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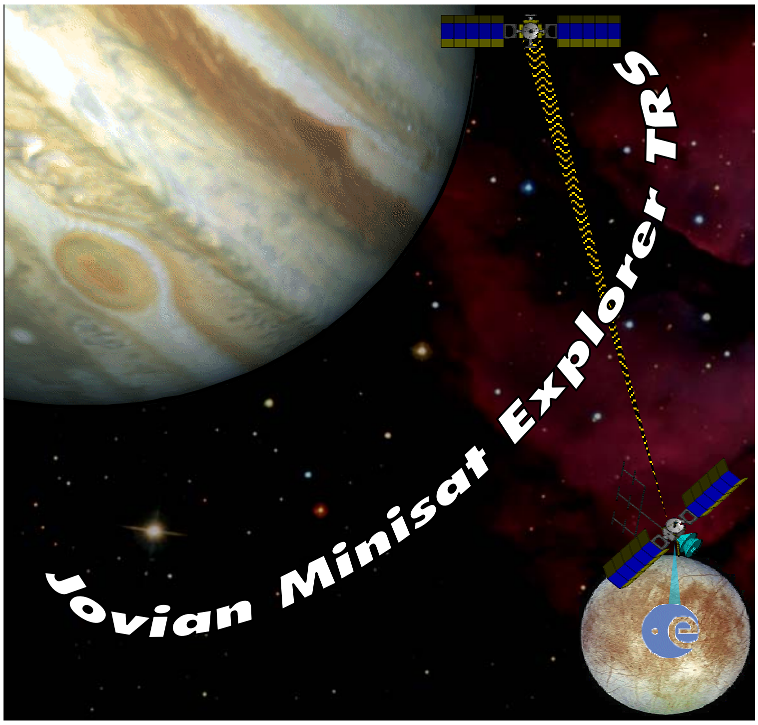
Study Overview of the JME



An ESA Technology Reference Study

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Scientific objectives:		
Primary Objectives	• Determine the presence or absence of a subsurface ocean (includes mapping of the ice thickness)	
	• Measure the global topography and the tidal effects at Europa	
	• Characterise the global geology and surface composition of Europa	
	• Observe Europa's magnetic field	
	• Measure the radiation environment around Europa	
Secondary Objectives	• Measure the plasma environment of Europa	
	• Imaging of the Jovian system	
	• Characterisation of the Jovian plasma and dust environment	
	• Determine presence and composition of a Europa atmosphere	
Strawman payload	**Jupiter Europa Orbiter**	**Jupiter Relay Satellite**
	• Miniaturised GPR	• Plasma Wave Instrument
	• Stereo micro-camera	• VIS-NIR camera
	• VIS-NIR mapping	• Magnetometer
	• Altimeter	• Dust Detector
	• Magnetometer	• Radiation monitor
	• γ-ray	
	• UV spectrometer	
	• Radiation monitor	
	• Radiometer	
Transfer:		
	• Soyuz Fregat 2-1b launch from Kourou	
	• 2 S/C composite transfer to Jupiter via a Venus-Earth-Earth GA	
	• Transfer duration ~ 6 years	
	• After Jupiter Orbit Insertion the S/C separate and both perform a tour of the Jovian system	
	• JEO will achieve orbit around Europa in 545 days	
	• JRS will achieve a highly elliptical orbit around Jupiter (~20 degree inclination w.r.t. equator) 449 days	
Operational orbit:	**JEO**	**JRS**
	200 km circular orbit, period = 2.3 h	12.7 R_j * 26.3 R_j (R_j=71492 km), period = 11.5 days
Mission Lifetime:	**JEO**	**JRS**
	• 6+1.5 years until Europa orbit insertion	• 6+1 years until Relay orbit insertion
	• ~ 60 days of science operations	• ~ 2 years of science & relay operations
Spacecraft details:	**JEO**	**JRS**
Stabilisation	3-axis	3-axis
Orientation	Nadir / JRS	JEO/Earth
Mass	Mass figures include 5-20% component margin (depending on maturity) and 20% system margin.	
Payload (kg)	30	14
Dry (kg)	**403**	**594**
Wet (kg)	**656**	**2274**
Included margin (wet) (kg)	122	562
Margin w.r.t. launcher (kg)	0 (after applying all margins, the remaining launcher capacity has been fully allocated to the payload)	
Radiation	~ 5.3 Mrad (4 mm Al shielding)	~1 Mrad (4 mm Al shielding), after 2 years of operation
Power (incl. margins) (W)	226	310
TM band	Ka, X	Ka, X
Antenna	HGA, MGA	HGA, MGA, LGA
Data storage (Gbit)	50	256
P/L power (W)	25	13
P/L data rate (kbps)	40	30
Challenges:		
	• Radiation: Very high radiation dose hardened systems (order of 1 Mrad) • Efficient high radiation compatible, low intensity, low temperature solar power generators • Development of solar concentrators: distance from Sun ~5.2 AU, hence solar flux ~1/25th wr.t. Earth flux • Thermal: Hot and cold case drivers (Venus fly-by and Jovian system respectively) • Low resource: Both P/L and S/C subsystems (including comms) must have low resource requirements. Significant effort needs to be invested in the developments of the Highly Integrated Payload Suite • Communications: high efficiency SSPA's, high data rate X-&KA-band transponders • Autonomy: Highly autonomous S/C during entire mission as well as for commissioning and ops around Europa • Planetary protection: JEO needs to be integrated while meeting the highest planetary protection requirements • Microprobe impact: microprobe systems must be of very low mass and must be able to survive very high g levels	

1 INTRODUCTION

1.1 Purpose of this document

This document has been prepared to give a concise overview of the Jovian Minisat Explorer (JME) study, which is being performed in the framework of the Technology Reference Studies (TRS). Its goal: the identification of technologies that are required to enable a mission to Europa. The presented configurations and budgets reflect the current status (November 04). More details on this study can be found in the extensive final report of this study [1]. Further analysis will be performed, especially concerning alternative power sources for the spacecraft. The instruments used in this study are part of a strawman payload derived from goals specified in [4], which was necessary to obtain a realistic spacecraft design. This selection is in not intended to preclude further inputs from the scientific community.

1.2 Technology reference Studies

ESA's Science Payload & Advanced Concepts Office has started a combination of activities that go by the name "Technology Reference Studies". The goal of the TRS's is to identify and possibly develop critical technologies that will be required for future scientific missions. This is done through the study of several challenging and scientifically relevant missions, which are not part of the ESA science programme, and focus on the medium term enabling technology requirements.

The TRS's share the same baseline: the use of one or more small spacecraft using a suite of highly miniaturised and integrated strawman payloads, with strongly reduced resource requirements. The purpose of this approach is to achieve the science objectives with a phased, cost efficient exploration, resulting in a reduced overall mission risk, when compared to a large "one-shot" mission. This overview will address the first phase of the phased approach, i.e. the first mission to Europa.

1.3 The Jovian Minisat Explorer

The Jovian Minisat Explorer TRS concerns the exploration of the Jovian system, and especially Europa, the smallest of the four Galilean moons orbiting Jupiter. This moon has been selected, as it is one of the few places where liquid water may be found in the solar system, making it one of the prime candidates for the search for life outside Earth.

The current scenario foresees two relatively small spacecraft (~ 600/400 kg dry mass): one will act as a relay spacecraft (Jupiter Relay spacecraft (JRS)) in a highly elliptical orbit around Jupiter, outside the high radiation zones, while the other (Jupiter Europa Orbiter (JEO)) will orbit Europa. The relay spacecraft will carry all subsystems that are not directly required for the Europa observation mission, as it will be subjected to less radiation than the Europa orbiter. It will carry the communication system providing the link between Earth and the JEO, data processing and data storage units as well as a small, highly integrated scientific payload suite dedicated to the study of the Jovian system. The Europa orbiter will include a highly integrated remote sensing payload suite and a communication system for communications with the JRS and Earth. The feasibility of a compact microprobe (< 1 kg) to perform in-situ measurement of the ice crust is also being assessed.

