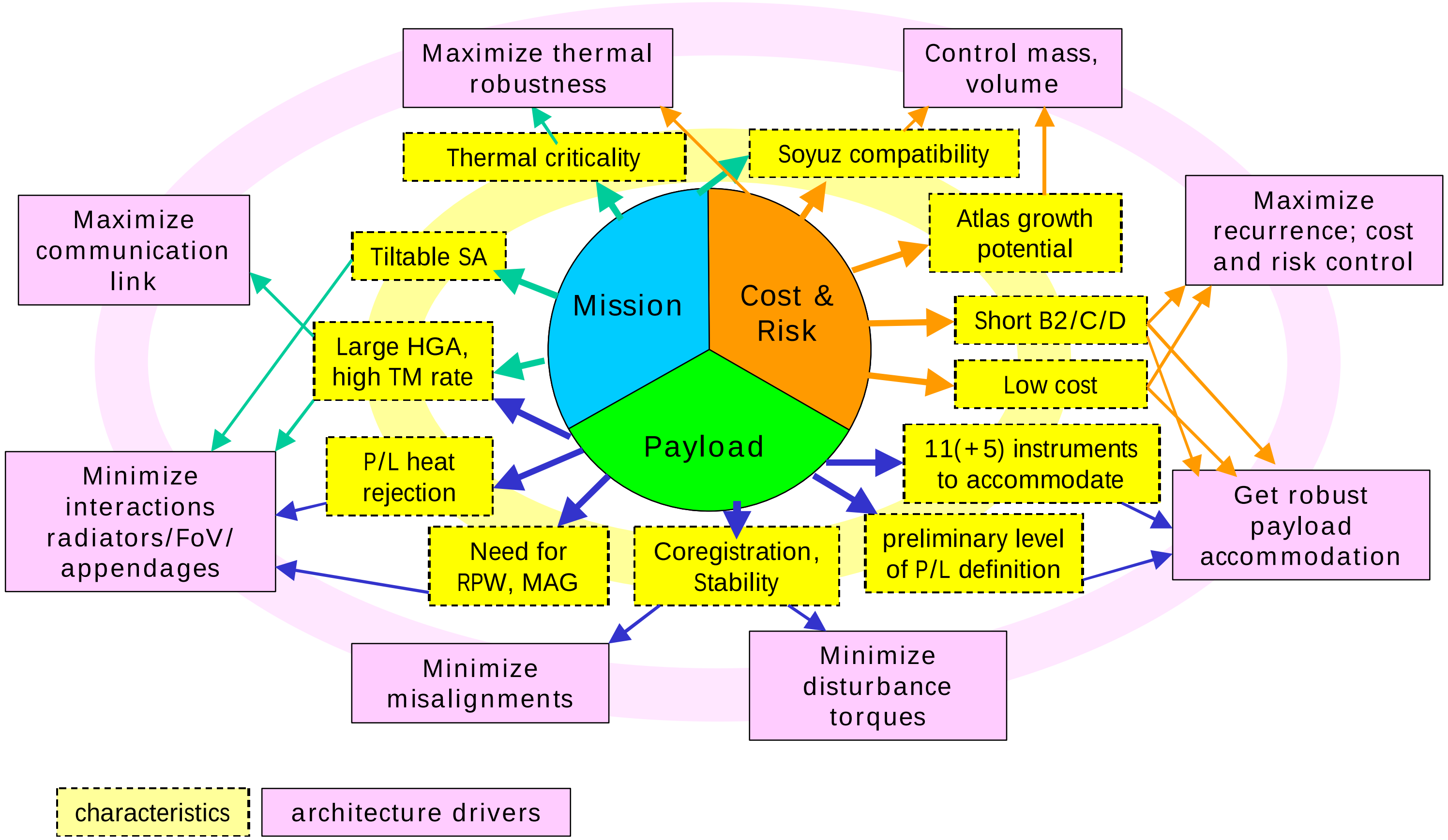
Choice criteria for Solar Orbiter architecture



Thales Alenia Space analyzed the technical and programmatic requirements and inferred the criteria used for the selection of the optimum design

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System design: maximizing heritage and science

- Extensive trade-offs conducted to select a configuration that best fits mission drivers.

- Special emphasis on configurations that combine:
  - low-cost, low-risk approach,
  - strong reuse of BepiColombo heritage,
  - modular design for a resilient schedule
  - maximum resources for Science.

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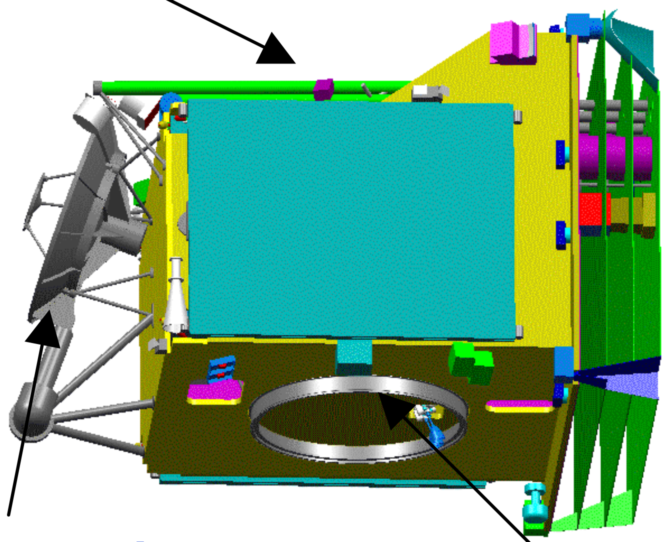
System design: maximizing heritage and science

- Ø Design: parallelepiped body shadowed by a Heat Shield.
- Ø Compact launch configuration:

=> decreases mass and minimizes loads on Heat Shield, HGA



Solar Orbiter in Launch configuration

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System design: maximizing heritage and science

- High Gain antenna and Solar Arrays managed in a series of configurations that:
  - increase the data link and power capabilities
  - and protect the BepiColombo heritage

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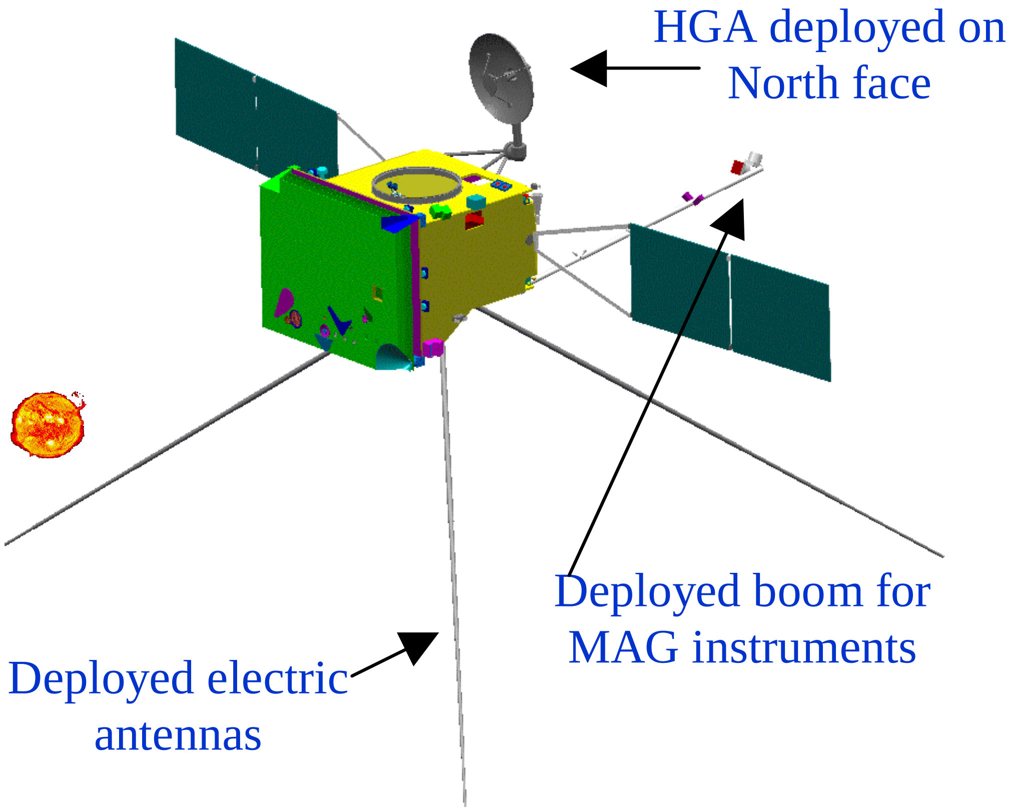
System design: maximizing heritage and science

- In cruise configuration all appendages are deployed.
- The Solar Array presents a face fully equipped with cells towards Sun
  => power for in-situ instruments and spacecraft heating.
- Deploying HGA towards the launcher interface face saves one cold face for thermal rejection.



Solar Orbiter in Cruise configuration

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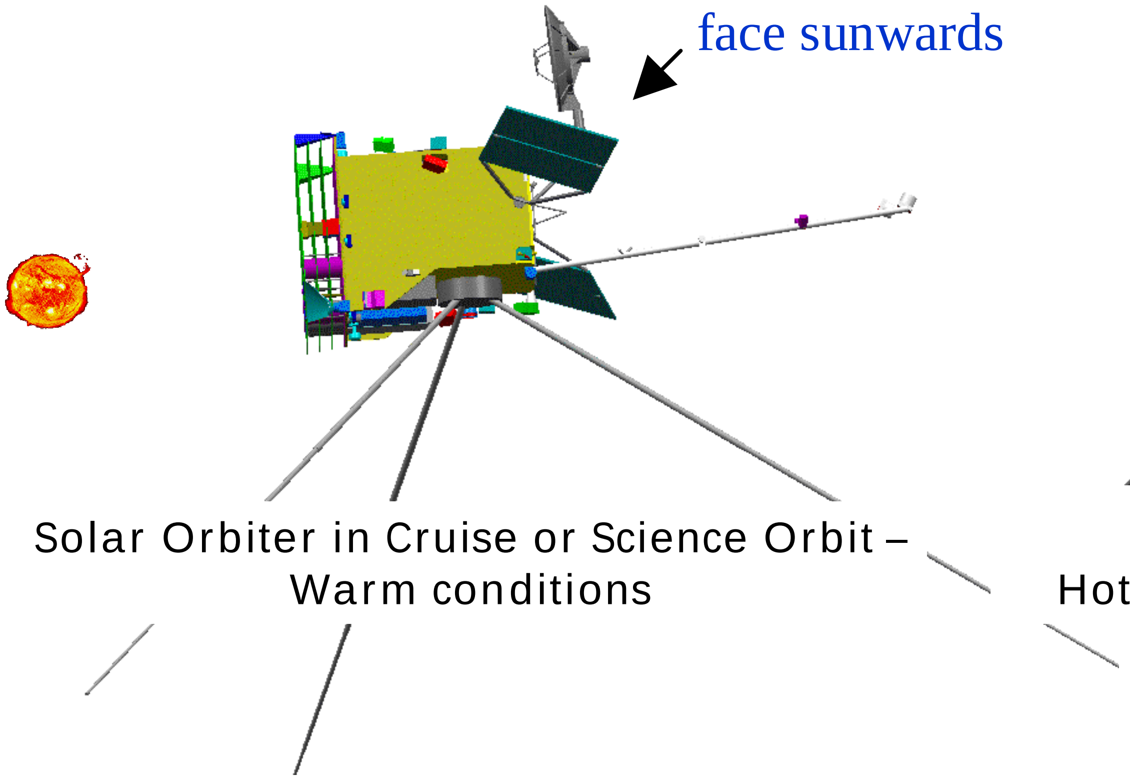
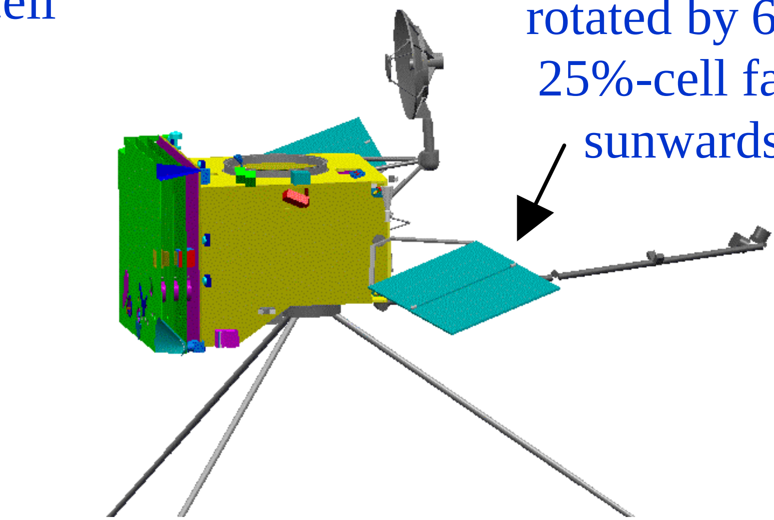
System design: maximizing heritage and science

- By rotating the two-faced Solar Array, the thermal qualification from BepiColombo is preserved, while the power generation is maximized



Solar Orbiter in Cruise or Science Orbit – Warm conditions



Solar Orbiter in Science Orbit
Hot conditions – Rotated Solar Array

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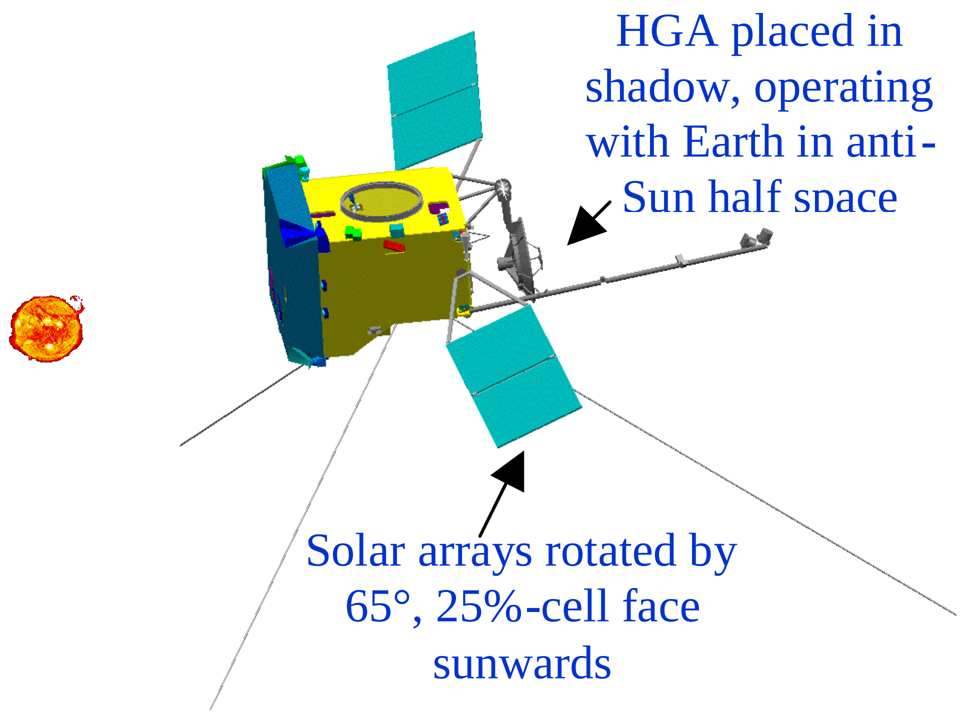
System design: maximizing heritage and science

- Second operational position for the HGA
- Can be placed in full shadow of the spacecraft at any time

=> Configuration further secures the adequacy of technological heritage



Solar Orbiter in Science Orbit – Hot conditions- Tilted Solar Array & shadowed HGA

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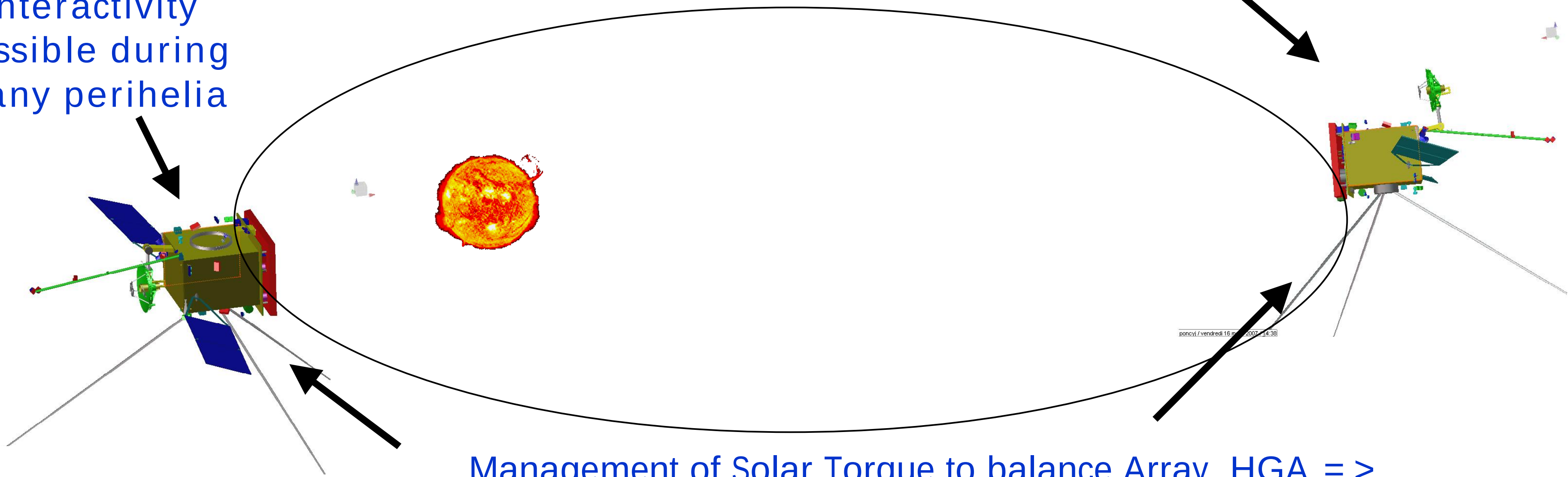
System design: a plus for science

Capability to use HGA in shadow at perihelion => Interactivity possible during many perihelia

Thanks to two-sided array, power margin increase on all science orbit => Payload can be fully on at any time



Management of Solar Torque to balance Array, HGA => target 0 thruster activation during 10-day observation campaign

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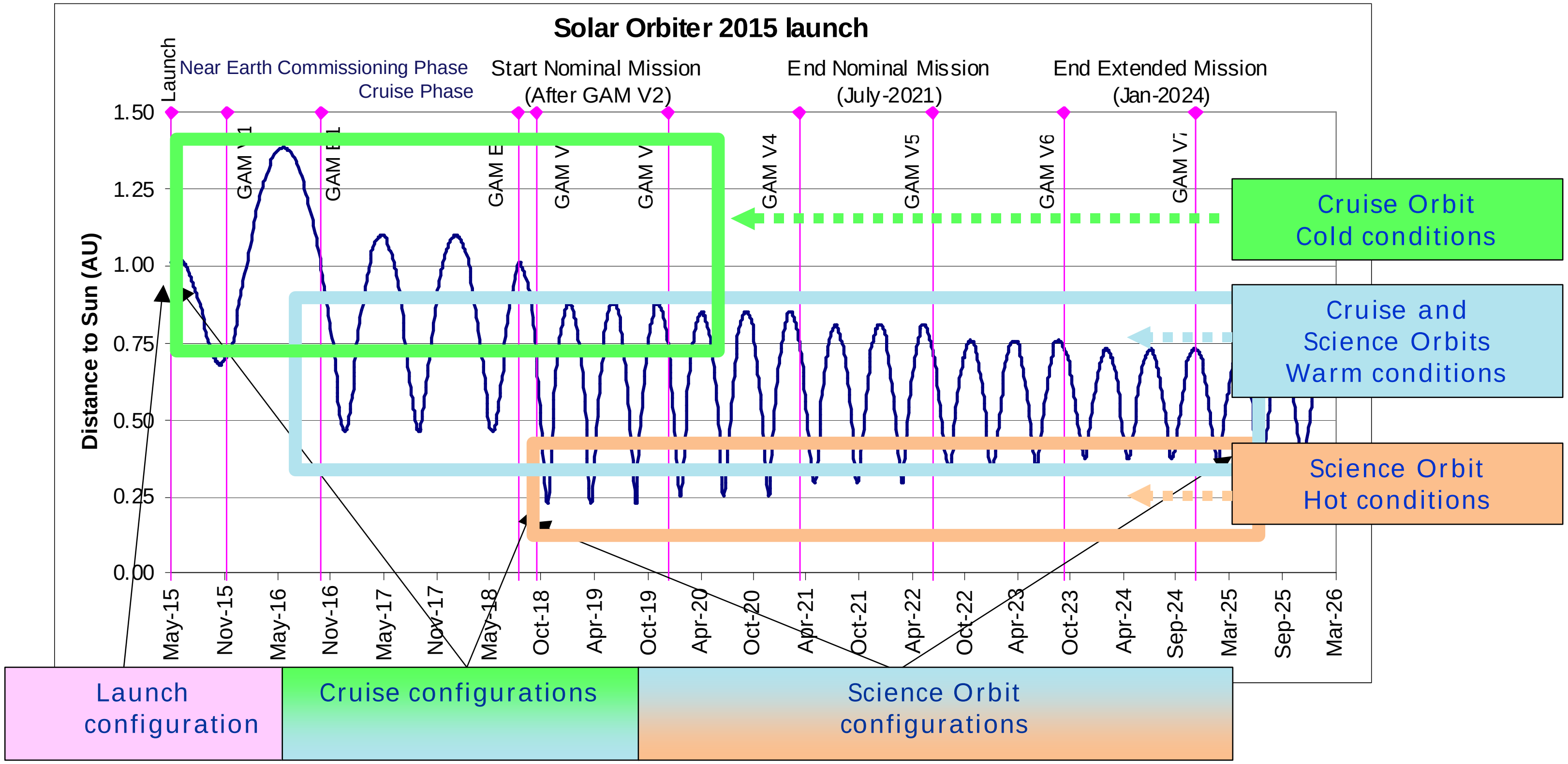
System design: robust to development uncertainties



The overlapping domains of the configurations enable to easily adapt in real time to the lessons learned in the future from the on-ground and in-flight phases of BepiColombo and Solar Orbiter, and to the positioning of the observations period.

