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Thermal Design, Analysis and Validation Plan of the Thermal Architecture for the SMILE Satellite Payload Module

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This document aims to provide a general description of the Payload Module concept for the SMILE satellite and a comprehensive description of the thermal design, analysis and future validation plan of the Thermal Architecture of the SMILE Satellite Payload Module (PLM), including the relevant thermal interfaces with the Platform and the Instruments.

Nomenclature

ASW = Application Software
BOL = Begining of Life
CAS = Chinise Academy of Sciences
CCD = Charge Coupled Device
CoG = Centre of Gravity
EOL = End of Life
ESA = European Space Agency
FoV = Field Of View
GMM = Geometrical Mathematical Model
HEO = High Elliptical Orbit
HW = Hardware
IF = Interface
LIA = Light Ion Analyzer
MAG = Magnetometer
MLI = Multi Layer Insulation
PF = Platform
PL = Payload
PFM = Proto-Flight Model
PLM = Payload Module
ECU = Extended Control Unit
PM = Propulsion Module
RF = Radio Frequencies
SC = Spacecraft
SMILE = Solarwind Magnetosphere Ionosphere Link Explorer
SSO = Sun Synchronous Orbit
STM = Strucutural Thermal Model
SVM = Service Module
SXI = Soft X-ray Imager
TCS = Thermal Control Subsystem
TMM = Thermal Mathematical Model
UVI = Ultraviolet Imager

I. Introduction

SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) is a collaborative science mission for the investigation of the solar wind interaction with Earth magnetosphere in order to further understand the Sun-Earth connection.

SMILE satellite would be launched into a High Elliptical Orbit (HEO) that would allow observing the specific regions in the near-Earth space where these interactions occur. The aim is to acquire several images and movies of the magnetopause, known as the boundary where the Earth's magnetosphere and the solar wind encounter and interact. SMILE mission will also study the polar cusps and the auroral oval, each of them occurring in each hemisphere.

This project is a joint science mission between European Space Agency (ESA) and the Chinese Academy of Sciences (CAS) for which Phase CD activities are currently on-going.

II. SMILE Satellite and Mission

SMILE satellite consists of a Platform (PF) composed by the Propulsion Module (PM) and the Service Module (SVM), both provided by CAS, and a Payload Module (PLM), which is provided by ESA. The PLM accommodates SMILE scientific instruments, the PLM Control Unit and Power Unit, the memory and the X-band communication system. The PLM is located on the top of the PF and shares the baseplate with PF for mass saving purposes.

The SMILE mission aims increasing our understanding of the connection between the interaction of the solar wind with the Earth's magnetosphere. SMILE satellite will study the nose and polar cusps of the magnetosphere and the aurorae at the North Pole while simultaneously monitoring the in situ plasma environment. In particular, SMILE will:

- Investigate the dynamic response of the Earth's magnetosphere to the solar wind impact in a unique and global manner
- Combine Solar Wind Charge eXchange X-ray imaging of the dayside magnetosheath and the cusps with simultaneous UV imaging of the Earth's northern aurora, while monitoring the solar wind conditions in situ
- The chain of events that drive Sun-Earth relationships

Two orbit options have been proposed to maximize the possible launcher candidates, and both the PF and the PLM design shall be compatible with them:

- Option 1: (shared launch on Soyuz or A62): injection into a 700 km circular SSO and argument of perigee 287.5 degrees. Then transfer to a HEO of 5000 km x 121000 km with inclination and argument of perigee identical to injection orbit.

- Option1.1: RAAN of final science operations orbit = 0 degrees (baseline)

- Option 1.2: RAAN of final science operations orbit = 165 degrees (back-up)

- Option 2 (VEGA-C): injection into a 700 km circular orbit with inclination of 70 degrees and argument of perigee 287.5 degrees. Then, transfer to a HEO of 5000 km x 121000 km with inclination and argument of perigee identical to injection orbit. RAAN of final science operations orbit = 206 degrees.

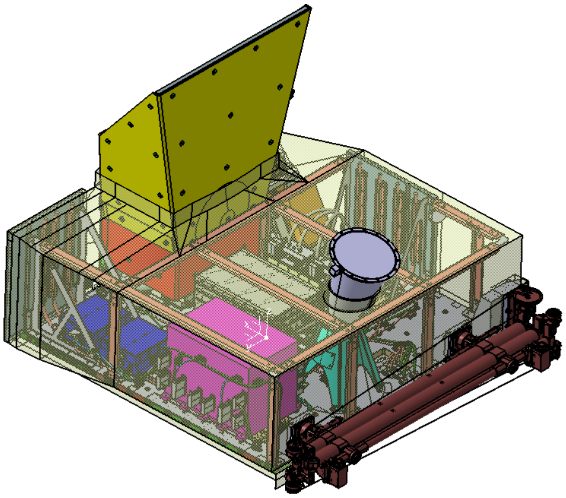

Figure 1. SMILE PLM Concept.

III. SMILE Payload Module Design

SMILE PLM concept is based on a supporting baseplate, shared with the SVM, with a configuration that optimizes the FoV of the three Instruments SXI, UVI and MAG and that houses all the units for the PLM operations.The SMILE payload consists of four instruments:

- Soft X-ray Imager (SXI): Capable of imaging the interaction between the solar wind and Earth's magnetic field. The development is under ESA lead.
- The Ultra Violet Imager (UVI): Capable of simultaneously imaging the entire northern auroral oval. The development is under ESA lead.
- Magnetometer (MAG): Capable of measuring the in-situ magnetic field. The development is under CAS lead.
- Light Ion Analyzer (LIA): Capable of measuring in-situ ions in all relevant parts of the orbit. The development is under CAS lead. LIA is currently located on the SVM. Therefore, no thermal analysis is being performed concerning LIA instrument at PLM level.