2 STUDYING THE JOVIAN SYSTEM

The Jovian system is often compared to a miniature solar system as a result of its dynamism, the massive amount of emitted energy, and its large number of satellites. This combination makes the Jovian system a very interesting destination for scientific missions. In particular Jupiter and its four Galilean moons can be considered as high priority targets for future exploration.

Table 2-1: Jupiter's main properties [2]

Jupiter Statistics	
Mass (kg)	1.900e+27
Mass (Earth = 1)	317.9
Equatorial radius (km)	71,492
Equatorial radius (Earth = 1)	11.21
Mean density (gm/cm^3)	1.33
Mean distance from the Sun (km)	778,330,000 (5.2 AU)
Mean distance from the Sun (Earth = 1)	5.2028
Rotational period (days)	0.41354
Orbital period (days)	4332.71
Mean orbital velocity (km/sec)	13.07
Orbital eccentricity	0.0483
Tilt of axis (degrees)	3.13
Orbital inclination (degrees)	1.308
Equatorial surface gravity (m/sec^2)	22.88
Equatorial escape velocity (km/sec)	59.56
Visual geometric albedo	0.52
Mean cloud temperature	-121°C
Atmospheric composition Hydrogen Helium	 90% 10%

2.1 Previous missions

Until now, a limited number of missions has studied the Jovian system: Pioneers 10 and 11 were the first, providing information on the Jovian radiation and magnetosphere in the early 1970s, followed by the Voyagers 1 and 2 at the end of the same decade, providing multi-band imaging, as well as radiation and atmospheric observations of Jupiter and the Galilean moons.
Ulysses was the first spacecraft to visit Jupiter (1992) since the Voyager missions in the 1970s, when it used Jupiter for a gravity assist to swing out of the ecliptic plane towards an orbit around the poles of the Sun. Its visit of Jupiter supplied valuable information on the Jovian radiation and magnetic environment. The last mission focussing on Jupiter was Galileo: launched in 1989 and has just ended its mission after being deliberately targeted into the Jupiter atmosphere. This spacecraft provided the most extensive study of the Jovian system until now, including in situ measurements of Jupiter's atmosphere by means of an atmospheric probe [3]. Finally, The Cassini-Huygens flyby of Jupiter in 2000 also provided valuable data on the Jovian radiation environment.

2.2 The scientific interest in Europa

The main scientific objective of the JME is to perform detailed remote sensing of Europa, with a potential deployment of a microprobe for in-situ analysis.

Table 2-2: Europa's main properties [2]

Europa Statistics	
Mass (kg)	4.8e+22
Mass (Earth = 1)	8.0321e-03
Equatorial radius (km)	1,569
Equatorial radius (Earth = 1)	0.246
Mean density (gm/cm^3)	3.01
Mean distance from Jupiter (km)	670,900
Rotational period (days)	3.551181
Orbital period (days)	3.551181
Mean orbital velocity (km/sec)	13.74
Orbital eccentricity	0.009
Orbital inclination (degrees)	0.470
Escape velocity (km/sec)	2.02
Visual geometric albedo	0.64

The main issues that need to be addressed in the study of Europa are [4]:

2.2.1 LOOKING FOR A SUBSURFACE OCEAN

Previous observations of Europa confirmed that its surface consists of an icy crust. Observational data suggests the presence of a metallic core and a rocky mantle. However, it's unclear whether the ice layer runs until the rock, or if the outer crust is partly liquid. Models based on gravity measurements provided by the Galileo spacecraft allow for an outer layer of water and ice, with a possible thickness up to 200 km. Galileo's detection of a magnetic field hints at a metallic core, further supporting the three layer model, depicted in Figure 2-1. Another theory suggests that the magnetic field is induced by the interaction of Jupiter's field and a salty subsurface ocean. Present data is not sufficient to determine the interior structure of the icy moon; more detailed observations will be necessary.

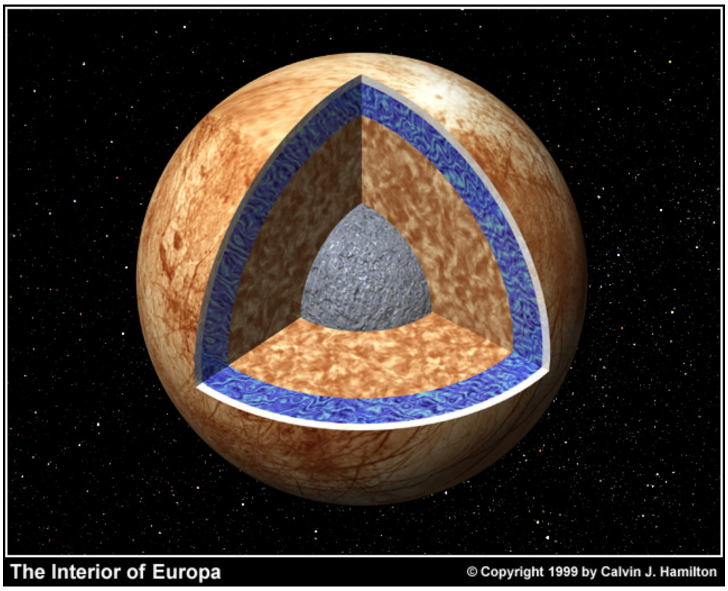

Figure 2-1: The three-layer model of Europa's interior

2.2.2 GLOBAL TOPOGRAPHY

Striking features have been observed on Europa's surface. These vary from surface cracks filled with darker material to impact craters. The most striking features concern the so-called triple bands: two parallel bands of dark matter separated by a lighter central band (see figure 2.2), that can reach lengths up to 1000 km and widths of 20 km. A range of theories exist on how these bands have formed, varying from tectonic activities causing fracturing of the crust, followed by intrusion of subsurface material, to explosive venting by geysers. After establishing the cause of these triple bands, the next step is to observe any possible degradation of the surface features over time.

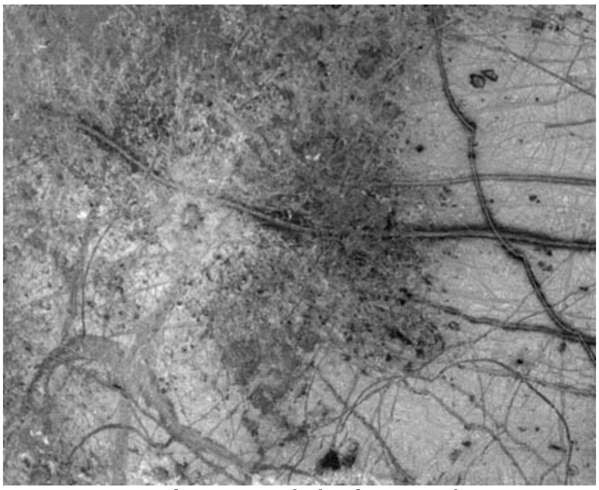

Figure 2-2: A view of Europa's cracked surface [NASA/JPL]

Observation of the impact craters, the cracks and other formations over time will provide information on composition, surface dynamics, as well as age. This last issue is contentious, since two age-models exist with a massive discrepancy between them. New data is required to shed light on this issue. Furthermore high-resolution images of particular features are needed to determine if large flows and outpourings exist to the surface.

2.2.3 COMPOSITION OF THE (SUB)SURFACE

Europa's surface shows dark bands, spots and mottled zones: the colour and spectral properties change over the surface and cannot only be attributed to a combination of water ice and sulphur. Therefore silicate minerals or other non-ice components are likely to be present. Observations have led to models where a zone of these non-ice materials (e.g. clay and salts) exists a few kilometres under the surface. Analyses of ejecta from impact craters as well as of mottled zones suggest an upwelling of material from the subsurface that could provide information on the materials present on and under the icy surface. The analysis should also focus on presence or absence of compounds that enable organic evolution, one of the necessary building blocks for life, as we know it.

2.3 The Jovian Minisat Explorer Study

This TRS requires sound scientific mission objectives, in order to assess the impact of the payload on the mission. The following objectives are based on the recommendations made by the Committee on Planetary and Lunar Exploration [4], which assessed the required investigations of Europa.

