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JUICE thermal architecture and performance

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JUICE - JUpiter ICy moons Explorer - is the first large-class mission in ESA's Cosmic Vision programme. Planned for launch in 2022 and arrival at Jupiter in 2030, it will spend at least three years making detailed observations of Jupiter and three of its largest moons, Ganymede, Callisto and Europa. It addresses the question of whether possible habitats of life are provided underneath the surfaces of the icy satellites and also probes Jupiter's atmosphere and magnetosphere. One of the main drivers is the low solar illumination received at Jupiter, that drives both the size and technology of the solar arrays, and the thermal control, that is designed to cope with hot and cold environments. JUICE spacecraft thermal control is characterized by several requirements such as a large variations of spacecraft external environment during the mission (Solar constant decreasing from 3342 W/m² closer to Sun than Venus down to 46 W/m² in Jovian environment), high planet flux during Venus flyby and Jupiter - Ganymede combined shadowing which generates long eclipses of up to 4.8 hours. The thermal design objective is then to provide the spacecraft with the flexibility required to achieve its operations throughout the whole range of specified environments and attitudes. The JUICE thermal control is designed with the objective to minimize the impact of the external environment changes on the spacecraft units and subsystems, to control heat loads/leaks from appendages (High Gain Antenna, Launch Vehicle Adapter and Solar Generator) through high efficiency Multi-Layers Insulation. Minimizing heating power demand especially during science and communication phases and minimizing hardware mass is a constant concern and solutions are found to build to a maximum extent a robust and passive design supplemented by heaters including innovative solution when mass efficiency is demonstrated with reasonable complexity.

Nomenclature

3GM = Gravity & Geophysics of Jupiter and Galilean Moons
AU = Astronomic Unit
Airbus DS = AIRBUS Defence and Space
BOL = Beginning of Life
Delta-V (ΔV) = change in velocity
DSM = Deep Space Maneuver
ELB = ELectronic Box
EMC = ElectroMagnetic Cleanliness
EOL = End of Life
EPC KaB/XB = Electronic Power Conditioner (Ka-Band / X-Band)
ESA = European Space Agency
ESD = ElectroStatic Discharge
EU = Electronic Unit
FPA = Focal Plane Assembly
GALA = GAnymede Laser Altimeter

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GALA ELU = GALA ELectronic Unit
GALA LEU = GALA Laser Electronic Unit
HGA = High Gain Antenna
IR = Infra-Red
JANUS = Camera system (Jovis, Amorum ac Natorum Undique Scrutator)
JANUS MEU = JANUS Main Electronic Unit
J-MAG = A magnetometer for JUICE
JMU = JUICE MAgnetometer Unit
JUICE = JUpiter ICy moons Explorer
KaT = Ka-Band Transmitter
MAJIS = Moons and Jupiter Imaging Spectrometer
MLI = Multi-Layer Insulation
MMH = Mono Methyl Hydrazine
NTO = Nitrogen Tetroxide Oxidizer
OH = Optical Head
OB = Optical Bench
PDR = Preliminary Design Review
PE = Proximity Electronic
PEP = Particle Environment Package
PCDU = Power Control and Distribution Unit
PRIDE = Planetary Radio Interferometer & Doppler Experiment
RDS = Receive and Digital Subsystem
RIME = Radar for Icy Moons Exploration
RIU = Remote Interface Unit
RWI = Radio Wave Instrument (part of RPWI instrument)
RPWI = Radio & Plasma Wave Investigation
RPWI EBox = RPWI ELEctronic Box
S/C = Spacecraft
SCM = Search Coil Magnetometer (part of RPWI instrument)
SSM = Second Surface Mirror
STRE = Star TRacker Electronic
SWI = Sub-millimeter Wave Instrument
TB/TV (test) = Thermal Balance (test)
TMM = Thermal Mathematical Model
TRL = Technology Readiness Level
TRSP = Transponder
TX = Transmitter (X-Band)
TRU = Transmiter and Receiver Unit
UV = Ultra Violet
UVS = UV imaging Spectrograph
VDA = Vacuum Deposited Aluminum

I. Introduction

This paper presents an overview of JUICE mission and JUICE spacecraft thermal control for both the Instruments and the Platform. It corresponds to the status at the Preliminary Design Review (PDR) that was successfully passed early 2017.

II. Overview of the mission

A. Overview of the mission

JUICE (JUpiter ICy moons Explorer) is the first large-class mission in ESA's Cosmic Vision programme. Planned for launch in 2022 and arrival at Jupiter in 2030, it will spend at least three years making detailed observations of Jupiter and three of its largest moons, Ganymede, Callisto and Europa. It addresses the question of whether possible habitats of life are provided underneath the surfaces of the icy satellites and also probes Jupiter's atmosphere and magnetosphere.

Figure 1 presents an artist view of JUICE Spacecraft in Jupiter tour, with a partial view of Ganymede in the foreground, Europa in the middle distance and Jupiter in the background.

Figure 1. Artist view of JUICE Spacecraft in Jupiter tour.

B. Overview of JUICE payload

The payload consists of 10 instruments plus one experiment that uses the spacecraft telecommunication system with ground-based instruments. This payload is aiming at addressing all of the mission's science goals which include in situ measurements of Jupiter's atmosphere and plasma environment, remote observations of the surface and interior of the three icy moons, Ganymede, Europa and Callisto.

A remote sensing package includes imaging (JANUS) and spectral-imaging capabilities from the ultraviolet to the sub-millimeter wavelengths (MAJIS, UVS, SWI). A geophysical package consists of a laser altimeter (GALA) and a radar sounder (RIME) for exploring the surface and subsurface of the moons, and a radio science experiment (3GM) to probe the atmospheres of Jupiter and its satellites and to perform measurements of the gravity fields. An in situ package comprises a powerful package to study the particle environment (PEP), a magnetometer (J-MAG) and a radio and plasma wave instrument (RPWI), including electric fields sensors and a Langmuir probe. An experiment (PRIDE) using ground-based very-long-baseline interferometry will provide precise determination of the spacecraft's position and velocity.

The **Table 1** below lists the JUICE experiments, their primary science contribution and key characteristics.

Table 1. JUICE instruments.