The three instruments are integrated within the SMILE Payload Module on an Al-honeycomb support panelmtogether with the following set of equipment which support the full operation of the instruments:

- PLM Extended Control Unit (PLM-ECU): Contains the processing resources for the flight mission software and the interfaces with the SVM central computer. It supports the communications (command and control) of the rest of PLM units (including instruments). It also includes the Power Distribution Unit in charge of managing the PLM power distribution network. It also accounts for the Mass Memory Unit providing permanent storage for all data susceptible of being downloaded to Ground, i.e. SVM, PLM and instruments house keeping data and instruments scientific data.
- X-Band Subsystem: Routes to Ground all PLM data coming from the PLM-ECU. Composed of the X-Band Antenna and a set of transceivers.
- Thermal Control Subsystem (TCS): Assures the temperature ranges (operational/non-operational) at every PLM unit interface.
- Harness Subsystem (power, signal and RF coax).

IV. SMILE PLM Thermal Architecture

The Thermal Architecture is in charge of providing the PLM (including the instruments and the interfaces with the SVM) with the necessary means, functions and support to achieve the requested science performances by maintaining appropriate thermal conditions (temperature ranges, thermal stability and gradients, among others) for all the mission phases and operating conditions.

The PLM thermal design concept, for what concerns the interface with the Platform due to the sharing concept, will be based on thermal decoupling from the PF thermal environment. The interface couplings (conductive and radiative) will need to be minimised by design to a suitable level and verified by analysis.

The PLM is responsible of the thermal control of all PLM equipment except during mission-level safe mode (or PLM OFF), with the exception of the sensor part of the instruments. For the Instruments, the PLM controls the interface temperatures and provides the routing of harness needed for their internal thermal control. The PLM provides also thermistors for monitoring purposes, to be acquired directly by the PF when PLM is OFF.

The instruments pointing constraints define an attitude of the satellite leading to privileged direction for radiators location on +X side, since it is always pointed towards the anti-sun direction. +Y/-Y sides are also very good candidates to act as radiators since they are always kept in shadows in nominal operation, and the only external heat input is due to the radiative coupling with the solar array and other protruding elements from the Platform. As a baseline, radiators will be aluminium plates (to protect also the PLM equipment versus radiation) with a high emissivity coating.

A heat pipe network collects the heat dissipated by the different PLM thermally coupled electronic units and transfers it to the radiator areas in +X and –Y sides. This solution offers the following advantages compared to a design based on doublers or straps:

- It is very flexible in terms of accommodation of equipment, allowing future modifications in the units location, and very efficient in terms of heat transport capability and radiator heat rejection capability.
- Due to the efficiency in the heat pipes heat transport, generating almost no gradients between the equipment and the radiators, the impact in mass of this solution is lower compared to a design based on straps or doublers, in which larger radiators are needed due to the gradient generated between the equipment and the radiators.
- It homogenizes the temperature of the different equipment for the different operational modes; minimizing the heaters power consumption for instrument electronic units (heat dissipated by ON units is transmitted to OFF units).

The heat pipe network solution imposes a limitation to the testing configuration of the PLM. For the heat pipes to perform properly, the condenser shall always be located in the same plane of the evaporator (no gravity assistance), or above the evaporator (gravity assisting to the return of the condensed fluid). For the PLM configuration, the possible test orientations are with the gravity oriented towards the –Z PLM axis, or with the gravity oriented towards the –X PLM axis. This limitation is perfectly compatible with the foreseen test orientations both at PLM and SC level.

PLM thermally coupled units have been grouped according to their design temperature ranges, in order to minimize the heater power consumption for non-operational modes. Instrument back-end electronics have been grouped together and connected to the –Y radiator, and PLM avionics have been grouped together and connected to the +X radiator.

As a baseline, PLM radiators will be 2 mm thickness (minimum) aluminium plates (to protect the PLM equipment versus radiation) with a high emissivity coating externally. Due to accommodation constraints, two mechanically separated radiator areas will be implemented, one on +X side (0.106 m2 including +20% trimming margin), and other on –Y side (0.104 m2 including +20% trimming margin).

Heat pipes mechanical attachment to the baseplate is performed via screws and thermal interface filler. Thermal filler is also installed between the electronic units baseplate and the heat pipes flanges to ensure a proper thermal contact.

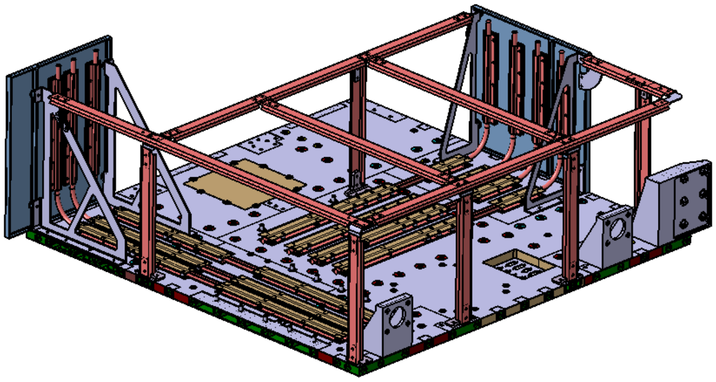

Figure 2. SMILE PLM Thermal Hardware. *3D Model showing PLM Thermal radiators with Heat Pipes and Interfiller. Secondary strucuture support for MLI tent is also shown in red.*

X-band antenna, including the support bracket, is treated as a thermally insulated unit, since it has a wider design temperature range (compared to other PLM thermally coupled units) and it receives solar fluxes and it is exposed to deep space. The antenna support is decoupled from the PLM baseplate via thermal washers. The parts of the antenna and antenna support which remain inside the PLM MLI envelope are isolated from the rest of the PLM by mean of a dedicated MLI. The antenna is externally white painted in order to minimize the solar fluxes absorption.