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A modular design that decouples deformations … and schedule

Two modules:

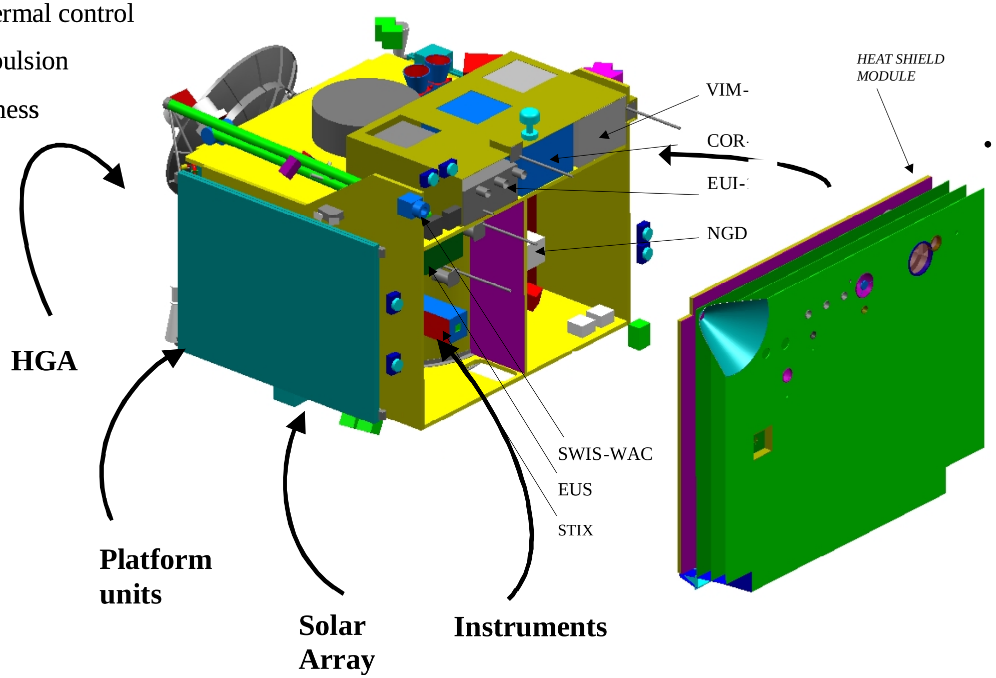
- Ø Main Module: Structure (excepted sun face), Thermal control, Propulsion, Harness
- Ø Heat Shield Module: Heat Shield with brackets, Sun face panel, Baffles, Doors, Doors mechanisms, Filters…

Main Module:

- Structure (excepted sun face)
- Thermal control
- Propulsion
- Harness

Heat Shield Module:

- Heat Shield with brackets
- Sun face panel
- Baffles
- Doors
- Doors mechanisms
- VIM filter



The modularity ensures mechanical decoupling and secures the schedule by parallelizing activities and risks

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A large spectrum of instruments

- The payload combines:
  - in-situ instruments (field analyses and particles collectors)
  - extensive all-spectrum remote observation of the Sun and the Corona.
- Thales Alenia Space has successfully accommodated the core payload and studied the possibility to accommodate the augmentation payload instruments

Instrument	Acronyms	Science goals
In-Situ Instruments		
Solar Wind Plasma Analyzer	SWA	Investigation of kinetic properties and composition (mass and charge states) of solar wind plasma
Radio and Plasma Wave Analyzer	RPW	Investigation of radio and plasma waves including coronal and interplanetary emissions
Magnetometer	MAG	Investigation of the solar wind magnetic field
Energetic Particle Detector	EPD	Investigation of the origin, acceleration and propagation of solar energetic particles
Dust Particle Detector	DPD	Investigation of the flux, mass and major elemental composition of near-Sun dust
Neutron Gamma ray Detector	NGD	Investigation of the characteristics of low energy solar neutrons, and solar flare processes
Remote-sensing Instruments		
Visible Imager and Magnetograph	VIM	Investigation of the magnetic and velocity fields in the photosphere
EUV Spectrometer	EUS	Investigation of properties of the solar atmosphere
EUV Imager	EUI	Investigation of the solar atmosphere using high resolution imaging in the EUV
Visible Coronograph	COR	Investigation of coronal structures using polarized brightness measurements in Visible
Spectrometer Telescope Imaging X-ray	STIX	Investigation of energetic electrons near the Sun, and solar X-ray emission

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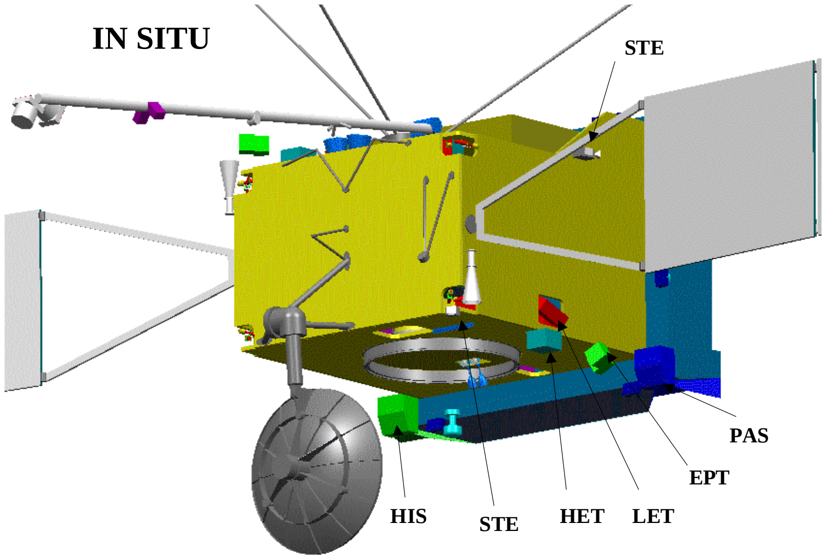
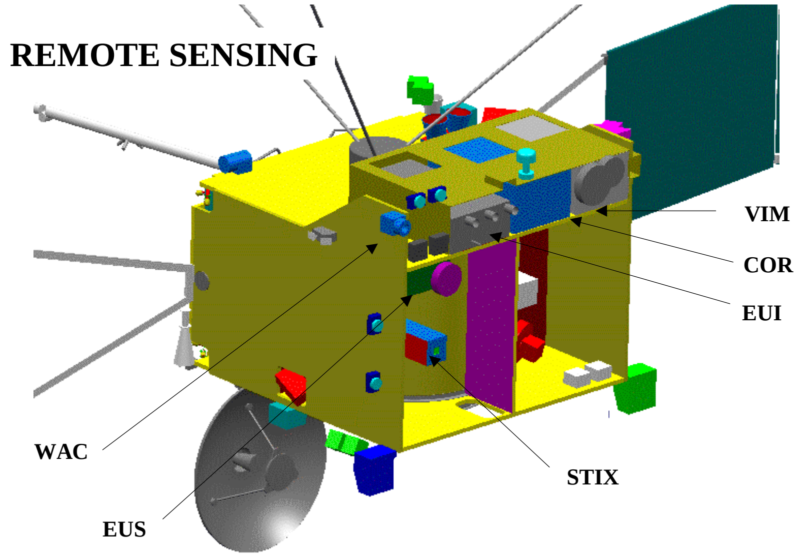
Instruments accommodation: thermal robustness and alignment performance





Gathering the remote sensing instruments and Star Trackers on one structure results into a very stable pointing and excellent co-registration performance

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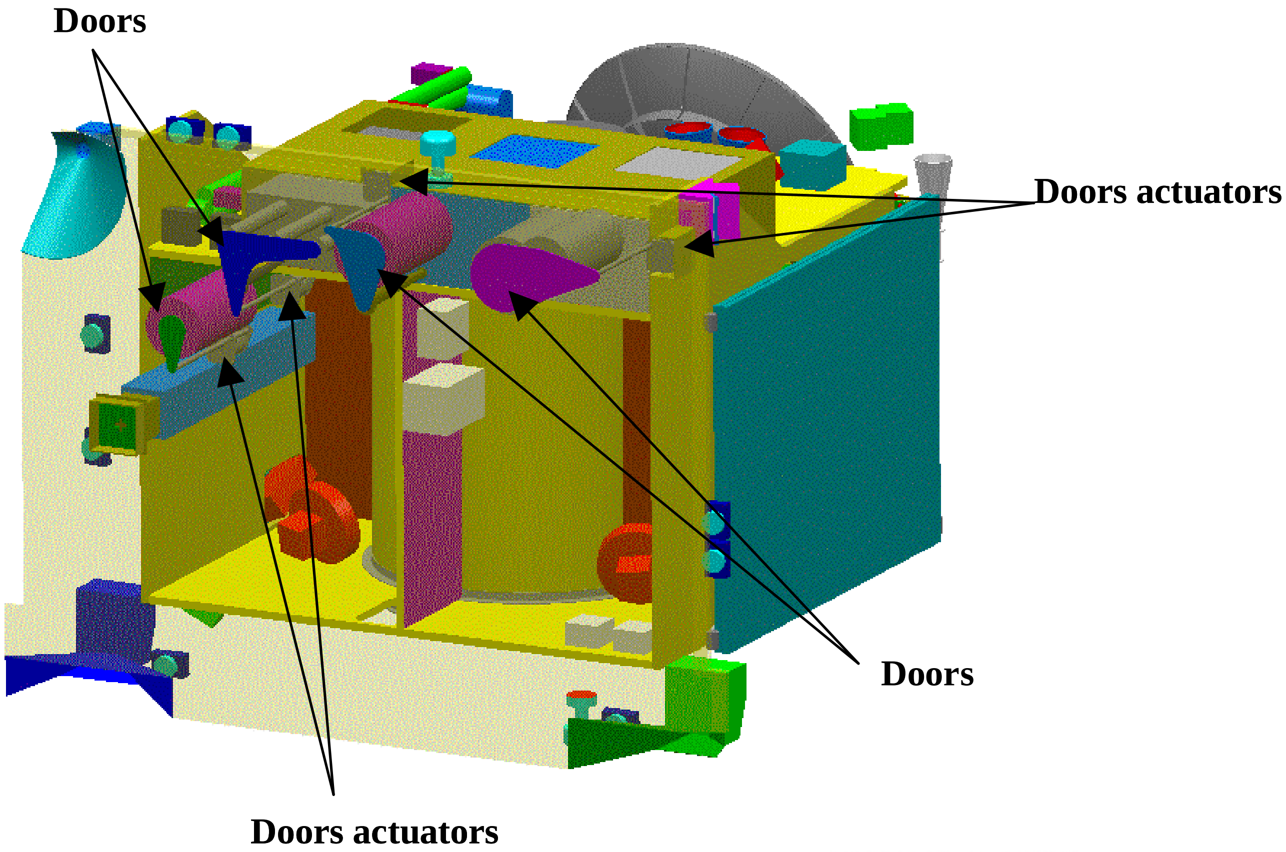
Instruments accommodation: doors

The doors and their mechanisms could be accommodated

They are part of the Heat Shield Module



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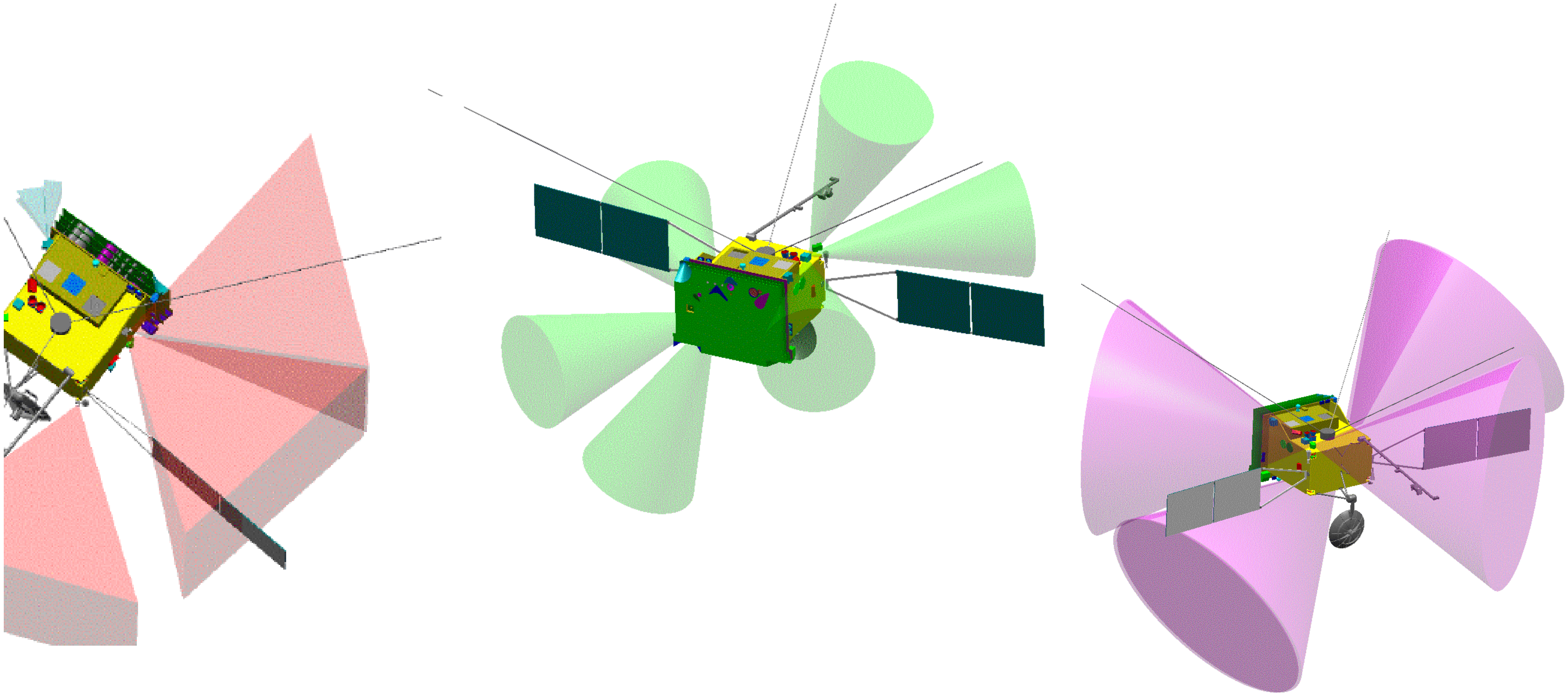
Instruments accommodation: fields of view



The fields of view of the in-situ instruments determine their accommodation on the spacecraft

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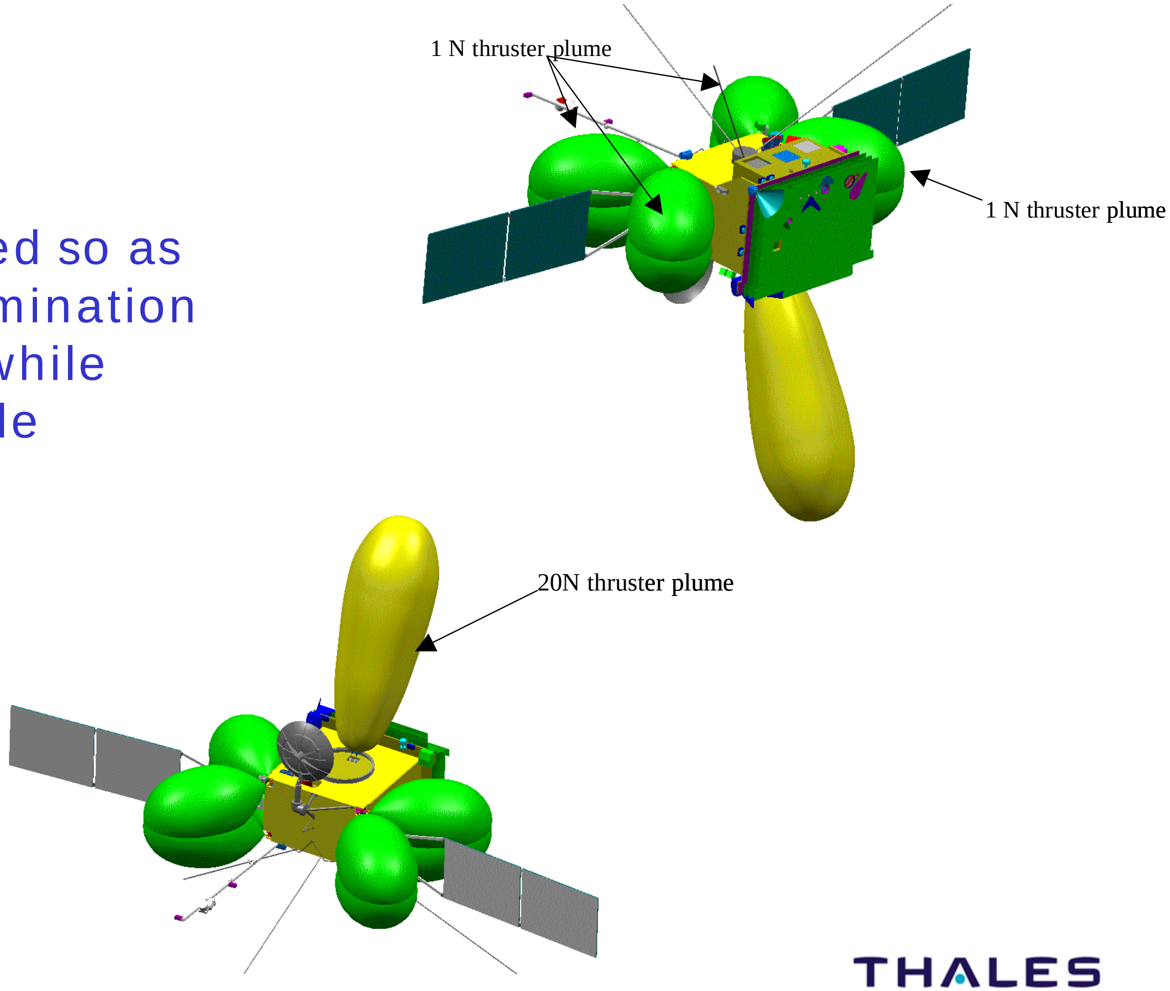
Thrusters configuration: away from Heat Shield

The thruster are positioned so as to avoid molecular contamination in the Heat Shield area, while ensuring orbit and attitude control performance



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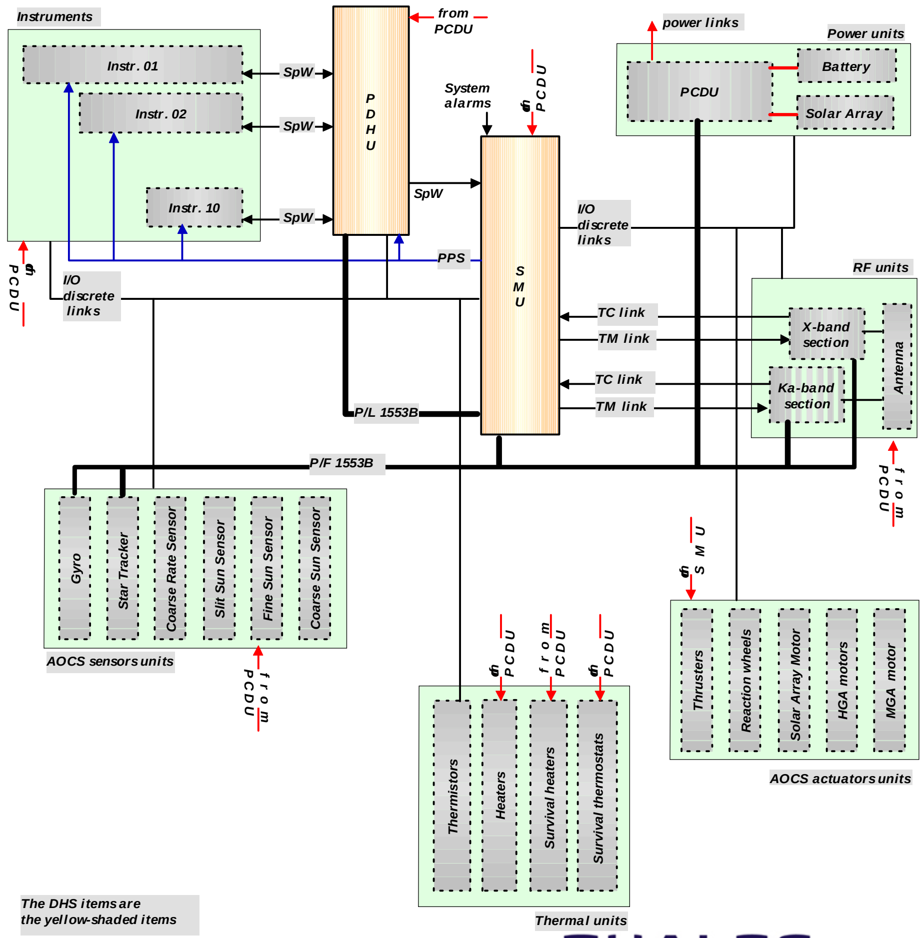
Functional architecture: combining the key heritages

- Maximization of recurrence + need to reduce risks => use the inherited subsystems most adapted to the technical challenges:
  - BepiColombo RF subsystem
  - BepiColombo power management and Solar Array
  - Herschel-Planck-type AOCS
  - Data handling from a Thales Alenia Space product line, able to interface RF, power, AOCS subsystems, instruments