For the purpose of this TRS, the top-level scientific objectives are:

- Determine the presence or absence of a subsurface ocean (includes mapping of the ice thickness)
- Measure the global topography and the tidal effects at Europa
- Characterise the global geology and surface composition (includes measurement of the geochemical environment of the (sub)surface
- Observe the moon’s magnetic field
- Measure the radiation environment

Objectives of secondary importance are:

- Measure the plasma environment of Europa
- Imaging of the Jovian system
- Characterisation of the Jovian plasma and dust environment
- Determine presence and composition of a Europa atmosphere

For more details, please refer to the JME Science Requirement Document [5]

3 THE STRAWMAN PAYLOAD

As explained before, it is not the goal of the TRS to fix the payload of an eventual mission to Europa. However the JME needs a representative strawman payload in order to design the mission. Therefore a selection has been made of payloads capable of addressing the scientific objectives stated in 2.3. This selection is summarised in the following tables and is based on [6]:

Table 3-1: The strawman JEO payload suite

Instrument	Abbreviation	Goal
Ground Penetrating Radar	ELRR	Mapping thickness ice layer, structure determination, topography, surface reflectivity
Stereo micro-camera	EUSCam	Topography, geology and surface composition
VIS-NIR mapping	EUVN-IMS	Topography, geology and surface composition
Radiometer	EuRad	Measuring Europa's surface temperature
Altimeter	EuLat	Topographical mapping, study of tidal processes
Magnetometer	EuMAG	Measuring Europa's magnetic field
γ-ray spectrometer	EuGS	Surface composition
UV camera	EuUVcam	Measuring the electron environment of Europa
Radiation monitor	EuREM	Analysis of Jovian radiation environment

Table 3-2: The strawman JRS payload suite

Instrument	Abbreviation	Goal
Radiation monitor	JuREM	Measurement of the Jovian radiation environment
Plasma Wave Instrument	JuPWI	Investigate plasma waves and radio emissions in controlling the scattering and/or loss of trapped radiation in the Jovian magnetosphere
Narrow angle camera	JuNaCam	Imaging the Jovian system, especially Jupiter
Magnetometer	JuMag	Mapping the electromagnetic field of the Jovian system
Dust Detector	JuDustor	Measure particle size and velocity distribution

These payloads are envisaged as highly integrated payload suites (HIPS): The use of miniaturised components as well as the sharing of common subsystems and functionalities allow for an optimal reduction in resource requirements. The reduction of the payload resource requirements has to be achieved without degrading the scientific return, which calls for the use of state-of-the-art micro- and possibly nano-technologies. This approach is especially appealing for the JME as the HIPS approach is compatible with the low resources available. Furthermore it is also beneficial in view of the high radiation environment: by miniaturising and integrating the payload in a compact volume, it will be easier to protect the payload within a shielded "box", limiting the required shielding mass. The HIPS approach enables a relatively low payload mass, when compared to more conventional instrument suites. The assessment of the HIPS payload suite [6] shows that (provided that the required HIPS technology is developed) the JEO HIPS requirements will be in the order of 32 kg and 25 W, while those of the JRS HIPS will be around 15.5 kg and 10.5 W. The radar, one of the most demanding instruments, has been assessed during a Concurrent Design Facility study at ESTEC, to understand what can be achieved with a low resource radar [7].

3.1 The JEO HIPS

The following table shows a summary of the strawman payload suite used for the JEO design.

Table 3-3: Summary of the JEO HIPS

Instrument	Mass (kg)	Power (W)	Aperture (mm)	Dimension (mm)	FOV (deg)	Pointing direction	Data rate (bps)
ELRR (50 MHz)	9.5	26.5	-	Stowed: 1.34*0.47x0.3 Deployed:10.0x2.0	-	nadir	28000
EUSCam	0.6	0.66	35	TBD	4	nadir	5093
EUVN-IMS	1.8	1.0	38	TBD	4	nadir	13221
EuRad	1.6	0.96	50	60x100x200	2.0 x 4.0	nadir	109
EuLat	2.0	2.5	40	100x100x300	0.2	nadir	3000
EuMAG	0.7	0.45	-	100x50x100	-	-	248
EuGS	3.6	1.0	80	110 (diam)	92.4	nadir	TBD
EuUVcam	0.7	0.62	20 x 20	40x40x100	0.1x1.0	nadir	200
EuREM	0.5	1.0	<1	100x50x100	60-100	limb/nadir	273
Boom	0.4	-	-	1500	-	-	-
DPU + CPS	2.0	3.41	-	200x100x50	-	-	
Shielding (20%)	4.7	-	-	-	-	-	
Structure	2.5	-	-	-	-	-	
Margin (10%)	3.1	3.0/1.2	-	-	-	-	
TOTAL	**33.9**	**32.9/12.8**	**--**	**--**	**--**	**--**	**28k/22.1k+**

Due to the limited resources available, not all instruments can be switched on simultaneously. Due to the resource requirements of the radar, this instrument must be independently operated from the rest of the payload. Therefore two science modes have been identified: one mode for the radar operation, the other for the remaining payloads. The total power and data rate in Table 3-3 have been subdivided in these two modes. The next figure provides a possible configuration of the JEO HIPS.

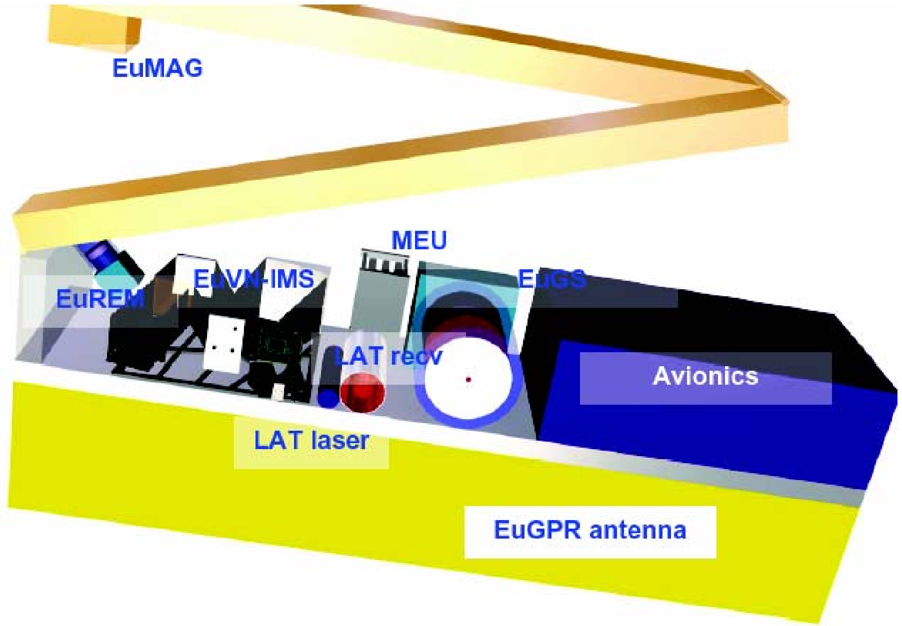

Figure 3-1: View of a possible configuration of the JEO HIPS [6]

The CDF study of the low resource radar resulted in the conceptual design of the *Europa Low Resource Radar*, ELRR. A 50 MHz frequency was selected for this ground penetrating radar as a compromise between too much clutter (at higher frequencies) and too much noise generated by the Jovian system at lower frequencies. The selected antenna is a triple three element Yagi, shown in the following figure.

