JUICE (Jupiter Icy Moon Explorer) Instruments Thermal Control and Interface

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JUICE (Jupiter Icy Moon Explorer) spacecraft will provide a thorough investigation of the Jupiter system in all its complexity with emphasis on the three potentially ocean-bearing Galilean satellites, Ganymede, Europa and Callisto, and their potential habitability. It will carry 10 state-of-the-art remote sensing, geophysical, and in situ instruments plus one experiment that uses the spacecraft telecommunication system with ground-based instruments. The main design drivers of JUICE mission are the very harsh radiation in Jupiter environment, leading to shield individually or collectively all the sensitive components, the stringent Electro-Magnetic Compatibility (EMC) requirements to fulfil the magnetic and electrical fields' measurement objectives and the low solar illumination received at Jupiter. This latter parameter 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 has to cope with a large variation of external environment during the mission: Sun flux will vary from 3300 W/m² in the inner Solar System down to 46 W/m² in Jovian environment and long eclipses will last up to 4.8 hours. All the instruments design are driven by their stringent thermal requirement and/or by environmental thermal constraints. Most of them are thermally decoupled from the spacecraft and have to cope with extreme environment variations but use as well Spacecraft resources such as heating power or, in some cases, thermally controlled cold fingers.

Nomenclature

ΔV	=	Delta-velocity (change in velocity)
AU	=	Astronomical Unit
CDR	=	Critical Design Review
EMC	=	Electro-Magnetic Compatibility
EOL	=	End of Life
ESA	=	European Space Agency
ESD	=	Electro-Static Dicharge
ESTEC	=	European Space Agency Technical and Engineering Centre
FM	=	Flight Model
GALA	=	Ganymede laser Altimeter
HAA	=	High Accuracy Accelerometer
HGA	=	High Gain Antenna
IR	=	Infra-Red
JANUS	=	Jovis, Amorum ax Natorum undique Scrutator (Jupiter & its moon's observer)

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JMAG	=	JUICE magnetometer
JUICE	=	Jupiter Icy Moon Explorer
KaT	=	K-band Transmitter
LIDAR	=	Light Detection and Ranging
LP-PWI	=	Langmuir Probe for Plasma Wave Investigation
MAG Boom	=	Boom carrying the JMAG magnetometers (and 2 RWI sensors)
MAJIS	=	Moons and Jupiter Imaging Spectrometer
MLI	=	Multi-Layer Insulation
OH	=	Optical Head
PEP	=	Particle Environmental Package
PFM	=	Proto-Flight Model
RIME	=	Radar for Icy Moon Exploration
RWI	=	Radio Wave Instrument
RPWI	=	Radio and Plasma Wave Investigation
S/C	=	Spacecraft
SCM	=	Search Coil Magnetometer
SLI	=	Single-Layer Insulation
STM	=	Structural and Thermal Model
SWI	=	Short Wave Instrument
TB/TV (test)	=	Thermal Balance / Thermal Vacuum (test)
TCS	=	Thermal Control System
TDM	=	Thermal Development Model
TMM	=	Thermal Mathematical Model
USO	=	Ultra-Stable Oscillater
UVS	=	Ultra-Violet Spectrometer
VDA	=	Vacuum Deposited Aluminium

I. Introduction

Jupiter ICy moons Explorer (JUICE) is the first L-class launch slot in ESA's Cosmic Vision Program foreseen in 2022. The objective of the JUICE mission is the investigation of Jupiter and its icy moons, Callisto, Ganymede and Europa. Besides probing Jupiter's atmosphere and magnetosphere, it addresses the question of whether possible habitats of life are provided underneath the surfaces of the icy satellites. The science objectives of JUICE mission are supported by 10 state-of-the-art scientific instruments, which accommodation, interface and design are mainly driven by thermal requirements and constraints.

II. JUICE Mission

A. JUICE mission overview

The mission scenario features a launch in May 2022 with Ariane 5 and starts with an interplanetary transfer that takes about 7.5 years. Figure 1 below illustrates the overall mission. Each fly-by or phase is marked with a number, corresponding to a phase or a fly-by, which is described below.

The transfer features several Earth fly-bys (*1.1*, *1.3* and *1.5* in Figure 1), one Venus fly-by (*1.2)* and one Mars fly-by (*1.4*) in order to minimize the total ΔV. The spacecraft is then injected around Jupiter (*2)* thanks to a Ganymede fly-by followed by an insertion maneuver, and several subsequent Ganymede fly-bys are used in order to reduce orbit energy. Later on, after a waiting period around Callisto during conjunction, the spacecraft initiates scientific measurements around Europa for 35 days (*4)*. This phase is critical in terms of radiation and planetary protection. The Jupiter high latitudes phase follows, with several Callisto fly-bys (*5*) during 6 months in order to raise the inclination with respect to Jupiter's equator up to 22° or even up to 30° for favorable launch scenarios. The spacecraft is then transferred from Callisto to Ganymede (*6*) through another fly-bys sequence, which ends with a capture maneuver into an eccentric orbit around Ganymede (*7*). Science will be performed on this eccentric orbit during 120 days (*8a*), followed by a circular phase at 500 km during 160 days (*8b*) before naturally crashing on the moon (*9*).

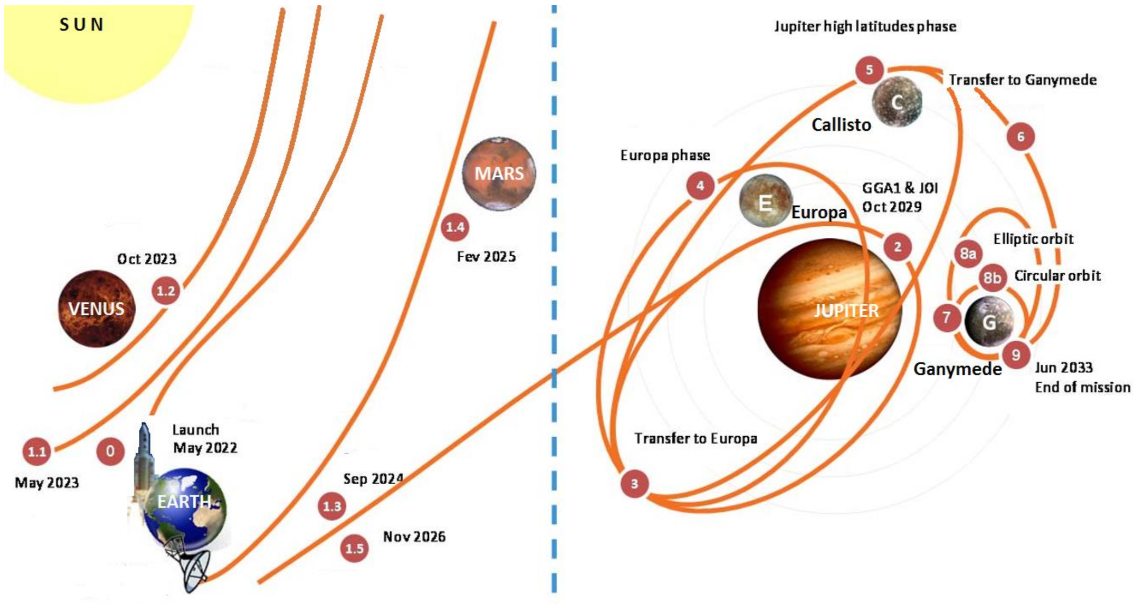


Figure 1: JUICE mission baseline scenario.

