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# The JUICE Mission to Jupiter and its Icy Moons

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## Abstract
JUICE (JUpiter ICy moons Explorer) is the first large mission in the ESA Cosmic Vision 2015-2025 programme. The mission was selected in 2012 and started its implementation phase in 2015. Planned for launch in April 2023 and arrival at Jupiter in July 2031, it will spend at least four years making detailed observations of Jupiter and its Galilean icy moons: Ganymede, Europa, and Callisto. The paper addresses the key design drivers which shaped the form and functionality of the spacecraft together with a global view of the mission strategy to reach Jupiter and to accomplish the observations. The global development history and the status at less than one year ahead of launch is presented as well.

## 1. Introduction and scientific objectives

Galileo Galilei's discovery of four large moons orbiting Jupiter four centuries ago hasted the Copernican Revolution and forever changed our view of the Solar System and universe. Today, Jupiter and its diverse collection of moons is seen as the archetype for giant planet systems both in our Solar System and around other stars throughout our Galaxy. A comprehensive characterisation of the Jovian system, from the churning gas giant and its enormous magnetosphere to the orbiting ice worlds in all their complexity, will allow to unravel the origins of the giant planets and their satellites and search for evidence of potentially habitable environments in the cold outer solar system.

JUICE (JUpiter ICy moons Explorer) is the first large mission in the ESA Cosmic Vision 2015-2025 programme. The mission was selected in May 2012 and started its implementation phase July 2015. Planned for launch in April 2023 and arrival at Jupiter in July 2031, it will spend at least four years making detailed observations of Jupiter and three of its largest Galilean moons. Figure 1 shows an artistic view of the JUICE spacecraft touring within the Jovian system.

The focus of the mission is on the study of the icy satellites of Jupiter, with special emphasis on the three ocean-bearing worlds Ganymede, Europa, and Callisto. Ganymede has been identified for detailed investigation since it provides a natural laboratory for analysis of the nature, evolution and potential habitability of icy worlds in general, but also because of the role it plays within the system of Galilean satellites, and its unique magnetic and plasma interactions with the surrounding Jovian environment. JUICE will determine the characteristics of liquid-water oceans below the icy surfaces of the moons. The mission will also characterise the diversity of processes in the Jupiter system that may be required in order to provide a stable environment at Ganymede, Europa and Callisto on geologic time scales, including gravitational coupling between the Galilean satellites and their long-term tidal influence on the system as a whole. The spacecraft will embark ten states of the art instruments to perform remote sensing, geophysics and in situ particles and fields measurements.