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SYSTEM JUSTIFICATION:
BUDGETS, TRADE-OFFS, ANALYSES

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Budgets: safe margins kept

- The system budgets have been consolidated with Concurrent Design Facility
- They comply with the system margins required at that stage: 20% on mass, power…
- The Solar Array sizing could preserve BepiColombo heritage while satisfying the power demand in Cruise mode

DRY MASS: 950kg including the 20% system margin

LAUNCH MASS:

1260kg (Soyuz)
including launcher adapter

POWER: 835 W (cruise)

In-situ can be kept ON up to 1.49 AU with the 20% system margin achieved

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System trade-offs: catching the robust solution

- Architecture trade-offs have been open or re-opened:
  (in blue a recall of selected design)
  - Face allocation: the architecture succeeds in freeing two cold faces (South, anti-Sun)
  - Heat Shield configuration: flat parallel layers are best also for optimized payload accommodation
  - Payload configuration: Remote-Sensing gathered on South face with Star Tracker
  - Solar Array configuration: selection of a rotation about East/West axis, preserving BepiColombo heritage
  - HGA storage and deployment: stowed anti-Sun, deployed towards North
  - Launcher interface: a 937mm-interface best fits needs (Soyuz) and heritage (central tubes)

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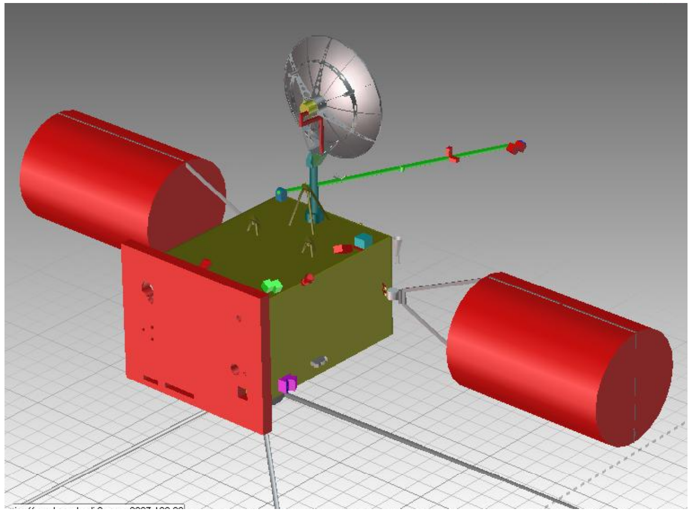
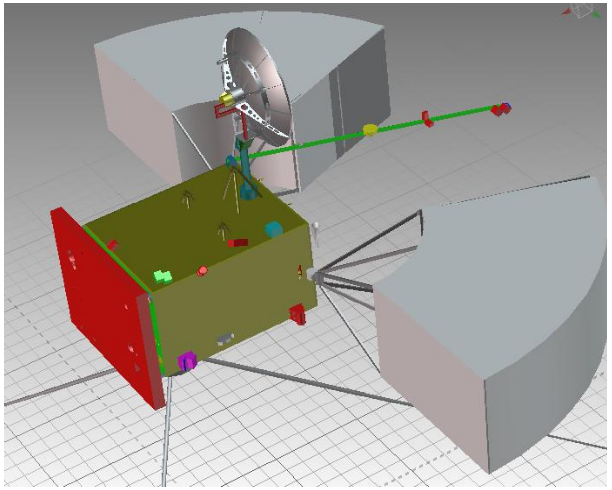
System trade-offs: Solar Array configuration

- The "rotating" Solar Array frees anti-Sun face from thermal coupling, while the "flapping" configuration minimizes the coupling to East and West at perihelion

- The rotating configuration is selected: it is the simplest and most efficient use of BepiColombo heritage and dual-faced configuration.



'Rotating' SA



'Flapping' SA

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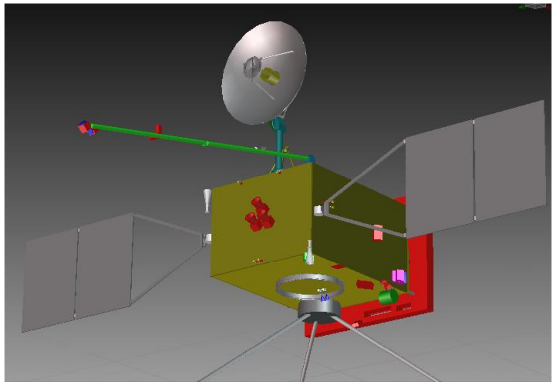
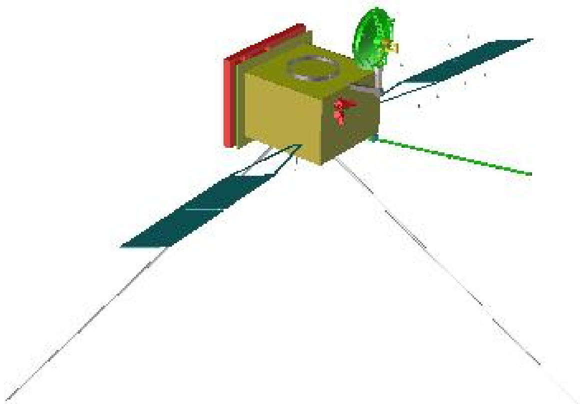
System trade-offs: Face allocation

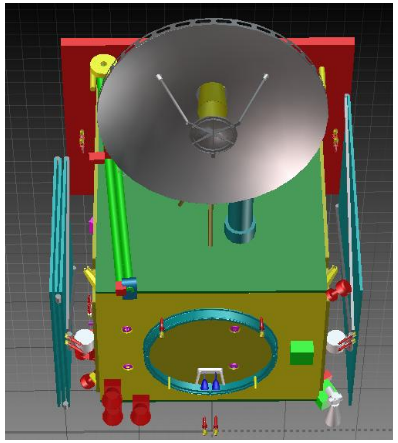
- Launcher interface on South face ? (configuration A)
- On North face ? (configuration A')
- Or on anti-Sun face ? (configuration B)
- Configuration A' has been found the most adapted to the maximization of heat rejection capability (two cold faces) and to the preservation of BepiColombo heritage.



Configuration A (



Configuration A'



Configur ation B

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A comprehensive justification effort

- The spacecraft design has been successfully analysis-proven by an extensive analytical effort

- AT SYSTEM LEVEL
  - mass and power system budgets,
  - link budget,
  - mass memory sizing,
  - molecular contamination,
  - particulate contamination,
  - magnetic contamination,
  - …

- AT SUBSYSTEMS LEVEL
  - mechanical resistance and loads
  - thermal sizing
  - thermoelastic distortions,
  - AOCS modes simulations,
  - Reaction wheels sizing,
  - FDIR and Safe mode analyses,
  - CPU sizing for computers,
  - Solar Array power analysis
  - Data rate analysis …

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System analyses

- The contamination has been analyzed:
  - Magnetic contamination
  - Molecular contamination
  - Particulate contamination

  ... so as to consolidate the choice of materials and the architecture

- The data link and the mass memory have been sized, without leading to new development

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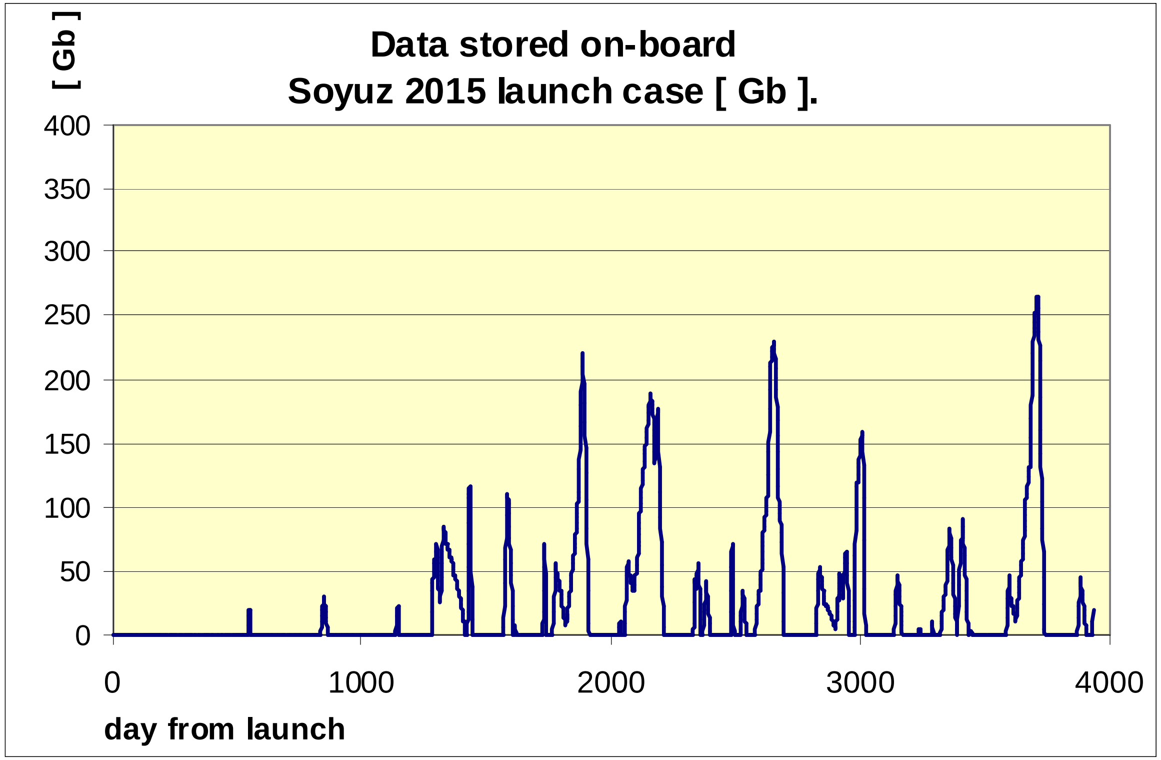
System analyses: link and MM sizing

- The maximum of on-board stored data is reached at the end of the mission and will amount to 260 Gbits.

- Total mass memory can be selected from 500 Gbits to 600 Gbits, allowing for an ample margin policy; large growth potential up to 2000 Gbits



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SUBSYSTEMS

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Heat Shield Module

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Heat Shield design: robustness and flexibility

- Its sound and simple design consists of several parallel heat barriers separated by gaps that radiate the heat to space.

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Heat Shield Design Drivers

- Ensure adequate structural performance in terms of stiffness and strength without exceeding in mass
- Ensure adequate thermal performance
- Provide mechanical interfaces to sustain the thermal barriers without thermo-structural problems
- Provide adequate cut outs and interfaces for instrument baffles
- Be simple and modular
- Provide an easy instrument accommodation
- Be testable separately from S/C body

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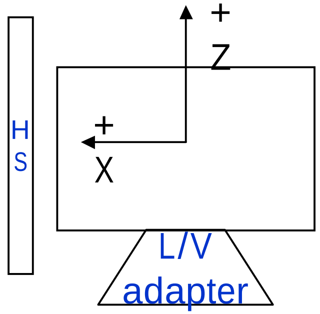
Heat Shield driving requirements - 1/2

"Adequate mechanical performance without exceeding in mass" means:

- First eigenfrequency: IP > 66 Hz, OOP > 35 Hz
(Soyuz ST2-B/Fregat or Ariane 5 environment)

- Maximum QSL X : 20 g Y : 15 g Z : 20 g

- Heat Shield mass < 65 kg



"Adequate thermal performance" means:

- Heat flow into the S/C: << 100 W in the worst operative conditions (0.22 AU, sun pointing, EOL)

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Heat Shield driving requirements – 2/2

The HS design shall guarantee:

- S/C shadowing when the X-axis is pointing within 5º of the sun (±1.25º, AOCS operation margin), (+ 1.33º sun semi angle)
- Alignment of the apertures and windows (low level of distortion)
- No mechanical interface with baffles and doors;
  baffles and doors to be mounted directly on the S/C sun panel
- Low outgassing and shatter levels to Instruments apertures
- Low electrostatic charge accumulation on the FS (electrically conductive materials)

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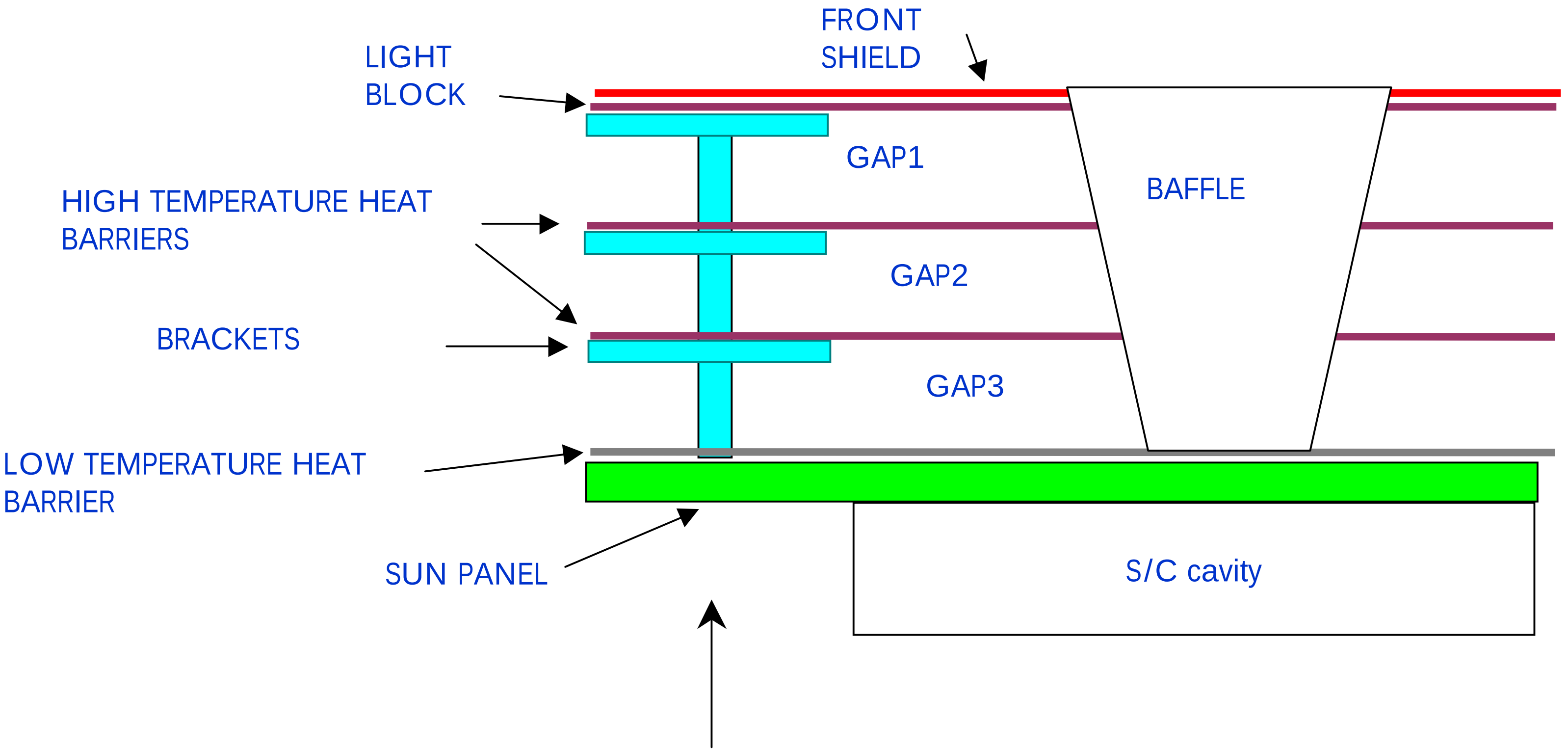
Design definition - 1/3

SELECTED DESIGN



THE SUN PANEL EXTENSION IS USED AS RADIATOR

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Design definition - 2/3

The Heat Shield is the only element specifically designed for the Solar Orbiter mission. It is composed of the following parts:

- FRONT SHIELD (FS), first layer facing sun, made of high emissivity, high temperature resistant fabric.
- LIGHT BLOCK (LB), second layer used to stop all radiation crossing the FS (slightly semi-transparent) and to create a low IR emittance surface, side gap. It is made of low emissivity metallic foil, separated from the FS by means of a ceramic scrim fabric.
- HIGH TEMPERATURE HEAT BARRIERS between gaps, low IR emittance metallic layers, where temperature exceeds 300 °C.
- LOW TEMPERATURE HEAT BARRIER (LTHB), barrier on the S/C wall, made of low IR emittance MLI, where temperature is lower than 300 °C.

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Design definition - 3/3

- <u>GAPS</u>, space between the previous components, to create apertures to space.
- <u>SUN PANEL</u>, S/C panel supporting the Heat Shield. It is made of a Al-honeycomb panel.
- <u>BRACKETS</u>, low conductivity metallic structures used to mount the layers on the sun panel.
- <u>BAFFLES</u>, open thin metal structures, provided with high • and • coating, which cross the HS layers and create the apertures for the scientific instruments (Remote Sensing Instruments).
- <u>DOORS with their mechanisms</u>

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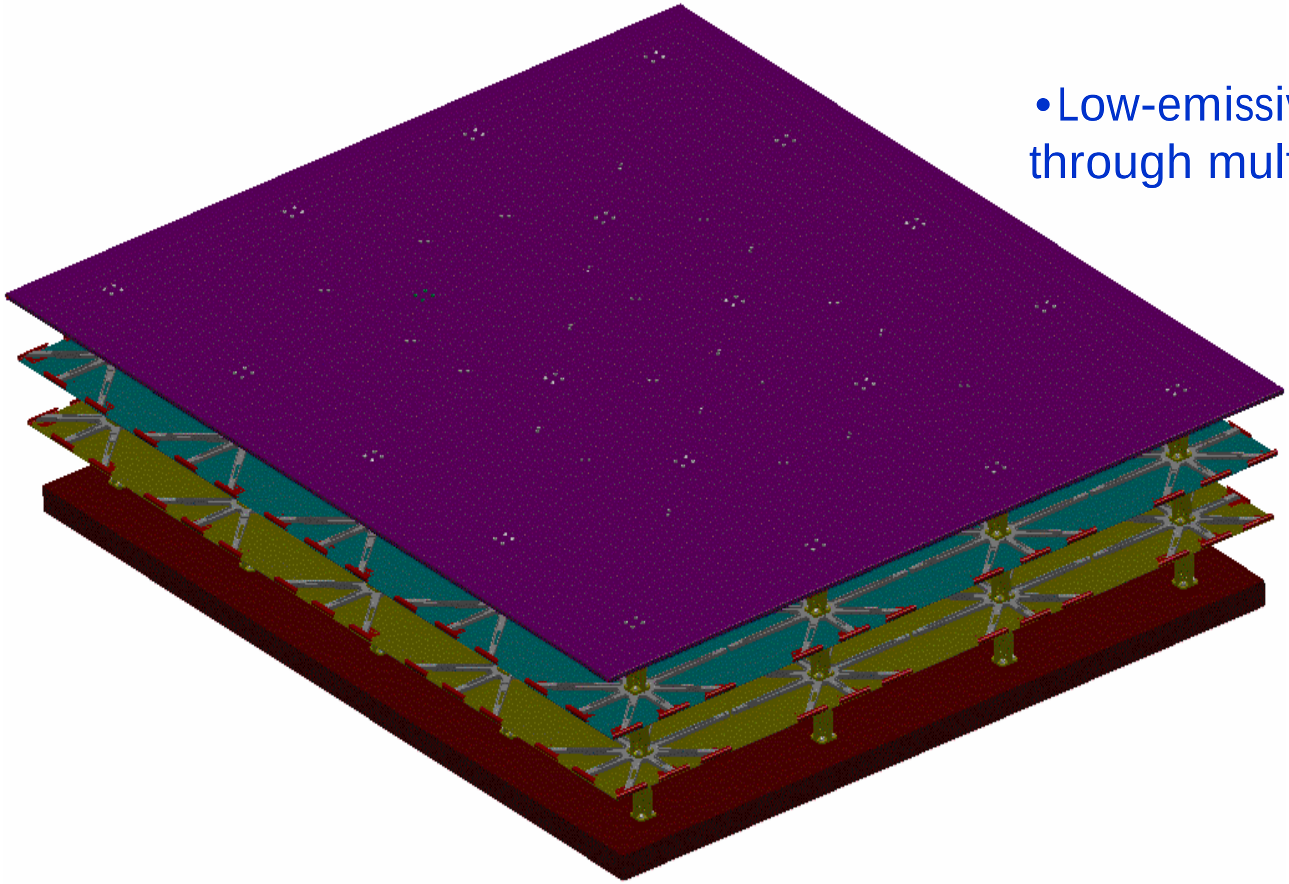
Cavity concept



• Low-emissivity cavities reject laterally the heat through multiple reflections

• The heat transmitted to the spacecraft by radiation is very low and quite insensitive to the thermo-optical properties of the Front Shield
(è design robustness)

• The heat transmitted by conduction through the brackets and baffles is low due to the loose contact with heat barriers, and to the poor conductivity