B. Main constraints and drivers

Beside the first mission requirement, which is to carry a large set of science payloads with various and sometimes-diverging interface and operation requirements to the Jovian system for in situ and remote measurements, the spacecraft design is mainly constrained by the ΔV, as for any interplanetary mission. Almost 2.4 km/s ΔV are performed by the spacecraft, which requires about 2.7 tons of propellant. The spacecraft design with two propulsion tanks, inherited from the new generation of telecommunication satellites, allows meeting the ΔV requirements for all launch opportunities, and provides even some additional propellant for a potential mission extension.

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

Finally, the radiations environment around Jupiter is a major mission driver, calling for a clear shielding strategy of the entire equipment and an in-depth screening of the electronic components. 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 robust operational autonomy.

C. Overview of JUICE Spacecraft

JUICE spacecraft is based on a structure featuring a 1.4 m central cylinder mounted on a cone to interface with the launcher via a standard 1666 mm diameter adaptor. The central cylinder hosts the two propellant tanks. As presented in Figure 2, JUICE spacecraft is customised to support the various payloads, with the following characteristics:

- The nadir face is located on the spacecraft +Z side, opposite to the main engine side. This face supports the remote sensing instruments, some of the PEP sensors and the 2 x 8 m long RIME radar antennas. These payloads are positioned away from propulsion plumes, minimising thermal loads and contamination.
- A large optical bench accommodates the 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, where payloads electronic boxes can safely be accommodated, in order to ensure limited distances between the sensors on the optical bench and their electronics inside the vault.
- A 10.6 m long boom supports the JMAG sensors, RWI antenna and SCM sensor. The boom is sized to meet the magnetic cleanliness requirements of JUICE.
- In addition to the PEP nadir units accommodated on the upper side +Z of the spacecraft, 2 additional PEP units are located on a secondary structure on the zenith part of the +X wall of the spacecraft, where they are protected from direct propulsion plumes without interfering with their fields of view.
- Two vaults along the central cylinder gather most of the payloads and platform electronic units. They provide an efficient shielding (with lead as main shielding material) against the harsh Jupiter radiation environment, a warm thermal environment (also beneficial to the tanks and to a part of the propulsion lines) and an Electro-Static Discharge (ESD) and Electro-Magnetic Cleanliness (EMC) tight cavity.

- A 2.54 m diameter High Gain Antenna (HGA) downloads an average of 1.4Gbits/day of science data and ensures telemetry and tele-command links for nominal operations and safe mode. It is also used for radio science experiment. During the whole mission, and particularly during the close to Sun phase, it is also given a thermal function to protect a large part of the spacecraft main body from the high solar flux, including the waveguides and the whole communication equipment, located just behind the HGA, inside -X vault.
- The solar array, with its two wings of five panels each, for a total surface of 85 m^2 along Y-axis, provides 780W at Jupiter, end of life condition.

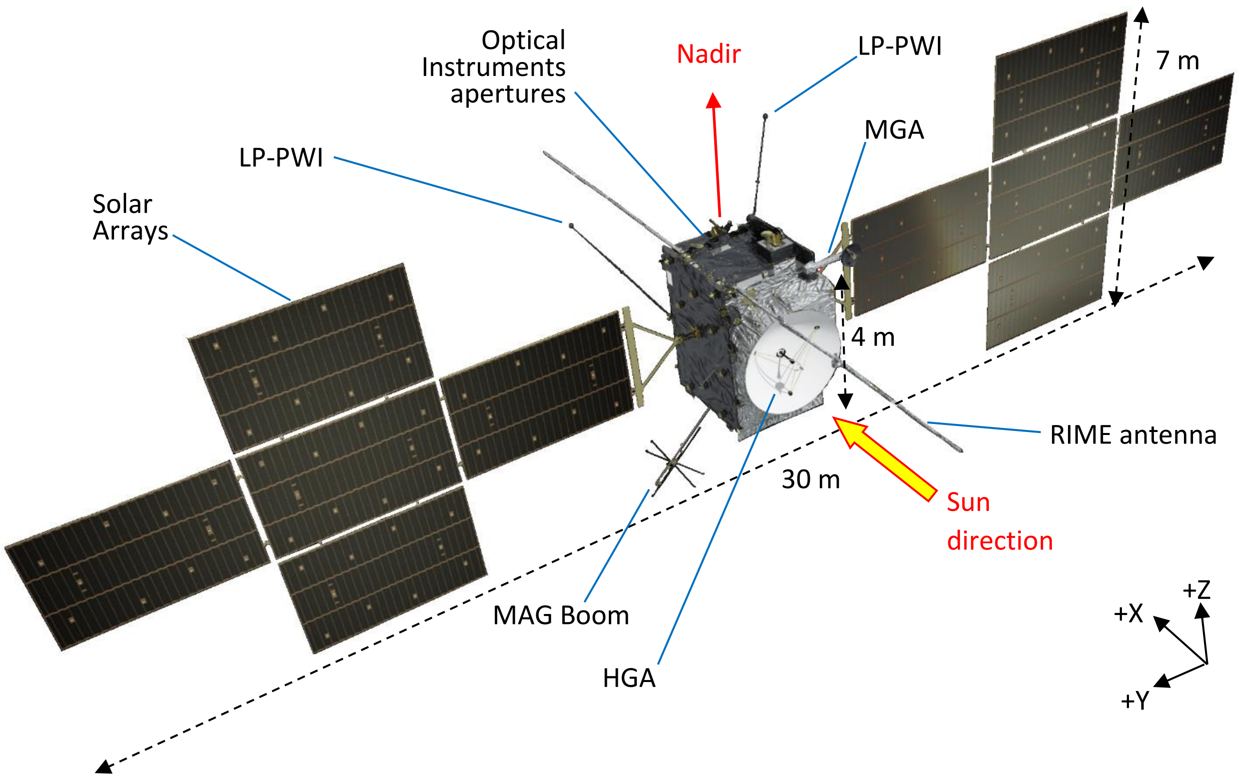


Figure 2: JUICE spacecraft general view, with deployed Solar Arrays, booms and antennas.

III. Overview of JUICE Instruments

The science objectives of JUICE mission are supported by 10 state-of-the-art scientific instruments, which can be categorized into three different families.