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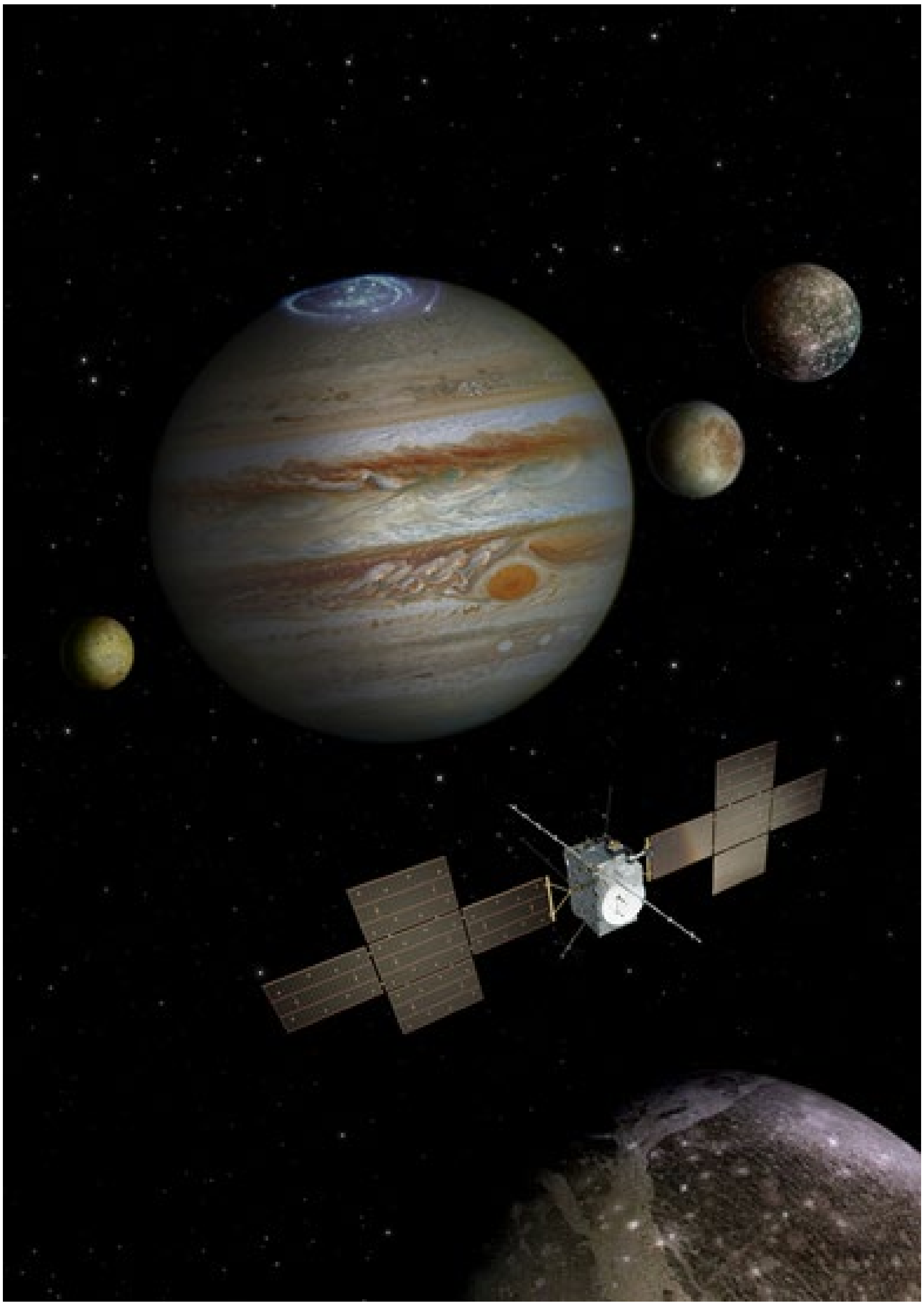

Figure 1: Artistic view of JUICE in the Jovian system

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## 2. Mission profile

Following a launch with Ariane 5 from the European Space Port of French Guiana, JUICE will make extensive use of gravity assist manoeuvres for reaching the Jupiter system while minimising the impulse changes to be achieved by the spacecraft propulsion system. Considerable effort was, and will still be in the future, dedicated to the optimization of the two elements of the mission profile: the cruise phase to reach Jupiter after the launch and the tour in the Jovian system. This is an optimization process based on celestial mechanics with multiple constraints, i.e., the mission core science objectives; the maximization of the useful mass inserted at the Jupiter system by minimizing the fuel consumption; the minimization of the transfer duration; the minimization of the total radiation dose accumulated until the end of the mission. The mission profile optimization together with the development and programmatic constraints resulted in a nominal profile featuring a launch on April 5th, 2023, arrival at Jupiter in July 2031 and insertion into an orbit around Ganymede in December 2034. Jupiter can be reached every year, but this will be possible only by launching within dedicated launch windows, lasting around 20 days, each year. The current nominal profile considers the launch on the opening of the April 2023 launch window. After launch a direct cruise to Jupiter is impossible, due to the spacecraft mass and launcher performances, and a series of gravity assist manoeuvres will be implemented allowing the spacecraft to build up energy, and therefore increasing its speed. The currently optimised mission profile foresees using an Earth-Venus-Earth-Earth gravity assist sequence, with some of the Earth gravity assists also combining a Moon flyby. After insertion into Jupiter orbit, JUICE will use multiple gravity assists via flybys of the Galilean satellites to shape a comprehensive orbital tour over a little more than four years. After reducing the orbit period with Ganymede and Callisto flybys, this tour will implement two close Europa flybys, followed by a series of Callisto flybys so as to rise the orbit inclination with respect to the equatorial plane of Jupiter. A dedicated series of Callisto and Ganymede gravity assists will then make it possible to approach Ganymede at a low velocity. Figure 2 gives a pictorial view of the various phases of the mission. During this unprecedented tour, Jupiter's magnetosphere and atmosphere will be continuously monitored. At the end of the tour, JUICE will be set in a polar orbit around Ganymede, becoming the first spacecraft ever to enter orbit around a moon in the outer solar system. The current end of mission scenario involves spacecraft disposal on Ganymede.