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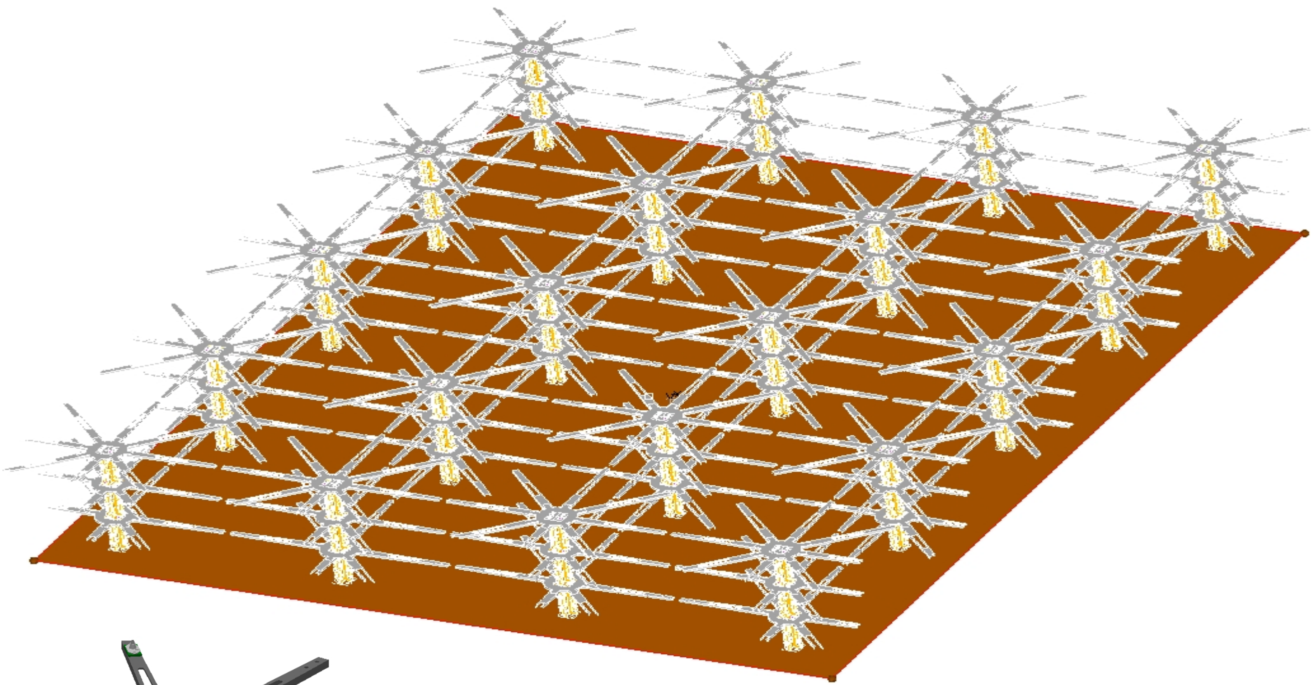
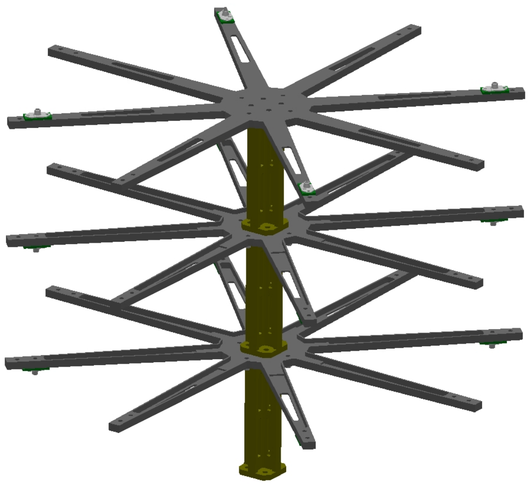
Mechanical design – 1/2

The isostatic bracket matrix structure guarantees a low level of distortion

The repetition of single elements, several times, until the desired dimensions simplifies the production and assembly of the whole HS thanks to its modularity





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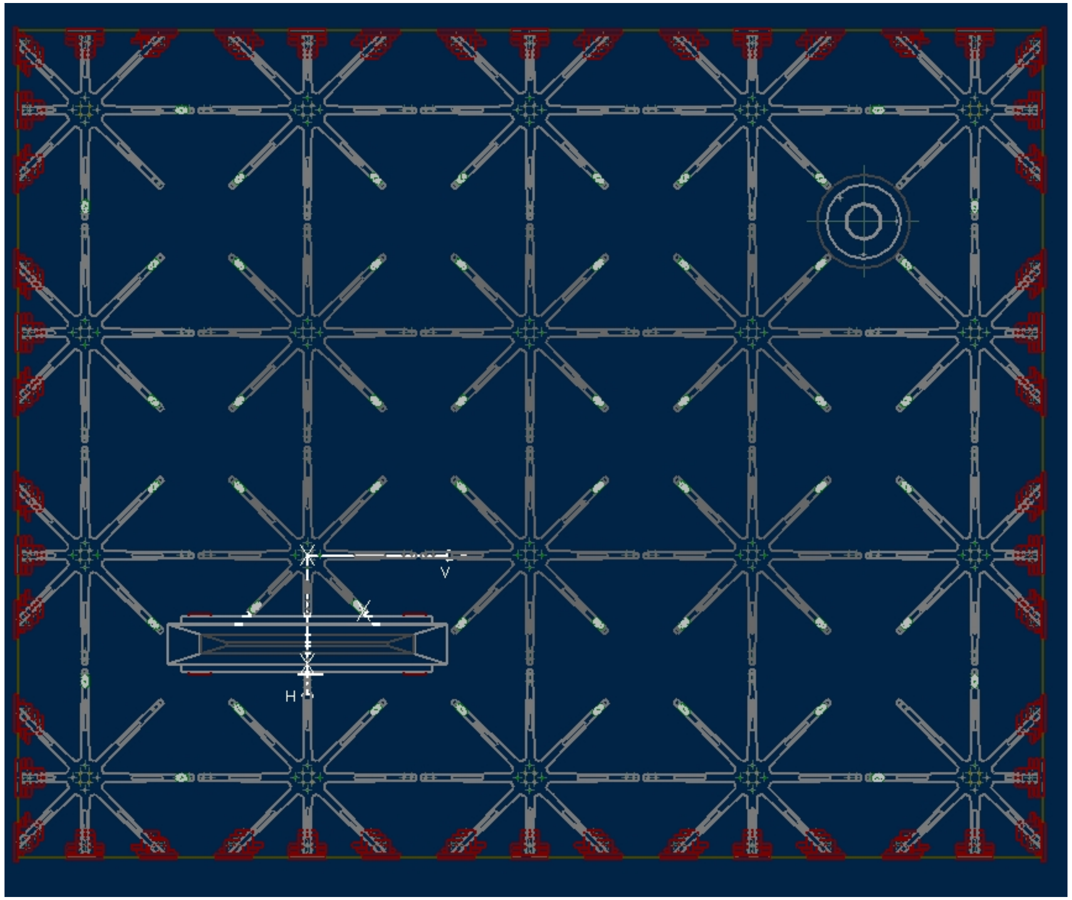
Mechanical design – 2/2

The bracket matrix structure also enables an easy instruments accommodation

Brackets can be easily shifted, and the star-supports can be cut or modified, without compromising the structural performance of the assembly (each bracket is designed to work as a stand-alone structure).



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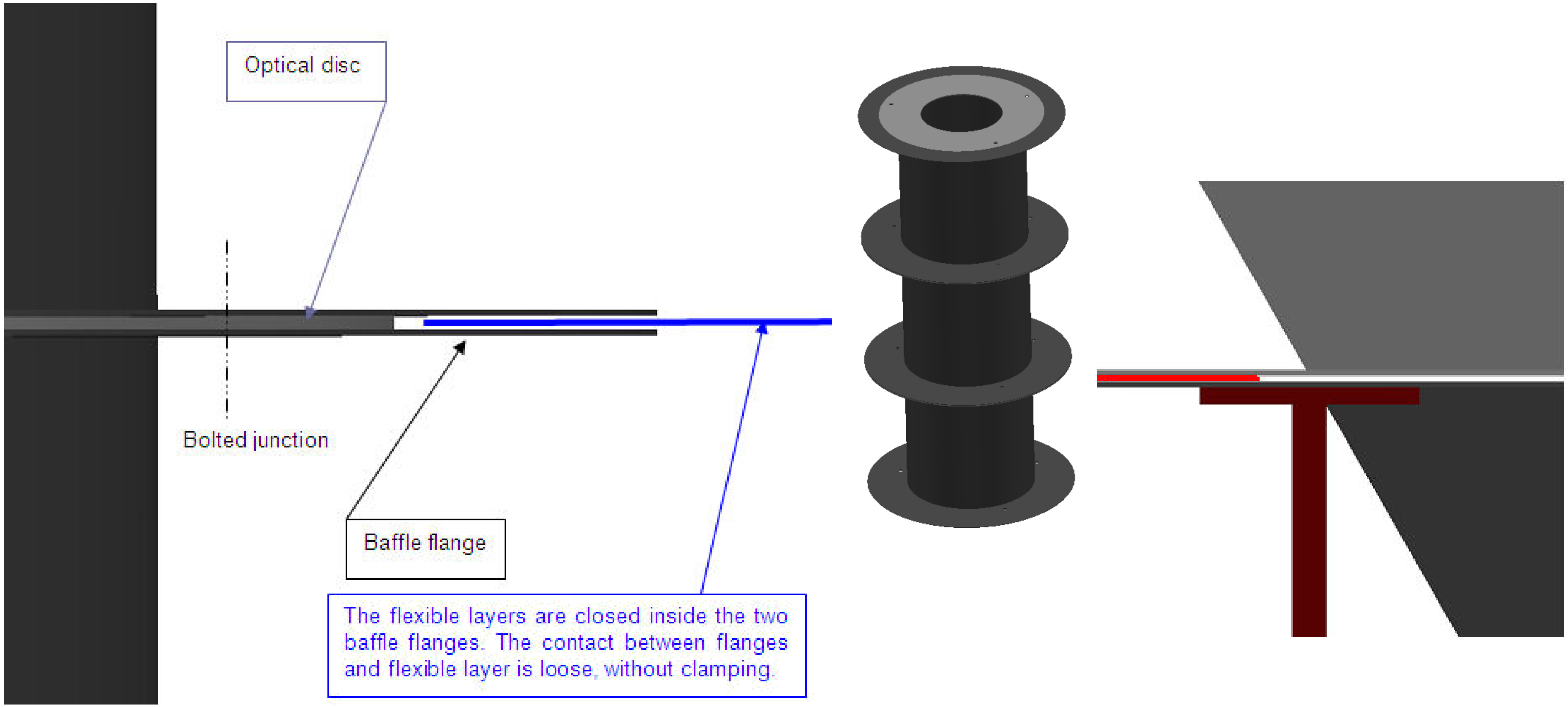
Example of interface with baffles



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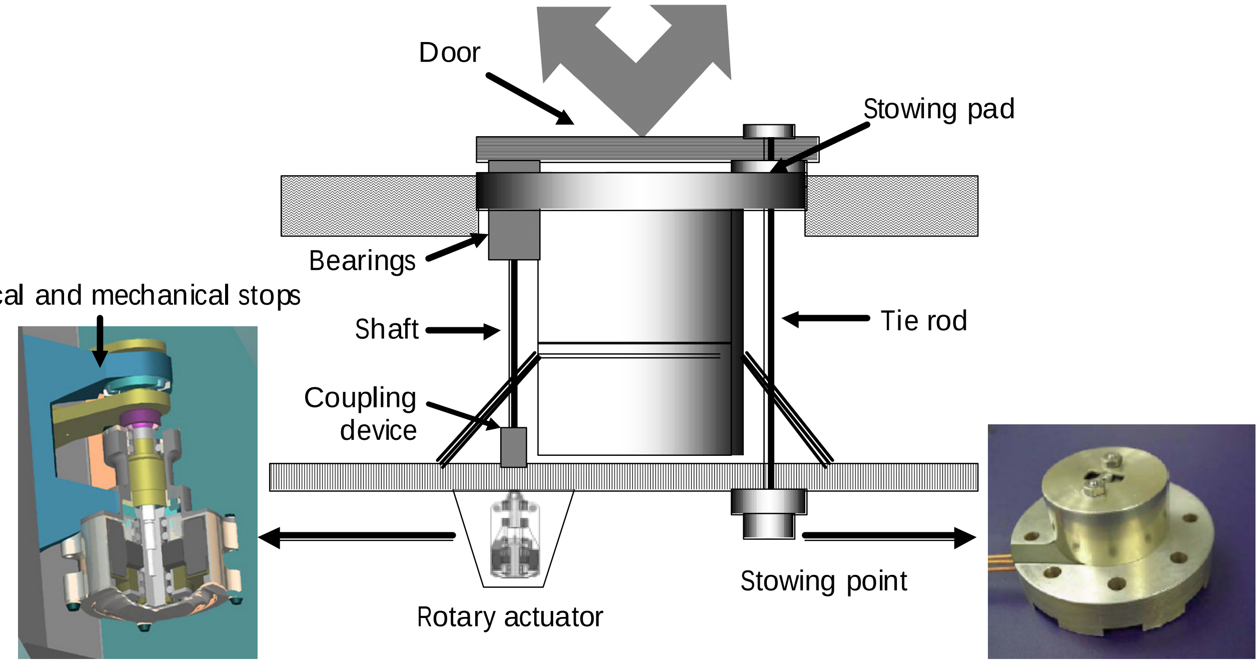
Doors design

Selected door solution:

- simplest kinematics preferred, to increase robustness
- bearing can be derived from an existing component.
- motor and the release nut are standard components.
- the door is a critical element, and should be subject of a specific TDA.



Actuator concept example

Release nut

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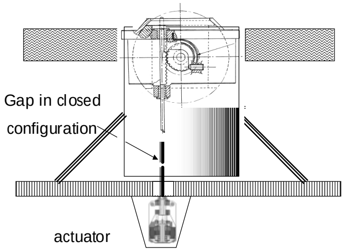
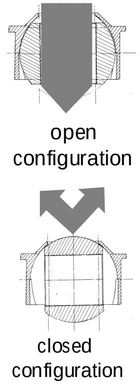
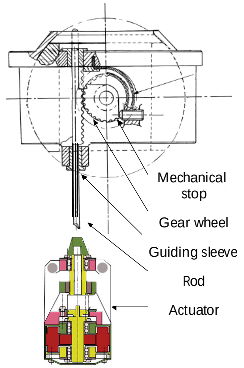
Doors trade-offs

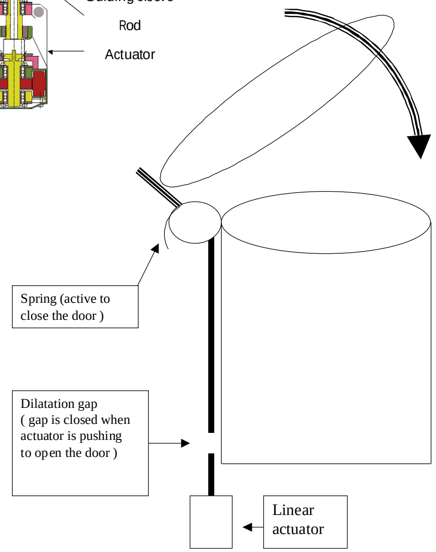
Several solutions traded-off relying on TAS mechanisms expertise:

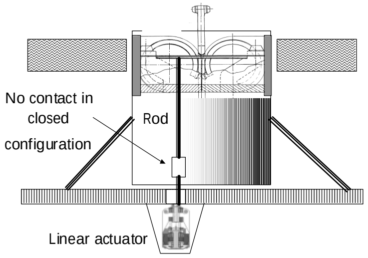
- rotating lid (SELECTED)
- flapping lid
- ball-joint
- eye-lid
- “butterfly”

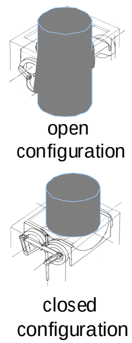


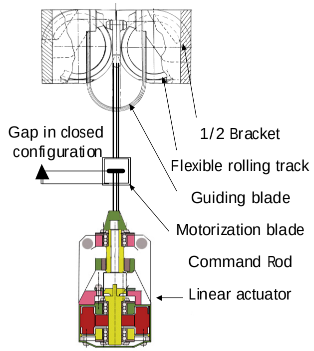












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HEAT SHIELD TRADE-OFFS

ARCHITECTURE
- Heat barriers // to sun face
- Heat barriers tilted w.r.t. sun face

MECHANICAL DESIGN
- OPTION 1 (frame structure)
- OPTION 2 (light structure)
  - HS connected through brackets (no frame)

THERMAL MATERIALS (*)
- FRONT SHIELD (**)
  - Flexible FS
  - Rigid FS
  - White FS
  - Black FS
- High Temperature Heat Barriers
  - Metallic barriers
  - Other materials

Selected option in yellow

(*) Selection of thermal materials through dedicated material screening test campaign.

(**) Two design options developed in parallel for flexible and rigid FS.

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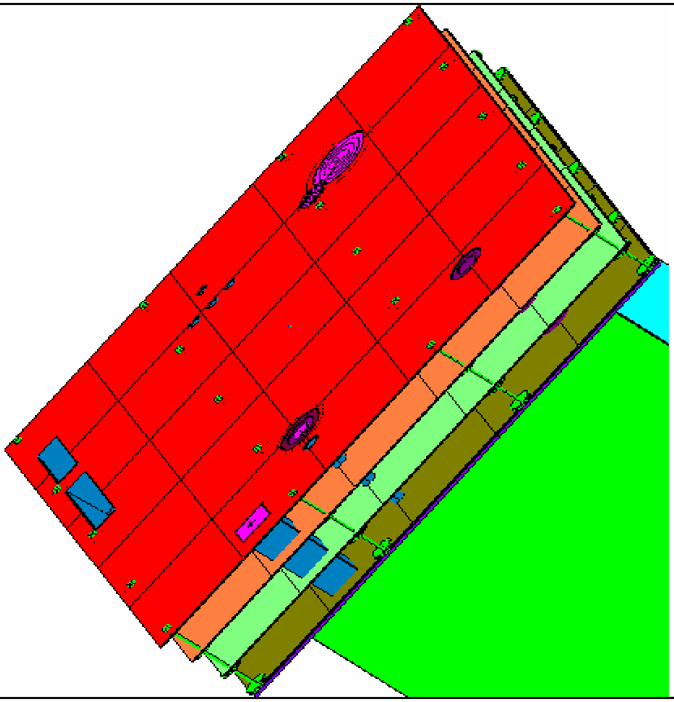
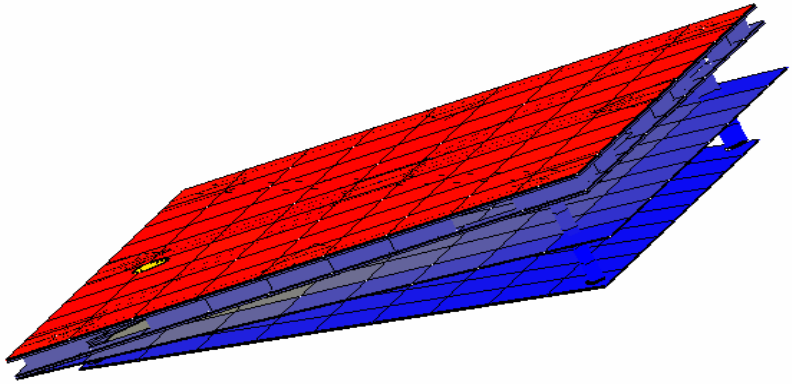
HS architectural trade-offs 1/2

DESIGN VARIABLES

- ***SHAPE:***
  a) HS parallel to the S/C sun panel.
  b) HS tilted versus the S/C sun panel.