For the connection between the baseplate and the Platform, a trade-off between titanium and glass fiber thermal washers has been performed, balancing thermal and mechanical performances. Given the very high number of mechanical connections (around 100 IF points) in the PF/PLM shared panel imposed concept, a solution with GFRP washers has been selected, to minimize the conductive heat flux from PF to PLM.

MLI blankets cover all the areas not used as radiator surfaces, in order to provide insulation from the external environment to all the instruments and PLM equipment. MLI blankets are designed to avoid interfering with instruments field of view and radiator areas. MLI blankets are shaped to avoid any undesired or uncontrolled reflection from the solar fluxes. A dedicated light frame to support the MLI blankets is implemented, where needed. MLI blankets allow for radiator area trimming (+/-20%) capability after thermal balance test.

Heating lines are used to compensate the equipment dissipation for non-operating modes, and in order to maintain the PLM equipment and instruments interfaces temperatures above minimum design temperatures. Heating lines are powered either by the PLM (controlled via triplets of thermistos, when the PLM-ECU is ON) or by the PF (controlled via triplet of thermistors, when PLM-ECU is OFF). Threee control modes (TCS Modes) have been defined with the associated status of each unit (SW-ON=Switch-on temperature, NON-OP=Non-operational range, OP=Operational range).

Table 1. TCS modes.

PLM TCS Mode	PLM-ECU	XBT	SXI-E	SXI-FEE	SXI-C	UVI-E	UVI-FEE	UVI-C	MAG-E
PLM SURVIVAL	SW-ON	NON-OP	NON-OP	NON-OP	NON-OP	NON-OP	NON-OP	NON-OP	NON-OP
PLM SAFE	OP	OP	NON-OP	NON-OP	NON-OP	NON-OP	NON-OP	NON-OP	NON-OP
PLM OPERATIONAL	OP	OP	OP	OP	OP	OP	OP	OP	OP

A. Thermal Design Drivers

PLM thermal design shall be compatible with the instruments thermal requirements by keeping the iterface temeprature and intruments electronic unit temeperatures (TRPs) within the requested temeprature ranges. Regarding the instrument thermal requirements, the more restricitive are listed below:

- SXI CCDs (SXI telescope detectors) optimum temeprature shall be kept at -95ºC during science nominal operation. SXI science operation are performed at altitubes above 50000km. In order to achive this temeprature, SXI intrument accounts with a dedicated radiator which shall be thermally decouple from the PLM.
- UVI Detector temeprature. The requirements for the UVI detector are less constringent than for SXI and it is requested an optimum temperature between -5ºC to +5ºC during science operation. UVI science operation

can occur for altitudes above 20000km. In order to achive this temeprature, UVI instrument accounts with a dedicated radiator which shall be thermally decouple from the PLM.

For the operational phase, these requirements are linked to overall observation performances, to guarantee that the contributions of thermally induced effects to the observation error budget remain below the allocation.

The thermal control performances shall be achieved for the SMILE PLM accommodation on SC +Z panel and taking into account the different options of High Eccentricity Orbit (5000 km x 121000 km), the injection orbit and the instruments pointing constraints.

The PLM thermal architecture shall be able to cope with the different SC attitude and equipment dissipation for all the different combinations of SC modes and PLM modes, including transitions between modes. The PLM thermal design concept is also driven by:

- The requirement to be as thermally decoupled as possible from the PF thermal environment
- The requirement to minimize the gradient within the baseplate for the phases in which the instruments are operating
- The maximum allowed power consumption of 84W, and the limitation of 6+6 heating lines of 1.5A provided by the Platform, when PLM ASW or instruments control software is OFF
- The maximum allowed power consumption of 155W (for the complete PLM) when PLM-ECU is ON
- The instruments/equipment power dissipation
- The PF radiative interfaces with the PLM (mainly the solar arrays and the PM)
- Export control regulations that apply to China (see Chapter VII).

V. SMILE PLM Thermal Analysis

To determine the thermal performances of SMILE PLM, a Thermal Mathematical Model has been built, representing the PLM with its relevant thermal properties, in order to compute the temperatures, radiative couplings and fluxes for SMILE mission. PLM TMM includes the preliminary TMMs of the payloads (SXI, UVI, MAG) and the Platform (SVM, PM and Solar Arrays).

A. Cases Definiton

Analysis cases have been selected to cover the worst envelope of hot and cold cases in both nominal operation and safe mode. Safe mode and survival cases have also been analysed in order to verify the performances in terms of heater power consumption. Selection and definition of the analysis cases has been based on:

- Environmental parameters: Solar constant, Albedo and Earth temperature.
- Assessment of proposed orbit options for the SMILE mission (considering orbit propagation).
- Satellite attitude during nominal operations and safe modes.
- PLM diagram modes of operation, addressing the different status of the PLM equipment and instruments with their associated power dissipations and thermal control modes.