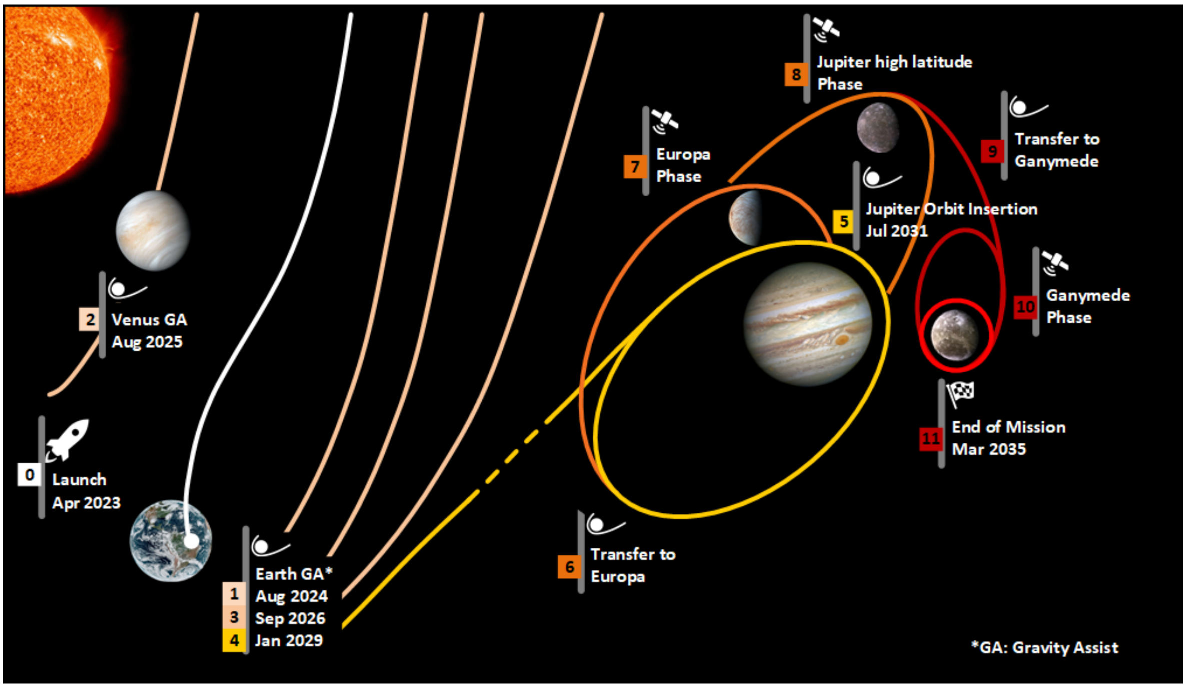


Figure 2: JUICE mission phases

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## 3. Spacecraft design challenges

Although JUICE can be viewed as a classical spacecraft in terms of conception and functional requirements, it includes numerous specific features that result directly from the mission needs or Jupiter's environment. These are briefly highlighted hereafter providing an overview of the challenges for the development of the space segment. Table 1 summarises the key parameters of the spacecraft, Figure 3 shows the spacecraft configuration with the key elements identified.