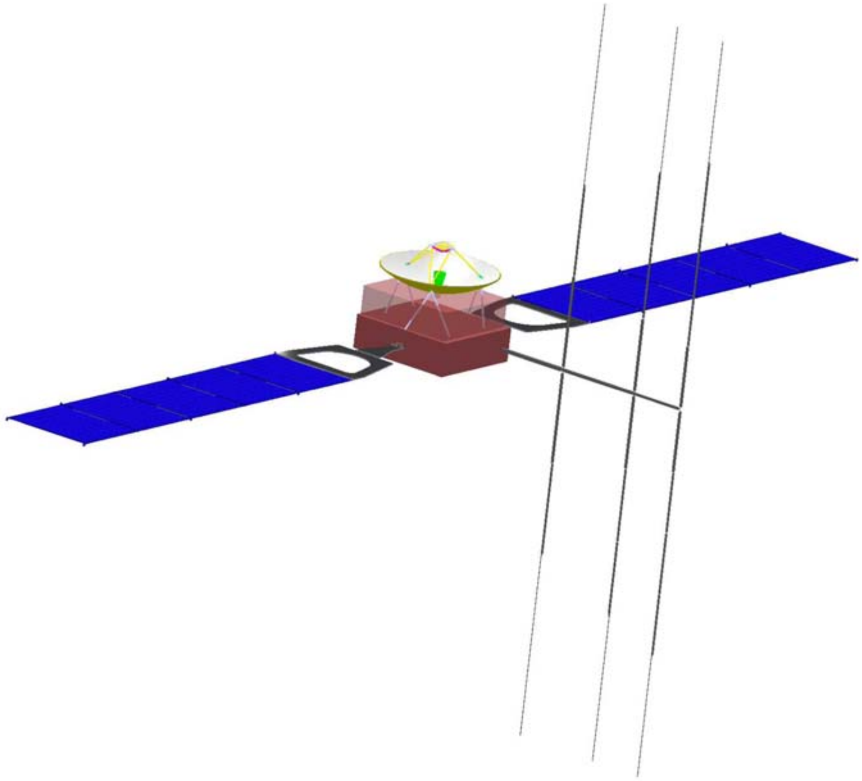

Figure 3-2: View of the deployed ELRR [7]

One of the main challenges lies in the accommodation of the antenna on the relatively small JEO. As a result of the reduced dimensions, the 12 x 2 m YAGI antenna needs to be folded into a small volume (1.34 x 0.47 x 0.3 m). To accommodate the antenna, a large number of hinges is required (~30), which poses a considerable risk for the deployment, especially after being folded for seven years. This issue will require significant attention, should such a mission be selected in future. Other critical areas concern the used materials (stiffness, high radiation compatibility) and accurate nadir and attitude pointing control. More details can be found in [7].

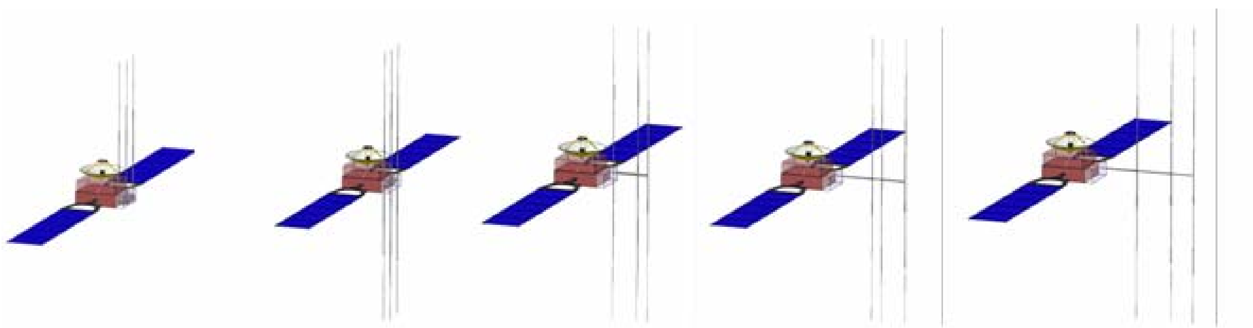

Figure 3-3: deployment sequence of the ELRR [7]

3.2 The JRS HIPS

The following table shows a summary of the strawman payload suite used for the JRS design.

Table 3-4: Summary of the JRS HIPS

Instrument	Mass (kg)	Power (W)	Aperture (mm)	Dimension (mm)	FOV (deg)	Pointing direction	Data rate (bps)
JuREM	0.5	0.9	<1	60x40x40	60-100	limb/nadir	273
JuPWI	3.7	2.1	N/A	100x200x120	-	-	3750
JuNaCam	1.7	1.0	100	300x180x105	2.0	nadir	9128
JuMag	0.7	1.5	N/A	100x50x100	-	-	248
JuDustor	0.7	1.0	100	263x177x177	120	limb/nadir	16
Boom	0.5	-	-	1500	-	-	-
DPU + CPS	2.0	3.1	-	200x100x50	-	-	-
Shielding (20%)	2.0	-	-	-	-	-	-
Structure	2.5	-	-	-	-	-	-
Margin (10%)	1.4	0.9	-	-	-	-	-
TOTAL	**15.7**	**10.4**	**--**	**--**	**--**	**--**	**13.4k**

The emphasis of this study lies on the science gathered by JEO. However, having a relay spacecraft orbiting Jupiter offers the rather unique opportunity to study the gas giant. Therefore the JRS has also been equipped with instruments capable of studying the Jovian environment. In view of the limited communication resources, the gathered data will not receive priority over the JEO data. However some JRS data could still be sent while JEO data is being dowlinked by the relay spacecraft. The remaining data will need to be stored onboard until all JEO data is sent. Clearly this will impose further requirements on the radiation tolerance of the memory as well as the other electronics.

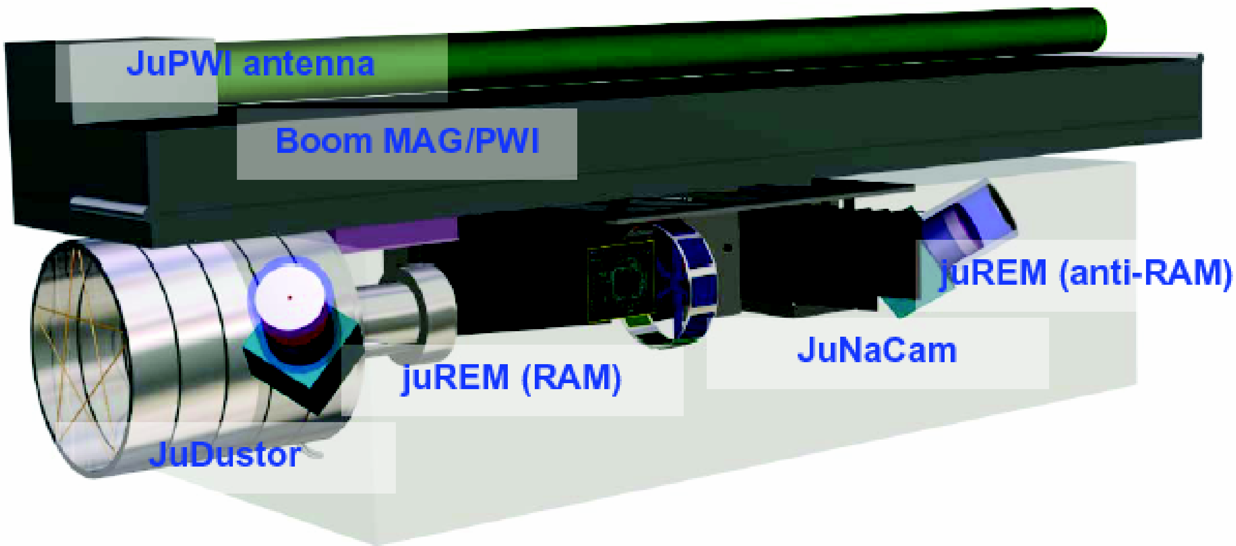

Figure 3-4: View of a possible configuration of the JRS HIPS [6]

3.3 Europa microprobe

The feasibility of a microprobe has been investigated [8]. This device would have to be in the 1 kg mass range. This mass budget is a severe limit for any probe, but for this first phase of the phased approach, it is already uncertain if such a small mass can be accommodated next to the previously described payload.

The probe would need to penetrate the icy surface of Europa to perform basic measurements of the ice crust with a very limited instrument suite. However, as Europa has no appreciable atmosphere, the probe will either need a propulsion system capable of decelerating it to a low impact velocity, or it will have to be able to withstand impact velocities in the order of 2 km/s. The first option will most likely require a propulsive system that will exceed the ~1 kg allocation by far (estimates range up to 50 kg). The second option will impose extreme structural requirements as well as highly complex attitude issues.