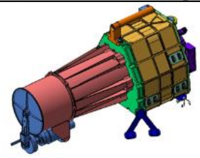
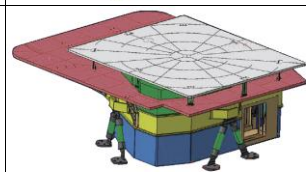
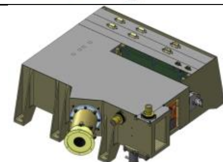
A. Remote sensing instruments

The remote sensing instruments are focused on observation of Jupiter and its icy moons, their surfaces and the composition of their atmospheres. This package includes spectro-imaging capabilities from the ultraviolet to the near-infrared, wide angle and narrow angle cameras and a sub-millimeter wave instrument:

- JANUS is a multispectral imager. From a high altitude, the instrument provides global mapping of the moons and context images around Ganymede and Callisto. From low altitude, it produces high-resolution images for target areas on the icy moons, with spatial resolution from 25 m/pixel down to 2.4 m/pixel.
- MAJIS is an imaging spectrometer operating in the visible and near-infrared bands. It is complementary to the JANUS visible imager. It contributes to the understanding of the Jovian system and its evolution.
- SWI, the Submillimeter Wave Instrument is a two bands spectrometer, concentrating on Jupiter stratosphere and more particularly on its molecules and vertical winds. It also provides information on the moons' atmospheres.
- UVS is a spectrometer operating in the Ultra-Violet (UV) bands; it is dedicated to atmosphere and aurora observation of Jupiter and its icy moons, which has never been done yet.

Table 1 below presents JUICE remote sensing instruments and their units.

Table 1: JUICE remote sensing instruments.

		Instrument name	Scientific purpose	Units *(illustrations correspond to the units in **bold** text)*	
Remote Sensing	*1*	**JANUS** (*Jovis, Amorum ax Natorum undique Scrutator*) (Jupiter & its moon's observer)	Moons geology, cloud morphology and dynamics		**Optical Head** + Proximity Electronic + 1 Main Electronic Unit
	2	**MAJIS** (*Moons and Jupiter Imaging Spectrometer*)	Chemistry – Atmospheric and surface composition		**Optical Head** + Main Electronic Unit
	3	**UVS** (*UV Spectrograph*)	Atmosphere of moons and aurora of Jupiter		**UVS**
	4	**SWI** (*Sub-millimetre Instrument*)	Jupiter wind and moons atmospheric temperature and composition		**Telescope and Receiver Unit (TRU)** + Main Electronic Unit

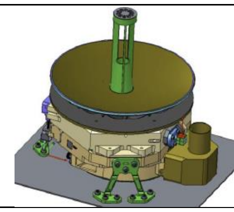
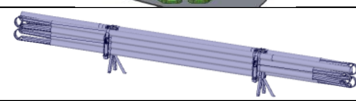
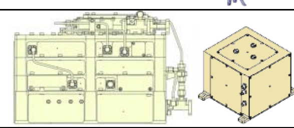
B. Geophysics instruments

The geophysics instruments are dedicated to the restitution of the surface topography, the sub-surface composition and the gravity fields. The geophysical package explores the surface and subsurface of the moons using laser altimetry and radar sounding, complemented by the radio science instruments, which probes the Jovian/satellite atmospheres and enables estimation of gravity fields. This set of instruments gathers the following instruments:

- GALA is a laser altimeter, operating as a bi-static LIDAR with a 1064 nm wavelength, providing moons' topographic information.
- RIME is a radar, using a 16 m dipole antenna provided by the spacecraft. Thanks to its low frequency, around 9 MHz, it can sound the sub-surface up to a few kilometers. It is therefore especially suited to ice body and ocean investigations.
- 3GM is the radio-science instrument. It includes an Ultra-Stable Oscillator (USO), a Ka band transponder (KaT) for radio-science and a High Accuracy Accelerometer (HAA), to measure non-gravitational effects acting on the spacecraft, as propellant sloshing and appendages flexible modes. The experiment relies on the spacecraft communications links and provides accurate range and range rate data from which moons' gravity fields are deduced.

Table 2 below presents JUICE geophysics instruments and their units.

Table 2: JUICE geophysics instruments.

Geo-physics	*5*	**GALA** (*Ganymede laser Altimeter*)	Moons shape and topography		**Transmitting and Receiving Unit (TRU)** + Laser Electronic Unit + Electronic unit
	6	**RIME** (*Radar for Icy Moons Exploration*)	Moons sub-surface study		**Antenna** + components + Main Unit
	7	**3GM** (*Gravity and Geophysics of Jupiter and Galilean Moons*)	Gravity field and moon interiors (S/C position)		**Ka- Band Transmitter** + **Oscillator** (USO)

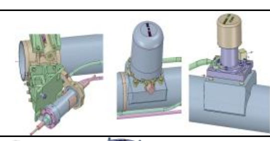
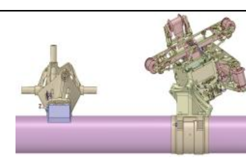
C. In-situ Particles and Fields

The in-situ instruments objective is to provide data on the Jovian environment, mainly on the Jupiter magnetosphere, the plasma and the fields surrounding the moons:

- JMAG is based on two fluxgates and a scalar magnetometer located at the end of a long boom provided by the spacecraft, to limit the spacecraft magnetic disturbances.
- RPWI, Radio and Plasma Wave Instrument, performs three types of observations to support the Ganymede plasma analysis: plasma waves electrical measurement (with 4 Langmuir probes LP-PWI), radio emission (RWI sensor) and alternative magnetic field (SCM sensor) measurements.
- PEP includes six sensors spread over four units to cover the 4π sr around the spacecraft. It observes plasma (positive and negative ions, electrons) and neutral atom flows over a wide energy range, with angular and spectral resolution. The aim is to understand the plasma and magnetosphere interactions, and particle weathering.

Table 3 below presents JUICE in-situ instruments and their units.

Table 3: JUICE in-situ instruments.

In-situ Particles and Fields	*8*	**JMAG** (*JUICE magnetometer*)	Magnetic Field (and Ganymede ocean)		**3 sensors** on the MAG Boom + Electronic Box
	9	**PEP** (*Particle Environment Package*)	Plasma environment and study of the neutral and ion composition of exospheres	 **6 sensors + card rack**	
	10	**RPWI** (*Radio and Plasma Wave Investigation*)	Plasma environment		**2 sensors** on the MAG Boom + 4 Langmuir Probes + Electronic Box

IV. JUICE Instruments main thermal requirements and accommodation

A. Instruments main thermal requirements

- *External remote sensing and geophysics units*

Table 4 below presents a simplified overview of the typical dissipations and the temperature ranges of the external remote sensing and geophysics instrument units. It is simplified in the way that the dissipation is split between several parts in the instrument and usually varies with the instrument mode. In the same way, some components may have specific temperature requirements.

Table 4: External remote sensing and geophysics units.

Instrument	Unit		Typical dissipation	Temperature range (°C)	
				Targeted operating (perfo)	Non-operating
JANUS	Optical Head (OH)		0.5 W	[-45, -40] (detector)	[-50, +60]
MAJIS	Optical Head (OH)	IR detector	0.3 W	[-213, -173]	[-223, +40]
		Telescope + visible detector	0.7 W	[-163, -93]	[-173, +40]
UVS	UVS		9.6 W	[-5,+30]	[-25,+45]
SWI	Receiving Unit (RU)	Warm components	6.5 W	[-50, +50]	[-60, +60]
		Cold components	1.5 W	[-150, -100]	[-200, +60]
GALA	Transmitting and Receiving Unit (TRU)		21.2 W	[+5, +30]	[-30, +40]
RIME	Antenna		0 W	[-186, +75]	[-186, +75]

- *In-situ units*

Table 5 below presents a simplified overview of the typical dissipation and the temperature range of the in-situ instrument units.