	 - No particular advantages for Instrument cooling. - Complication of design.
a) HS parallel to sun panel	b) HS tilted versus sun panel

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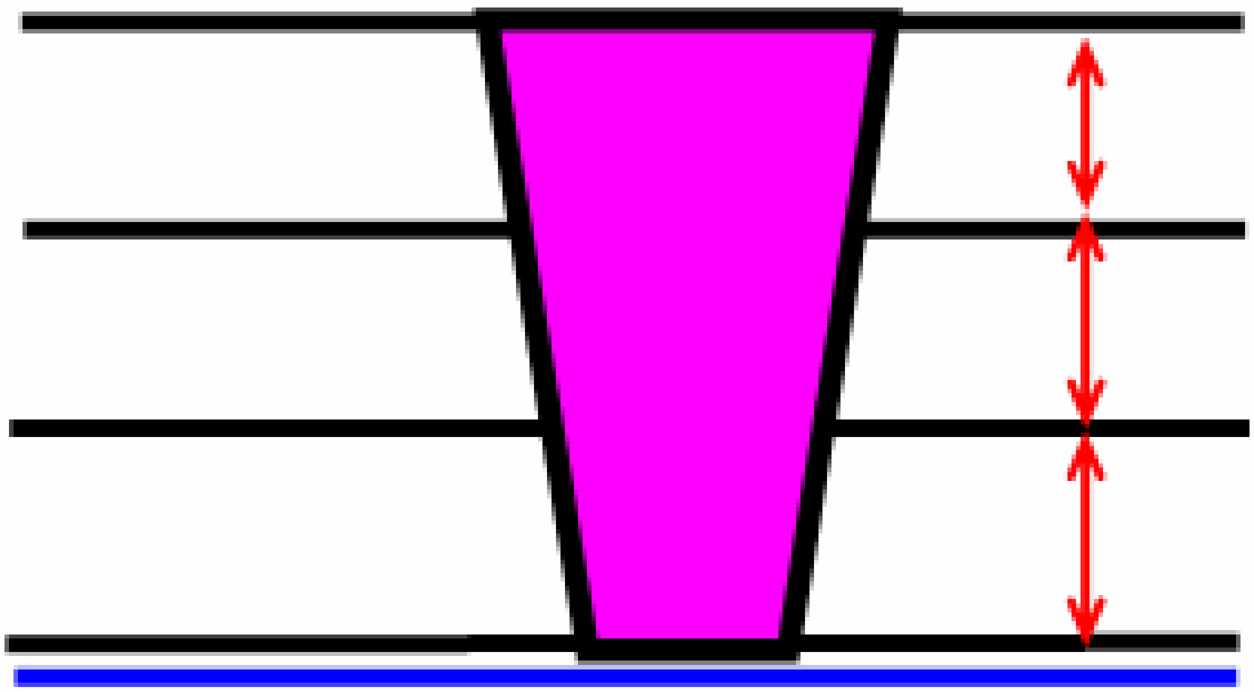
HS architectural trade-offs 2/2

DESIGN VARIABLES

- ***DIMENSIONS:***
  - Number and thickness of gaps



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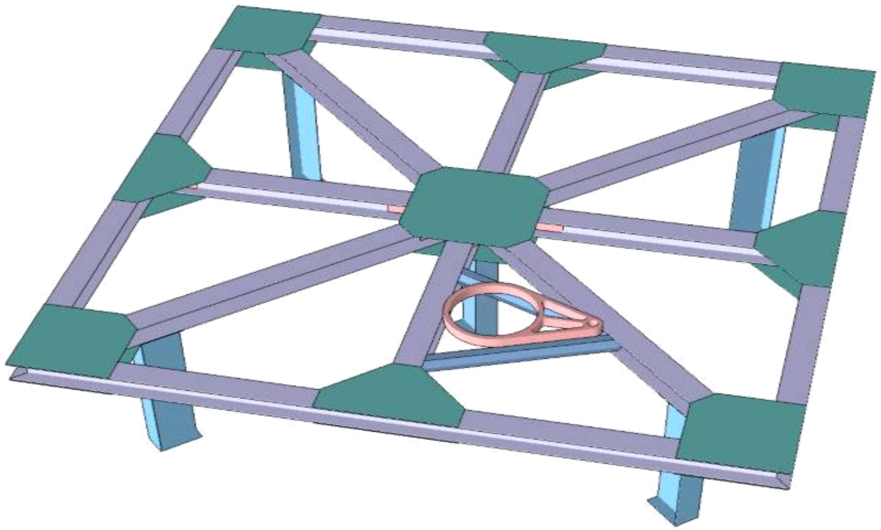
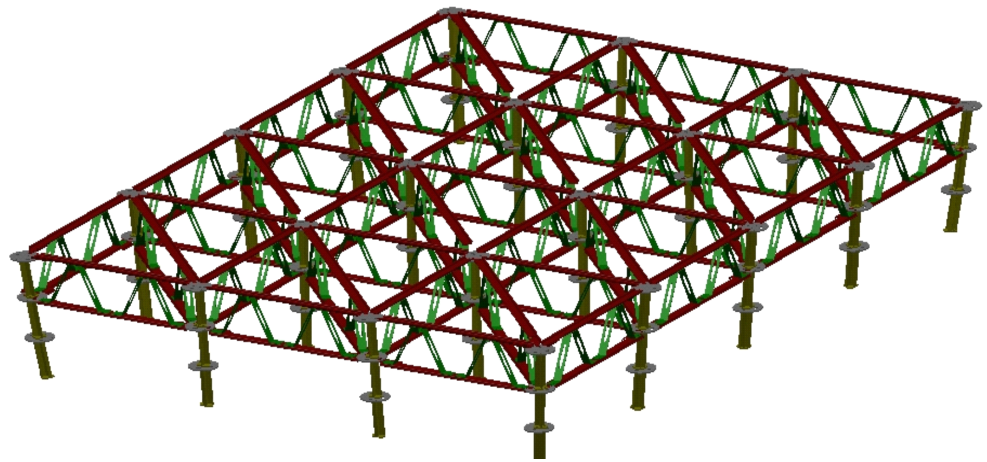
DESIGN VARIABLES

- ***SUPPORTS (FRAME & BRACKETS)***
  a) Limited number of brackets (4-5) to hold the frame supporting the layers.
  b) Several interconnected brackets (16-20) to support the layers (no frame).
  c) Several independent brackets (16-20) to support the layers (no frame).





a) Frame + brackets	b) Brackets only
• Higher mass • Not adequate mechanical interfaces to HTHB1-2 • Thermoelastic issues	- Lighter - Potentially free from thermoelastic issues

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Materials trade-offs

DESIGN VARIABLES

- MATERIALS (selected through dedicated material screening test campaign)
  - FS: rigid plate or flexible fabric, with low/high solar absorptance and high IR emittance
  - LB: layer(s) of low IR emittance material
  - HTHB: layer(s) of low IR emittance material
  - LTHB: conventional MLI
  - Structures: high temperature resistant metal (> 500 °C): steel, titanium, low or high IR emittance
  - Baffles: high temperature resistant metal (> 500 °C): steel, titanium, high IR emittance.

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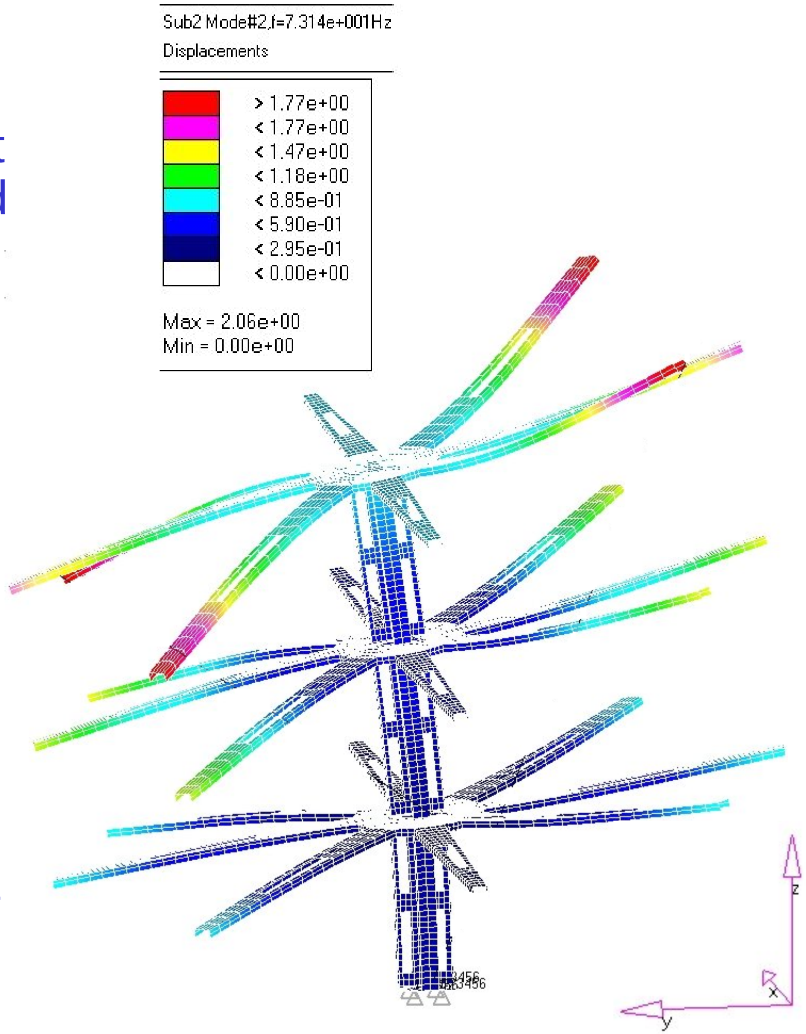
Mechanical analysis

- FEM developed for the different typologies of brackets (central, border, corner), including all bracket components and bolts. Non-structural mass distributed on the brackets.
- Each bracket typology has been analyzed to find:
  - First eigenfrequencies (IP, OOP)
  - Safety factors for the worst combinations of QSL + dynamic loads
  - Strength w.r.t. thermoelastic loads.
- Dynamic displacements used to evaluate minimum looseness (> 5 mm) of flexible layers versus support structure (between two consecutive attachment points) necessary to avoid ripping them during launch.



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Mechanical performance
(two FS design options)

- DYNAMIC ANALYSIS
  - HS fundamental frequencies

a) Flexible FS	(IP) = 72.8 Hz	(OOP) = 73.1 Hz
b) Rigid FS	(IP) = 72.5 Hz	(OOP) = 43.3 Hz

- STRUCTURE MARGINS OF SAFETY SUMMARY
  - Launch loads analysis

a) Flexible FS	MoS(IP) = 0.92	MoS(OOP) = 0.82
b) Rigid FS	MoS(IP) = 0.20	MoS(OOP) = 0.82

  - Thermoelastic analysis

a) Flexible FS	MoS >> 1
b) Rigid FS	MoS >> 0.32

- MASS BUDGET

a) Flexible FS	77 kg
b) Rigid FS	91 kg

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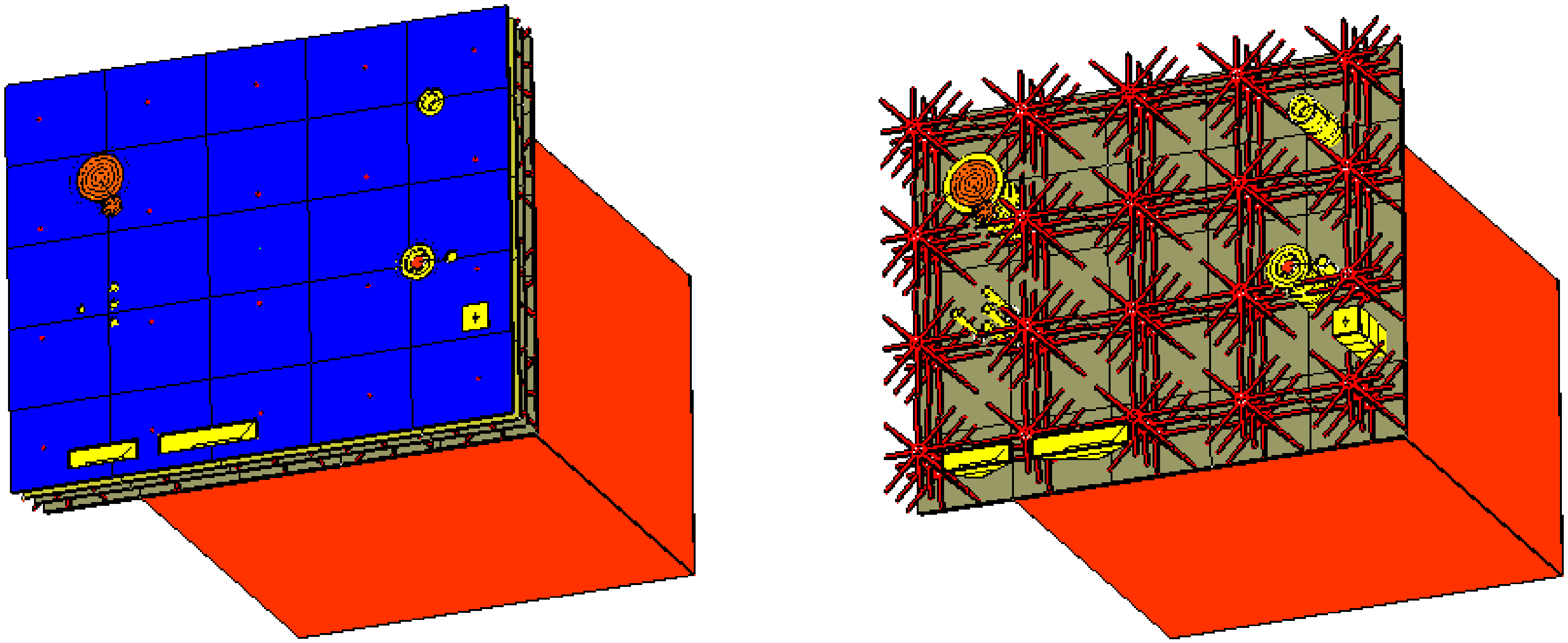
HEAT SHIELD MODULE

Thermal simulations have enabled to select the design



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HEAT SHIELD MODULE

Thermal analyses:

- predicting Heat Shield temperatures è 615 °C max.
- Predicting Heat into S/C è 40 W max.
- determining interface conditions for instruments

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Heat Shield development: an efficient approach for the Assessment Phase

- The development has focused on demonstrating a thermal performance and thermo-mechanical stability, which can be reliably extrapolated to the desired lifetime.

- A two-pronged approach:
  - Test of materials samples, to establish basic materials properties and their stability in time and environment,
  - Test of a representative breadboard to provide overall verification of the selected design. The choice to develop a full-scale model mechanically representative also permits the breadboard to be reconfigured to STM for mechanical characterisation.

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Materials Sample Screening Test

The following candidate materials were selected for Solar Orbiter HS application:

1. Flexible hybrid fabric Type 1 (Nextel-Ti)	(Front Shield)
2. Flexible fabric Type 2 (Carbon)	(Front Shield)
3. Rigid Heat Shield Material (CFRC)	(Front Shield)
4. Nickel foil	(part of HTHB)
5. Quartzel Net separator	(part of HTHB)
6. Double Al Upilex	(part of LTHB reflector)
7. Nomex scrim	(part of LTHB fabric separator)
8. Titanium foil	(part of HTHB)
9. Keplacoat-covered Titanium	(Front Shield)

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Screening tests plan

Material è	1	2	3	4	5	6	7	8	9
All sample lots (Lot1 + Lot2 + Lot3)									
Visual inspection (+ dim. measurement)	x	x	x	x	x	x	x	x	x
Cleaning / baking	x	x			x				
Lot 1									
Thermo-optical properties	x	x	x	x				x	x
Surface electrical resistance	x	x	x						x
Mechanical tests	x	x	x	x				x	x
Scanning Electron Microscopy (SEM)				x				x	x
Lot 2									
Thermal endurance (TET)	x	x	x	x	x			x	x
Visual inspection (+ dim. measurement)	x	x	x	x	x			x	x
Thermo-optical properties	x	x	x	x				x	x
Surface electrical resistance	x	x	x						x
Mechanical tests	x	x	x	x				x	x
Scanning Electron Microscopy (SEM)				x				x	x
Lot 3									
Outgassing TML/CVCM	x	x	x		x	x	x		x

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Screening tests

a, e and surface electrical resistance measurement results

Material	•	•
Carbon fiber	0.80	0.60
Nextel	0.21	0.89
Titanium foil	0.42	0.10
carbon-carbon	0.78	0.58
kepla-coat	0.90	0.78

Surface electrical resistivity	(Req. < 1 GΩ/sq)	
sample	av. value	status
Nextel fabric	> 1 GΩ	non compliant
Nextel-Ti hybrid fabric (TAS patent)	~ 200 k•	compliant
Carbon-carbon	0,15 •	compliant
Carbon-fiber fabric	0,16 •	compliant
Kepla-coat	> 1 GΩ	non compliant

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HEAT SHIELD BREADBOARD TEST

BREADBOARD CHARACTERISTICS:

- Full Scale (2.17 x 1.75 m)
- With representative thermal I/F towards S/C
- With two dummy baffles in a conservative location (one cylindrical with dummy door and one wide-field pyramid)

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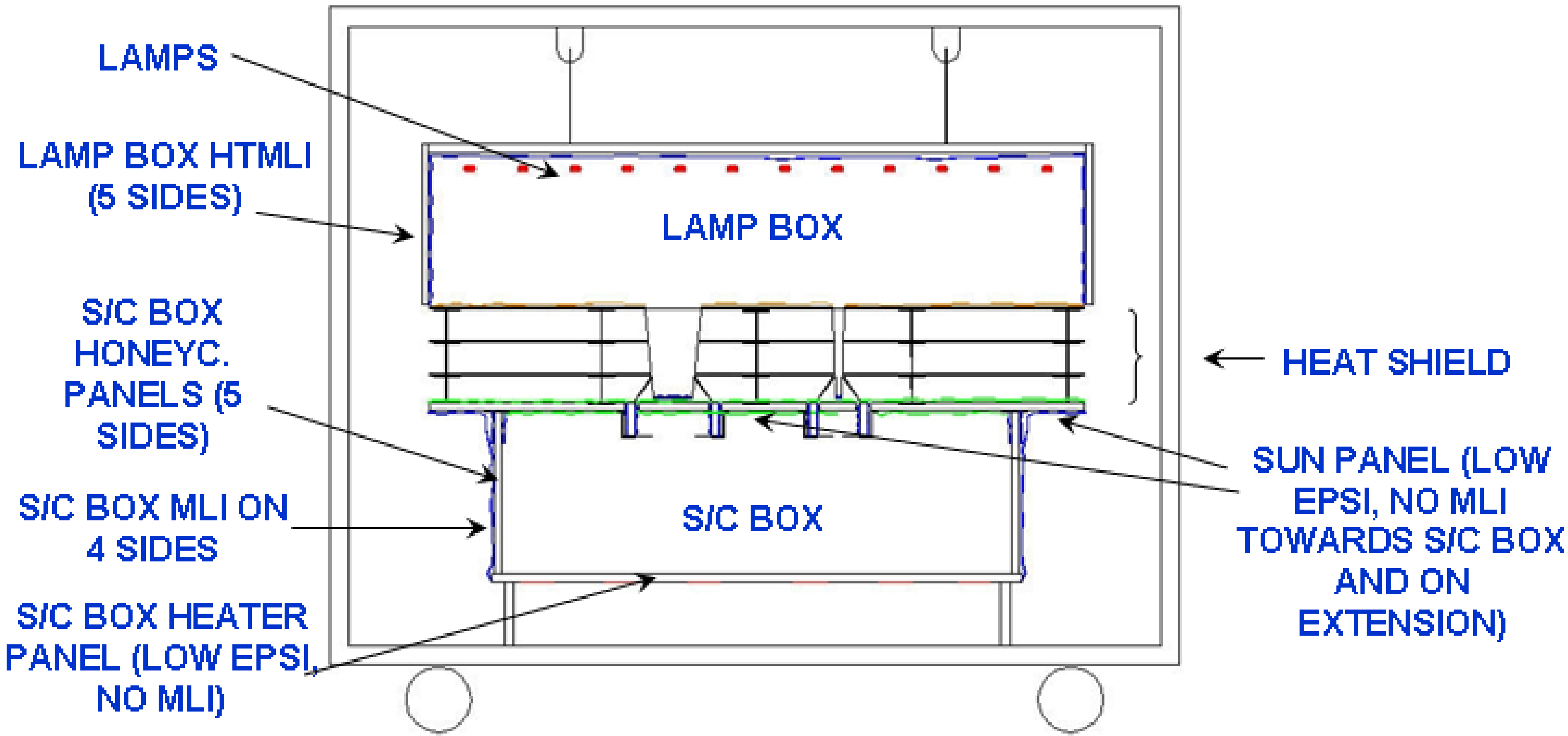
HEAT SHIELD BREADBOARD TEST



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HEAT SHIELD BREADBOARD TEST

LAMP BOX (used to achieve for the FS the expected flight temperatures):

- INFRARED LAMPS, made of Quartz with an internal electrical resistance made of tungsten.
- HIGH TEMPERATURE MLI, used to limit the heat delivered to the chamber from the lamp box.
- FRAME, used to support the lamps and the HTMLI.

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HEAT SHIELD BREADBOARD TEST

SENSORS:

THERMOCOUPLES, of two types:

- 160 TC type T (Cu-Constantana) for T -200 / +300 °C
- 80 TC type K. For T +300 / 980 °C (max temp. due to insulation)

FLUXMETERS, to measure the heat flux across the following interfaces:

- Between each foot of the baffles and the sun panel
- Between each attachment of the sun panel with the S/C box lateral panels.