Along this section, these points will be discussed in order to further explain the logic followed for the selection of the worst cases for the thermal analysis of SMILE PLM Thermal Design.

Environmental parameters have been derived from the three epochs of the year in order to cover the differences in hot and cold scenarios depending on the external environment (around Equinox EQ, winter solstice WS, and summer solstice SS). Hot cases occur during the Winter Solstice, as it is the epoch of the year when the solar constant is maximum (1420 W/m2). On the other hand, cold cases can occur either around the equinoxes, as eclipse phases take place, or during Summer Solstice, since the solar constant has the minimum value (1320 W/m2).

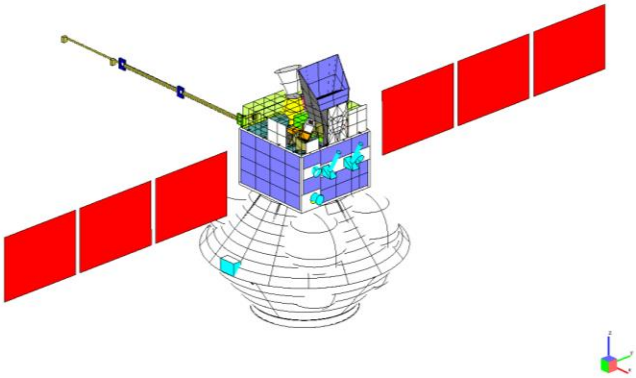

Figure 3. SMILE PLM GMM. *Including Instruments and PF delivered GTMMs.*

For the equinox epoch a dedicated assessment has been performed on the maximum eclipse duration. The date for which maximum eclipse duration occurs within mission nominal life-time have been used for the thermal analysis. Eclipse maximum duration depends on orbit definition. For option 1.1 (baseline), it was found to be 62 minutes on 22/03/2023; for option 2, maximum duration is 75 minutes, and the date corresponds to 15/10/2022. In any case, the impact of the eclipse duration is not very relevant compared to the complete orbit duration of more than 50 hours.

EOL thermo-optical properties for external surfaces and maximum interface temperatures have been considered for hot cases, and BOL properties and minimum interface temperatures for cold cases.

Orbit propagation due to third-body perturbations highly affects these orbit parameters, especially increasing the altitude of perigee from the initial value of 5000km up to values of more than 10000km depending on the orbit option. For the definition of COLD/HOT cases, the increase of altitude in perigee will have an impact on the overall PLM thermal performances, as long as Earth and Albedo fluxes that the satellite receives will decrease while the altitude of perigee increases. Therefore, initial orbit values have been kept for HOT cases, and orbit propagated values have been used for the COLD cases definition.

- SC attitude in operational modes is driven by three modes of operation of the SMILE PLM:
- Full Science, where nominal science operations occur for altitudes above 50000km.
- Communications (X-Band): segment in which data communications with the ground station can occur; communications are allowed for altitudes below 15000km. At the moment of downloading, the antenna shall point towards the ground station, currently considered Nadir.
- Power Optimization: Solar arrays pointing to sun whenever the satellite is neither performing science operations nor X-band communications.

The Earth fluxes at perigee pass also play a relevant role for the PLM radiators absorbed fluxes, depending on the SC attitude. A dedicated assessment of Earth fluxes for altitudes below 15000km was performed showing the sensitivity of the PLM radiators to the SC pointing during the communication segment. At the moment of communication, antenna pointing to nadir, radiators located on +X side of the PLM were receiving less Earth fluxes than if the SC was sun-pointing. Therefore, following a similar strategy to the one selected for the orbit parameters, in order to retain these highest fluxes in the HOT cases, communications pointing is performed at the highest altitude possible for this segment (at 15000km) and for COLD cases it is kept at the perigee pass, receiving less fluxes due to the communications pointing.

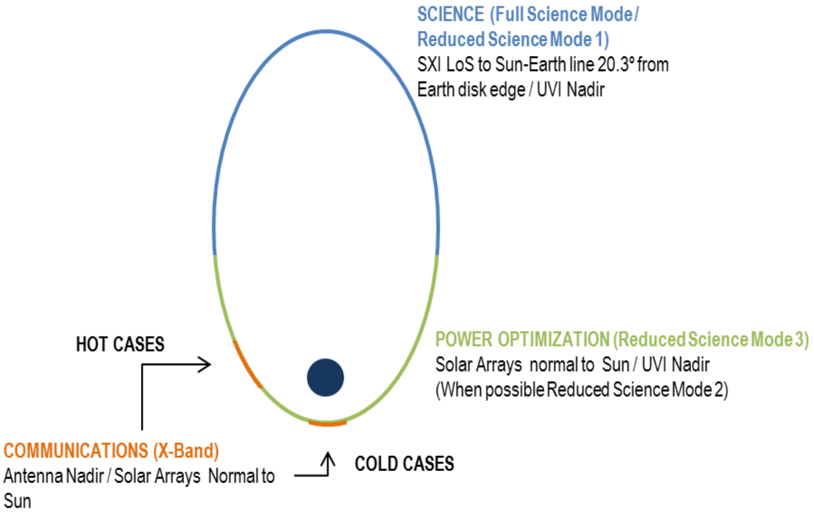

Figure 4. Nominal SC Attitude Segments.