Table 5: In-situ particles and field instrument units.

Instrument	Unit	Typical dissipation	Temperature range (°C)	
			Operating	Non-operating
JMAG	InBound Sensor (MAGIBS)	0.1 W	[-75, +60]	[-150, +80]
	OutBound Sensor (MAGOBS)	0.3 W	[-75, +60]	[-150, +80]
	Scalar Sensor (MAGSCA)	0 W	[+15, +70]	[-150, +80]
PEP	Jovian Energy Electron spectrometer (JoEE)	1.9 W	[-30, +35]	[-35, +40]
	Jupiter Energetic Neutral atoms and Ions sensor (JENI)	8.9 W	[-30, +35]	[-35, +50]
	Time-of-flight mass spectrometer (NIM)	0 W	[-43, +40]	[-70, +146]
	JDC	13.0 W	[-30, +55]	[-45, +65]
	Jupiter energetic Neutral Atom sensor (JNA)	10.8 W	[-30, +55]	[-45, +65]
	Jovian Electron and Ion analyzer (JEI)	0.7 W	[-45, +40]	[-50,+70]
RPWI	Langmuir probes (x 4) (LP-PWI)	0 W	[-196, +121]	[-196, +121]
	Search Coil Magnetometer (SCM)	0.2 W	[-160,+60]	[-180,+90]
	Radio Wave Instrument (RWI)	0.4 W	[-180,+60]	[-180,+100]

- *Instrument units that need to be located close to their sensing unit*

A few sensing units require to have an electronic unit or some component very close to the detector, to limit loss of signal. Table 6 gathers these units and presents their typical dissipation and their temperature range.

Table 6: In-situ particles and field instrument units.

Instrument	Unit	Typical dissipation	Temperature range (°C)	
			Operating	Non-operating
JANUS	Proximity Electronic Unit (PEU)	6.9 W	[-20, +20]	[-30, +60]
RIME	Center Matching network (CMN)	0 W	[-37,+55]	[-37,+55]
	Terminal Matching network (CMN)	0 W	[-60, +60]	[-60, +60]
PEP	Card Rack (CR)	53.3 W		
RPWI	Langmuir probes pre-amplifier (x 4)	0.3 W	[-60, +50]	[-60, +50]

- *Electronic units which can be away from their sensing unit*

All the other instrument units are electronic boxes that can be accommodated away from the sensing units without jeopardizing the quality of the transferred data. Table 7 below presents their typical dissipation (most of the time, it corresponds to the most dissipative mode) and their temperature range.

Table 7: Temperature ranges of the instrument electronics that can be away from their sensing unit.

Instrument	Unit	Typical dissipation	Temperature range (°C)	
			Operating	Non-operating
JANUS	Main Electronic (ME)	32.1 W	[-20, +50]	[-30, +60]
MAJIS	Main Electronic (ME)	26.1 W		
SWI	Main Electronic (ME)	24.3 W		
GALA	Laser Electronic Unit (LEU)	20.3 W		
	Electronic unit (ELU)	18.3 W		
RIME	Transceiver (TX)	7.9 W		
	Receiver and Digital assembly (RDS)	25.7 W		
JMAG	Electronic Box (MAGELB)	12.8 W		
RPWI	Electronic Box (EBox)	13.6 W		
3GM	Ka Transponder (KaT)	33.7 W		
	Ultra-Stable Oscilator (USO)	4.5 W	[-20, +50] (*)	[-40, +50]

(*): Rate of temperature change must be < 0.5°C over period of 1000 s during measurement

B. Instruments accommodation

Instrument unit's accommodation is mainly driven by the requested sensor field of view, by the needed proximity of some units to their sensors or, at the opposite, by the need to operate some sensors as far away as possible from the magnetic or electric disturbances potentially generated by the rest of the spacecraft. Besides, the remote sensing instrument optical heads have a stringent co-alignment specification, which leads to mount them on a very rigid and stable structure, called the optical bench. Figure 3 presents the instrument apertures or sensors location on the Spacecraft.

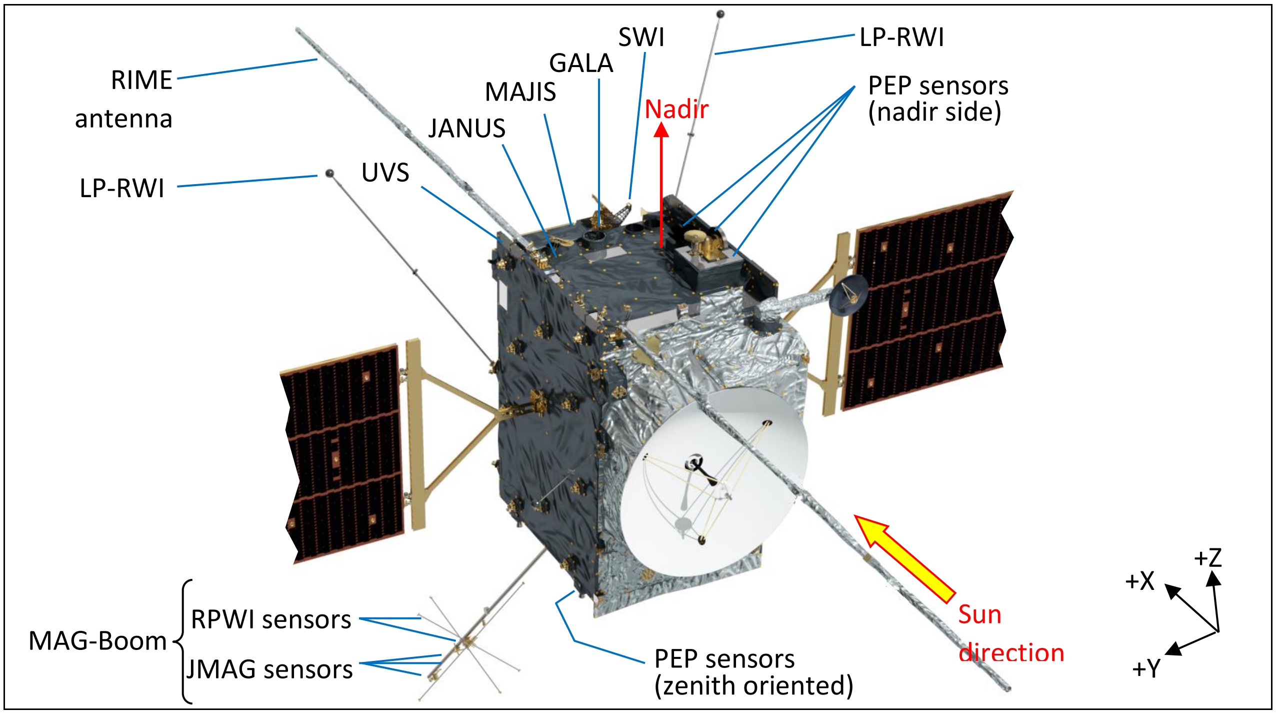


Figure 3: Overview of JUICE Instruments.