HEATERS:

- ON SUN PANEL TO SIMULATE HEAT FROM OTHER BAFFLES

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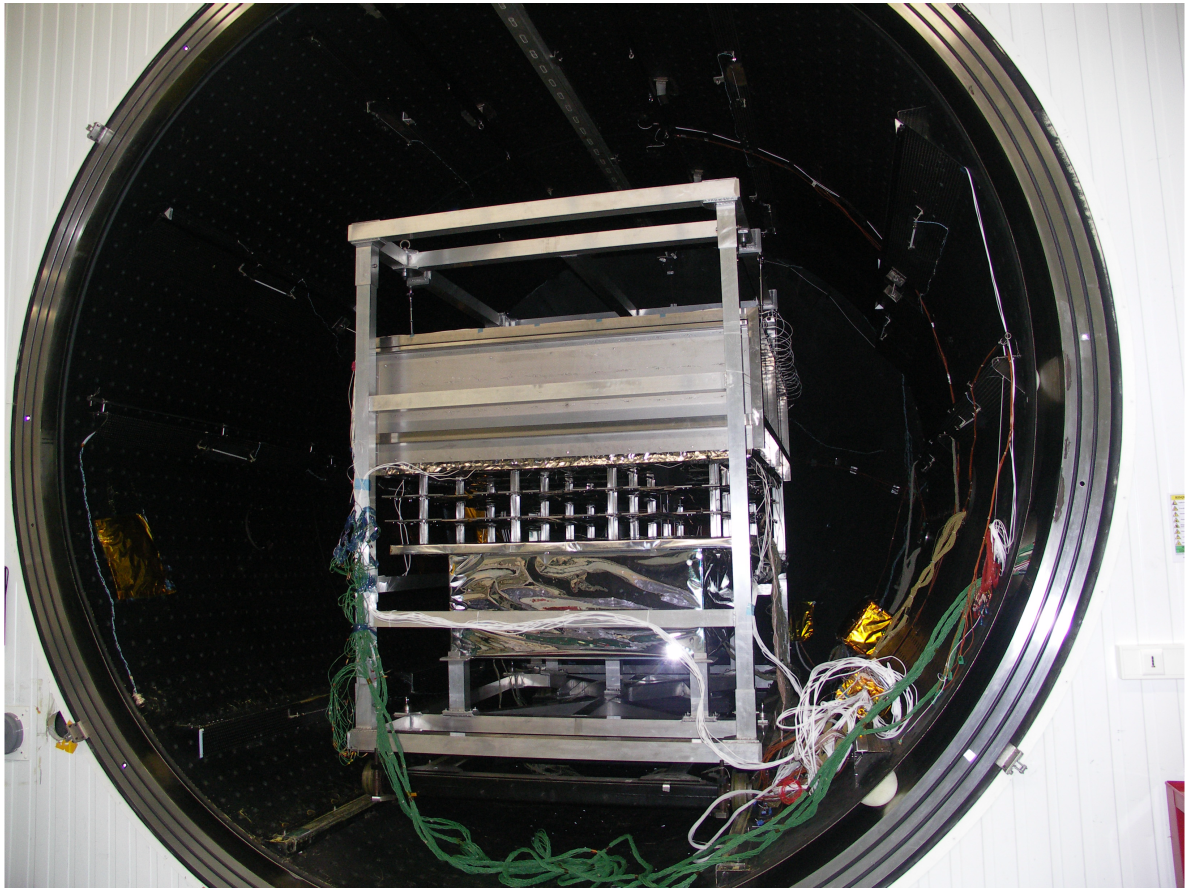
HEAT SHIELD BREADBOARD TEST

TEST SCOPES:

- MEASUREMENT OF HEAT FLUXES INTO S/C FROM HS
- VERIFICATION OF MATERIALS AT HIGH TEMP. IN FLIGHT HS CONFIGURATION
- TEST RUN IN CANNES 70m^3 CHAMBER



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HEAT SHIELD BREADBOARD TEST

TEST PHASES:

PHASE	NOTE	FS TEMP. [C]	S/C TEMP. [C]	SUN PANEL HEATER POWER [W]
1	Cold 1	100	0	30
2	Cold 2	100	40	30
3	Intermediate 1	400	40	30
4	Intermediate 2	500	40	30
5	Nominal worst hot 1	620	40	30
6	High start	700	40	30
7	Ph. 5 repeated	620	40	30
8	Nominal worst hot 2	620	0	30
9	Nominal worst hot 3	620	40	10
10	Nominal worst hot 4	400	40	10
11	Extreme worst hot	700	40	10

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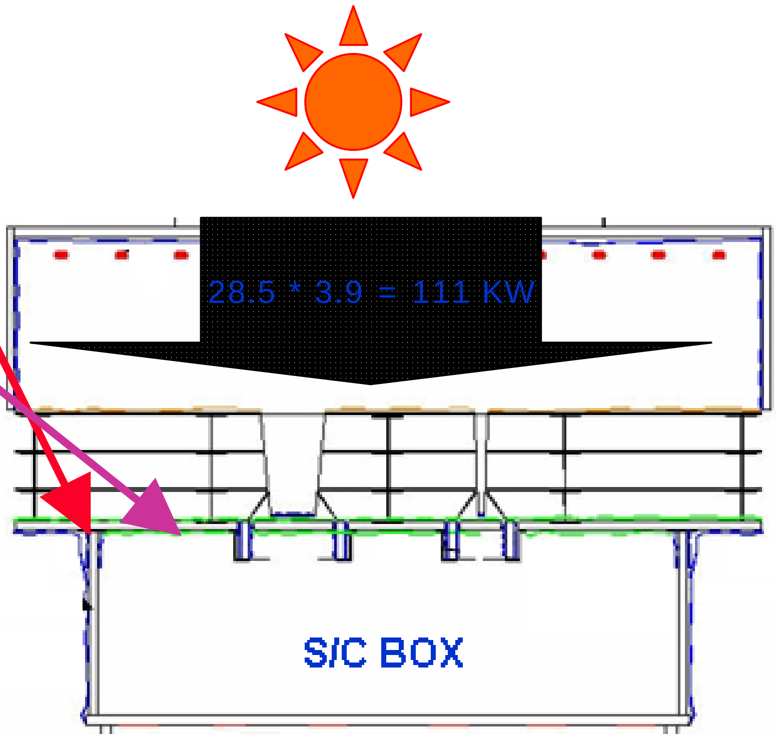
HEAT SHIELD BREADBOARD TEST

TOTAL FLUX INTO S/C												
PHASE		1 10	2 11	3	4	5	6		7	8	9	
Q fluxmeters		-8.0	-22.0	5.0	12.0	22.0	30.0	22.0	10.0	23.0	5.0	31.0
Q MLI		-1.8	-6.6	3.7	7.6	12.4	13.5	12.8	14.7	11.7	3.4	13.0
Flux into S/C TOTAL		-9.8	-28.6	8.7	19.6	34.4	43.5	34.8	24.7	34.7	8.4	44.0
Uncert Q Fluxmeters	0.1	-0.8	-2.2	0.5	1.2	2.2	3	2.2	1	2.3	0.5	3.1
Uncert Q MLI	0.5	-0.9	-3.3	1.9	3.8	6.2	6.7	6.4	7.4	5.8	1.7	6.5
Uncert TOTAL		-1.7	-5.5	2.4	5.0	8.4	9.7	8.6	8.4	8.1	2.2	9.6
Flux into S/C TOTAL + uncert		-11.5	-34.1	11.1	24.7	42.7	53.2	43.5	33.1	42.8	10.6	53.5
Flux into S/C TOTAL - uncert		-8.1	-23.1	6.4	14.6	26.0	33.7	26.2	16.4	26.5	6.2	34.4



111 kW on HS è 44 W into S/C

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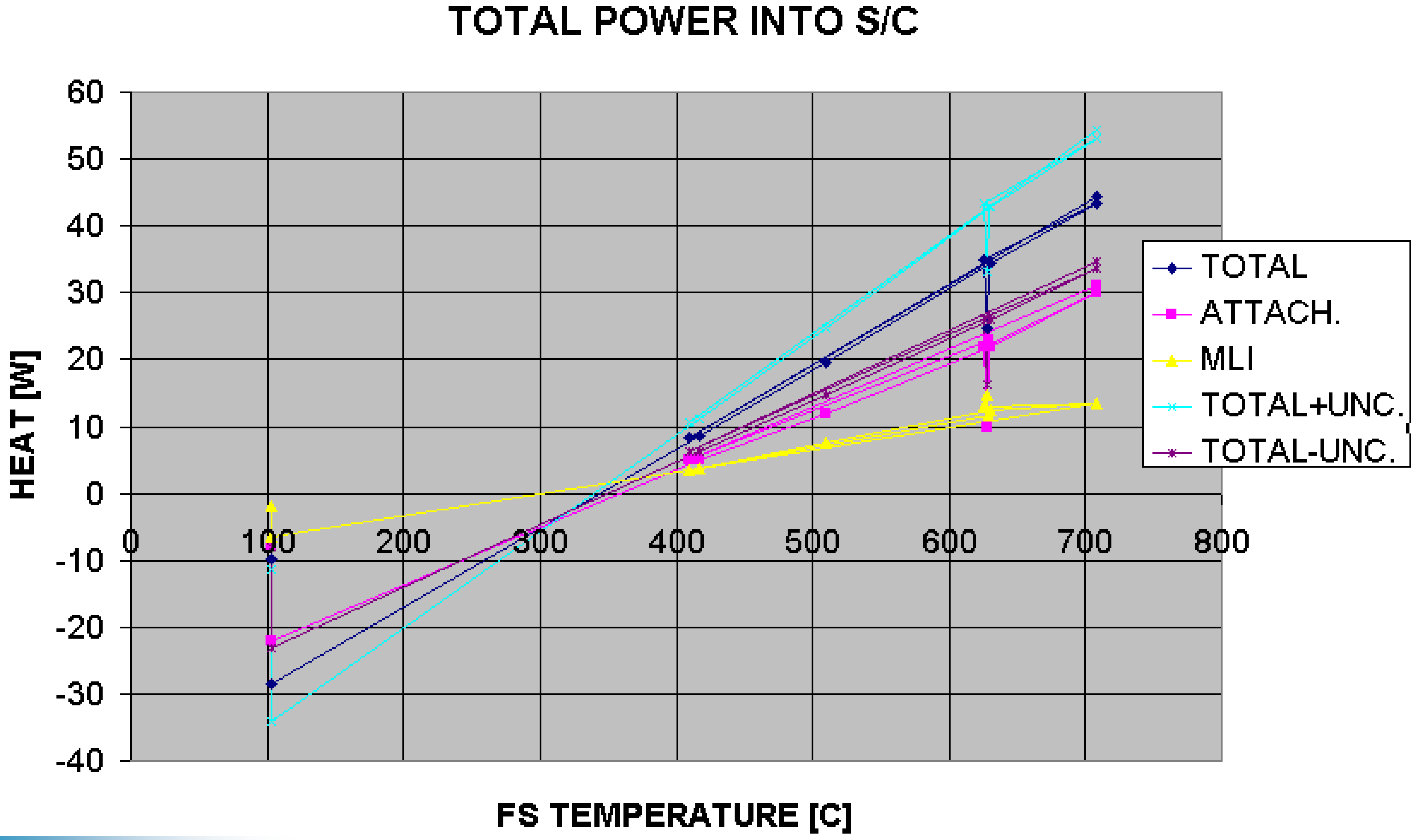
HEAT SHIELD BREADBOARD TEST



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HEAT SHIELD BREADBOARD TEST

TEST RESULTS SUMMARY:

- Total heat load into S/C (in hot case) 34 W nominal, from 27 to 42 W taking into account uncertainty
- Heat load into sun panel from baffle dummies is very small (< 1W)
- Heat load into sun panel from brackets: -30 to 122 W
- Heat load into sun panel from LTHB < 0: LTHB cools the sun panel (max -15 W)

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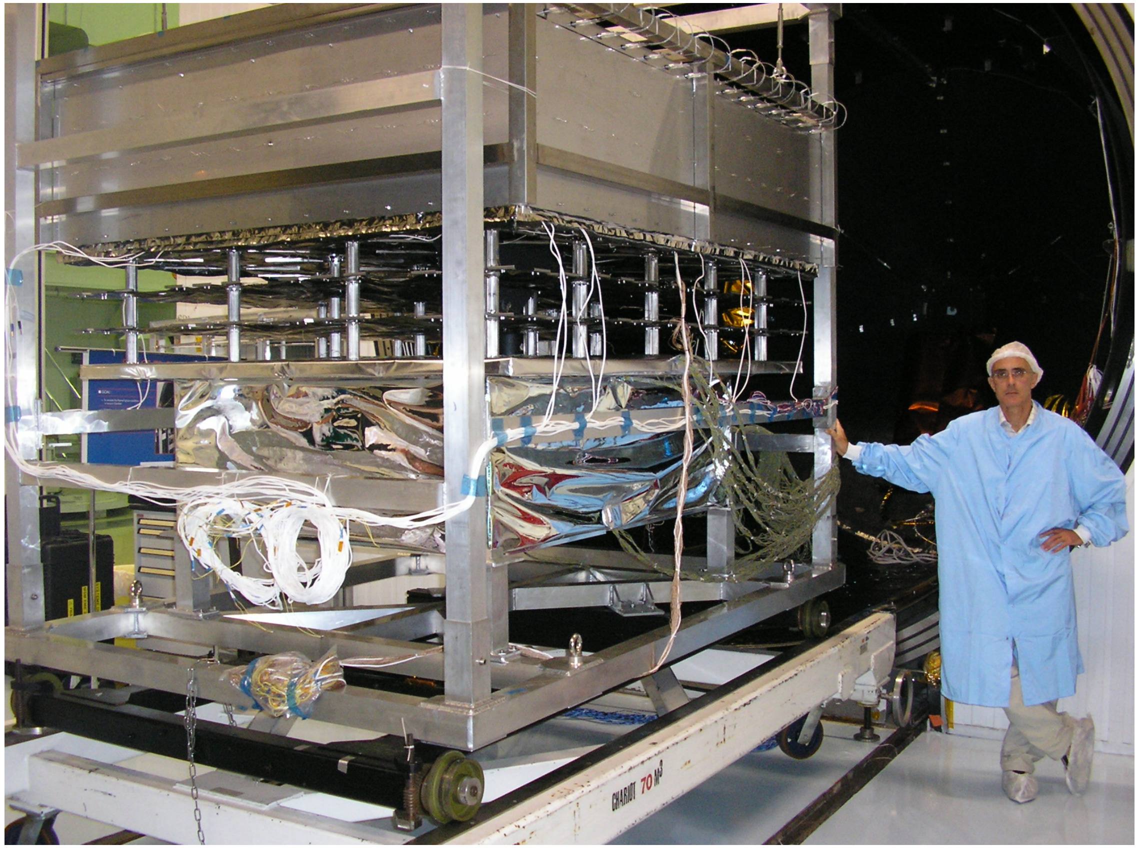
Heat Shield concept: validated in thermal vacuum



The test set-up has measured in a straightforward way the heat load transferred to the regulated spacecraft simulator.

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HEAT SHIELD BREADBOARD TEST

à HEAT SHIELD DESIGN CONFIRMED.

à HEAT LOAD INTO S/C TOLERABLE

à TAYLORING TO FOLLOW P/L NEEDS POSSIBLE, IN TERMS OF:

- Ø Gap height
- Ø Emissivity of sun panel extension
- Ø Use of heat pipes to transport heat towards extension
- Ø Emissivity of brackets

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SPACECRAFT THERMAL CONTROL

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THERMAL DESIGN

The thermal design for Solar Orbiter consists of the following major elements:

- Heat Shield (HS)
- Radiators for platform and scientific instruments
- Multilayer insulations
- Heaters

The Heat Shield is the only element specifically designed for the mission.

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THERMAL DESIGN - RADIATORS

RADIATORS FOR PLATFORM EQUIPMENT:

- Located on Anti-Sun, East, West, South faces
- Constant Conductance Heat Pipes (ammonia) used on Anti-Sun
- Variable Conductance Heat Pipes (ammonia + N2) used for Battery radiator
- Dedicated radiator for Adaptor ring on north face

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THERMAL DESIGN - RADIATORS

RADIATORS FOR P/L EQUIPMENT:

- Radiators for cold fingers of COR, EUI, EUS on south face, to guarantee cold finger at < -60 °C. Heaters for HP thawing and temperature regulation.
- Radiators for hot fingers of COR, EUI, VIM, STIX on south face, and for EUS on west face, to guarantee hot finger at < +20 °C. With VCHP (ammonia + N2) , to stabilize temp. and reduce heater power in cold case.
- Local radiators dedicated to WFC, SWA-PAS, SWA-HIS
- Radiators for in-situ P/L, on south, east, west faces

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THERMAL DESIGN – RADIATORS SIZING

Family	Item	Radiator location on S/C side	Area [m2]	Notes
SUMMARY	S/C side	RADIATOR AREA		
		Used [m2]	Available [m2]	Margin [%]
	Antisun	1.301	1.819	28
	East	0.560	1.916	61
	West	1.379	1.916	28
	South for cold fingers	0.984	1.514	35
	South for others	1.060	1.514	30
	On antisun side of COR1, EUI1, VIM1	0.290	0.290	
	AAD and FSS	0.030	local	
	Total →	5.60	8.68	

Radiators have comfortable growth potential, illustrating the robustness of the spacecraft thermal design

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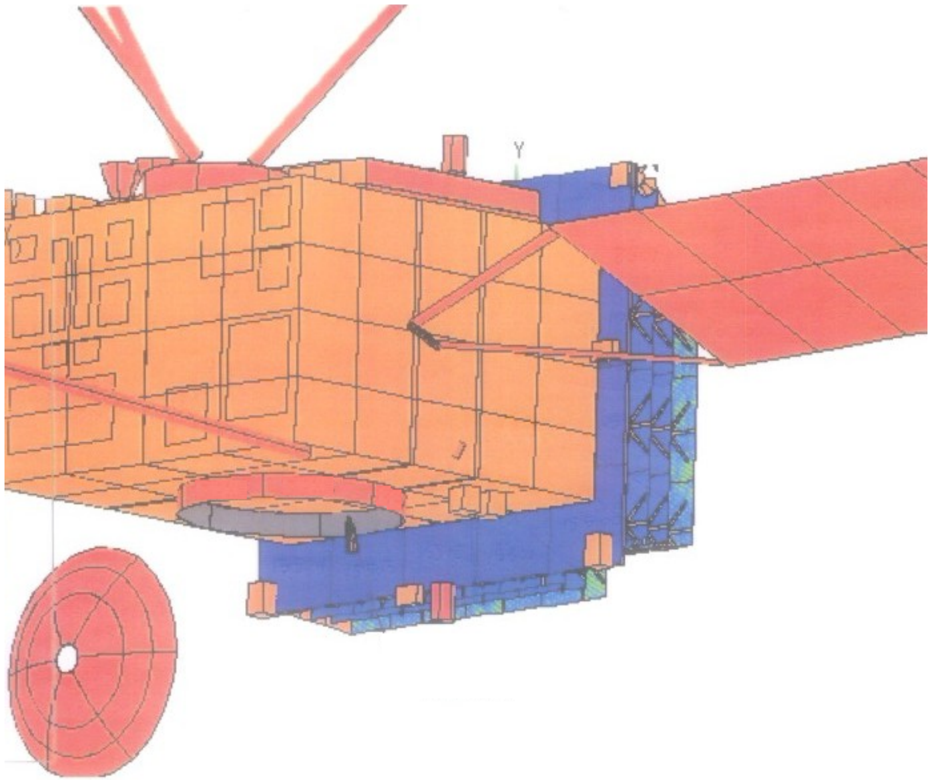
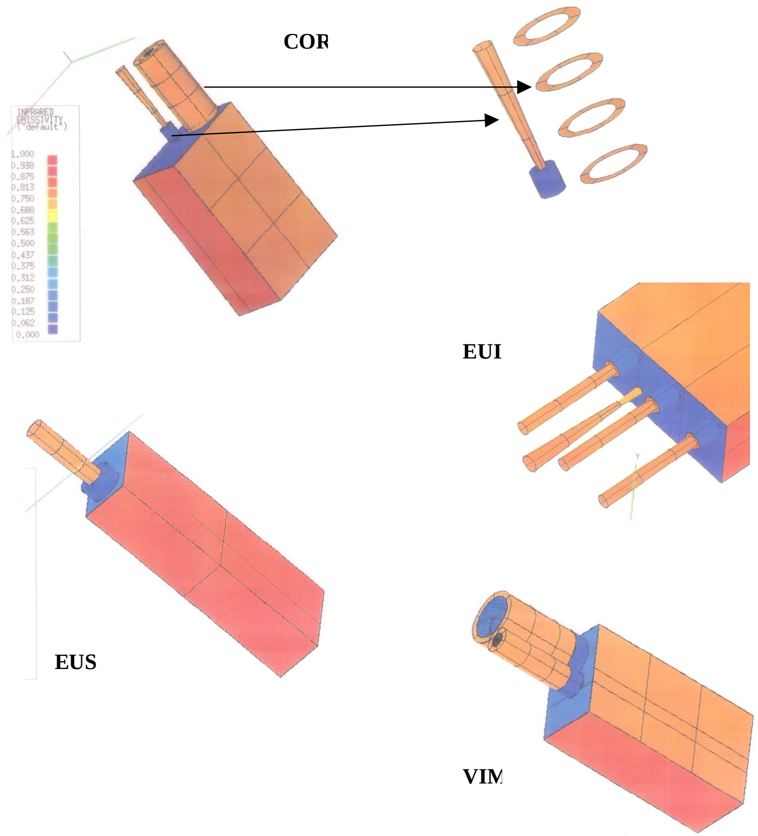
THERMAL ANALYSIS - MODELLING





The unified modelling assesses interactions between all elements of the spacecraft, including the instruments, the Heat Shield and the appendices.

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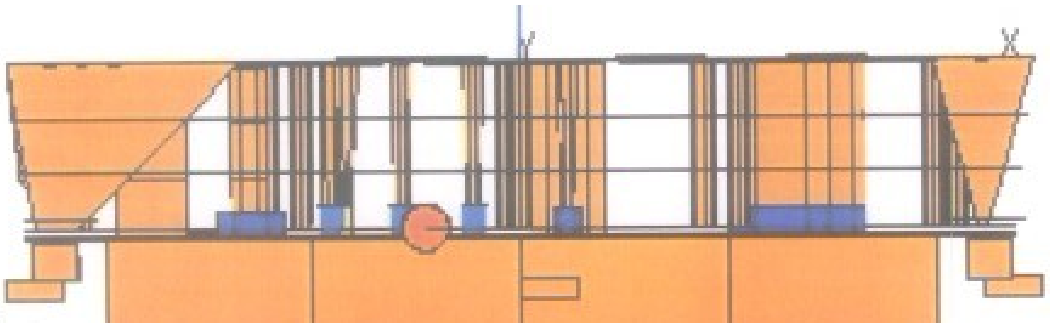
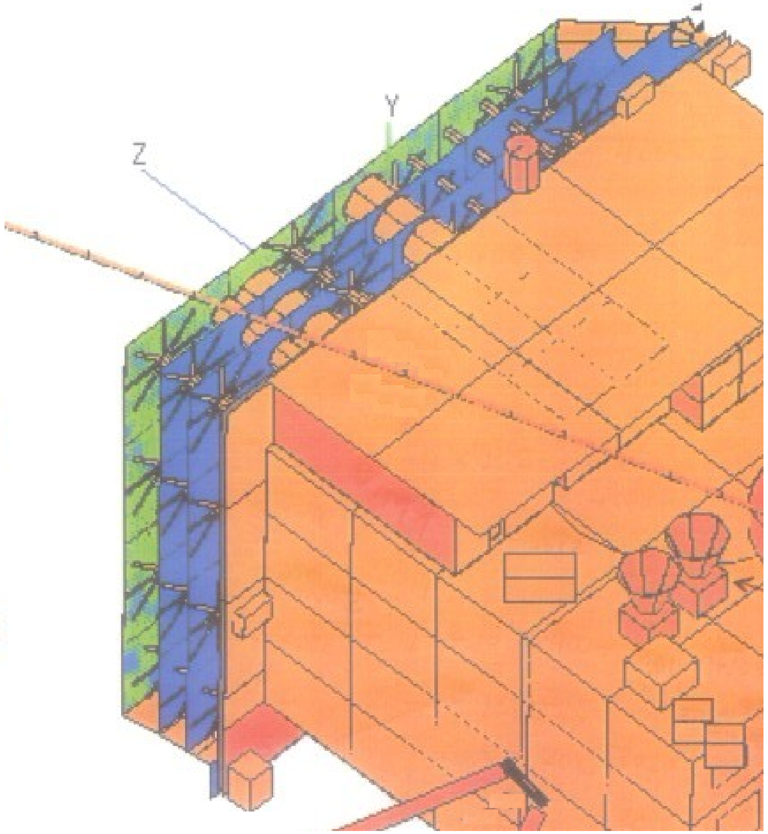
THERMAL ANALYSIS - MODELLING

The detailed modelling of the heat Shield and all its baffles, in flight configuration, has enabled to elaborate the flight predictions.