The key challenge of the study was therefore to provide a design for the EMP that would undertake useful science while meeting the severe mass budget of 1 kg. Chances of anything surviving impact at 2 km/s is practically zero: not even hardened military projectiles are generally expected to survive such impact velocities. In order to withstand these impact velocities, the designs only function because the projectile impacts along a specific axis. In this way the payload (power, electronics, etc) can be aligned along the direction of deceleration. In terrestrial designs, this is achieved by using atmospheric stabilisation. A probe that lands on an atmosphereless body faces two problems: decelerating to a survivable velocity and aligning itself to impact on a preferred axis so that hardening of the probe is effective. Several options were considered to provide the probe with attitude stabilisation, including gravity and active stabilisation. However, it was concluded that such options either can not work or will consume so much of the mass budget that little or nothing will be left for the scientific payload.

As no realistic scenario was identified for this situation, it was decided to relax the mass constraint by assuming that a propulsive system could be added, capable of reducing the impact velocity to 500-600 m/s. The required mass of a deceleration system without attitude control system is expected to be at least 4.5 to 5 kg. As shown in the mass budgets later on, the accommodation on the JEO of such a mass will be a challenge.

Allowing for an impact velocity of ~500-600 m/s still leaves the problem of aligning the probe for impact. An active stabilisation unit would again consume the (revised) mass budget, so an attitude independent design was suggested – a spherical steel shell. A spherical design allows the EMP to be entirely independent of impact attitude. However, it provides some other major design challenges. First, a hollow sphere is not the ideal shape for a device due to impact solid ice at 500 m/s. Most spheres will erode or collapse on impact. However, consultation with weapons experts arrived at a design which uses glass microspheres to pack out the interior voids. Two key properties of the microspheres is that they are very good at dissipating shocks, and also accommodating deformation by allowing components to move with respect to one another. The impact of the probe on Europa will cause a shock wave to propagate through the wall of the shell which will be released on the internal shell wall, potentially spraying the interior with high velocity shards of steel. The microspheres reduce this effect, greatly increasing the chances of internal elements surviving. The EMP is also designed to deform to some extent, a critical feature of survivability for the probe.

Having identified a potential design for the probe, the remaining question was whether useful, even important, science could be achieved using the system. One of the (if not the) key question(s) is whether there is liquid water beneath the ice crust. If only a semi-solid slush exists, the chances of life forms existing, no matter how basic, become much smaller. After consultation with PSSRI, a seismometer or geophone was proposed as the main instrument for this study. This is designed to 'listen' to the surface of Europa at very low frequencies (0-100 Hz). Seismic/acoustic events caused by cracking in the ice (due to tidal forces exerted by Jupiter) or by random meteor impacts, can propagate for thousands of kilometres in ice and water. If there is an ice/water interface then there will be 'echoes' caused by partial reflection of the seismo-acoustic waves at these interfaces. These can be captured and de-convolved to show the layers, their depths and constitution. Such techniques are routinely used terrestrially in fields such as oil prospecting and underwater warfare. To enhance the scientific package of the probe, other instruments were also proposed that would meet the mass, power and volume budgets, including temperature sensors that could measure the thermal flow in the crust of Europa, accelerometers that could measure the deceleration and hence the surface hardness of the ice and strain gauges that could measure the deformation of the probe. Figure 3-5 provides an illustration of the payload concept.

Figure 3-5: Illustration of the Europa Microprobe concept [8]

Table 3-5 shows the indicative parameters for this probe. This design is the first iteration of a lengthy design process, required to achieve a feasible probe design, should the production of such a probe be pursued. The shown figures do not include any structural analysis and it is not expected that the assumed wall thickness will be adequate. Extensive modelling and hardware testing will be required to establish the actual behaviour on impact. Furthermore it is unclear of the payload and communication system will survive the still very high deceleration loads experienced during impact (mean decelerations of 50'000 g can be expected).

Table 3-5: Indicative parameters for the Europa Microprobe [8]

Item	Unit	Value
Radius of payload cavity	cm	2.5
Remaining volume for payload	cm^3	65.5
Mass of payload components	g	133.2
Volume of payload components	cm^3	36.1
Remaining volume for micro-sphere packing	cm^3	29.3
Mass of packing	g	51.4
Mass of steel shell (1kg – payload – packing)	g	815.5
Volume of steel shell	cm^3	101.9
Diameter of probe	cm	6.8
Thickness of shell walls	cm	0.9
Mean power consumption of probe	W	4
Power density of battery	Wh/Kg	377
Power available	WH	26.4
Probe lifetime	h	6.6

As explained, the microprobe study is at conceptual level: the presented figures are based on the allowable mass of 1 kg, and do not pretend to be a fully tested and feasible design. Some improvements can be expected by better battery performance and the use of a Radioisotope Heating Unit (RHU). In this way the duration of the probe’s lifetime could be significantly increased.

The performed study provides an interesting starting point for eventual further studies. However it cannot be concluded that a microprobe is feasible with the current level of technology available: a large effort is clearly required in this field. At the moment of writing a second microprobe study is being concluded, which investigates a significantly larger payload accommodation (20 kg total mass). Such a probe concept could be foreseen for the second Phase of the JME system, where most of the JEO payload is removed and substituted by a microprobe platform with multiple probes and an attitude control system.

4 MISSION ANALYSIS

This chapter gives a summary of the performed mission analysis for this mission. After taking various options into consideration (all chemical and a hybrid option consisting of electrical and chemical propulsion), the all-chemical solution was selected, mainly because of the lower spacecraft complexity and lower operational costs.

4.1 Launch

The spacecraft composite is assumed to be launched from Kourou with a Soyuz-Fregat 2-1b in the 2010-2025 timeframe. To maximise the payload in orbit, the Soyuz will place the composite in a highly elliptical GTO orbit, rather than performing a direct escape. This allows for a significant increase in payload compared to performing the escape manoeuvre with the Fregat upper stage; with this strategy the launcher will be able to deliver a payload in excess of 3000 kg, after which the spacecraft composite will perform the Earth escape manoeuvre using its own propulsion system. The following scenarios refer to a fully chemical propulsion approach with gravity assists.

4.2 The Transfer Phase

The transfer from Earth to Jupiter will be achieved by performing a series of Gravity Assists (GA). Mission analysis revealed that for an all-chemical propulsion system, the best performance is obtained with a Venus-Earth-Earth gravity Assist (VEEGA) sequence. The best performance in this case is a trade-off between the minimal Delta-V manoeuvres and the shortest transfer time. Figure 2-1 [9] shows a VEEGA transfer trajectory in 2009. Even if 2009 is not a realistic launch date in view of the inadequate preparation time, the figure is shown to provide a graphical overview of the sequence. The JOI (Jupiter Orbit Insertion) capture orbit is a 900.000km by 20 million km orbit.

Table 4-1 provides a summary of transfers between 2010 and 2020. Transfers in the period 2014-2016 are not shown, as they are very unfavourable.

Table 4-1: Summary of Transfer characteristics [10]

Launch Date	Earth escape DV (m/s)	Mid course DV (m/s)	JOI DV (m/s)	Total DV (m/s)	Mass after JOI (kg)	Arrival Date	Duration (years)
19-Jul-10	1186	400	1509	3095	1119	30-Jan-17	6.5
31-Jul-11	1430	360	1304	3094	1119	3-Jul-17	5.9
21-Apr-12	1301	15	1256	2572	1322	26-Sep-18	6.4
7-Oct-13	1475	14	1304	2792	1232	30-Dec-19	6.2
1-Jan-17	1321	113	1438	2872	1201	15-Dec-22	5.9
25-Jun-18	1306	370	1239	2915	1185	25-Jul-27	9.1
8-Feb-20	1906	86	1273	3265	1060	9-Apr-26	6.2

The table shows that the best launch opportunity occurs in 2012. However, due to the cyclic repetition of the launch windows, linked to the orbits of Earth, Venus and Jupiter around the Sun, similar results are also obtained after approximately 12 years. Additional analysis revealed the following Delta V requirements for the period 2020-2032, showing that 2023 indeed provides an attractive launch window. Other launch windows (e.g. 2018, 2020, 2024, 2029) are less attractive due to unfavourable alignment of the relevant planets.