During satellite operation in safe mode, the satellite will be rotating with the solar arrays pointing normal to the sun with an accuracy of the sun sensors of half cone angle of 30º. This has been taken into account in the definition of the survival analysis cases, considering the worst attitude of the satellite in terms of received thermal loads.

PLM Modes have been also considered gathering the units status and the thermal control mode. For the thermal analysis cases the following modes have been considered:

- PLM-OFF: All units are OFF, thermal control mode is PLM SURVIVAL.
- PLM SAFE: Only the PLM-ECU is SAFE mode and all the instruments are OFF, thermal control mode is PLM SAFE.
- PLM IDLE: Only the PLM-ECU is ON and all the instruments are OFF, thermal control mode is PLM OPERATIONAL. This mode is previous to start operations and the instruments are kept at their switch-on temperature.

- PLM OPERTIONAL: PLM-ECU and all the instruments are in FULL SCIENCE MODE, thermal control mode is PLM OPERATIONAL.

According to the PLM Modes thermal control strategy of the active thermal control defined based on three Thermal Control modes, identifying the temperature ranges in which the different PLM equipment must be controlled, for each thermal control mode (see Table 1).

PLM units nominal dissipation varies according to the PLM configuration for the thermal analysis and according to the PLM modes, including system margin of +20% for hot cases and -20% for cold cases.

B. Uncertainty Margin

The following uncertainty margin (UM) policy has been applied:

- In general, UM is +/- 10ºC (corresponding to Phase B status). A sensitivity analysis has been performed to calculate the uncertainty margin, which has been proven to be below 10ºC for all the PLM equipment (except for the X-band coupler).
- For X-band coupler, UM is +21/-10ºC, based on unsertainty analysis performed, and not part of the scope of this paper.
- For SXI CCD, UM of +/-20ºC has been according to instrument detailed thermal analysis.
- For the X-Band Antenna, UM of +/-15ºC has been applied, since no reduced thermal model is available.
- For actively controlled equipment, the heaters threshold has been defined to maintain the PLM equipment at least 3ºC above the minimum design temperature, and the duty cycle has been set to be below 75%.
- For heater power budget with respect to the calculated power consumption, the heaters threshold has been defined to maintain the PLM equipment at least 10ºC above the minimum design temperature. In this case no subsystem margin has been considered, and only the system margin (20%). Minimal bus budget has been used for the sizing of the heating lines (23V). Nominal bus voltage is 30V within a range from 23V to 35V.
- Dissipated power for hot and cold cases include the system margin (+/-20%) as a worst case.

VI. SMILE PLM Thermal Analysis Results

Several cases as described in previous section have been assessed to show compliance of the proposed SMILE PLM Thermal Design. For the sake of simplicity, only the relevant dimensioning cases results are presented along this chapter.

A. PLM Nominal Operation

The PLM in operational mode has been assessed for COLD and HOT scenarios. For the COLD Operational case the PLM in IDLE mode has been considered, with the SC in nominal pointing but with the intruments electronic units switch-off and controlled at their minimum operational design temperature. This case leads to the dimensioning of the heater power budget in operational mode (see section C of this Chapter). For this case, duty cycles of the PLM Operational heating lines are presented.

For HOT case temepratures are presented in next table. Operational heaters in this case never switch-on.

Table 2. Hot nominal operational case summary results.

Label	HOT OP		Design Temperature	
	Min [ºC] Predicted	Max [ºC] Predicted	Min [ºC]	Max [ºC]
XBT_MY_TRP	5.9	38.3	-20.0	50.0
XBT_PX_TRP	5.4	37.8	-20.0	50.0
COUPLER_TRP	-0.8	63.9	-40.0	100.0
MAG_E_BOX_TRP	-2.7	40.1	-25.0	50.0
UVI_E_BOX_TRP	-3.4	41.8	-30.0	50.0
ANTENNA	-1.1	52.0	-154.0	120.0
PLM_ECU	7.0	39.3	-20.0	50.0
SXI_BEE_TRP	-2.9	39.8	-20.0	55.0
SXI_FEE_TRP	-6.4	42.3	-20.0	45.0

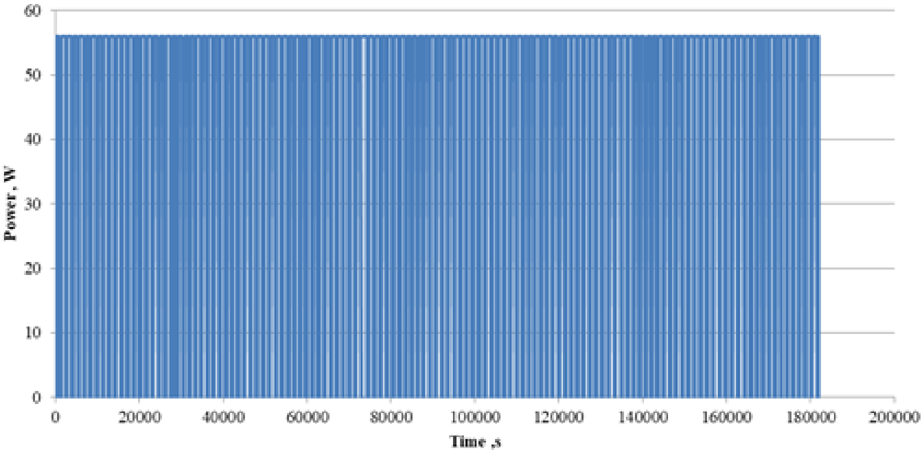

Figure 5. PLM MY Operational Heating lines. *Duty cycles of the operational heating lines controlling the the Instruments electronic units (SXI-BEE, UVI-E, MAG-E) for PLM IDLE mode.*