Table 1: Spacecraft main parameters

| | |
|---|---|
| Launch mass | ~ 6.1 tons |
| Spacecraft dry mass | 2 450 kg |
| Propellant tank capacity | 3 650 kg |
| Solar array size | 85 m$^2$ |
| Power (Jupiter EoL) | ~ 800 W |
| Memory (Jupiter EoL) | 1.25 Tbit |
| Data rate | >1.4 Gbit/24 h |
| Communication round trip | ~ 90 min |

EoL: End of Life

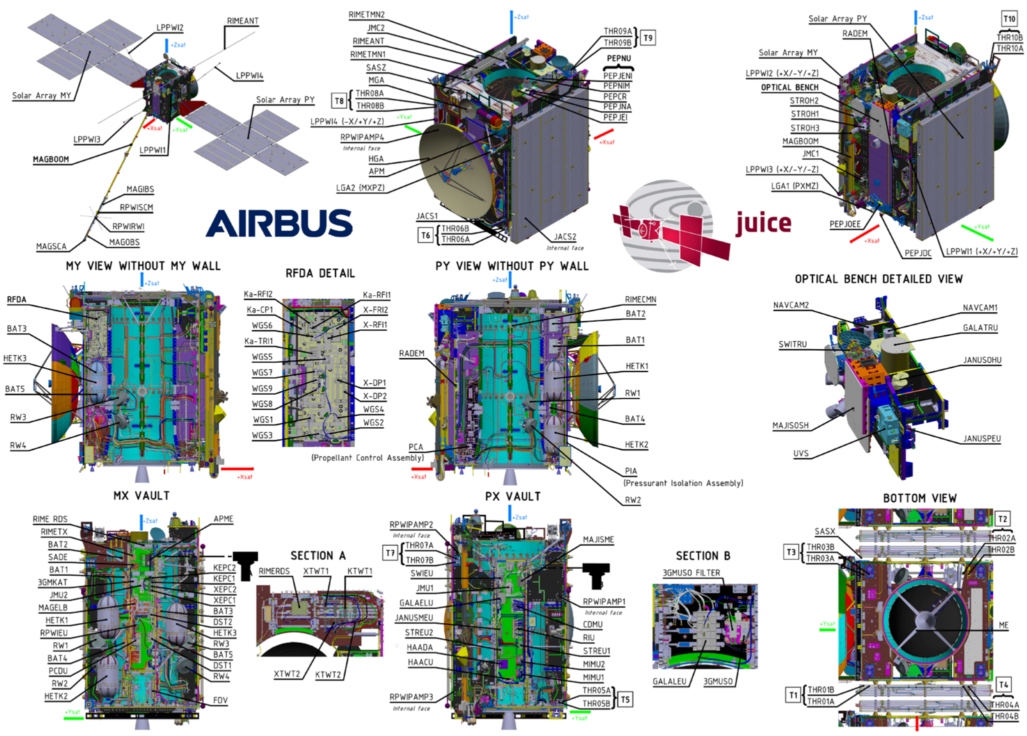


Figure 3: Spacecraft design views

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### 3.1 Radiation environment

The radiation environment at Jupiter is harsh, dominated by electrons and with an important proton contribution. Significant effort was spent for improving the radiation environment model at Jupiter and the spacecraft shielding model so as to derive realistic figures for the shielding mass and the radiation dose at the end of life. The total ionising dose around the various electronics boxes shall not exceed 50 krad by the end of the mission. Moreover, the long cruise duration must be taken into account for the reliability of critical components, such as thruster latch valves and reaction wheels. Harsh radiation also proved to be a challenge for the solar array, with a predicted degradation of power generation at Jupiter of more than 25% over the four years of mission. The solar cells have been specifically protected by a layer of coverglass to shield them from radiation.

### 3.2 Power availability

At Jupiter, the solar constant is about 27 times lower than on Earth, thus implying a very scarce solar flux on the solar array active area. The solar array surface is 85 $m^2$ – comparable to that used for the most demanding telecommunication spacecraft – however providing less than 1 kW by the end of life at Jupiter. At Jupiter the solar cells will face a specific Low Intensity Low Temperature (LILT) environment, in which the cell efficiency is more difficult to predict. Special efforts were invested in the characterization and qualification of triple junction solar cells for JUICE, in particular at Fraunhofer Institute and ONERA, in order to build up a reliable power generation model. The lack of power is one of the major design drivers since it has numerous implications on the spacecraft design, in particular: need for a multi-deployment of the solar array in orbit; need for a solar array drive mechanism for maintaining quasi-normal sun illumination conditions on the solar panels; need for rotation of the spacecraft when in orbit around Ganymede; limits on communication and associated data rate; instrument power limitations, constraining the operations with impact on the on-board software; last but not least, need for a large battery on board for coping with sun eclipses and operations during flybys where, to achieve the required instrument pointing, the solar panels cannot be optimally oriented. Every source of power loss has been chased in the spacecraft Power Conditioning and Distribution Unit (PCDU), in all power converters of the various platform and instruments units and in the power distribution cables.