Table 4-2: Details of High Thrust transfers using VEE GA sequence in 2020-2030+ [11]

Launch Date	Earth escape DV (m/s)	Mid course DV (m/s)	JOI DV (m/s)	Total DV (m/s)	Mass after JOI (kg)	Arrival Date	Duration (years)
16-May-23	1180	288	1245	2712	1264	2-Aug-29	6.2
26-Oct-24	1836	87	1321	3244	1067	21-Jan-32	7.2
13-Aug-26	1520	4	1364	2889	1195	20-Sep-32	6.1
20-Nov-29	1314	555	1353	3222	1075	19-Apr-37	7.4
9-Oct-29	1404	33	1983	3420	1009	11-Jun-37	7.5
23-May-31	1324	175	1445	2944	1175	18-Aug-37	6.2
1-Jan-33	1445	57	1261	2763	1244	20-Aug-39	6.6

Two different cases are shown for 2029 launch, the first using a 3:1 Earth resonant intermediate orbit instead of the nominal 2:1.

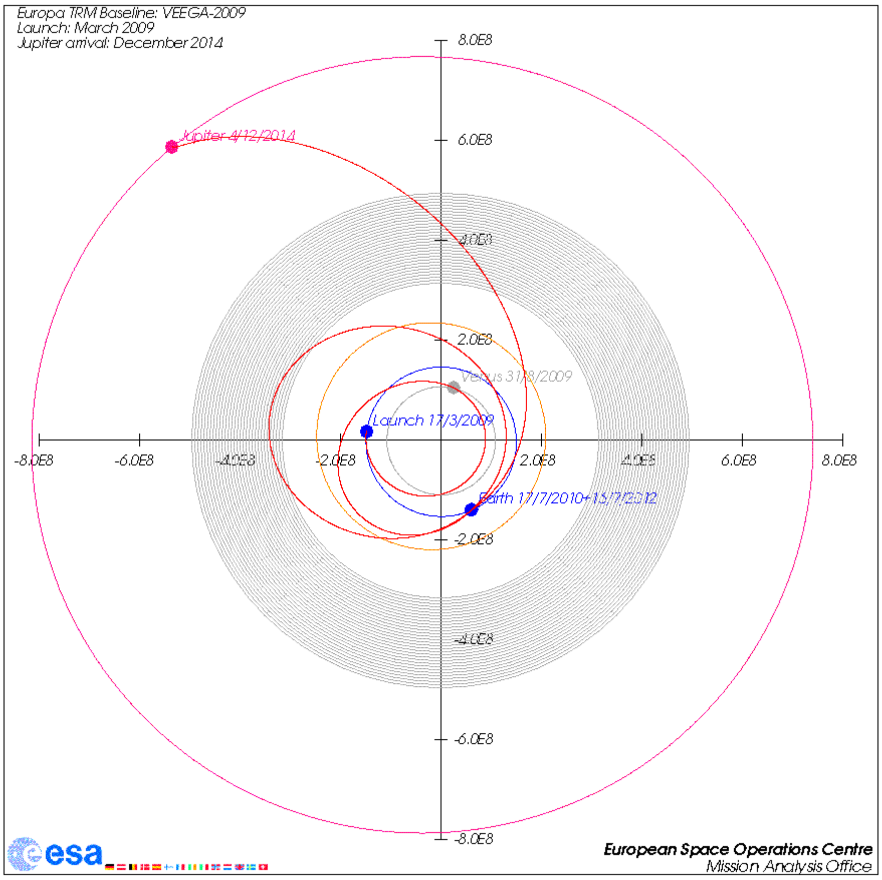

Figure 4-1: Ecliptic plane projection of the VEEGA-2009 transfer [9]

4.3 The Jovian Tour

After the transfer from Earth to Jupiter, the spacecraft must leave its elliptical orbit around the Sun, to achieve an orbit around Jupiter. Once the spacecraft composite arrives in the vicinity of Jupiter, a capture manoeuvre must be performed. To do this, a considerable change in velocity magnitude and direction is required. Two fundamental strategies can be applied:

- Acceleration in deep space to reduce approach speed at Jupiter
- Reliance on (several) manoeuvres and GA within the Jovian system to capture from high-speed approach.

In general, direct manoeuvres require large amounts of propellant and tend to take less time when compared to gravity assist manoeuvres and vice versa, as shown in Table 4-3. The table shows the required velocity change from the capture orbit to an 900.000 km x 50.000.000 km intermediate orbit, from which the final target orbit can be acquired.

Mission analysis [10] has shown that the most attractive tour strategy option (optimal Delta-V vs. insertion time ratio) is achieved by the second option: When performing an impulsive manoeuvre at the point of closest approach to Jupiter, the Jupiter Orbit Insertion (JOI) manoeuvre inserts the spacecraft into an eccentric orbit (respective perijove and apojove radii at approximately 5 and 250 R_J) with a orbit period of 6 months. At the apojove, another manoeuvre raises the perijove and retargets the spacecraft so that it will perform a swing-by at Ganymede.

Table 4-3: Capture implications for alternative strategies [10]

Approach	Delta-V	Time to capture orbit from initial approach to Jupiter
Direct capture, $V_{infinity}$ = 5.5km/s	1030 m/s	120 days
Ganymede GA then capture burn, $V_{infinity}$ = 5.5km/s	340 m/s	120 days
Reduce approach speed to 4 km/s, then Ganymede GA Or Reduce approach speed to 3.5 km/s, then Io GA	0	180 days
Reduce approach speed to 3km/sec, the capture through Lagrange point transit	50 m/s	1200 days
Reduce approach speed to 0 km/s, then capture burn	150 m/s	320 days

Once captured, the two spacecraft will tour of the Jovian system, performing a series of swing-by's at the Galilean moons (see Figure 4-2 for the capture manoeuvre principle using gravity assist manoeuvres or GAM). Finally, one or more impulsive manoeuvres will insert the spacecraft into their respective final orbits.

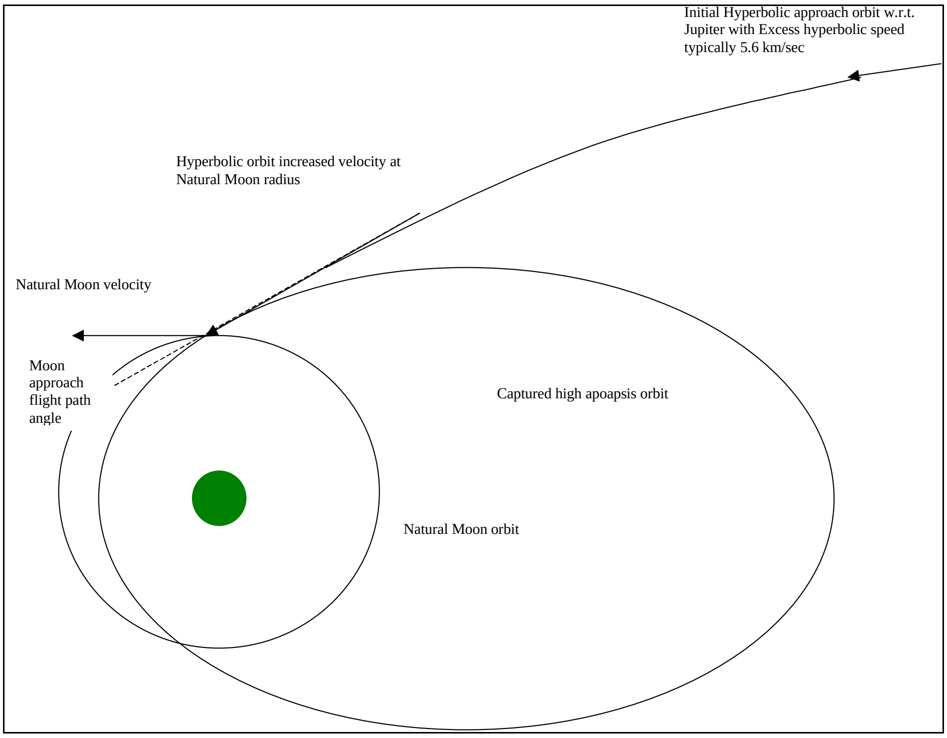

Figure 4-2: Principle of planetary capture using GAM at a natural moon [10]

The tour strategies differ considerably for the two spacecraft: The JEO will target a 200km circular orbit around Europa, while the JRS will target a highly elliptical Jupiter orbit, outside the main radiation belts, to reduce radiation exposure. The final parameters for this orbit will be optimised in subsequent mission analysis activities. The choice is influenced by required Delta-V, eclipses, communication links with JEO and radiation dose.