Table 8 presents the different constraints concerning the instrument units accommodation.

Table 8: Accommodation of the instrument units.

Units mounted on nadir side with co-alignment requirement	Units mounted on nadir side (with a large field of view)	Unit mounted on zenith side (with a large field of view)	Units to locate away from the spacecraft	Units that can be located together in a vaults
JANUS OH MAJIS OH UVS SWI TRU GALA TRU	RIME antenna PEP NIM PEP JEI PEP JNA PEP JENI	PEP JDC PEP JoEE	RPWI sensors (SCM, RWI) JMAG sensors (MAGOBS, MAGIBS, MAGSCA) RPWI LP-PWI	All the other electronic units (cf. Table 7)
Proximity units	**Proximity units**		**Proximity units**	
JANUS PEU	PEP CR RIME CMN and TM		LP pre-amps	

- 5 remote sensing instruments have their aperture nadir oriented and are mounted on an optical bench. The optical bench hosts also two navigation cameras and the star tracker optical heads. As MAJIS OH and SWI TRU require the coldest temperature, they are located on the upper part of the optical bench and are granted the access to the cold side (+X) of the spacecraft to accommodate a radiator. UVS benefits as well of such a privileged position, to radiate its dissipation. GALA TRU and JANUS OH are located on the lower part of the optical bench, with only a direct access to nadir side (+Z) for their radiator.
- JANUS PEU has to be mounted close to JANUS OH, but it can use the cold side of the spacecraft to radiate its dissipation.
- PEP sensors are mounted on dedicated brackets to maximize their field of view. PEP CR has consequently to be mounted on +Z side, for proximity reason.

- RPWI and JMAG sensors have to be as far away from the spacecraft. A 10.6 meter long boom hosts the 5 sensors. Similarly, the 4 LP-PWI are mounted at the ends of 3 m long booms. Their pre-amplifiers are accommodated inside the spacecraft cavity, at the bottom of each of these booms.
- All the other instrument electronic units can be mounted inside the two vaults, with the platform units, to benefit of the collective thermal control.

V. JUICE Instruments thermal interface and thermal design

A. Instruments unit thermal categories

As a general principle, all the instruments sensing units are thermally decoupled from the spacecraft, to facilitate parallel and relatively independent design activities, analysis, development and verification of both the spacecraft platform and the instruments. Interface temperature ranges and maximum allowed interface fluxes between the instrument and the spacecraft were preliminary defined early in JUICE development, and were updated to take into account system constraints or feasibility difficulties. Instrument unit categories were early established to define the type of thermal interface with the spacecraft and to set responsibilities (between spacecraft prime contractor and instrument teams) concerning the thermal control of the sensors, sizing and operating the heating lines. Table 9 below presents the 6 different unit thermal categories used to define and manage thermal interface between the instruments and the spacecraft.

Table 9. JUICE instruments unit thermal categories.

Cat.	Environment	Definition	Which Instrument units?
Cat. 1	Internal units	Conductively controlled by the S/C.	All the instrument electronic boxes except PEP CR
Cat. 2		Radiatively controlled by the S/C (and conductively insulated).	LP-PWI pre-amplifiers
Cat. 3	External units, partially coupled to the external environment	Thermally decoupled from the S/C.	UVS, MAJIS OH + All In-situ sensors + PEP CR
Cat. 4		Thermally decoupled from the S/C with a separated radiator (also thermally decoupled from the S/C)	SWI TRU
Cat. 5		Thermally decoupled from the S/C but requiring a cold finger (S/C provided) for a thermally decoupled part.	GALA TRU + SWI TRU + JANUS OHU
Cat. 6		Conductively coupled and controlled by the S/C with part of the unit coupled to the external environment.	*Not used (initially foreseen for PEP sensors)*

B. Conductively and collectively controlled units (category 1)

- *Conductively and collectively controlled units (category 1)*

Category 1 encompasses all the electronic boxes, which can be mounted away from the instrument sensing part and which Unit Reference Point (URP) (located on the unit baseplate or very close to the baseplate) does not require particularly narrow operating temperature range or specific thermal stability. All these units are located in the two vaults to benefit of the shielding provided by the lead reinforced walls. They are collectively controlled with the platform units and their operating and non-operating temperature range comply with the other units in the vault.

As some avionic platforms remain permanently ON, they share their heat with the other electronic boxes to maintain a minimum temperature without any need of additional heating power or a limited amount of heating power. Conductive coupling between units is performed with a network of heat-pipes. 2 or 3 surface heat pipes are used per unit, which ensures redundancy in case of an unlikely heat-pipe failure. The surface heat pipes are then coupled to external wall embedded heat-pipes to spread the heat along a single radiator per vault. It is noteworthy that a few instrument electronic boxes need local stable temperature. This is the case for the USO's clock (cf. Figure 5), insulated and actively maintained at a warmer temperature than the unit URP. On the other hand, JMAG electronic box (MAGELB) uses a local Peltier Thermo-Electric Cooler to keep one of its components' temperature stable. Figure 4 presents –X vault's platform and instrument electronic units, mounted on heat pipes and connected to the radiator (+Z oriented). The instruments unit are labelled in blue. An external view of –X vault radiator is provided in Figure 4.

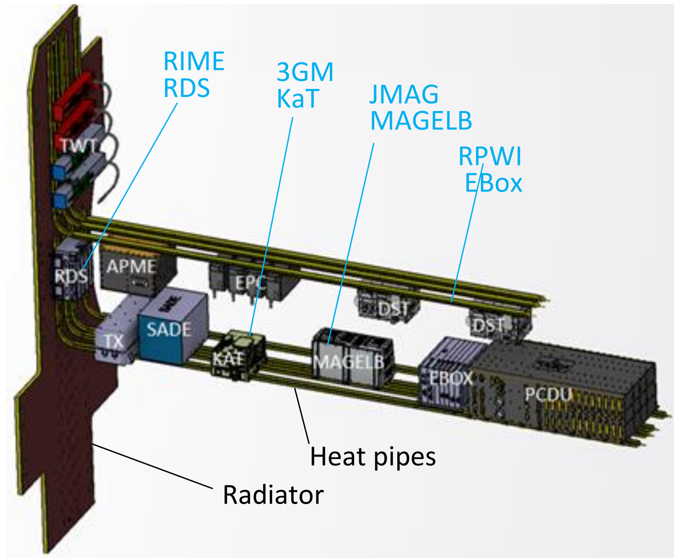


Figure 4: -X vault with platform and instrument units, heat-pipes and radiator (+Z oriented).

Figure 5 presents +X vault's platform and instrument electronic units, mounted on heat pipes and connected to the radiator. Only USO (on the bottom right corner) is not conductively coupled to the heat pipes but benefits of the radiative environment of the vault. An external view of +X vault radiator is provided in Figure 5.