### 3.3 Propulsion system

The overall $\Delta V$ to be achieved by the spacecraft is 2.6 km/s, leading to a substantial amount of propellant, in excess of 3 tons for an overall spacecraft mass a little more than 6 tons. The highest $\Delta V$ manoeuvres are the orbit insertion when arriving at Jupiter (900 m/s) and the orbit insertion around Ganymede ending with the 500 km altitude polar orbit (660 m/s for orbit insertion and altitude reduction). The remaining propellant will be used for controlling the spacecraft during the cruise and the Jupiter tour. The impact on the spacecraft architecture is the accommodation of a large volume of bi-propellant in two tanks and the development of a dedicated support structure.

### 3.4 Thermal control

The spacecraft must cope with a large dynamical range of solar flux, being hottest during the Venus gravity assist fly-by and coldest during long sun eclipses at Jupiter, which can last almost five hours. The entire spacecraft has been designed for operations in the very cold environment at Jupiter with minimum heating power consumption and is covered by multi-layer insulation blankets. During the Venus gravity assist and the entire cruise in the inner part of the Solar system, the high gain antenna will be used as a sunshield, so as to avoid forcing the spacecraft design to accommodate for this hot case in full (a method which was also used in the Cassini mission to Saturn). Specific efforts in spacecraft design and assembly have been invested in the limitation of thermal leakage at Jupiter (notably within cables) in order to take advantage of the natural heat dissipation of the units and minimize the necessary heater power. The solar cells of the solar array must withstand a large temperature range: from -230°C during eclipses at Jupiter to +160°C at Venus.

### 3.5 Navigation and autonomy

When at Jupiter, the distance from Earth to the spacecraft varies from about 4.2 to 6.4 AU (Astronomical Unit, with 1 AU being 150 000 000 km). These large distances result in long round-trip communication delays, varying from about 1:10 hr to 1:47 hr, which affects the spacecraft and operations concepts. Significant on-board autonomy is required, in particular for the critical insertion manoeuvres at Jupiter and Ganymede, with direct implication on the spacecraft avionics and on-board software development and verification. A dedicated optical camera, able to precisely image the

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limbs of the moons, is implemented on board to allow autonomous software controlled navigation during the critical fly-by operations.

### 3.6 Electromagnetic cleanliness

JUICE is one of the most electromagnetically clean spacecrafts ever built. The instruments measuring fields and particles are very sensitive to electromagnetic disturbances. For example, they are designed to measure extremely tiny fluctuation of the magnetic fields which will give hints of the amount of salty liquid water below the icy crust of the moons. Therefore, they must measure the space electric/magnetic fields and not the disturbances generated by the spacecraft. As an example, the spacecraft generated magnetic field shall be less than 1 nT ($10^{-9}$ Tesla) which is 50000 times less than the Earth magnetic field. In order to achieve such unprecedented electromagnetic cleanliness performance, several measures have been taken at design and manufacturing level. The design of the spacecraft most emissive units has been adapted (use of very accurate clocks to synchronize power converters, avoidance of magnetic material, internal shielding), the spacecraft provides a Faraday cage hosting the majority of the electronics units (these vaults are also used to protect the units from intense radiation at Jupiter), and the most sensitive instrument sensors have been placed at the tip of a 10.6 meter deployable boom to increase distance shielding.

## 4. Scientific instruments

The spacecraft carries a suite of ten state-of-the art scientific instruments. As shown in Table 2, they are grouped in three packages. The remote sensing package includes spectro-imaging covering the ultraviolet to the near infrared range, an optical imager and a submillimetre wave instrument. The geophysical package includes a laser altimetry and a radar sounding for exploring the surface and subsurface of the moons; the package is complemented by a radio science instrument enabling estimation of the gravity fields. The in-situ package includes a magnetometer, a radio and plasma wave instrument and a particle multi-sensor package. The payload suite is complemented by a radiation monitor, which is part of the platform hardware. The spacecraft telecommunication subsystem will be able to support an experiment, PRIDE (Planetary Radio Interferometry and Doppler Experiment), which will use ground based Very Long Baseline Interferometry to improve the ephemerides of the Galilean moons.