	Instrument	Key characteristics
1	**3GM** *(Gravity & Geophysics of Jupiter and Galilean Moons)*	A radio science package comprising a Ka transponder and an ultra-stable oscillator. 3GM will be used to study the gravity field - up to degree 10 - at Ganymede and the extent of internal oceans on the icy moons, and to investigate the structure of the neutral atmospheres and ionospheres of Jupiter (0.1 - 800 mbar) and its moons.
2	**GALA** *(GAnymede Laser Altimeter)*	A laser altimeter for studying the tidal deformation of Ganymede and the morphology and topography of the surfaces of the icy moons. GALA will have a 20 m spot size and 0.1 m vertical resolution at 200 km.
3	**JANUS** *(Camera system)*	An optical camera to study global, regional and local morphology and processes on the moons, and to perform mapping of the clouds on Jupiter. JANUS will have 13 filters, a 1.3 degree field of view, and spatial resolution up to 2.4 m on Ganymede and about 10 km at Jupiter.
4	**J-MAG** *(A magnetometer for JUICE)*	A magnetometer to characterize the Jovian magnetic field, its interaction with the internal magnetic field of Ganymede, and to study subsurface oceans of the icy moons. The instrument will use fluxgates (inbound and outbound) sensors mounted on a boom.
5	**MAJIS** *(Moons and Jupiter Imaging*	A hyper-spectral imaging spectrometer for observing tropospheric cloud features and minor species on Jupiter and for the characterization of ices and minerals on the surfaces of icy moons. MAJIS will cover the visible and infrared wavelengths from 0.4 to 5.7 microns, with spectral resolution of 3-7

	Spectrometer)	nm. The spatial resolution will be up to 25 m on Ganymede and about 100 km on Jupiter.
6	**PEP** *(Particle Environment Package)*	A plasma package with sensors to characterise the plasma environment in the Jovian system. PEP will measure density and fluxes of positive and negative ions, electrons, exospheric neutral gas, thermal plasma and energetic neutral atoms in the energy range from <0.001 eV to >1 MeV with full angular coverage. The composition of the moons' exospheres will be measured with a resolving power of more than 1000.
7	**RIME** *(Radar for Icy Moons Exploration)*	An ice penetrating radar to study the subsurface structure of the icy moons down to 9 km depth with vertical resolution of up to 30 m in ice. RIME will work at a central frequency of 9 MHz (1 and 3 MHz bandwidth) and will use a 16 m antenna
8	**RPWI** *(Radio & Plasma Wave Investigation)*	A radio plasma wave instrument to characterize the radio emission and plasma environment of Jupiter and its icy moons. RPWI will use a set of sensors, including two Langmuir probes to measure direct current electric field vectors up to a frequency of 1.6 MHz and to characterize thermal plasma and medium- and high-frequency receivers, and antennas to measure electric and magnetic fields in radio emission in the frequency range 80 kHz- 45 MHz.
9	**SWI** *(Sub-millimeter Wave Instrument)*	A sub-millimeter wave instrument to investigate the temperature structure, composition and dynamics of Jupiter's stratosphere and troposphere, and the exospheres and surfaces of the icy moons. SWI is a heterodyne spectrometer using a 30 cm antenna and working in two spectral ranges 1080-1275 GHz and 530-601 GHz with spectral resolving power of ~107.
10	**UVS** *(UV imaging Spectrograph)*	A UV spectrometer to characterize the composition and dynamics of the exospheres of the icy moons, to study the Jovian aurorae, and to investigate the composition and structure of the upper atmosphere. The instrument will perform both nadir observations and solar and stellar occultation sounding. UVS will cover the wavelength range 55-210 nm with spectral resolution of <0.6 nm. Spatial resolution will reach 0.5 km at Ganymede and up to 250 km at Jupiter.

C. Mission scenario

The mission scenario features a launch in mid-2022 with Ariane 5 (backup in 2023), and with a maximum launch mass in the order of 5 tons. The interplanetary transfer takes about 7.5 years with several Earth fly-bys, one Venus fly-by and possibly one Mars fly-by in order to minimize the total ΔV. The spacecraft is injected around Jupiter thanks to a Ganymede fly-by followed by an insertion maneuver, and several subsequent Ganymede flybys are used in order to reduce orbit energy. After several moon fly-by sequences (Europa, Calisto), the spacecraft is then transferred to Ganymede with a capture maneuver into an eccentric orbit around Ganymede. Science will be performed on this eccentric orbit during 150 days followed by a circular phase, at 500 km.

Among the back-up scenarios, several of them feature a Sun closest approach at a distance of 0.64 AU from the Sun, after 1.5 years cruise (which represents more than 15000 equivalent solar hours) and Deep Space maneuvers at a distance of 0.89 AU from the Sun.

The **Table 2** below summarizes both the nominal scenario and a synthesis of the worst hot cases found in back-up scenarios.

Table 2. JUICE nominal scenario and worst hot case scenario summary.

		Nominal scenario	**Back-up scenarios**
Launch	Earth	01/06/2022	> 01/06/2022
Fly-by	Earth (1)	31/05/2023	1 fly-by Venus 1 or more Earth fly-by 0 or 1 Mars fly-bys
	Venus	23/10/2023	
	Earth (2)	02/09/2024	
	Mars	11/02/2025	
	Earth (3)	26/11/2026	
Arrival	Jupiter	07/10/2029	> 07/10/2029
Duration:		7.4 years	> 7.4 years
Closest distance to Sun: (***solar flux at that distance***)		0.72 AU (*2633 W/m^2*)	0.64 AU (*3333 W/m^2*)
Closest Deep Space Maneuver to Sun: (***solar flux at that distance***)		0.91 AU (*1648 W/m^2*)	0.89 AU (*1723 W/m^2*)

Figure 2 illustrates one the worst hot cases found among the back-up scenarios which features both a Sun closest approach at 0.64 AU, after about 1.5 years after launch and Deep Space maneuver at 0.89 AU from the Sun.