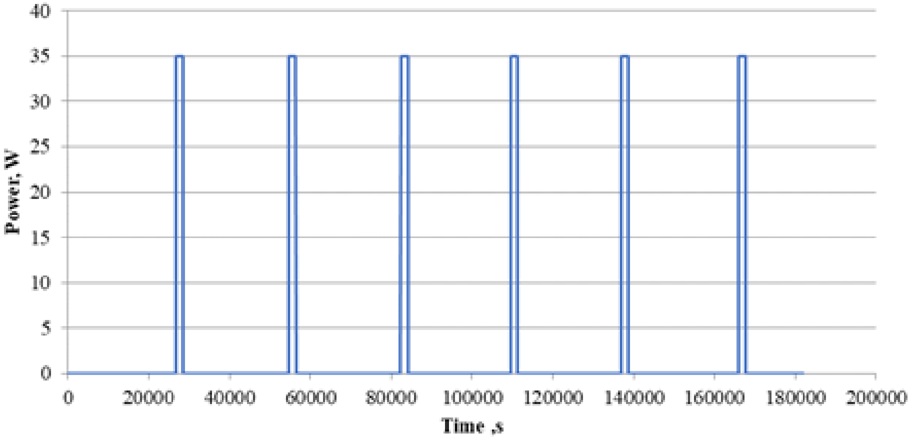

Figure 6. PLM PX Operational Heating lines. *Duty cycles of the operational heating lines controlling the the PLM-ECU and the Transcivers for PLM IDLE mode.*

During nominal operations the PLM Thermal Design shall also ensure the approapiate interfaces to the payloads to perform their science operations. Particulary, for SXI, the instrument with cryogenic temepratures ranges at the CCDs during nominal operations.

SXI science operations take place for altitudes above 50000 km, from 15300s to 166500s (elapsed time considered t=0s from perigee). According to SXI mission requirements, the SXI-CCD operating temperature shall be between -110°C and -95 °C during science segment, above 50000km. The calculated temperature evolution of the SXI-CCDs is shown for the hot nominal operational case. According to Figure 7, it is observed that the CCD can operate at its optimum temperature for the complete orbit, even considering an uncertainty margin of +20ºC for the hot nominal operating case. For this case, the PLM is considered in Full Science Mode and the hot environment definition explained in Chapter V.

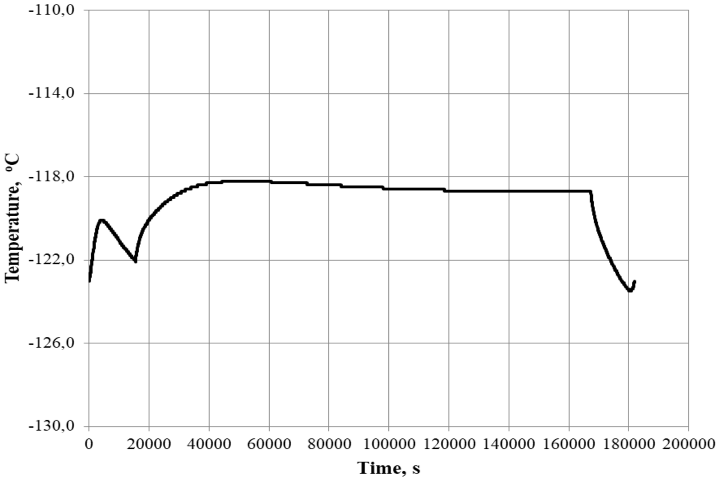

Figure 7. SXI CCD Calculated Temperature Evolution. *Calculated temperature evolution for SXI-CCDs for hot nominal operational case.*

B. Survival Robustness Cases

Transient cases for 1 hour duration have been analyzed to show robustness of the SMILE PLM Thermal Arquitecture to lost of attitudes from the SC. Two survival cold cases, one simulating the lost of SC attitude at exit of the eclipse from PLM Operational to PLM OFF, and the second cold case simulating that the SC losses attitude from SC in Safe mode (stabilized survival) with the PLM OFF. Out of this two cold cases defintion, the second one is the more restrictive as the PLM starts from survival temperatures and the power needs to be enough to keep the PLM for one hour at minimum non-operating range without any external flux to the PLM (sun perpendicular to –Z SC side). Additionally to the two cold caseses, hot cases have been also considered. In this case the PLM radiator are exposed to sun for 1h, considering as initial temepratures the maximum temperatures from the hot operating case. As there are two PLM radiators, one in a different side of the PLM, two hot cases have been aslo analyzed.

Table 3. Cold robustness cases summary results.