Table 2: JUICE instrument suite

| | | **Instrument Name** | **Scientific purpose** |
|---|---|---|---|
| **Remote Sensing** | 1 | Jovis, Amorum ac Natorum Undique Scrutator (**JANUS**) | Moons geology, cloud morphology and dynamics |
| | 2 | Moons And Jupiter Imaging Spectrometer (**MAJIS**) | Chemistry - Atmospheric & surface composition |
| | 3 | UV Spectrograph (**UVS**) | Atmosphere of moons & Aurora of JUPITER |
| | 4 | Sub-mm Wave Instrument (**SWI**) | JUPITER Wind + JUPITER<br>Moons atmospheric temperatures and composition |
| **Geophysics** | 5 | GAnymede Laser Altimeter (**GALA**) | Moons shape & topography |
| | 6 | Radar for Icy Moons Exploration (**RIME**) | Moons sub-surface study |
| | 7 | Gravity & Geophysics of Jupiter and Galilean Moons (**3GM**) | Gravity field and moon interiors (S/C position) |
| | 11 | ***PRIDE*** | *Ephemerides of the Jovian system* |
| **In situ Particles and Fields** | 8 | JUICE Magnetometer (**J-MAG**) | Magnetic field (& Ganymede ocean) |
| | 9 | Particle Environment Package (**PEP**) | Plasma environment & Study of the neutral and ion composition of exospheres |
| | 10 | Radio & Plasma Wave Investigation (**RPWI**) | Plasma environment |

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## 5. Industrial consortium

The spacecraft has been built by a large European industrial consortium made of 83 companies, led by Airbus Defence and Space, with number of contracts totalling 116. Within the global time span of the mission the industrial actors were mostly active in the development phase (design, manufacturing and test of the hardware and associated software) which started in 2015 and will end in 2022. The structure of the consortium with the key players is shown in figure 4.