4.3.1 THE JEO TOUR

Once separated from the JRS, JEO will start its tour towards Europa, via a series of gravity assist manoeuvres and a number of propulsive manoeuvres, among which a Europa pericentre burn. In this way the initial elliptical orbit around Jupiter is transformed into a circular orbit around Europa.

Presently the tour configuration envisages 4 gravity assist manoeuvres at Ganymede, to obtain a pericentre of 200 km above the Europa surface. Next, 6 Europa gravity assists are performed, with a small propulsive burn at the apocentre to finally achieve the 200 km circular orbit around Europa. The current scenario envisages a radiation exposure exceeding 3 Mrad (4 mm Al) for the JEO tour, and a total duration of 545 days.

The tour manoeuvres require a Delta-V of 350 m/s, followed by a Europa capture manoeuvre of 920 m/s.

4.3.2 THE JRS TOUR

The same rationale applies for the JRS orbit insertion strategy, namely a trade-off between Delta-V, required time and experienced radiation dose. For the JRS the tour will be shorter, as the spacecraft will remain in an orbit around Jupiter, requiring a lower Delta-V. The total radiation dose will be much lower than for the JEO, as the spacecraft will remain in a much higher orbit, outside the main radiation belts, thus reducing the exposure to high radiation levels.

The target orbit is chosen to be resonant with Europa, to provide a good communications solution. Therefore a 12.7 R_j x 27R_j orbit was selected, which provides a relatively benign radiation exposure, while providing a 3:1 resonant orbit (i.e. 10.6 days). This means that time required for three Europa revolutions around Jupiter is equal to one orbital period of JRS around Jupiter. This guarantees an optimal communication window between JEO and JRS every 10.6 days.

To achieve this orbit, 4 gravity assists are required at Ganymede, which will reduce the apocentre of the initial JRS orbit. At this point a pericentre raising GAM at Callisto is used to keep the JRS outside the main radiation belts. Finally, one more Ganymede gravity assist is used to reach the 3:1 resonant orbit. The total time from first pericentre to JRS orbit insertion is 449 days, resulting in a total radiation dose of 74 krad (4 mm Al) during the transfer.

The total Delta-V required for this tour is 280 m/s. The next table gives an overview of the entire mission sequence.

Table 4-4: Delta V overview for the selected mission profile [1]

Mission phases		chemical propulsion	chemical/electrical propulsion
Launch		Launch by Soyuz with Apogee at 420000km	
Apogee raising	Strategy	apogee raise to 400 000km by impulse DeltaV	
	duration	2 days	
	deltaV	790m/s	
Earth Escape	Strategy	Escape by impulse DeltaV	L-E-E GA with SEP
	duration	_	3.3 years @75mN/ton
	deltaV	660 m/s	~2900 m/s
Interplanetary Transfer	Strategy	V-E-E GA	direct route
	duration	6 years	2.4 years
	deltaV	115 m/s	115 m/s
Jupiter orbit insertion	Strategy	Ganymede GA + impulse DeltaV	
	duration	_	
	deltaV	700 m/s	
Transfer	Strategy	JRS: Ganymede-Callisto GA sequence - JEO Ganymede-Europa GA sequence	
	duration	JRS: 450 days - JEO: 550 days	
	deltaV	JRS : 280m/s - JEO: 350 m/s	
JEO insertion	Strategy	impulse DeltaV	
	duration	_	
	deltaV	920 m/s	

4.4 The Operational Phase

After the approximately 7-year mission to reach the final orbits, the main science phase of the mission begins. The JRS will remain in its highly elliptical orbit for approximately two years, mainly acting as a data transfer station but also performing measurements of the Jovian system. Both spacecraft will also perform science operations during their tours, to maximise the science return (e.g. measurements of the Jovian radiation environment and possibly of Ganymede and Callisto during the flyby's).

The JEO operational phase will be completely different. As a result of the strong orbit perturbations caused by Jupiter and the limited propellant available, the JEO will have a highly time constrained operation phase, before the orbiter will crash on the icy surface of Europa. Analysis [9] has shown that a circular orbit between 50 km and 300 km provide the maximum lifetime of 60 to 66 days (maximum around 150 km), as shown in the next figure.

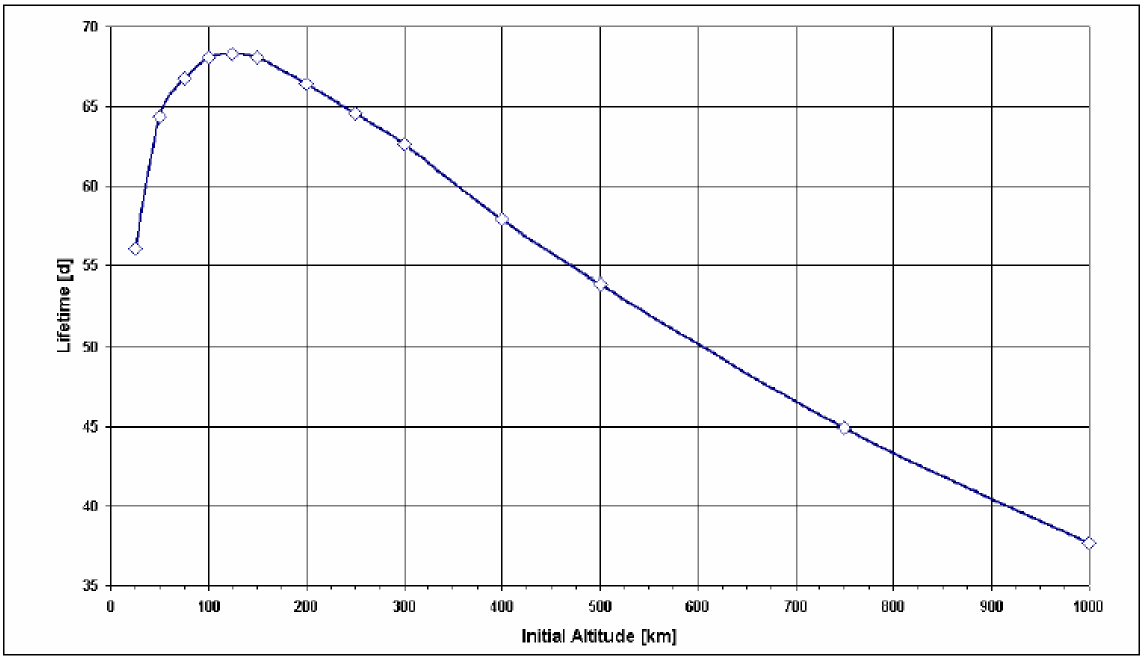

Figure 4-3: Variation of lifetime as a function of the initial altitude [9]

However, the mission duration is not only limited by orbital mechanics: the received radiation dose in 60 days will exceed 2 Mrad (4 mm Al), raising the total radiation dose in excess of 5 Mrad (4 mm Al). Therefore the 60-day mission must be seen as the maximum mission duration, even if the orbital lifetime could be increased with station keeping manoeuvres. For this study a 60-day observation period of Europa is taken as the design case.

A further limitation lies in the illumination of the spacecraft: the lower the orbit, the longer the eclipse periods of the spacecraft and the larger the battery capacity requirement. This additional mass will directly impact the payload mass and therefore requires a careful trade-off. At this point an orbit altitude of 200 km has been selected as a compromise between science and spacecraft requirements. Clearly the JRS orbit must be chosen is such a way that JEO can uplink all its science data before crashing onto Europa or succumbing to the lethal radiation dose.

4.5 Europa Coverage

The following picture [9] shows the coverage quality for the nominal, circular, polar 200 km orbit. The Europa surface area is subdivided into a grid of 4º width in longitude and 3º width in latitude. For each element in the surface grid, the number of times the satellite passes directly overhead is counted, subject to the condition that the respective part of the Europa surface must be sunlit at the time of the pass.