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THERMAL ANALYSIS – SYNTHESIS OF RESULTS

- All Platform units are within the requirements
- The instruments are accommodated thermally
- Modified thermal requirements for EUI detectors, VIM mirrors and APS, and STIX front grid, would enable further gains on thermal control cost, radiators and heating budget

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MECHANICAL DESIGN

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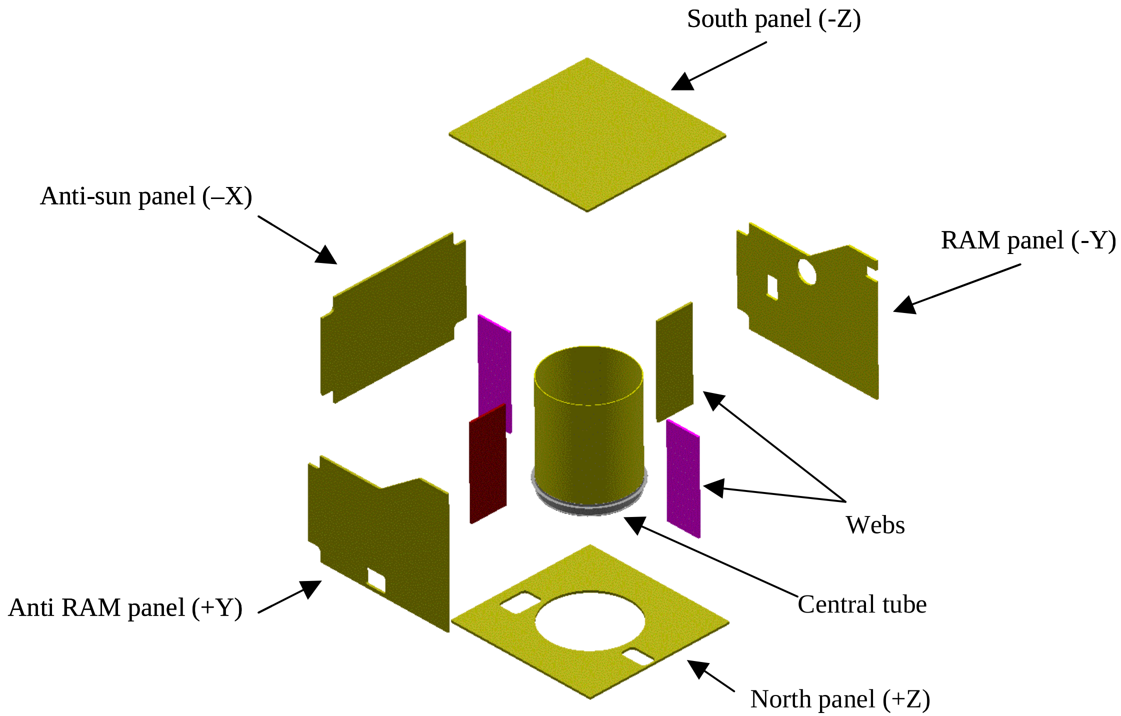
A light structure thanks to central tube, 937mm architecture

- parallelepiped box organized around a central tube and a set of webs and panels
- main dimensions are (without heat shield module) :
  - width (Y_{mech}) :1750 mm
  - height (Z_{mech}): 1184 mm
  - depth (X_{mech}) : 1755 mm



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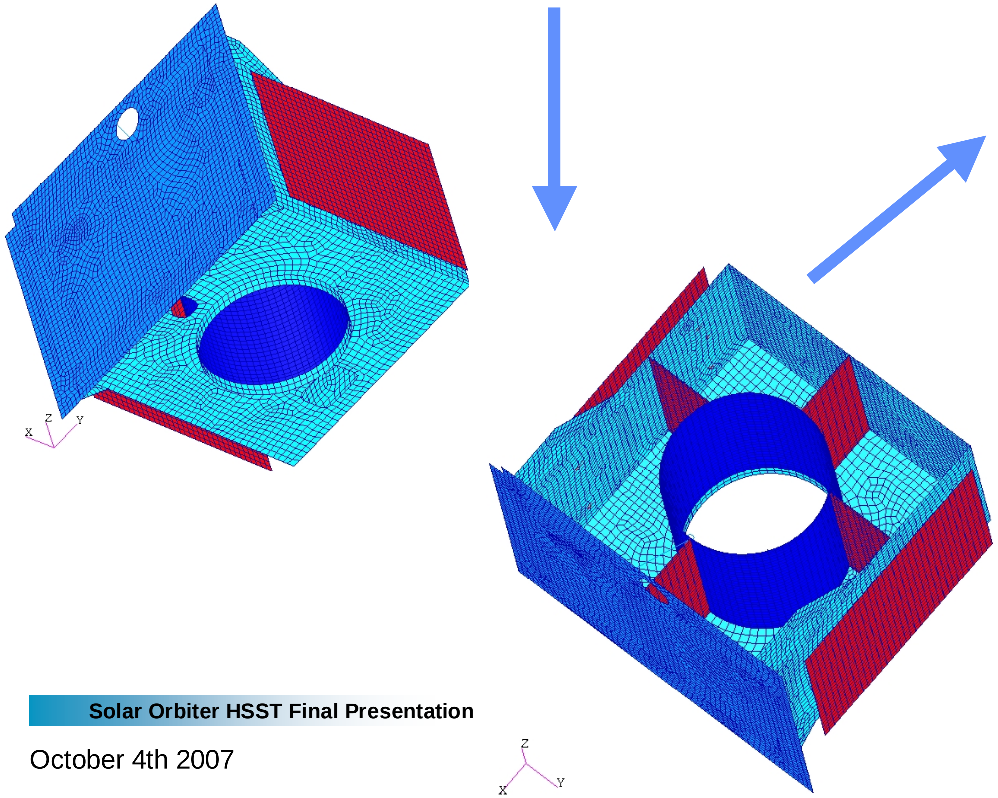
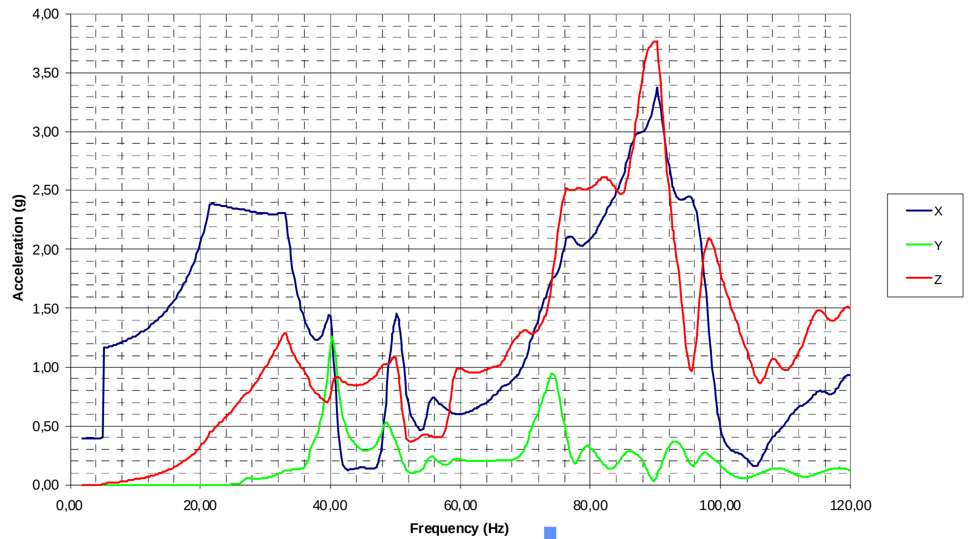
Mechanical behaviour assessed through detailed analyses

- The thorough Finite Element Model enabled to run analyses for modal, sine, quasi-static, thermoelastic distortion behaviours





- Mechanical requirements inferred for all units, instruments

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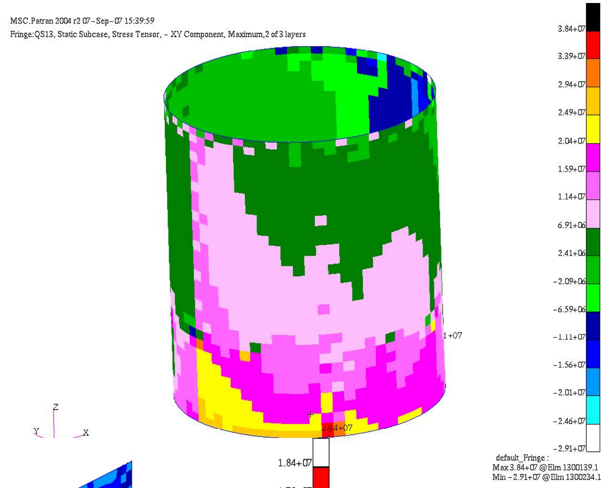
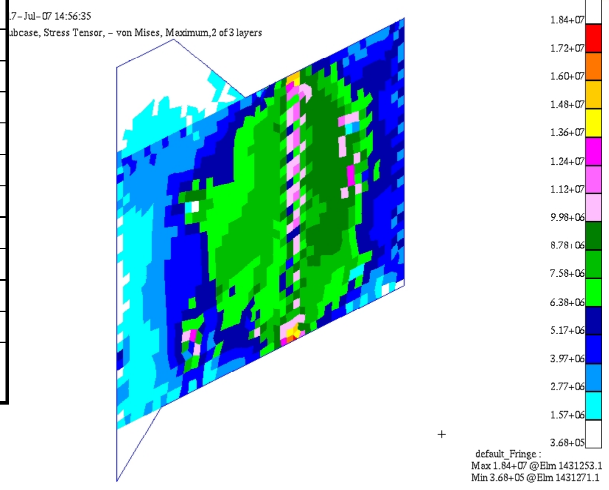
Mechanical sizing: large margins

- The structure is sized by the stiffness requirements, hence generating comfortable margins versus quasi-static loads (>110%)

Part	Load case	Computed stress level [MPa]	Safety margin
Central tube	LC 21	$\sigma_{longitudinal}=101.0$	1,13
	LC 43	$\sigma_{lateral}=36.2$	1.74
	LC 13	$\tau=38.4$	2.12
+ X panel	LC 25	$\sigma_{VM}=35,1$	2.36
- X panel	LC 27	$\sigma_{VM}=27,2$	4.54
+ Y panel	LC 27	$\sigma_{VM}=18,4$	7.19
– Y panel	LC 24	$\sigma_{VM}=22.1$	5.82
+ Z panel	LC 25	$\sigma_{VM}=50,2$	2.00
– Z panel	LC 13	$\sigma_{VM}=52,5$	1.25
+ X web	LC 25	$\sigma_{VM}=61,3$	1.46
- X web	LC 25	$\sigma_{VM}=50,0$	2.84
+ Y web	LC 27	$\sigma_{VM}=59,7$	2.22
- Y web	LC 23	$\sigma_{VM}=62,9$	2.05
He Tank support	LC 14	$\sigma_{VM}=35,1$	7.35
Launch vehicle adapter	LC 24	$\sigma_{VM}=52.3$	3.42





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AOCS AND FDIR

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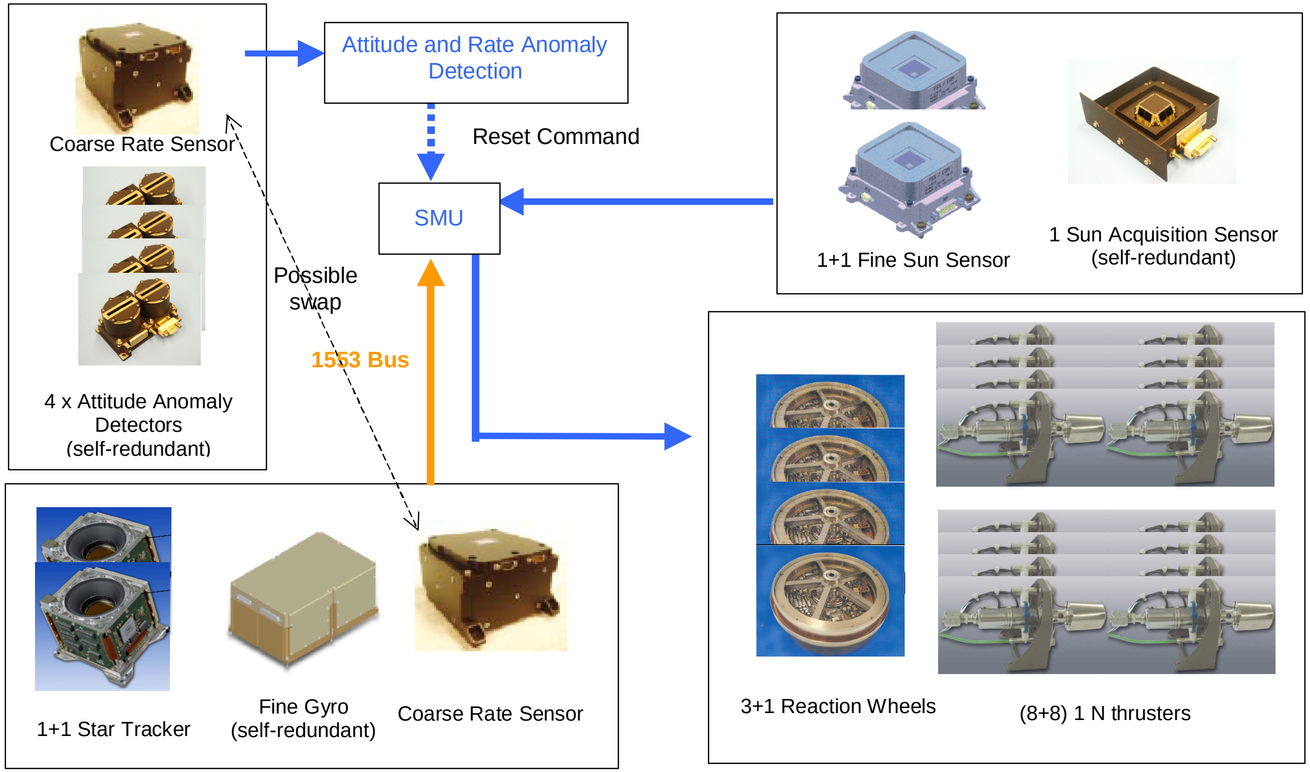
AOCS: inheriting the reliability of the Herschel pointing

- Given criticality of sun-pointing=> compulsory to re-conduct the AOCS and safe mode designs from Herschel-Planck.

- Also beneficial to Solar Orbiter in the nominal modes thanks to high HP performance

- Some units have to be adapted due to the difference in thermal environment but off-the-shelf hardware can always be found that satisfy the needs of Solar Orbiter without at worst more than a delta-qualification.



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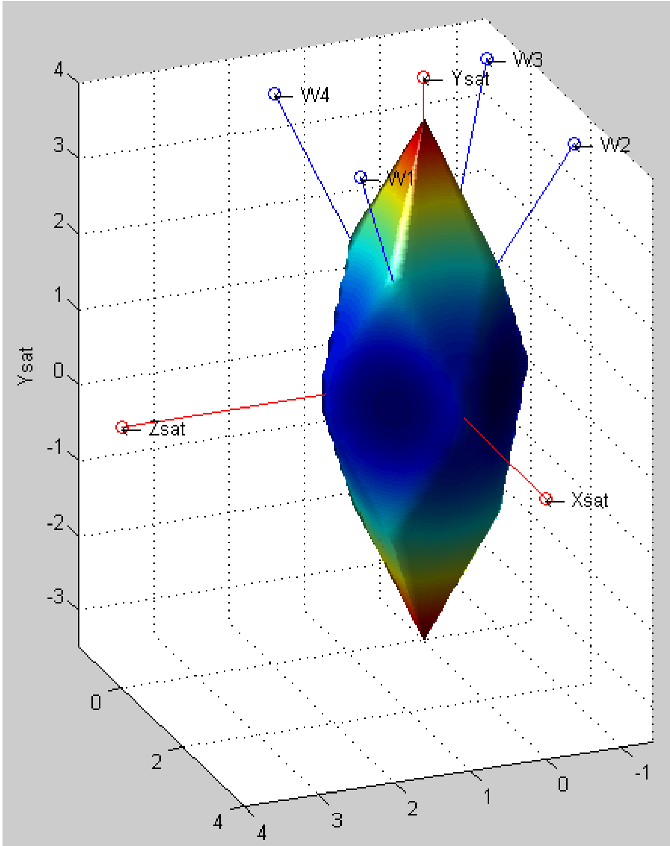
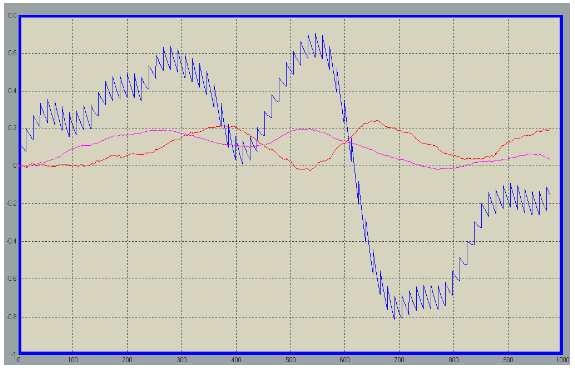
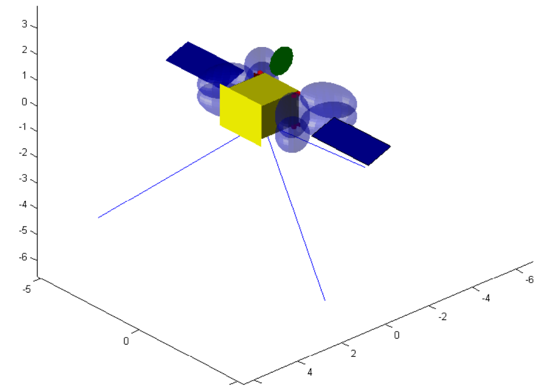
AOCS: accurate and secured Sun pointing

- Analyses confirm the performance and the safety of the AOCS design:
  - Mode simulations have been run
  - With solar torque management, wheels sizing
  - And safe mode reactivity evaluation







Wheels provide ability to compensate for Solar torque for the 10-day observation periods

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TTC SUBSYSTEM

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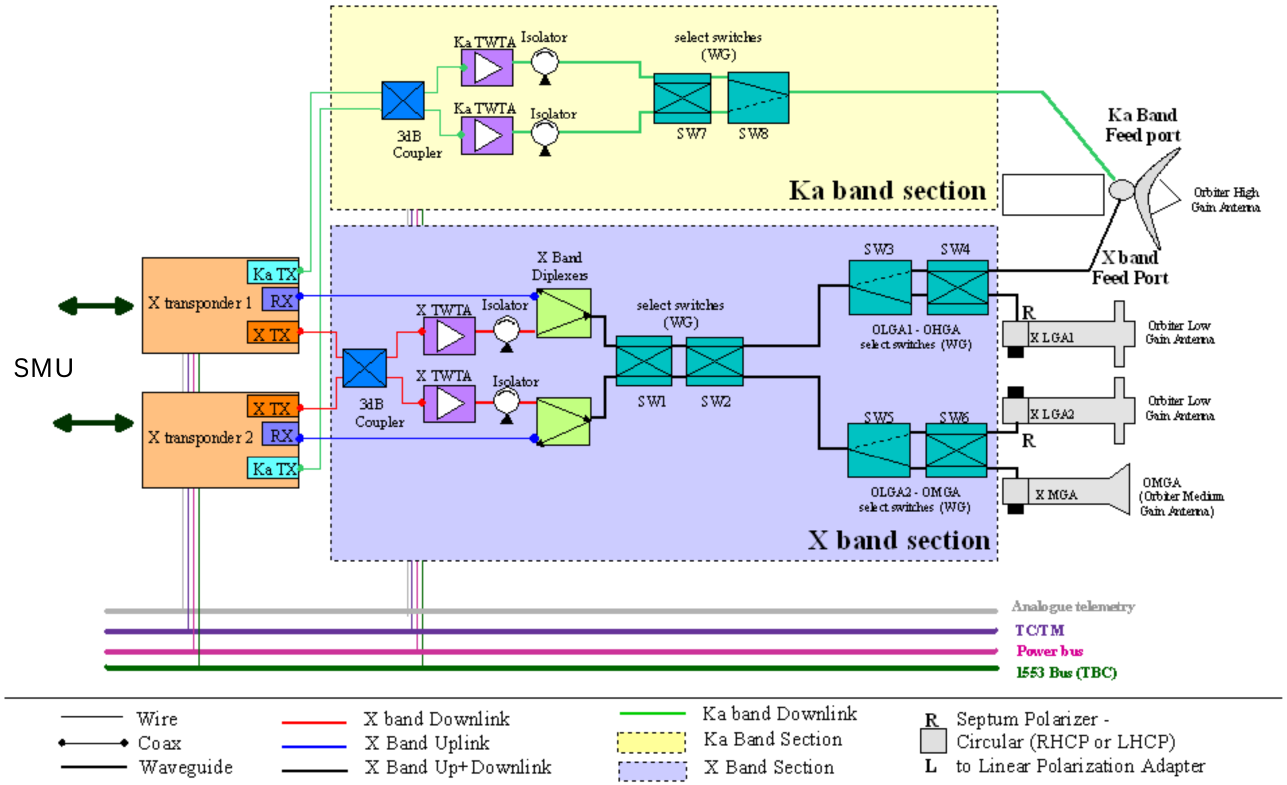
TTC RF subsystem: inherited from BepiColombo