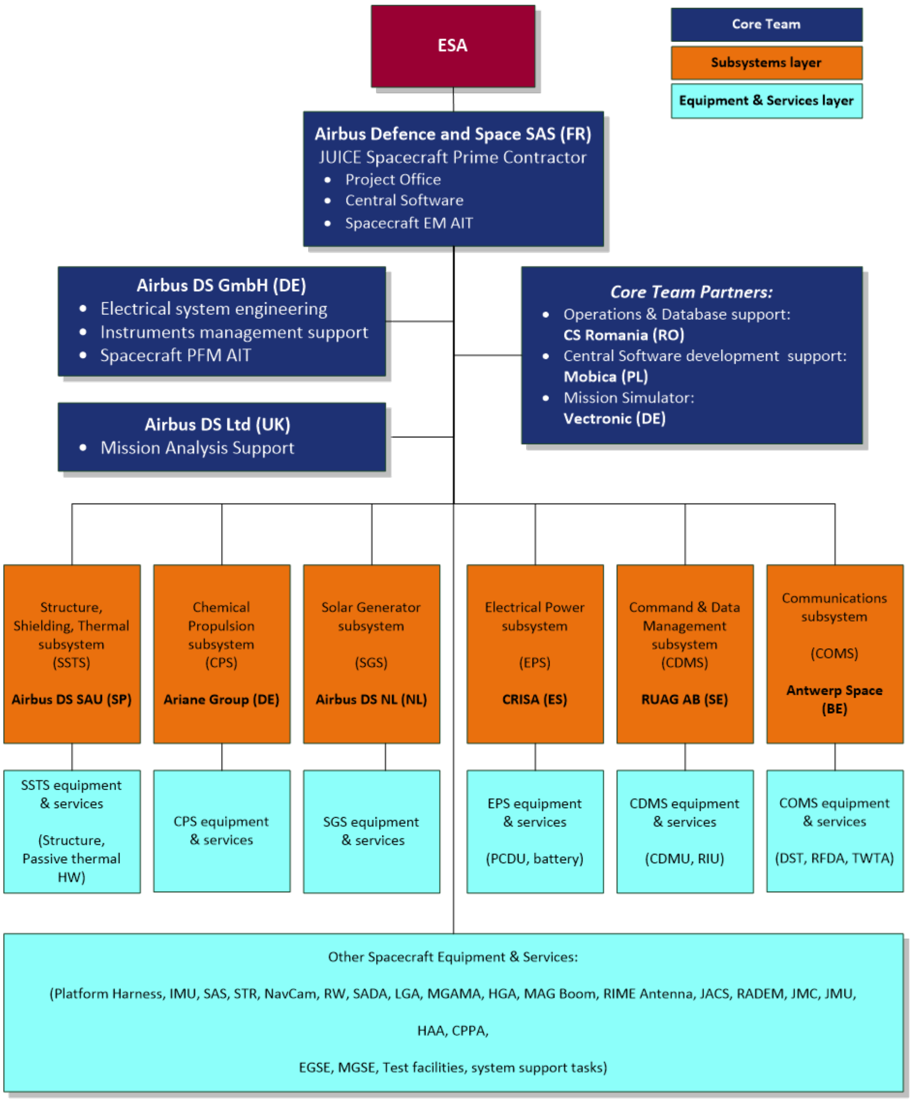


Figure 4: JUICE industrial consortium

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## 6. Program status

At less than one year to launch, the spacecraft environmental test campaign is in full swing. It started in summer 2021 at ESA technology centre (ESTEC) with the Thermal Balance and Thermal Vacuum test performed in the Large Space Simulator, which allowed to verify the adequacy and performances of the thermal control system and therefore the capability of the spacecraft to withstand the harsh thermal environment it will see in space. After arrival of the spacecraft in Airbus premises in Toulouse in August 2021, the spacecraft assembly was progressively completed in full flight configuration, including all instruments flight hardware. Conducted and radiated electromagnetic compatibility tests were performed in November 2021 and April 2022 respectively, the latter in the Mistral chamber (Airbus Toulouse, Astrolabe premises). Since then, the two solar array wings have been integrated onto the spacecraft, which is now under final preparation for mechanical tests (sinus vibration, acoustic and shock) that will be conducted in June 2022. The spacecraft environmental test campaign will be concluded in Airbus Toulouse over the last six months of 2022, with propulsion tests, a complement of thermal vacuum test in full flight configuration and final functional tests at the end of year to demonstrate JUICE readiness for flight. Mission tests are also foreseen, covering the most critical phases of the mission and rehearsing the flight operations together with the ESA Mission Control Centre. JUICE will be shipped beginning January 2023 to the European Space Port in Kourou, French Guiana, for launch on one of the last Ariane 5 on April 5$^{th}$, 2023.

Figures 5 and 6 show the spacecraft in its flight configuration during the Thermal Balance and Thermal Vacuum test and during the Radiated Electromagnetic Compatibility test in the anechoic chamber. Figure 7 summarises the global development flow and key milestones of the programme, from selection of the concept mission to spacecraft disposal on Ganymede. It gives an example of the timespan of a large planetary mission.