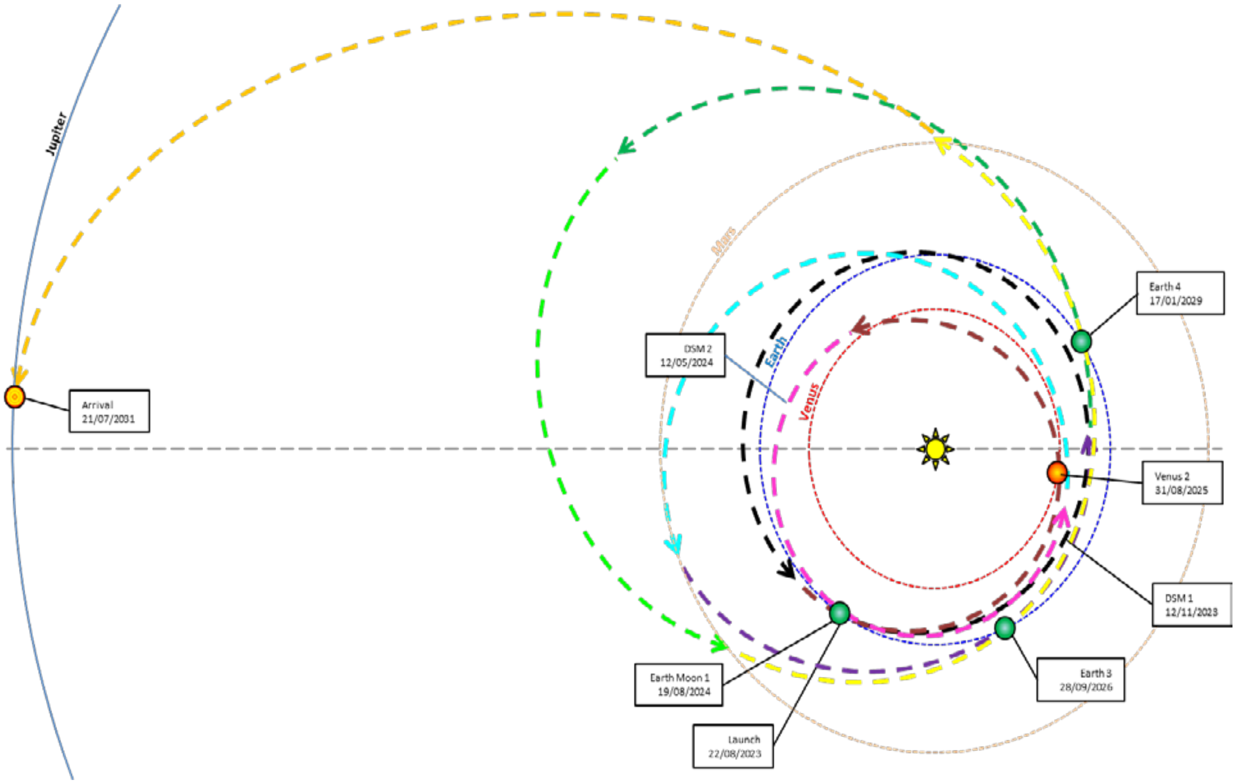


Figure 2. Illustration of one of the back-up scenarios featuring both hot cases for Sun closest approach (at 0.64 AU) and Deep Space maneuvres (at 0.89 AU).

D. Overview of the main drivers of the mission

- *Required delta V*

As for any interplanetary mission , the spacecraft design is mainly constrained by the required delta V, which corresponds to almost 2.4 km/s to be performed by the spacecraft. This results in about 2.7 tons of propellant contained in two propulsion tanks inherited from the new telecom satellite platform (Eurostar NEO), which cover all launch opportunity scenarios, including margin for a potential extension of the mission.

- *Low solar illumination at Jupiter*

Another driver is the low solar illumination received at Jupiter, that drives both the size and technology of the solar arrays, and the thermal control, that shall be designed to cope with a cold environment at Jupiter.

- *Harsh radiation environment*

Radiation environment around Jupiter is a major mission driver, calling for a clear shielding strategy of all equipments and an in-depth screening of electronic components.

- *Other drivers*

Other drivers are the number of flybys leading to implement an accurate navigation, the long distance communications with the Earth requiring a large High Gain Antenna (HGA) and a rugged operational autonomy.

III. Spacecraft configuration

A. Overall spacecraft

1. Appendages

Figure 3 and Figure 4 present an overview of the entire spacecraft with all appendages deployed.

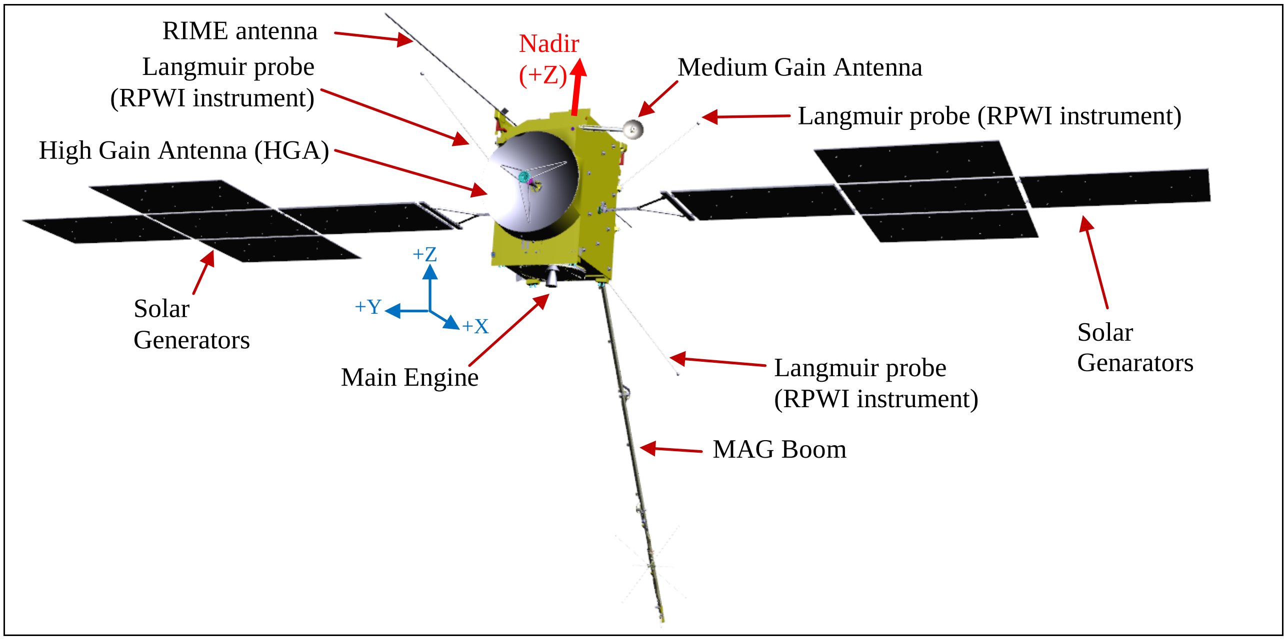


Figure 3. JUICE spacecraft with MLI (HGA side + Main engine side) (status at PDR).

JUICE appendages encompass:

- Large solar generators

The solar array with two wings of five panels each for a total surface of 97 m^2 along the Y axis provides 820 W at Jupiter, end of life conditions.

- A 10.6 m long boom (called MAG Boom)

The boom supports the JMAG sensors, RWI antenna and SCM sensor and is sized to meet the magnetic cleanliness requirements of JUICE while avoiding innovative design and deep modification of platform electronic or need for massive shielding.

- Four 3 m long Langmuir probes (which are part of RPWI instrument)
- The Medium Gain Antenna mounted on a boom and a mechanism allowing rotations around 2 axis.
- 2 x 8 m long antennas provided for the RIME radar instrument

RIME antenna is positioned away from propulsion plumes, minimising thermal loads and contamination from propulsion plumes and residuals.