Label	**SVV COLD after ECLIPSE (PLM OP to PLM OFF)**		**SVV COLD from Stabilized SVV (PLM OFF to PLM OFF)**		**Design Temperature**	
	Min [ºC] Predicted	**Max [ºC] Predicted**	**Min [ºC] Predicted**	**Max [ºC] Predicted**	**Min [ºC]**	**Max [ºC]**
XBT_MY_TRP	-20.4	6.3	-29.7	-19.6	-30.0	60.0
XBT_PX_TRP	-20.5	5.9	-29.7	-19.9	-30.0	60.0
COUPLER_TRP	-22.5	13.7	-35.9	-28.2	-40.0	100.0
MAG_E_BOX_TRP	-23.6	2.1	-42.9	-36.4	-55.0	80.0
UVI_E_BOX_TRP	-23.3	1.6	-42.7	-36.3	-55.0	80.0
ANTENNA	-94.6	-42.9	-87.2	-58.1	-154.0	120.0
PLM_ECU	-19.9	7.0	-29.1	-20.0	-30.0	60.0
SXI_BEE_TRP	-23.6	2.0	-42.6	-36.2	-55.0	70.0
SXI_FEE_TRP	-25.5	-1.4	-42.7	-36.6	-55.0	70.0

Table 4. Hot robustness cases summary results.

Label	**SVV HOT (Sun to PX side)**		**SVV HOT (Sun to MY sdie)**		**Design Temperature**	
	Min [ºC] Predicted	**Max [ºC] Predicted**	**Min [ºC] Predicted**	**Max [ºC] Predicted**	**Min [ºC]**	**Max [ºC]**
XBT_MY_TRP	18.3	42.7	10.5	38.3	-30.0	60.0
XBT_PX_TRP	17.8	42.7	10.4	37.8	-30.0	60.0
COUPLER_TRP	17.3	64.1	11.9	64.1	-40.0	100.0
MAG_E_BOX_TRP	11.1	40.1	20.0	44.9	-55.0	80.0
UVI_E_BOX_TRP	11.4	41.8	21.3	44.9	-55.0	80.0
ANTENNA	-45.8	52.0	-8.7	52.2	-154.0	120.0
PLM_ECU	19.2	42.4	11.2	39.3	-30.0	60.0
SXI_BEE_TRP	11.0	39.8	19.8	44.9	-55.0	70.0
SXI_FEE_TRP	13.6	42.3	13.5	42.3	-55.0	70.0

For Survival Cold Case which is demanding power (from PLM OFF to PLM OFF) the heater power consumption is presented in next section.

C. Heater Power Consumption

For SMILE PLM heater sizing and power budget calculation, cold cases with the PLM in safe and survival modes have been analyzed. Particulary, heater power consumptions for power budget computation have been calculated to show compliance to the power budget allocation given by the SC.

For heater power budget computation, as previously discussed, the heaters thresholds have been defined to maintain the PLM equipment at least 10ºC above the minimum design temperature. In this case no subsystem margin has been considered, and only the system margin (20%) has been added. Minimal bus budget has been used for the sizing of the heating lines (23V), with a nominal bus voltage of 30V within a range from 23V to 35V.

For the transient cases described in Section B, the requirement for heater consumption was provided in Energy (Wh). For the total calculation, the power consumed by the instruments is summed with the power consumed by the PLM when they are all OFF, as the total power budget provided by the PF when the PLM is OFF is also shared with the isntruements. Whener the Intruments electronic boxes (E-box) are ON the power budget is not shared with the PLM. All power and energy budgets remain within allocation.

Table 5. Heater power budget results.

Heating Lines:	**Installed power [W] @23V**	**AVERAGE POWER, W**			**ENERGY, Wh**
		COLD OP (TCS PLM OP)	**SAFE (TCS PLM SAFE)**	**Stabilized SVV (TCS PLM OFF)**	**SVV COLD from Stabilized SVV (PLM NON-OP to PLM OFF)**
PLM equipment PX (PLM-ECU ON)	35	0	30.3	NA	NA
PLM equipment MY (PLM-ECU ON)	56	47.2	0	NA	NA
SXI-CCDs (SXI-Ebox ON)	6	4.6	NA	NA	NA
UVI Detector (UVI-Ebox ON)	5	4.7	NA	NA	NA
PLM equipment PX (PLM-ECU OFF)	56	NA	NA	42.9	56
SXI-CCDs (SXI-Ebox OFF)	6	NA	2.9	3	3.3
UVI Detector (UVI-Ebox OFF)	5	NA	5	0	1
TOTAL		47.2	30.3	45.9	60.3
TOTAL w SYSTEM MARGIN (20%)		56.6	36.3	55.1	72.4
POWER BUDGET [W]		**122**	**122**	**84**	**NA**
ENERGY BUDGET [Wh]		**NA**	**NA**	**NA**	**100**

VII. SMILE PLM Validation Plan

SMILE Thermal Validation plan is based on two models, the Structural Thermal Model (STM) and the Proto-Flight Model (PFM), starting the qualification of each model from Instruments level to PLM level and, finally, Satellite level. This model philosophy allows the independent verification of the PLM and, up to certain level, the Instruments models.

A. Structural Thermal Model (STM)

For the STM campaign, the Instruments STMs will be delivered to the PLM for the thermal qualification of the PLM STM. After PLM STM campaign, the qualified PLM is delivered to China for the SC STM Campaign under CAS responsibility. The delivery of the STM to China becomes one of the design drivers of the PLM due to the export control regulations that apply (EAR500 series of materials cannot be exported to China).

The PLM STM is composed of:

- Flight standard structure
- Flight standard thermal control MLIs, radiators and heat pipes
- Flight representative thermal control heaters, thermistors (may be substituted by thermocouples)
- Mechanical and thermal dummies of the PLM units are aluminum boxes with the same footprint, dimensions, mass, CoG and surface treatment that the flight ones and equipped with test heaters to simulate the power dissipation
- MAG, UVI and SXI STM models (already qualified in their STM campaigns)
- Harness dummy with flight representative mass and equivalent distribution, in particular for the areas in which the PLM to SVM mechanical interfaces are located
- Test thermocouples to acquire temperatures in relevant areas during thermal tests.