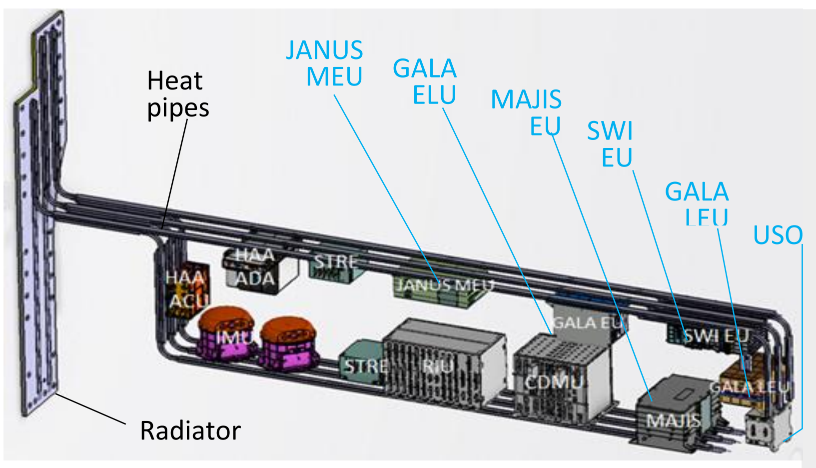


Figure 5: Vault +X with platform and instrument electronic units.

- *Conductively and individually controlled units (category 1)*

JANUS Proximity Electronics (JANUS PE) close to the instrument detectors to limit signal disturbance. It is mounted on a dedicated bracket close to the instrument optical head and is coupled to its own radiator with a flexible high conductance thermal strap. As a category 1 unit, the spacecraft prime contractor is given the responsibility of the thermal control of this unit. The radiator and the strap (made of pyrolytic graphite) is thus provided by the spacecraft, which also ensures the active thermal control with a dedicated heating line, three thermistors to keep the unit within the required temperature range. The total conductance (JANUS PE to its radiator is 0.31 W/K. The radiator area is 0.066 m^2 and it is mounted on +Y side.

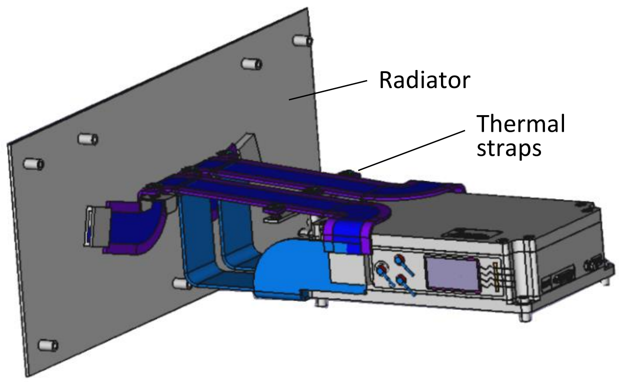


Figure 6: JANUS PE cold finger thermal strap and radiator.

C. Radiatively controlled units (category 2)

Only one set of instrument units (the 4 LP-PWI pre-amplifier boxes) is radiatively controlled by the spacecraft. As for the proximity electronics mentioned previously, each of the LP-PWI pre-amplifiers need to be very close to the LP baseplate. As they have a very small dissipation (around 300 mW) when switched on, they can be simply mounted conductively decoupled on the external spacecraft wall inner side and wrapped with MLI. The interface conductance is lower than 0.03 W/K. Their thermal control is mainly driven by the various heat leakage through the harness towards the external probe, through the insulating washers and through the MLI. Individual heating lines are foreseen to keep them warm enough when non-operating and possibly when operating as well.

D. Thermally decoupled units (categories 3 and 4)

UVS and MAJIS OH operate at various temperatures and need to be thermally decoupled from the spacecraft's optical bench. In-situ sensors (PEP, JMAG, and RPWI) have a much less stringent alignment requirement than the optical instruments but they are generally located on the most remote parts of the spacecraft:

- 4 LP-PRWI are located on the edges of the platform.
- 3 JMAG sensors + 2 RPWI sensors are mounted on the last segment of the deployable MAG-Boom.
- All the PEP sensors and the Card Rack (CR) are located on the external walls.

Therefore, these units are thermally decoupled from the spacecraft, with a specified interface conductance lower than 0.03 W/K, and a specified maximum heat exchange of ±1 W with the spacecraft. They have their own thermal control (heating lines for the operating mode whenever needed and/or for the survival mode –operated by the spacecraft). This choice facilitates the development and the verification of each unit's thermal control, independently from the spacecraft development.

- *UVS*

UVS is thermally decoupled from the optical bench thanks to low conductive titanium blades. The majority of the exterior of the instrument is blanketed with MLI, except a 0.138 m^2 opening on the top part of the instrument, which is white painted (AZ-2000-IECW) and acts as a radiator. The main aperture and the solar port baffle inner surface have radiative couplings to the environment and are black painted (Z307). Figure 7 below presents UVS instrument without MLI and with MLI (thermal model).

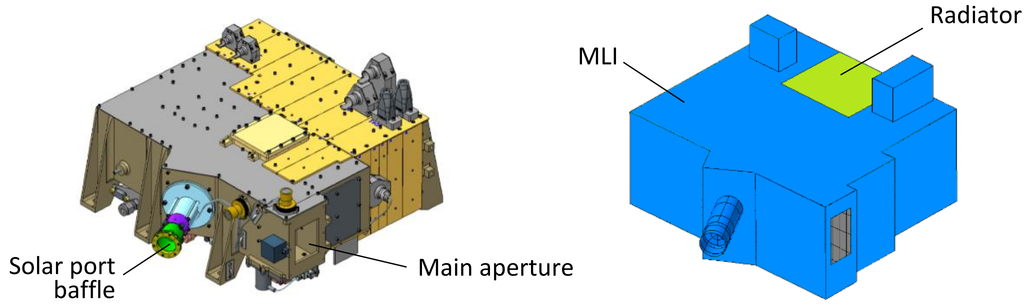


Figure 7: UVS without MLI and white paint (left) and with MLI and white painted radiator (right).

- *MAJIS Optical Head (OH)*

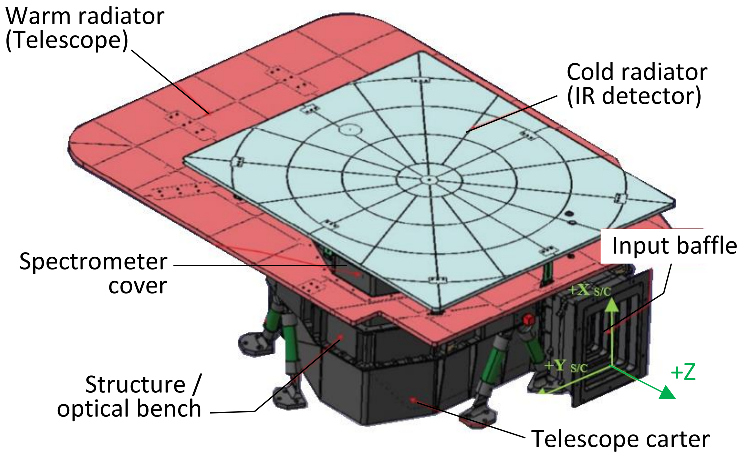


Figure 8: MAJIS Optical Head.