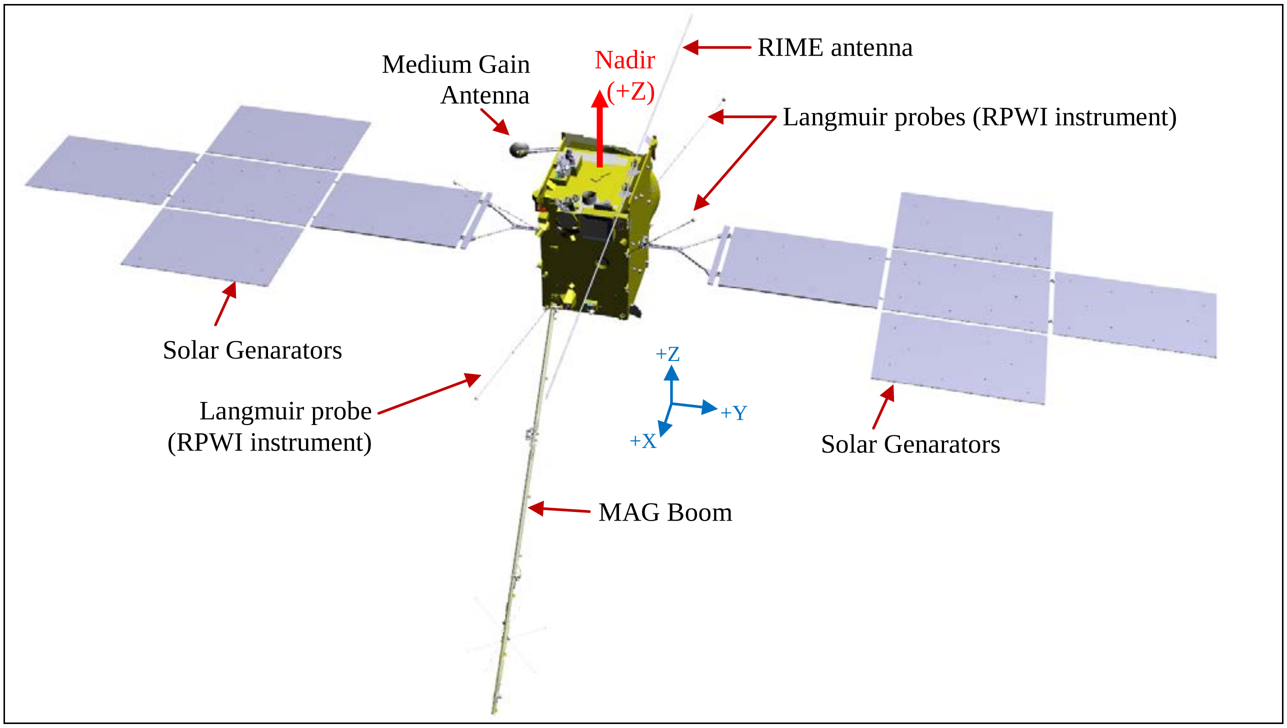


Figure 4. JUICE spacecraft with MLI (Nadir side + cold radiator side) (status at PDR).

2. Spacecraft main body

JUICE spacecraft is based on a structure featuring a 1.4 m diameter central cylinder mounted on a cone to interface with the launcher via a standard 1666 mm diameter adaptor. The central cylinder hosts two propellant tanks, six shear walls and four lighten external walls. The other main features are:

- *High Gain Antenna (HGA)*

A 2.54 m diameter High Gain Antenna (HGA) is mounted on the -X side to download an average of 1.4 Gbits/day of science data, and to ensure TeleMetry (TM)/TeleCommand (TC) links and Radio Science Experiment (RSE). As we can see in Figure 3, HGA is also accommodated on -X side to protect equipments from the high solar flux during the “Sun Closest approach” phase of the interplanetary transfer, this side being permanently oriented towards the Sun.

- A nadir face opposite to the main engine face.

Besides the 2 Navigation Camera’s and the optical instrument’s apertures (JANUS, GALA, MAJIS, SWI, UVS), this face supports also 4 PEP sensors. A series of sunshield protect the instrument from direct Sun illumination during the cruise, when –X is Sun oriented.

- Optical Bench

An optical bench accommodating payloads with stringent pointing requirements close to Star Tracker Optical Heads and Navigation Cameras. The optical bench is positioned close to one of the vaults in order to ensure limited distances between sensors on the optical bench and the related proximity electronics inside the vault.

- 2 zenith oriented PEP sensors

Two PEP units are mounted on a secondary structure located on the zenith part of the +X wall of the spacecraft, where they are protected from the direct propulsion plumes without interfering with their fields of view.

The Figure 5 below shows JUICE spacecraft with nadir face on top. PEP sensors (nadir oriented and zenith oriented are highlighted, so are the nadir pointed instruments mounted on the Optical Bench.