PLM STM will be submitted to thermal balance test (no thermal cycling), which will allow:

- Qualification of the PLM Thermal Control subsystem
- Verification of the performance of the thermal control hardware
- Validation of Thermal Mathematical Models, as result of the correlation of the test predictions with the test results, including temperature distribution and heater power consumption
- Verification of the thermal interfaces between PLM and Instruments, and PLM equipment

In the frame of SMILE cooperation mission, for SC STM involvement and support of the PLM team will be provided to CAS to properly define the necessary inputs to perform the Satellite tests and also the AIT activities. Satellite STM thermal balance test, including the qualified PLM STM, will allow for the verification of the thermal interfaces between the PF and the PLM.

B. Proto-Flight Model (PFM)

Similar to STM campaign the qualified Instruments PFMs are delivered to the PLM for the PFM campaign at PLM level and then, the PLM with the instruments are integrated in the PF PFM for the complete SC PFM Environmental Test campaign. The PLM PFM is composed of:

- Flight structure
- Flight thermal control
- PFM models of the different PLM units
- MAG, UVI and SXI PFM models.
- Flight Harness

The PLM PFM will be submitted to thermal balance and thermal cycling under vacuum tests. The main objectives of SMILE PLM PFM thermal tests are listed below:

- Verification of the system proper functioning under extreme hot and cold temperatures
- Verification of the PLM thermal control performances:
    - Verification of the PFM TMM as part of the thermal control qualification
    - Demonstration of the suitability of the thermal control design
    - Verification of the performance of the thermal control hardware
    - Verification of the active thermal control parameters in flight configuration, including survival heaters
- Verification that thermal interfaces with the Platform and instruments remain within the specified range as used in the Instruments thermal balance test

Functional tests will be performed at extreme hot and cold temperatures in vacuum conditions during the thermal cycling test.

- Test levels are defined to ensure that all equipment maximum temperatures are:
    - above maximum predicted temperature, and
    - as close as possible to maximum qualification temeprature, and
    - with no equipment temperature above maximum qualification temeprature
- To ensure that all equipment minimum temperatures are:
    - below minimum predicted temperature, and
    - as close as possible to minimum qualification temeprature, and
    - with no equipment temperature below minimum qualification temeprature
- Test duration: 3 cycles +1 back up to be decided during test.

After PLM proto-flight qualification campaign, it will be delivered to ESA for integration on the satellite PFM. Both PLM and Satellite PFM test campaigns are held in Europe.

C. Thermal test Configuration

The thermal control subsystem qualification requires a test in vacuum, in steady state conditions, and in representative environmental flight conditions. The simulation of the environmental flight conditions, in particular the external solar fluxes can be performed by two means: with a Sun simulator to reproduce the UV fluxes, or with infrared means to simulate the equivalent flux absorbed by the external surfaces. The simulation of Earth fluxes, if needed, shall be done with infrared means. The simulation of albedo fluxes, if needed, is usually done with infrared means as well. For SMILE PLM test campaign the need for solar simulation has been assessed, as the use of IR means is a simpler solution and cheaper. Five different thermal analysis cases have been considered in order to understand this impact on SMILE PLM thermal design performances and to provide a quantitative assessment of the impact of sun reflections and sun trapping on critical elemntes (e.g. SXI-CCDs). To that end the thermo-optical properties of the external surface of the PLM MLI tent and the raditive couplings with the SXI Baffle have been considered as the sensitivity parameters for this analysis.

Table 6. Sensitivity analysis for sun simmulation.

Parameters	Baseline	Case 01	Case 02	Case 03	Case 04	Case 05
MLI PLM (Alpha)	0.55	1	0.05	0.55	0.55	0.55
MLI PLM (Epsilon)	0.85	0.85	0.85	0.85	0.85	0.85
MLI PLM (Solar Specularity)	0%	0%	0%	100%	0%	0%
External radiative couplings (PLM MLI-SXI)	Yes	Yes	Yes	Yes	No	Yes
Solar fluxes	Absorbed	Absorbed	Absorbed	Absorbed	Absorbed	Direct x $\boldsymbol{\alpha}$

In general, minor temperatures differences are observed when assessing the sensitivity of SXI-CCD temperatures to the sun reflections or sun trapping. The impact of reflected fluxes are mainly coming from the Platform (Case 05, where no sun reflections from the external surfaces of thw PF are considered). At PLM level, differences remain below 2ºC (below typical uncertainty after TB test).

Table 7. Delta temperature SXI-CCD.

	Case 01	Case 02	Case 03	Case 04	Case 05
Max. Delta SXI- CCD Tª [ºC]	+ 0.8	- 1.1	- 0.5	+ 1.5	- 2.2

VIII. Conclusion

SMILE PLM thermal design has been proposed, as a conclusion of several analysis. Proposed thermal design is compliant with the SMILE PLM driving requirements, as confirmed by the system coupled thermal analysis, with sufficient margins. In particular:

- SXI CCD temperatures are within the requested optimum temperature range of -95ºC to -120ºC with the current SXI thermal design and radiator accommodation.
- All PLM equipment are within their design temperature ranges, for the envelope of analyzed cases.
- Allocated budgets to the thermal control are respected for all modes.
- Validation plan has been proposed and justified, in particular, the use of IR means only for thermal tests (no sun simulation).

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