The thermal design of MAJIS OH is based on a passive cooling approach, with two staged white painted aluminium radiators, a cold one and a warm one. The cold radiator has an area of 0.41 m^2 and is devoted to the IR focal plane assembly only, for which an operative temperature lower than 90K has to be achieved in the warmest environmental condition, corresponding to Ganymede 500 km circular orbit. The warm radiator has a total area of 0.53 m^2, but part of it is hidden by the cold radiator, and only 0.31 m^2 sees cold Space. It is used to cool down the optical head and the visible/near-infrared detector to a temperature lower than 140 K. Both radiators are well visible in Figure 8, which presents MAJIS Optical Head.

Besides the radiators and the instrument aperture, the overall optical head is insulated with MLI, to limit the heat inputs from the environment and the spacecraft. The cold radiator back side is also equipped with MLI. The instrument mechanical layout is presented in Figure 8. The layout of the passive radiators determines the choice of placing the elements of the spectrometer on the upper side of the optical bench to minimize the distance between the IR detector and its radiator. The 3 bipods, made of carbon fiber with titanium heads and feets, support the instrument on the spacecraft optical bench. The cold radiator is mounted on the top of the instrument with fiberglass blades and insulating washers to limit the conductive leakage from the warm part to the cold radiator. Heaters are foreseen for the safe mode during the cruise phase and for decontamination purpose. Less than a watt is necessary to keep the detectors within their non-operating temperature ranges. The decontamination is more demanding, with an avarage of 26 W consumed to warm up both the OH bench (20 W) and IR focal plane assembly (6).

E. Thermally decoupled units requiring a cold finger (category 5)

GALA TRU, JANUS OHU and SWI TRU are thermally decoupled units mounted on the optical bench, following the same specification as the categories 3 and 4 (cf. previous paragraph). They have dissipative components and some of them have to operate at low temperature, which require for each of them a radiator. However, two constraints were identified:

- Each radiator would protrude outside the dedicated volume initially foreseen for these instruments.
- These radiators are mounted on the nadir side of the spacecraft, with other items in their fields of view and this is not fully under instrument team's control.

The thermal control responsibility of GALA TRU, SWI TRU warm components and JANUS OHU focal plane was then transferred to the spacecraft thermal control system. This leads to define early thermal interface, instrument heat load and required temperature ranges. The thermal control of these components is performed with a flexible thermal strap, a radiator and a heating line. As seen by the instruments, this is called a cold finger.

- *GALA TRU cold finger*

Figure 9 presents GALA TRU cold finger, which uses 2 parallel pyrolytic graphite thermal straps, provided by Airbus Defence and Space Spain. They provide a total conductance of 0.44 W/K between the instrument interface and the radiator, including end fittings contact. GALA TRU radiator maximum area is 0.1153 m², and will be trimmed, if needed, after the thermal tests. The thermal decoupling between GALA TRU radiator and spacecraft structure is 0.03W/K thanks to Vetronite washers. Figure 11 and Figure 14 show GALA TRU and its cold finger radiator integrated on the spacecraft optical bench.

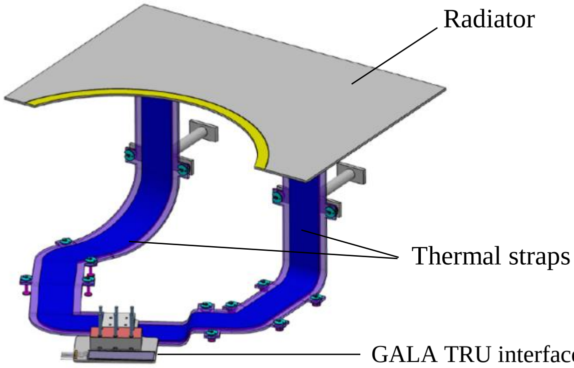


Figure 9: GALA TRU focal plane assembly cold finger thermal straps and radiator.

- *JANUS OH focal plane assembly cold finger*

As illustrated in Figure 10, JANUS optical head unit cold finger monitoring plate is connected by 2 thermal straps providing a total conductance of 0.24 W/K at -50°C, including end fittings thermal contact qualities for both endings. The thermal straps are also provided by Airbus Spain. JANUS optical head unit radiator is decoupled from the optical bench with MLI and its area is 0.032 m². It is also decoupled from the spacecraft structure with thermal washers (conductance less than 0.016 W/K). Figure 8 illustrates JANUS OH focal plane assembly cold finger. As for all the cold fingers, the interface includes a monitoring plate equipped with heaters (1 nominal + 1 redundant) and a triplet of thermal sensors (platinum probes PT1000). Figure 11 shows JANUS OH and its cold finger radiator integrated on the spacecraft optical bench.

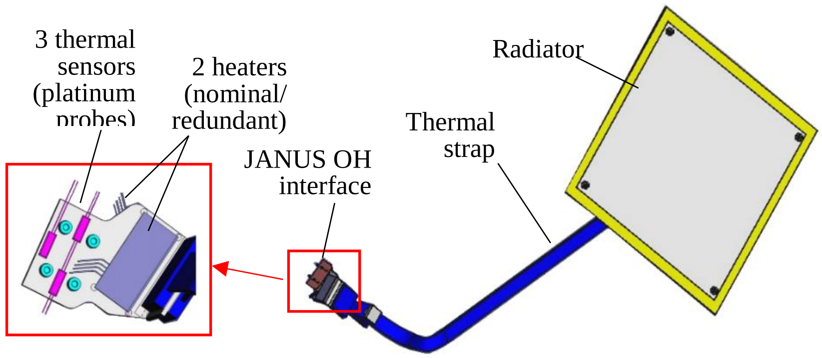


Figure 10: JANUS OH focal plane cold finger thermal strap and radiator.

- *SWI TRU warm components cold finger*

The SWI TRU warm component (pre-amplifiers) cold finger consist in a high conductance thermal strap providing a total conductance of 0.217W/K. The radiator maximum area is 0.0142 m² and it is decoupled from the spacecraft structure with thermal washers, ensuring a conductance lower than 0.01W/K. The radiator is located on nadir side, and is visible in Figure 13.

Figure 11 shows the optical bench with the five instruments sensing units. Some of them have their own radiators (MAJIS OH, UVS, SWI TRU cold components) and the other ones (JANUS OHU, GALA TRU, SWI warm components) have a spacecraft provided radiator linked to a high conductance thermal strap (cold finger).

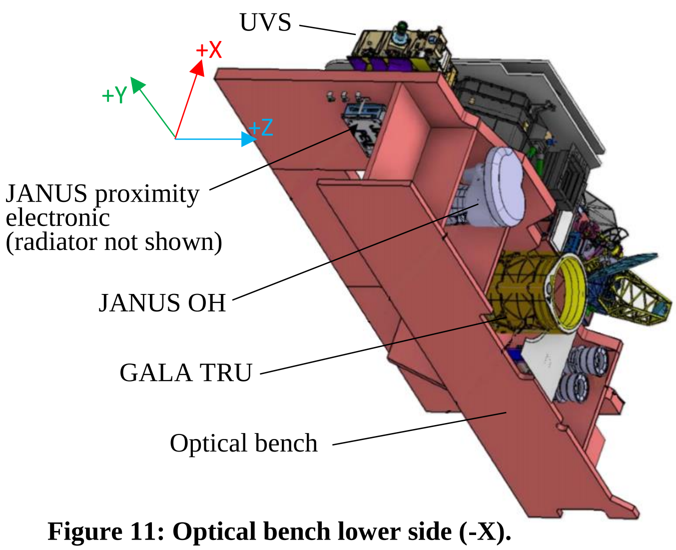


Figure 11: Optical bench lower side (-X).