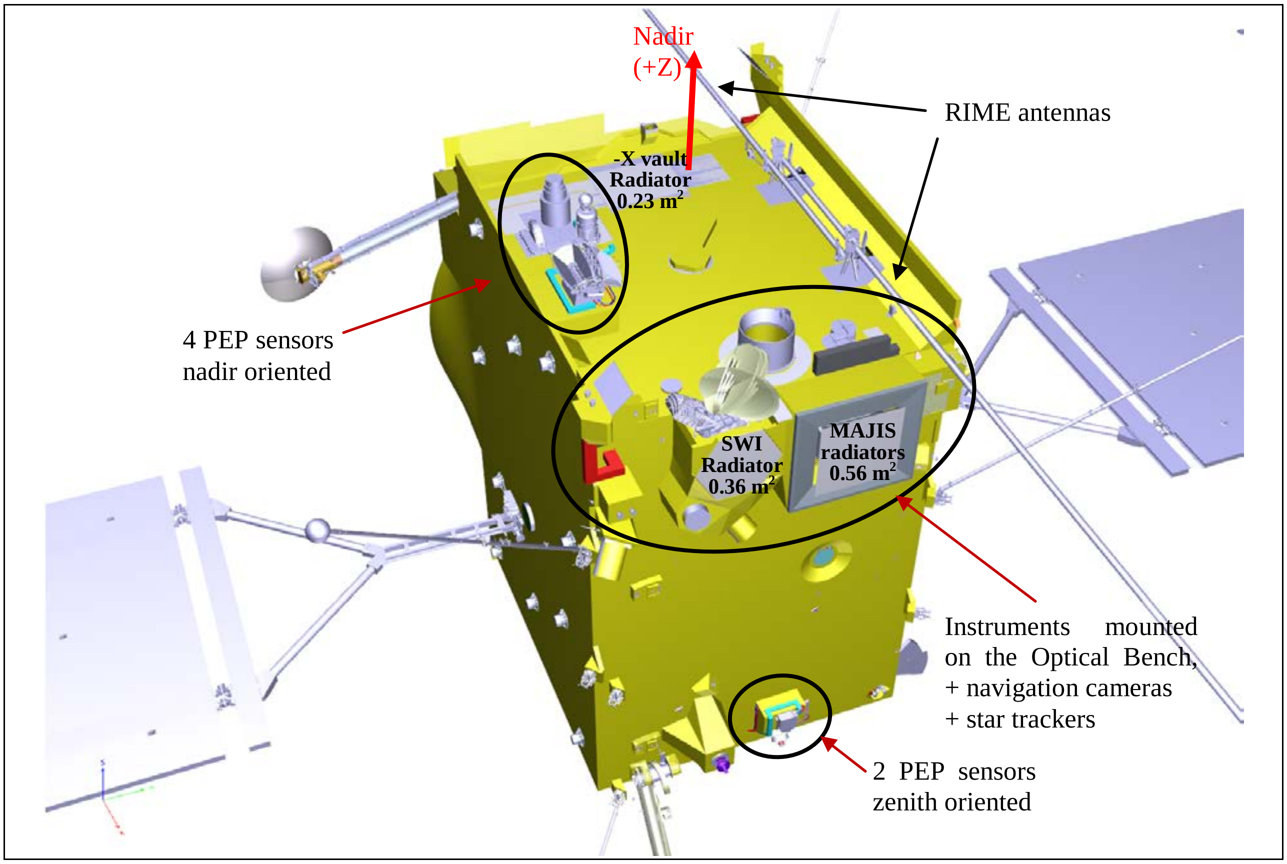


Figure 5. JUICE spacecraft with MLI and main radiators (status at PDR).

3. *Spacecraft main internal parts*
    - 2 vaults

Two vaults along central cylinder gather most of the payloads and platform electronic units in order to provide an efficient shielding (with lead or other shielding material) against the harsh Jupiter radiation environment. They provide as well a warm thermal environment for these electronic boxes which is also beneficial for the tanks and the propulsion hardware. Besides, they represent an ElectroStatic Discharge (ESD) and ElectroMagnetic Cleanliness (EMC) tight cavity for these units. Figure 6 presents two views of +X vault (left side) and -X vault (right side) with the central cylinder and +/-Y external walls. Most of the Spacecraft units are mounted inside one of these vaults. In the figure, the Instrument electronic units' labels are written in red, Platform units' labels are written in black.

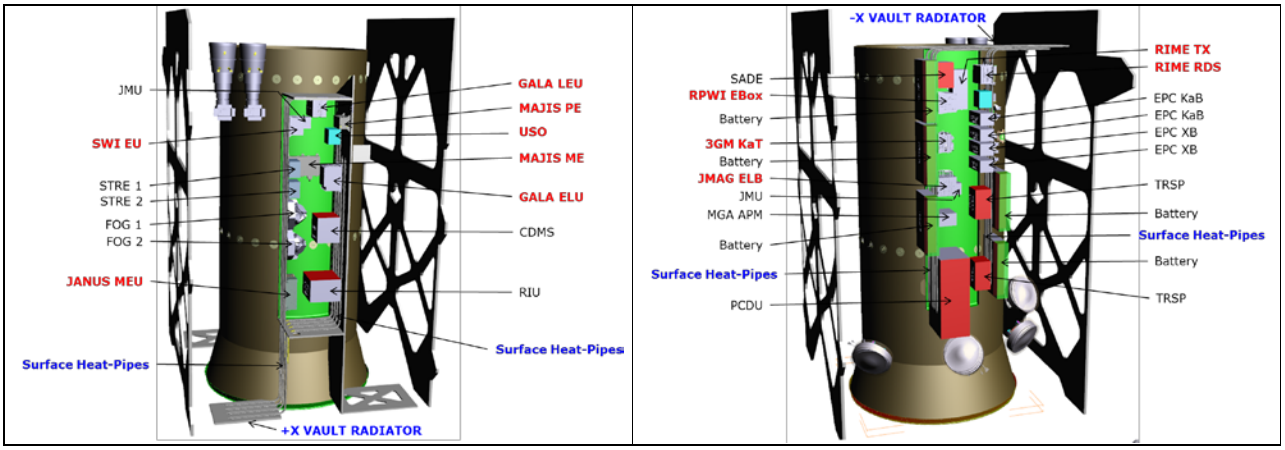


Figure 6. JUICE spacecraft vaults (+X and -X vaults) with central cylinder and +/-Y external walls.

- *Propulsion system*

A 425N bi-propellant (NTO/MMH) main engine aligned with the main thrust axis to perform main mission maneuvers (Jupiter Orbit Insertion, Ganymede Orbit Insertion …) with assistance of 2x4 20N bi-propellant thrusters used for attitude control and as backup to the main engine in case of failure. 2x6 10 N bi propellant thrusters complement the Chemical Propulsion System actuators to provide a pure torque capability about the 3 axes.

4. *Spacecraft mass and power overview*

The Table 3 below summarizes JUICE mass and power main characteristics.

Table 3. JUICE mass and power main characteristics (at PDR).

Mass	Spacecrraft dry mass	2 270 kg
	Propellant tank capacity	3 650 kg
	Maximum launch mass (at nominal date)	5 264 kg
	Instruments mass	224 kg
Power	Solar array total power	820 W (End Of Life)
	Available power for Instruments	180 W
	in Ganymede Circular Orbit 500 km	230 W (360 W during ½ hour)

IV. Spacecraft thermal design

1. *Thermal Control System objectives*

JUICE spacecraft Thermal Control System (TCS) is in charge of maintaining all spacecraft equipment within their allowed temperature ranges during all mission phases. In particular, it provides the thermal environment and interfaces requested by the Instruments.

The TCS shall fulfill the main following objectives:

- to minimise the impact of the external environment variation on the Spacecraft units and subsystems,
- to control heat loads and heat leaks from appendages through conductive insulation and Multi Layers Insulation (MLI) blankets,
- to minimise heating power demand especially during science and communication phases,
- to contribute to instruments pointing performance by minimising temperature gradient fluctuation between instruments and star-trackers interfaces on the Optical Bench,
- to challenge design complexity versus performance gain, favour robustness and heritage while allowing final trimming after Thermal Balance (TB) test for heating power reduction optimization.
- to minimize hardware mass.

2. *Platform Thermal Control System principles*

Hardware and technologies are selected regarding temperatures and radiations resistance and Technology Readiness Level (TRL) level higher than 5 before the PDR. JUICE TCS mainly relies on passive thermal control (MLI, radiators, heat pipes, loop heat pipes) assisted by an actively controlled heating system via software and control thermistors. Full redundancy of the heating lines is provided. Each heater line is software-controlled using its own temperature sensor triplet and an average voting algorithm (middle temperature value is selected). The lines are simply switched on or off if the actual temperature is respectively lower or higher than the respective temperature set point which is adjustable by ground command. Fine heater control with precise proportional integral algorithm is available when required. Each individual thermal control loop can be enabled and disabled from ground.