- All critical parts of the dual band X+Ka BepiColombo RF system, especially the HGA and the MGA are reused.
- BepiColombo heritage secured by placing mechanisms and RF rotary joints in permanent shadow



The recurrence is preserved from BepiColombo, with increased power in science orbit thanks to a Cosmo-inherited dual-mode amplifier

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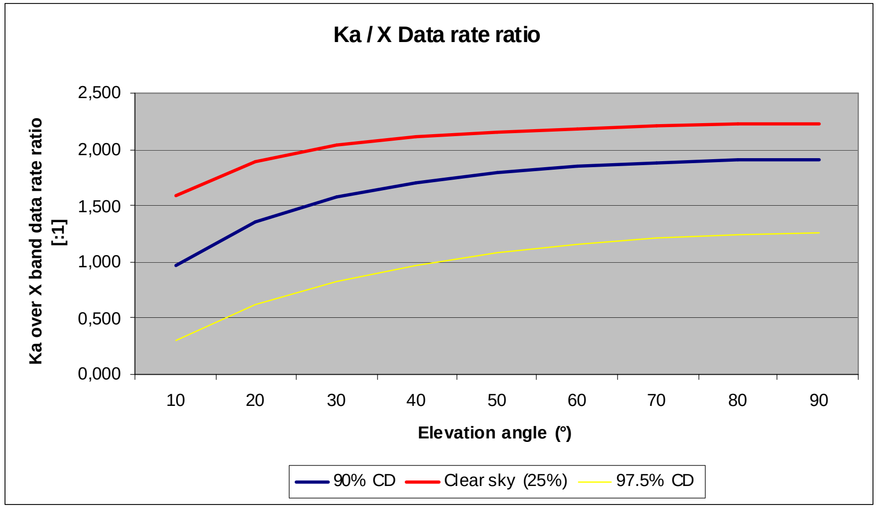
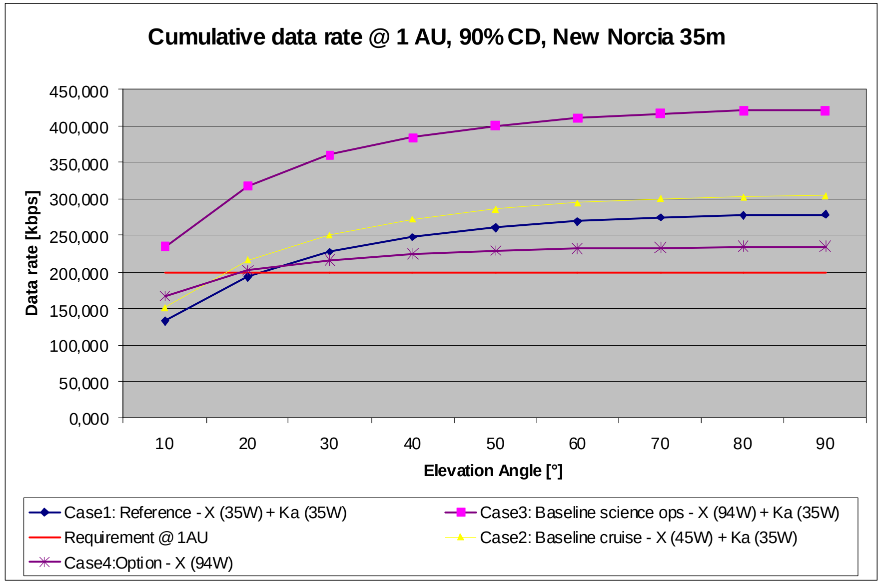
TTC RF subsystem: trade-offs and analyses

- Dual band X+Ka traded off versus X-band only => confirmed to preserve BepiColombo heritage and to keep large transmission capabilities
- Increase in power with dual-mode amplifier to benefit from power generation surplus in science orbit, with minimal impact on qualification status
- Data rate analyzed
- Compliance with required data rate confirmed





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POWER SUBSYSTEM AND SOLAR ARRAY

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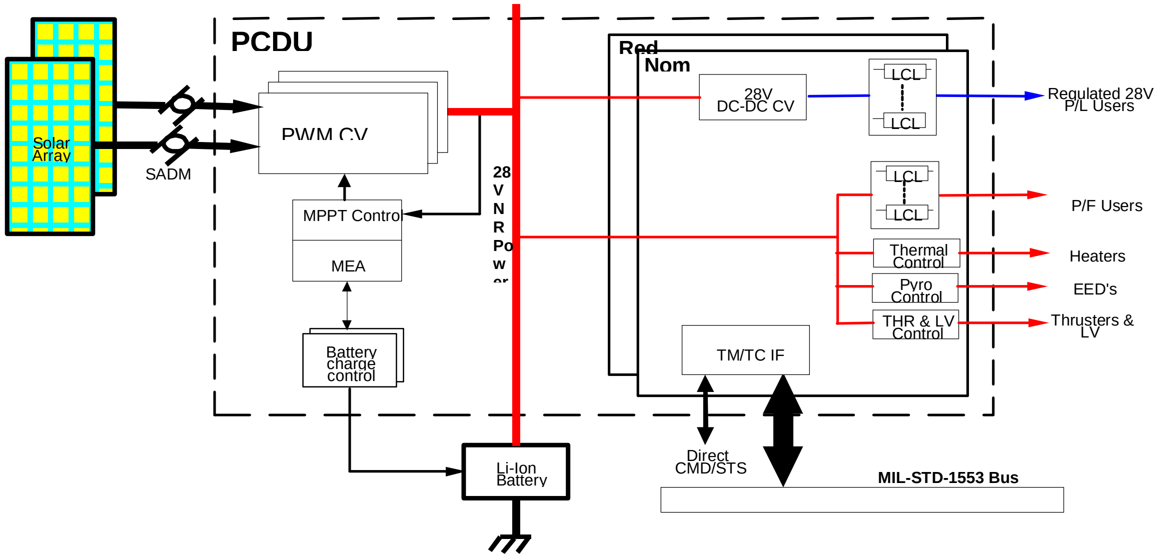
Power subsystem: Keeping BepiColombo heritage

- Subsystem identical to BepiColombo, with adaptation of Solar Array
- Boost versus buck regulation traded-off => buck selected to keep BepiColombo heritage and performance
- 65° Solar Array tilt angle kept as limit to secure power regulation



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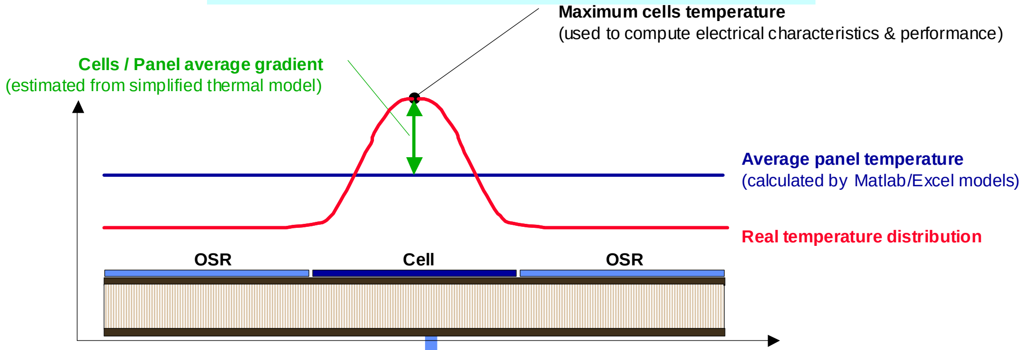
Power subsystem:
Adaptation of Solar Array

- Reuse of substrate of larger BepiColombo panel
- Reuse of all cells, OSR, network, bonding technologies
- Adaptation of cells/OSR ratio:
  - 100% cells for cold face
  - 0% and 25% cells on hot face

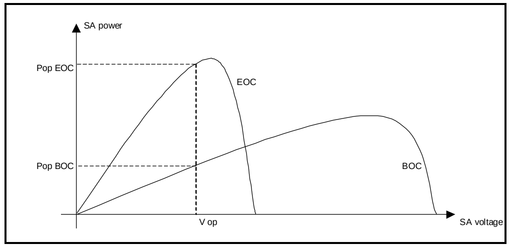
Cells-OSR thermal behaviour



BepiColombo thermal limits

maximum operating temperature for cells	250°C (incl margins)
maximum survival temperature	300°C (incl margins)

Optimisation of regulation



Hot and cold faces network design

PVA part		
String length	12 s // 25 s	12s // 25 s
Number of string per panel	8 p & 6 p // 3p	34p // 17p & 17p
Total number of cells per panel	168 // 75	408 // 425
Total number of cells per array	336 // 300	1632 // 1700

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DATA HANDLING SUBSYSTEM

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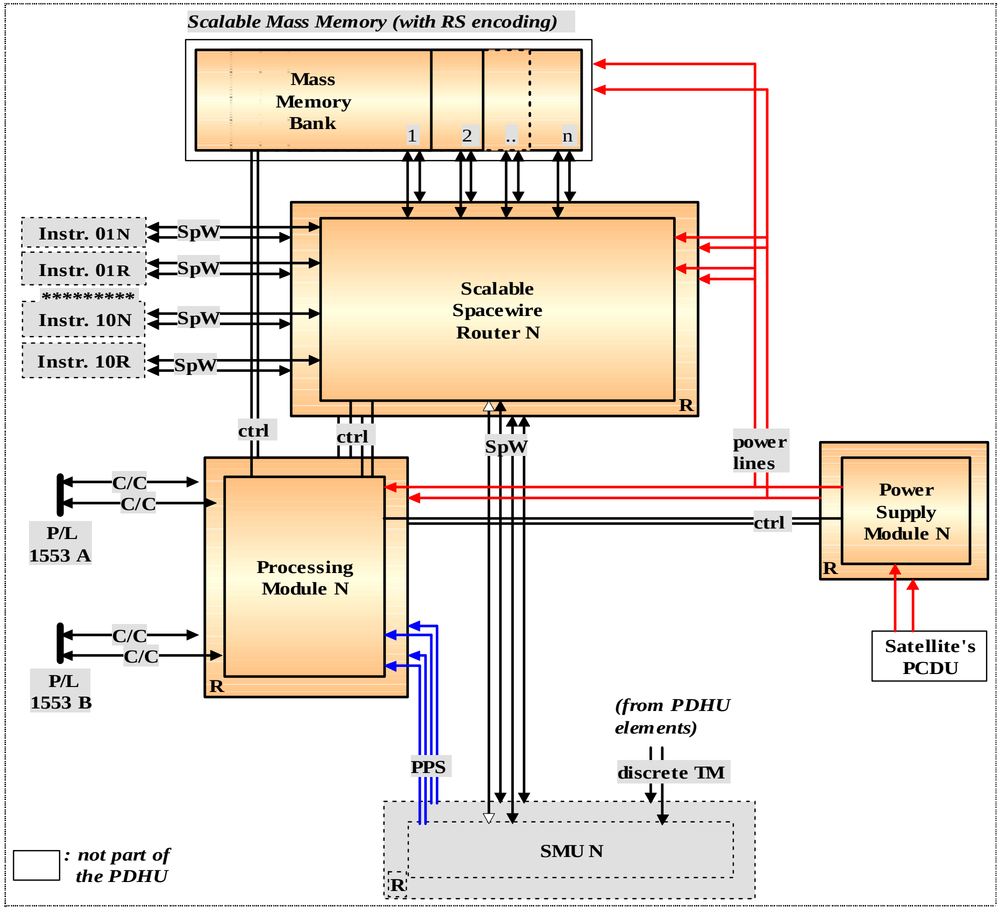
Data handling:

Easily interfaced, high MM capacity

- Data handling shall have enough flexibility to interface subsystems from different heritage (TTC+Power, AOCS), along with a large number of instruments.
- Shall be low-cost, available from a product line well in place in 2011-2015 when Solar Orbiter is built, and flying before Solar Orbiter.
- => led to select the Thales Alenia Space generic avionics



Thales Alenia Space generic PDHU includes Mass Memory with very large modular capacity up to 2000 GBits

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Data handling: Trade-offs and sizing

- Trade-off for SpaceWire network: science data only or science+C/C data => Solar Orbiter can support science+C/C data through SpaceWire
- Trade-off for re-use of HP spares => Use of a product line contemporary of 2011-2015 found safer, including cost-wise (constraints on Solar Orbiter mission would be too large, and obsolescence would pose issues for components)
- Compatible with radiation environment

Task	Figure (bytes)
Attitude Management	240 000
Thermal Regulation	30 000
Power Management	80 000
Instruments Management	35 000
PDHU management	5 000
System Management (TC,TM,FDIR,OBCP,MTL)	350 000
I/O system	120 000
Real Time Kernel	120 000
Dynamic data (stacks, heaps, ...)	200 000
TOTAL without dynamic data	980 000
TOTAL with dynamic data	1 180 000

EEPROM occupancy rates, software CPU workload have been budgeted and are within the required 50% maxima for both SMU (central computer) and PDHU (payload interface and MM electronics)

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ASSEMBLY, INTEGRATION, VERIFICATION AND SCHEDULE

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Consolidating cost and schedule feasibility

Thales Alenia Space has:

- Ø assessed the heritage
- Ø inferred the necessary models at all levels
- Ø elaborated an Assembly, Integration and Verification plan and a schedule
- Ø assessed costs and drivers

t Positive conclusions on cost and schedule feasibility

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Heritage (1/3)

- Category D limited to Heat Shield Module

Satellite items	category	rationale
Heat Shield Module	D	Specific STM model needed
Heat Shield (thermal layers + brackets)	D	TDA needed (started in HSST phase)
Sun panel	B/C	HW & technologies qualified
Baffles	D	TDA needed
Doors with mechanisms	C(*)	(*) TBC; Existing products and technologies, with applicability to HSM environment to be qualified; TDA TBD
Main Module		
Structure	B/C	HW & technologies qualified
Thermal Control	B/C	HW & technologies qualified, Optional delta-qual to use the standard heat pipes in cold conditions with frozen-ammonia (TBC)
Harness	B/C	HW & technologies qualified
Propulsion		Proteus architecture (flight proven)
tank	A	Qualified with US manufacturer; European back-ups
thrusters	A	Qualified

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Heritage (2/3)

Satellite items	category	rationale
AOCS		
Star Tracker	B	BepiColombo, with delta-qualification for radiations
AAD	C	Recurrence Herschel Planck, delta/design qual: thermo-optical coating on front baffle for operation under partial illumination; addition of a radiator
FSS	B	Development Galileo+Globalstar2; delta-design for reduced baffle
CSS	A	Large European heritage on ESA missions; Baffle not needed (TBC)
RW	A	In flight heritage on Spacebus 4000 platform
Coarse gyro	A	Being developed, first FM sept 2007
Fine gyro	A	Spare Herschel –Planck baselined
DHS		
SMU	B	GMES heritage; From GMES to SO: may need radiation delta-qual TBC
PDHU	C	From GMES, with increase of Mass Memory capacity (additional internal modules,) and delta-qualification for radiations (including scrubbing)

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Heritage (3/3)

- Extensive BepiColombo heritage for power and TTC

Satellite items	category	rationale
Power supply		
PCDU	A/B	BepiColombo recurrence, updates TBC depending on MPPT
battery	A	Large European heritage on Li-Ion product
solar array	B	Qualified on BepiColombo for 60% cell ratio; Delta-qualification needed for Solar Orbiter cell ratios and radiation environment
solar array drive mechanisms	B/C	Qualified on BepiColombo, potential adaptation of rotation amplitude (TBC)
TT&C		qualified
Low Gain Antenna	A/B	Heritage from BepiColombo (environmental/RF power delta-qual TBC)
Transponder	A	Heritage from BepiColombo
MGA (incl mechanisms)	A/B	Heritage from BepiColombo (environmental /RF power delta-qual TBC)
HGA (incl mechanisms)	A/B	Heritage from BepiColombo (environmental /RF power delta-qual TBC)
TWTAs	A	Heritage from BepiColombo (X TWTA) and Cosmo/Radarsat (Ka TWTA)
RFDN (Switches, Diplexer, waveguides…)	B/C	Heritage from BepiColombo and Radarsat (potential RF power delta-qual for X-band elements, TBC)

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A resilient integration flow

- The spacecraft modularity concept enables parallel and flexible integration flow isolating schedule risks between:
  - Main Module
  - Heat Shield Module
  - Instruments

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JOINT MISSION WITH NASA SOLAR SENTINELS

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Impacts of Joint mission with NASA’s Solar Sentinels

- Thales Alenia Space has assessed:
  - Impacts on link budget
  - Impacts on power demand
  - Launch environment on top of Sentinels stack
  - Accommodation of Wide Field Coronagraph
  - Interest of a 1666mm-interface to avoid intermediate adapter

- Positive conclusions on feasibility of the joint mission, with a potential affordable penalty on structure mass due to quasi-static load environment (depending on actual ratio longitudinal load/lateral load)

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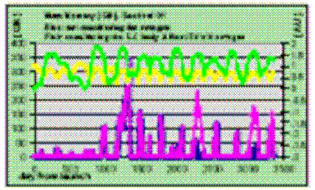
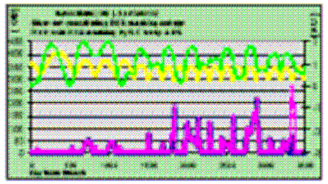
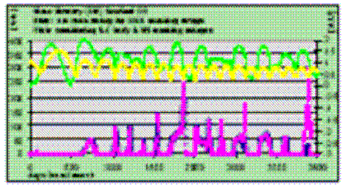
Impacts of Joint mission with NASA's Solar Sentinels

- Impacts on link budget:

=> MM needs 350 Gbits for mission 1, can be accommodated (=> 600 with margins)



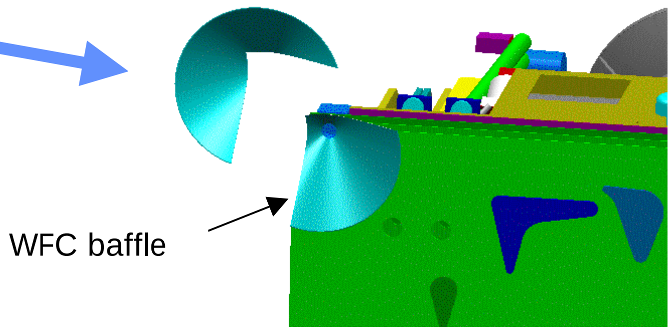




- Impacts on power demand

BepiColombo Solar Array substrate can be kept if in-situ are off between 1.49 AU and 1.51 AU

- Accommodation of Wide Field Coronagraph



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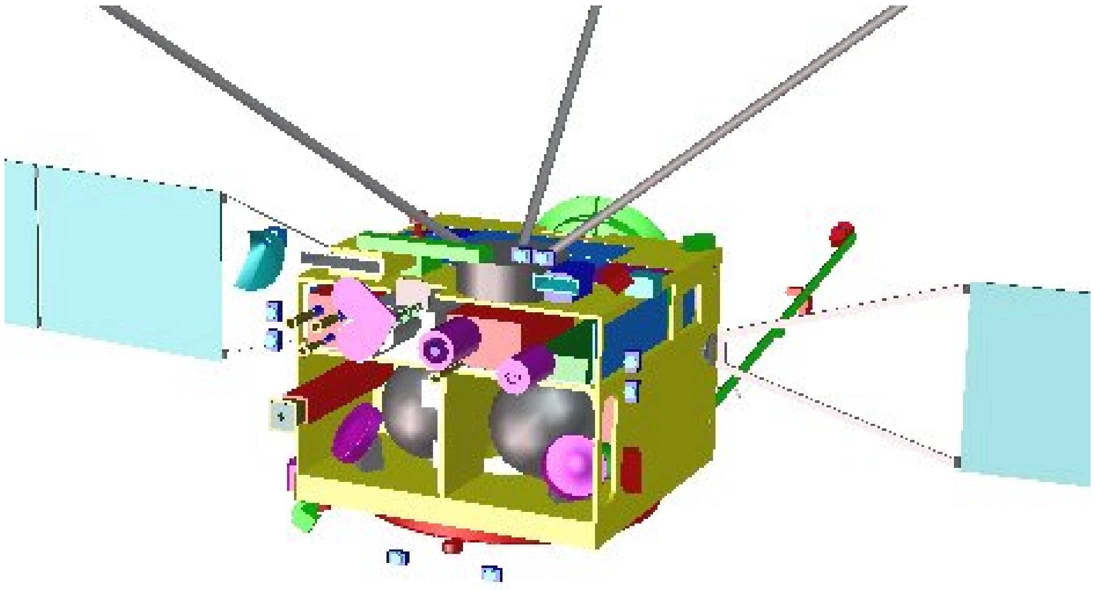
Impacts of Joint mission with NASA's Solar Sentinels

- Trade-offs carried out for launcher interface
- Adopting a 1666mm-interface presents assets in the case of combined mission with Solar Sentinels:

=> saves the cost of development of an adapter,

⇒ but leads to abandon the central tube and thus endangers the compatibility with a stand-alone Soyuz mission by increasing the satellite mass.



⇒ not retained, 937mm interface shall be kept

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CONCLUSION

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Conclusion

- Ø Two major conditions have been achieved to control the cost and schedule of the Solar Orbiter programme:

1. The system configuration elaborated by Thales Alenia Space enables to reuse HGA, Solar Array technology from BepiColombo while satisfying the science objectives.

2. The modular and flexible Heat Shield design has demonstrated its thermal robustness by test, enabling to master the upcoming phases of its development

- Ø Achievements on Heat Shield development and maturity gained on system & subsystems design and requirements enable to start the Definition Phase upon ESA's final decision on Solar Orbiter mission.

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