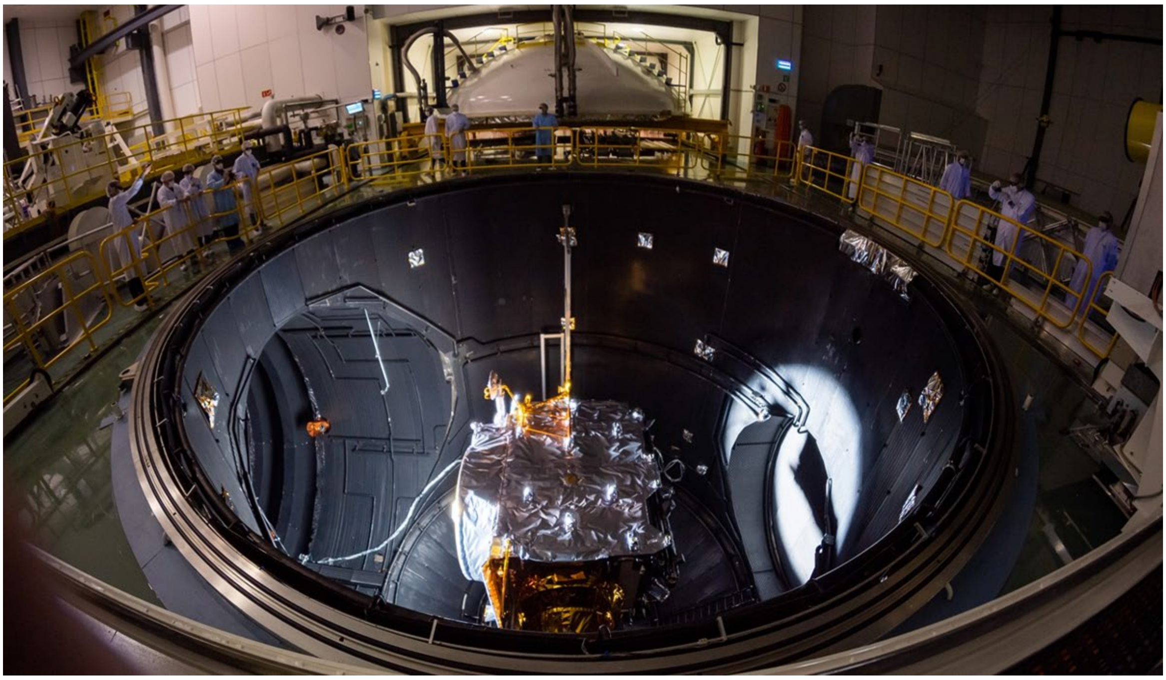

Figure 5: JUICE in the ESA Large Space Simulator before starting the thermal test (Noordwijk, June 2021)

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Figure 6: JUICE during the electromagnetic compatibility test (Airbus Toulouse, April 2022)

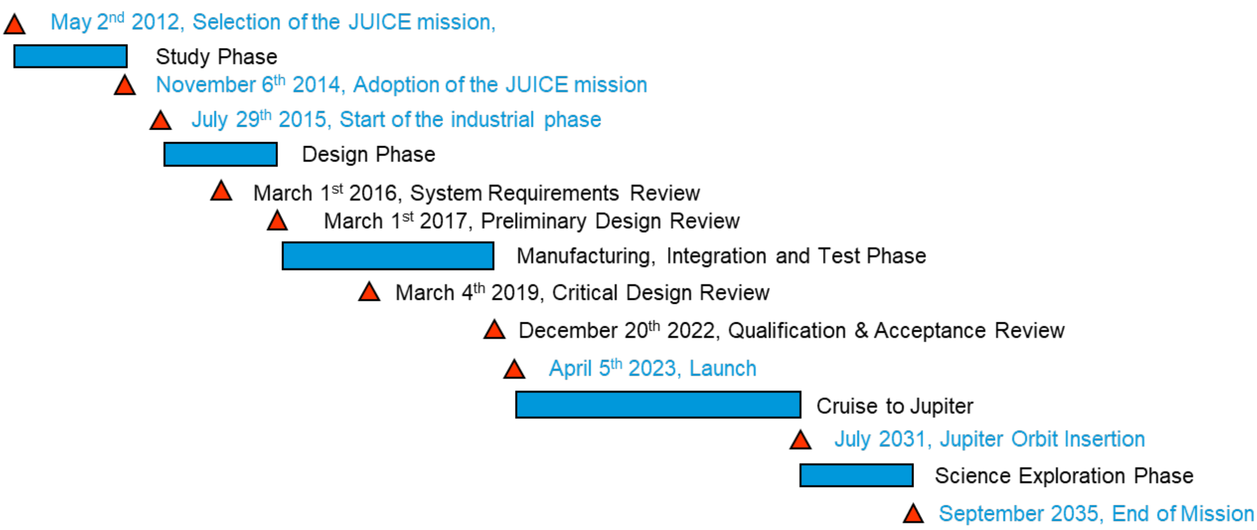


Figure 7: JUICE mission global development schedule

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