To reduce the heat loads through the large appendages (HGA, LJF), external coatings and conductive couplings through interfaces are optimised. In particular, the HGA acts as a thermal sunshield, particularly during the cruise to Jupiter and the Sun closest approach. The spacecraft is insulated with MLI blankets to the maximum extent, the external covered surface represents more than 40 m^2. When necessary some sunshields are installed to protect sensitive thermal parts such as the launcher adapter ring, the thrusters and instruments on nadir side which avoids to open radiator.

A high performance MLI is used to cover extreme hot cases (Sun Closest Approach and Venus fly-by) and cold conditions (Jovian tour). Thermal decoupling is implemented in-between structural parts when no sensitive thermal elements are installed on the structure, favouring thermal link towards tanks or external elements such as thrusters, Chemical Propulsion System lines or appendices to reduce heating need.

JUICE spacecraft Thermal Control System controls particularly the following spacecraft elements,

- the vaults +/-X which comprise most of Platform units and Instruments electronics,
- the Chemical Propulsion System including tanks, lines, propellant and pressurant panels, main engine and thrusters,
- the Optical Bench,
- outside vaults units such are the batteries, the Solar Array Drive Mechanisms (SADM), the Reaction Wheels and the thrusters.

JUICE MLI will be designed and manufactured by RUAG Austria, and should be optimized (in term of efficiency vs. mass) with a number of layers between 15 to 25. External layer of Sun exposed MLI during Sun closest approach phase will be STAMET coated black kapton 160XC to guarantee a high electrical conductivity while the ratio solar absorptivity / emissivity leads to tolerable temperatures on the first external layers. The other sides, which remain in the shade during the hottest part of the cruise have black kapton 160XC as external layer.

A high insulation efficiency is required for the MLI to limit heat leaks in cold Jupiter environment and thus limit needed heating power to keep JUICE units within their temperature ranges. The targeted MLI efficiency is presented in Table 4. It relies on past project such as GAIA or on-going project such as EUCLID. Besides, preliminary MLI characterization tests have confirmed the feasibility of such MLI efficiency and a real scale Thermal Demonstrator Model of JUICE MLI will be manufactured and tested in ESTEC beginning of 2018.

Table 4. Targetted MLI efficiency for JUICE external MLI.

Median MLI temperature	-200°C	-100°C	0°C	+100°C
Linearized efficiency	0.004 W/m^2/K	0.0085 W/m^2/K	0.018 W/m^2/K	0.038 W/m^2/K

For the PDR thermal analysis, external MLI are modelled with a combination of linear coefficient (equivalent surface conductance) and a radiative coefficient (equivalent emissivity). Large MLI and small MLI (typically smaller then 100 cm^2) use different sets of coefficients as presented in the .These coefficients cover the targeting MLI efficiency (presented in Table 4) in a conservative way:

Table 5. Radiative and conductive MLI coefficients for JUICE external MLI thermal analysis (PDR status).

	linear coefficient	radiative coefficient
Large MLI	0.0014 W/m^2/K	0.007 m^2/m^2
Small MLI	0.0028 W/m^2/K	0.014 m^2/m^2

3. *Instrument thermal control and thermal interface*

Table 6 below presents JUICE instruments accommodation on the Spacecraft, their thermal control principles and their typical operational temperature range.

It exists mainly 3 types of Instrument unit thermal interface:

- Instrument units which are conductively controlled by the Spacecraft (highlighted in pink in the table).
- Instrument units which are thermally decoupled from the Spacecraft but require a cold finger provided by the Spacecraft for an internal part (highlighted in green in the table).
- Thermally decoupled units with a fully independent thermal control (highlighted in blue).

Table 6. JUICE instruments accommodation and thermal control principle.

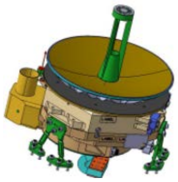
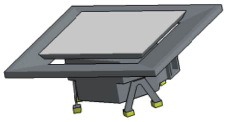
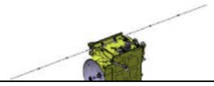
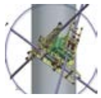
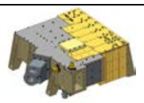
	Instrument	Accommodation	Thermal control / Operational design temperature range
1	**3GM**	2 units in the vault	- 1 unit mounted on heat-pipes, 1 unit mounted on one of the vault walls, - Conductively controlled [-20 / +50°C].
2	**GALA** 	2 units in the vault	- Mounted on heat-pipes. - Conductively controlled [-20 / +50°C].
		Transmiter and Receiver Unit (TRU) mounted on a bracket which is on the Optical Bench (OB)	- Thermally decoupled from the OB. All dissipative components are thermally controlled by a S/C cold finger (+5 / +30°C). The cold finger encompasses a high efficient flexible thermal strap and 2 mini Loop Heat Pipes coupled to a radiator on S/C nadir side.. Ultimately, GALA detector are thermally controlled with a Peltier thermo-electric cooler to guarantee a better thermal stability. The TRU has survival, anti-contamination and decontamination heaters.
3	**JANUS** 	1 unit in the vault	- Mounted on heat-pipes. - Conductively controlled [-20 / +50°C]
		Proximity Electronic on a bracket	- Controlled by a S/C cold finger [-20 / +20°C]. The cold finger encompasses a high efficient flexible thermal strap coupled to a radiator on S/C nadir side.
		Optical Head (OH) mounted on the Optical Bench (OB)	- Therrmally decoupled from the OB. OH Focal Plane Assembly (FPA) is thermally controlled by a S/C cold finger (-45 / -40°C). which encompasses a high efficient flexible thermal strap coupled to a radiator on S/C cold side. JANUS OH has operational heaters in its optical cavity, survival heaters for its mechanisms (door and filter wheel).
4	**J-MAG**	1 unit in the vault	- Mounted on heat-pipes. - Conductively controlled [-20 / +50°C]
		3 sensors mounted on the Boom	- Therrmally decoupled from the Boom - 2 of the 3 sensors have heaters (survival and operational mode)
5	**MAJIS** 	1 unit in the vault	- Mounted on heat-pipes. - Conductively controlled [-20 / +50°C]
		Optical Head (OH) mounted on the Optical Bench (OB)	- Therrmally decoupled from the OB. The OH and 1 of the detectors are passively cooled with a radiator on S/C cold side with a targeted operational temperature < -140°C. The IR detector is thermally decoupled from the OH structure and is passively cooled with a second radiator, targeting an operational temperature below -183°C. The OH has survival, anti-contamination and decontamination and operational heaters.
6	**PEP** 	6 sensors + 1 electronic box, all mounted on brackets or on a shared structure	- Therrmally decoupled from the S/C - The electronic box has its own radiator Most of the sensors have decontamination and/or survival heaters. They operate at various temperature range, usually close to [0 / +30°C]
7	**RIME** 	2 units in the vaults + matching network units on S/C wall	- 2 units mounted on heat-pipes, matching network unitsconductively coupled to one of the S/C walls, - Vault units conductively controlled [-20 / +50°C], matching metwork units in wider temperature ranges
8	**RPWI**   	1 unit in the vault	- Mounted on heat-pipes. - Conductively controlled [-20 / +50°C]
		2 sensors mounted on the Boom	- Therrmally decoupled from the Boom - 1 of the 2 sensors has a heater (survival mode)
		4 langmuir probes mounted on the external walls	- Therrmally decoupled from the S/C - The release mechanisms are controlled with heaters until full deployment
9	**SWI** 	1 unit in the vault	- Mounted on heat-pipes. - Conductively controlled [-20 / +50°C]
		Transmiter and Receiver Unit (TRU) mounted on a bracket which is on the Optical Bench (OB)	- Thermally decoupled from the OB. - In the TRU, the mixers are passively cooled with a radiator on S/C cold side with a targeted operational temperature < -140°C. A High efficiency flexible thermal strap connects the mixers to a dedicated radiatorwhich is mounted on the same bracket as the TRU - Also in the TRU, the E-Band Amplifiers are thermally controlled by a S/C cold finger (-50 / +0°C) which encompasses the same kind of high efficient flexible thermal strap and a radiator on S/C nadir side.
10	**UVS** 	Mounted on the OB with decoupling blades	- Therrmally decoupled from the S/C UVS has its own radiator on S/C cold side and survival heaters.