VI. Overview of instruments radiators

A. +X radiators (Spacecraft cold side)

Figure 12 presents an overview of the spacecraft main body's +X side ("cold side"), -Y side and -Z side. The SWI cold component radiator, the MAJIS radiators, the UVS radiator and the JANUS OH cold finger radiator are located on +X, which is never Sun illuminated during the cruise and nominal science operation in Jovian environment.

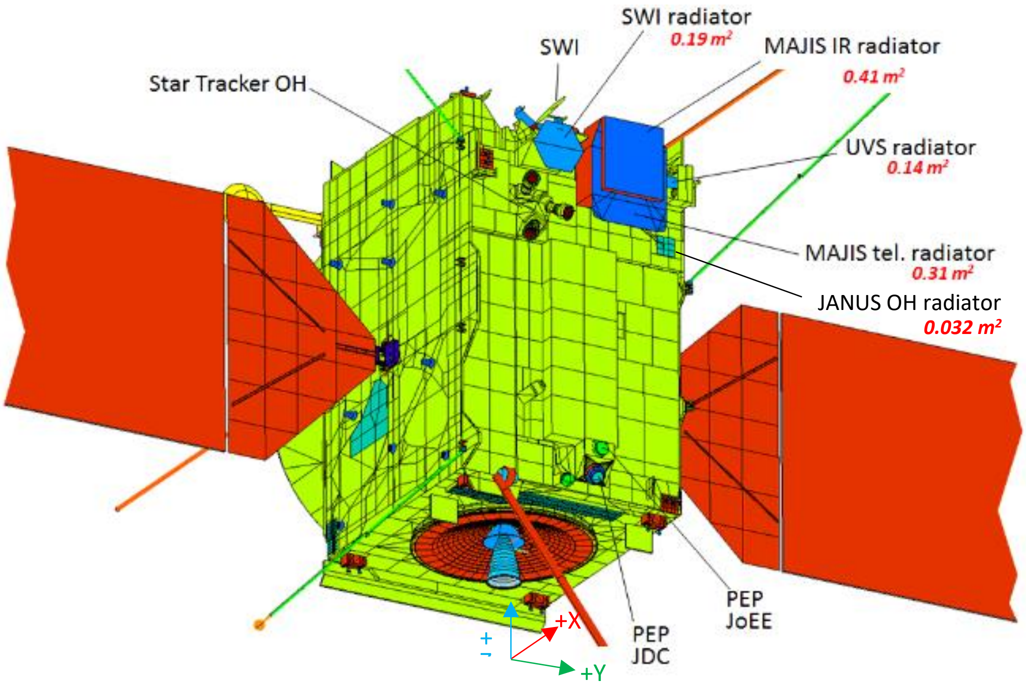


Figure 12: Overview of +X side radiators (MAJIS, SWI, UVS).

B. +Z radiators (Nadir side) and -Z radiator

Figure 13 presents the spacecraft main body's +Z side ("nadir side"). Several instrument units have their radiator on this face (GALA TRU, SWI warm component, PEP card rack). The –X vault radiator is also located on this side, and is the largest radiator on the spacecraft. On the opposite side (-Z), there is only one radiator, coupled to +X vault, as presented in Figure 14.

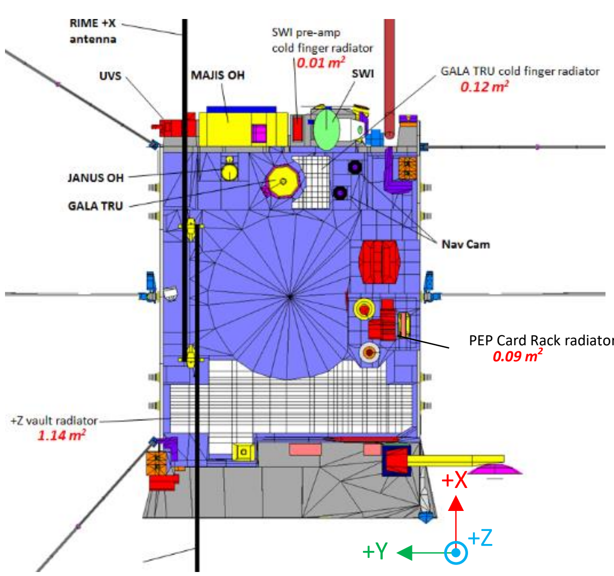


Figure 14: Overview of +Z side (nadir).

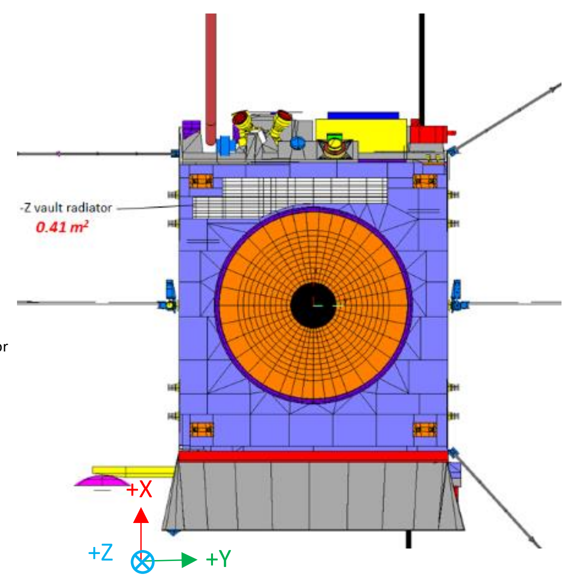


Figure 13: Overview of -Z side.

VII. Conclusion

Most of the instruments design have stringent thermal requirements and all of them have to cope with extreme environment variations, which drives their accommodation and their design. Most of them are thermally decoupled from the spacecraft but use as well spacecraft resources such as heating power or, in some cases, thermally controlled cold fingers. The early definition of the thermal interface, including some flexibilities to account for design update and evolution of some constraints have allowed both the spacecraft and the 10 instruments to go into parallel and relatively independent development. All the instruments have passed their Critical Design Review (CDR) in 2018-beginning 2019 and the spacecraft has also successfully completed the system level CDR beginning of 2019. The next step is the manufacturing of the Flight Models, to be delivered and integrated before Summer 2020 to prepare and perform the spacecraft thermal vacuum test.

VIII. References

[1]R. Peyrou-Lauga and J. Zabaleta Araujo, "JUICE (Jupiter Icy Moon Explorer) MAG-Boom Thermal Design and early Thermal Verification", *ICES-2019-020, 2019*, Boston, 2019.

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[3]R. Peyrou-Lauga and A. Darel, "JUICE thermal architecture and performance", *ICES-2017-1, 2017,* Charleston, 2017.