Figure 7 presents a simplified overview of main instrument thermal control and their thermal interface with the spacecraft. The emphasis is laid on the remote sensing instruments mounted on the Optical Bench.

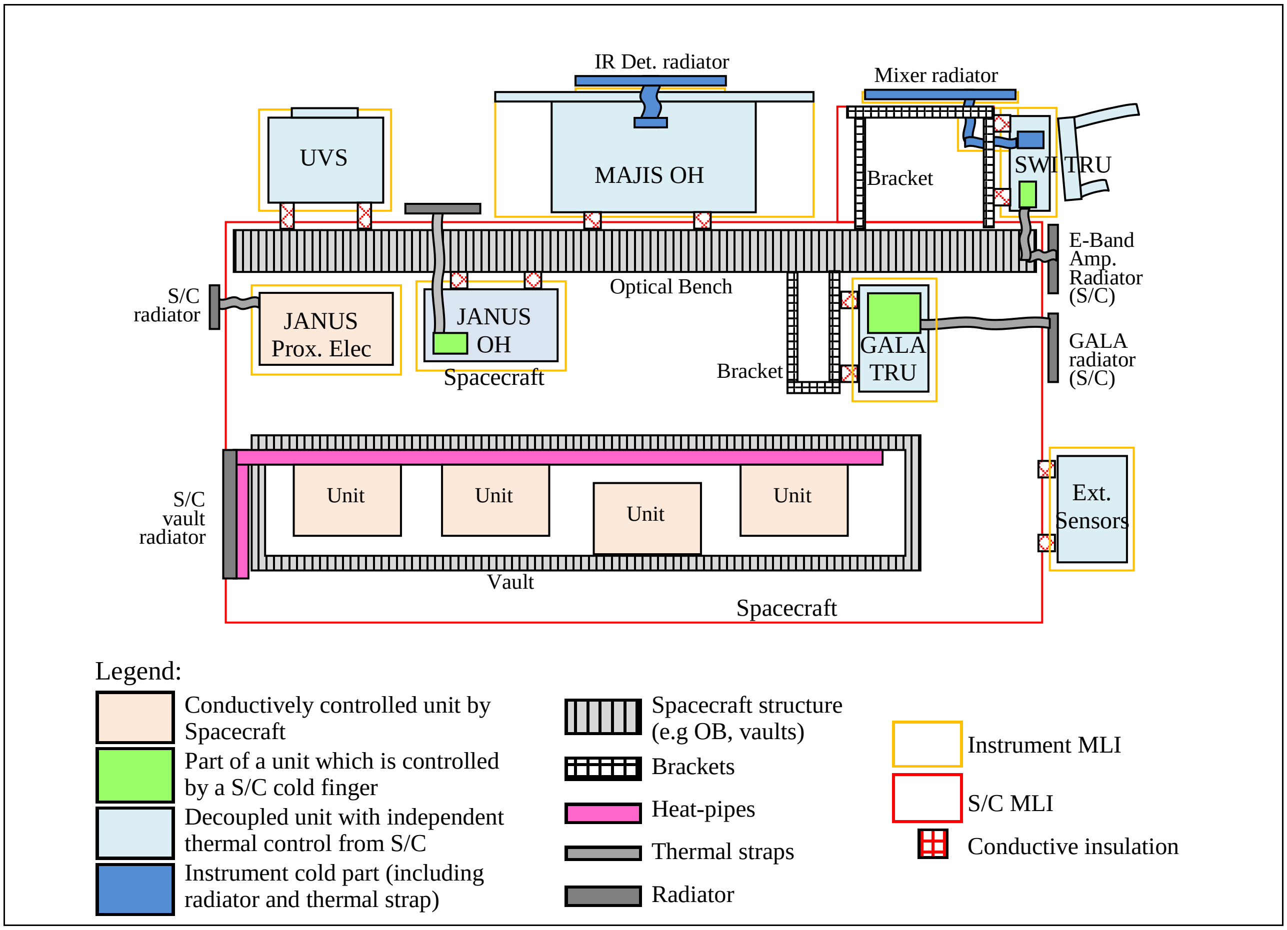


Figure 7. Simplified overview of main instrument thermal control and thermal interface with the spacecraft.

The accommodation of the Instrument on the Optical Bench is illustrated below in Figure 8 (PDR preliminary design). Star Trackers Optical Heads and Navigation Cameras are also mounted on the Optical Bench.

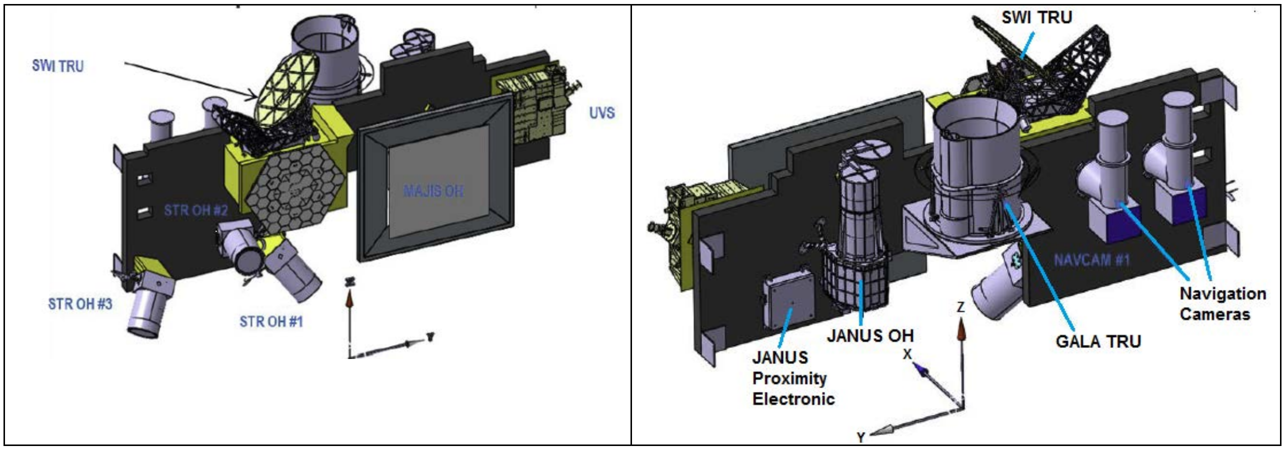


Figure 8. Accommodation of the Instrument on the Optical Bench (viewed from +X side –left- and from –X side –right-).

V. Overview of JUICE Spacecraft thermal analysis

1. *Thermal model overview and thermal analysis cases*

Figure 9 below presents an overview of JUICE thermal model.

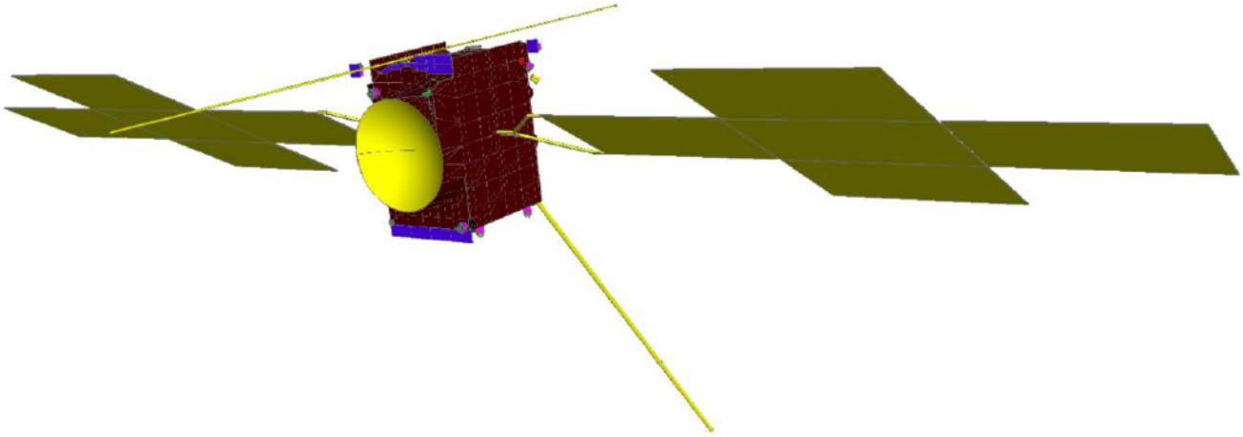


Figure 9. JUICE external model - global view.

The thermal analysis of the S/C was carried out by analysing the following six scenarios:

- Sun Closest Approach (SCA) with communication units full dissipation:
  The Sun Closest Approach (SCA) case corresponds to the highest solar flux encountered during the mission (3342 W/m^2 @ 0.64 AU) with a high value of dissipation (communication mode ~423 W). This is the "worst case hot" scenario for the spacecraft, -X vault in particular. This case is also a design case for the radiators of elements on the -X side that are exposed to Sun flux (-Z side Sun Analog Sensor (SAS) and -X side thrusters)
- Venus Gravity Assist (VGA):
  This case has an important solar flux combined with the Venus albedo flux. This is a potential hot case for elements with low inertia.
- Mars Proximity:
  This is the hottest case for –Z side and thus, the main design driver for the LJF coating.
- Cold Cruise:
  The Cold Cruise case-scenario corresponds to the lowest solar flux encountered during the mission. This is the Spacecraft lowest case, and was used for the sizing of heater lines.
- Europa flyby:
  The Europa flyby scenario is an ESA design scenario and has a high transient dissipation (particularly on the instruments) on a very cold thermal environment.
- Ganymede Circular Orbit at 500 km altitude (GCO-500):
  GCO-500 is an ESA design scenario, and has the highest sustained dissipation of payload.

The Europa flyby and GCO-500 scenarios constitute the main sizing cases for the +X vault radiator and the instrument radiators.

2. *Thermal analysis results overview*

Sun Closest Approach (SCA) is the main sizing case for -X radiators, and once properly sized, no hot temperature specifications are exceeded during the SCA worst case (at 0.64 AU from the Sun), which confirms the validity of the thermal design adopted for this hot case. Batteries and Reaction Wheels are the two set of units showing the most reduced margin.

The Venus Gravity Assist case corresponds to an important incoming solar flux (2655 $\mathrm{W/m}^2$) combined with the albedo flux from Venus (Albedo coefficient 78% with 229K planet temperature). This case is run as a potential hot case for elements with low thermal inertia. No hot temperature specifications are neither exceeded during Venus Gravity Assist worst hot case. Even considering the transient effect of the Venus albedo flux, component and structure temperatures are below those of Sun Closest Approach (an average of 3°C).

In Jupiter environment, the hot cases represent Europa fly-bys with the majority of the Instrument ON, but during a limited duration. Ganymede Circular Orbit represents as well one of the operational hot cases, which are used to size +X and –X vault radiators, and some of the Instrument local radiators. All units remain in their operational temperature range.

The cold cases are logically to found in Jupiter environment. Cold cruise case with minimum Platform dissipation and all Instruments not operating is used to size the Spacecraft heating lines and check the heating power remains into the allocation. It's worth noting Ganymede Circular Orbit case includes long eclipse, up to 4.8 hours in Jupiter shadow potentially combined with Ganymede eclipse, which constitute a transient cold case for several external parts (Solar Generators, antennas, external instruments), for which predicted temperature comes close to design temperature lower limits for some of them.

VI. Conclusion

JUICE project has successfully passed its Preliminary Design Review early 2017 and the Thermal Control System meets all its requirements, particularly in term of operational and non-operational temperature ranges during cruise cold and hot cases, during Jupiter tour including the various fly-bys and the final Ganymede Circular Orbit. The needed heating power during the different phases is also within the power budget allocation for the Thermal Control System. This relies mainly on the an adequate accommodation of the various units, Instrument and subsystems inside the Spacecraft, but also on a highly efficient thermal hardware, such as thermal condutive insulation or Multi-Layer Insulation (MLI). A preliminary verification is thus foreseen early 2018 with a real-scaled Thermal Demonstrator Model with flight similar MLI This should allow to confirm the thermal performance and help reducing thermal uncertainties.

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