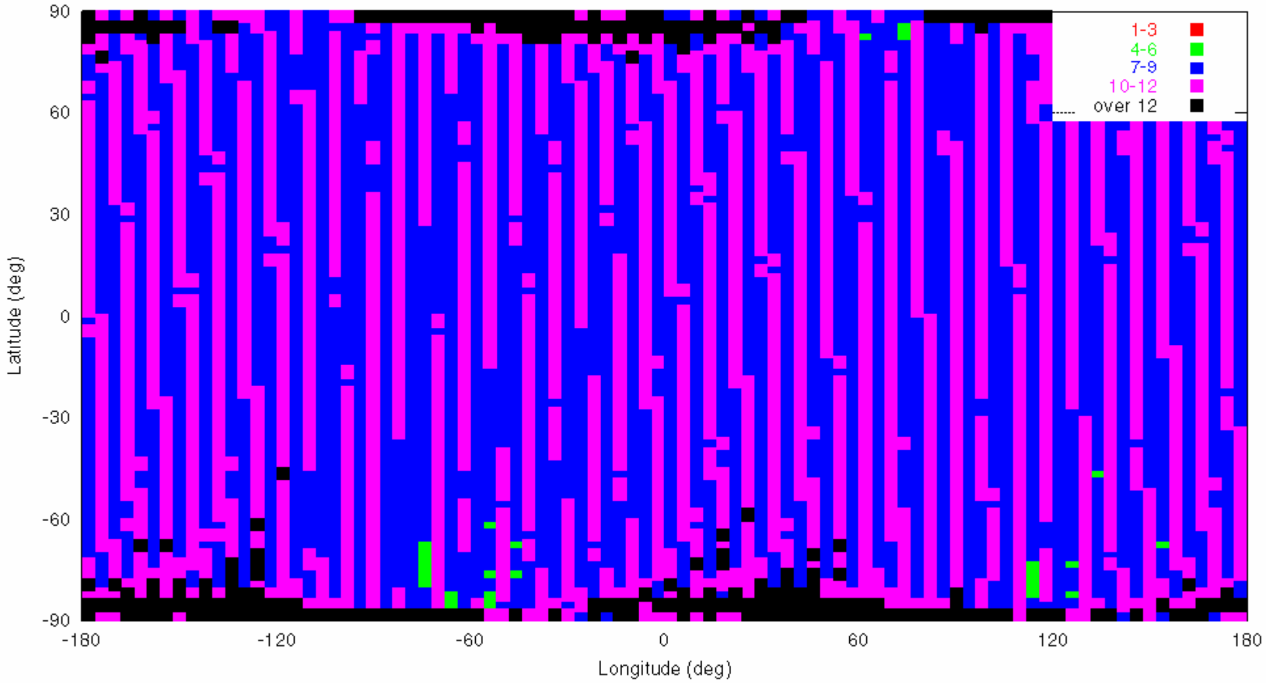

Figure 4-4: Surface coverage quality for the nominal case [9]

The spacecraft "sees" every point of the sunlit surface at least 7 times during the 66 days until it hits Europa. Most of the surface can be imaged more frequently than that, especially the polar regions.

4.6 Radiation environment and internal discharge

The radiation environment of the Jovian system is very severe. This is especially the case for the JEO spacecraft. The next tables provide an insight in the radiation doses that are expected, based on the Divine-Garrett radiation models.

Table 4-5 shows the expected radiation dose as a function of (Aluminium) shielding thickness for the main phases of the JME.

Table 4-5: JEO total radiation dose assessment as function of shielding thickness [1]

Environment	4 mm shielding (krad)	8 mm shielding (krad)	10mm shielding (krad)
Jupiter Tour	3170	805	350
dose per day around Europa	35	12	7
60 days around Europa	2100	720	420
Total	5270	1525	770

Table 4-6 shows the expected radiation for the two JME spacecraft.

Table 4-6: JEO and JRS total radiation dose assessment [1]

Environment	JEO	JRS
Jupiter Tour	350krad behind 10mm Al	74krads behind 4mm Al
	9.e14 e-/cm² on solar cells*	2.2 e13 e-/cm²on solar cells*
Operational orbit	420krads behind 10mm Al	450krads/year behind 4mm Al
	1.15e15 e-/cm² on solar cells*	1.4 e14 e-/cm²/yearon solar cells*

*= The presented figures are likely to underestimate the damage caused by protons to GaAs solar cells. It is expected that the representative equivalent dose could increase by a factor of 3-4.

The aluminium shielding thickness is used to assess the amount of shielding that is required. However, mass gains can be achieved by using different materials, such as Tantalum, as shown in the next table. Tantalum shielding is therefore recommended when the required aluminium shielding thickness exceeds 4mm.

Table 4-7: Mass gain by replacing Aluminium shielding by Tantalum shielding [1]

Environment	4 mm shielding (krad)	8 mm shielding (krad)	10mm shielding (krad)
Dose	5.3 Mrad	1.5Mrad	770Krad
Equivalent Ta shielding	0.651mm	1.1mm	1.3mm
Mass gain in percents	**~0%**	**> 12 %**	**20%**

For comparison: the Galileo equivalent Al shielding was 7.5mm

Another issue that needs attention is the internal discharging. Internal charging refers to the accumulation of electrical charge on interior, ungrounded metals or on or in dielectrics inside the spacecraft. Internal discharge can occur close to electronics equipments, causing significant upset or damage to satellite electronics.

The following figure shows the energy electrons must have to penetrate aluminium (10 mils ~0.25mm). Note also that 10^{10} to 10^{11} electrons/cm² are needed on the interior of a spacecraft to possibly cause internal discharges.

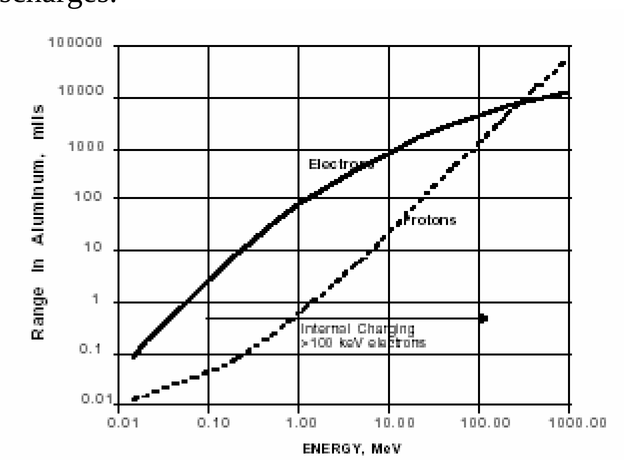

Figure 4-5: Approximate average electron and ion penetration ranges in aluminium [1]

Anomalies can be avoided by limiting isolated conductors on the inside of the spacecraft radiation shield. This solution was successfully implemented for Galileo programme: isolated conductors were subjected to <3cm², ungrounded conductors with length greater than 25cm were not allowed.

5 THE SPACECRAFT

This chapter provides the main characteristics of the spacecraft. After giving the rationale for the two spacecraft configuration, their current configuration and tentative payloads will be briefly discussed.

5.1 The composite

The composite consists of two spacecraft: the Jupiter Relay Satellite and the Jupiter Europa Orbiter. The propulsive manoeuvres of the composite will be performed by the JRS until and including the Jovian Orbit Insertion (JOI) burn. The propulsion system for the JME is all-chemical, to limit the spacecraft complexity and cost. Once the JOI has been performed, the composite will be separated into the JRS and JEO, which will perform their separate tours. As soon as the composite is separated from the Fregat upper stage, the JEO and JRS solar arrays will be deployed, to provide the power required during the transfer. The Venus fly-by will bring the composite at its closest approach to the Sun and due to the high albedo of Venus, the spacecraft will be exposed to high temperatures. Since the GaAs LILT solar cells are not designed for the very high temperature and flux, the back of the solar arrays will be covered with Si-cells, to provide power during the critical hot case. In this way the main solar array will be turned away from the Sun. This will require a more complex power regulation for the spacecraft, but it is the only way to avoid damage. Analysis indicated that restrictions on thermal emission through the cells should not be a problem for the panels as a result of the use of OSR (Optical Solar Reflectors).

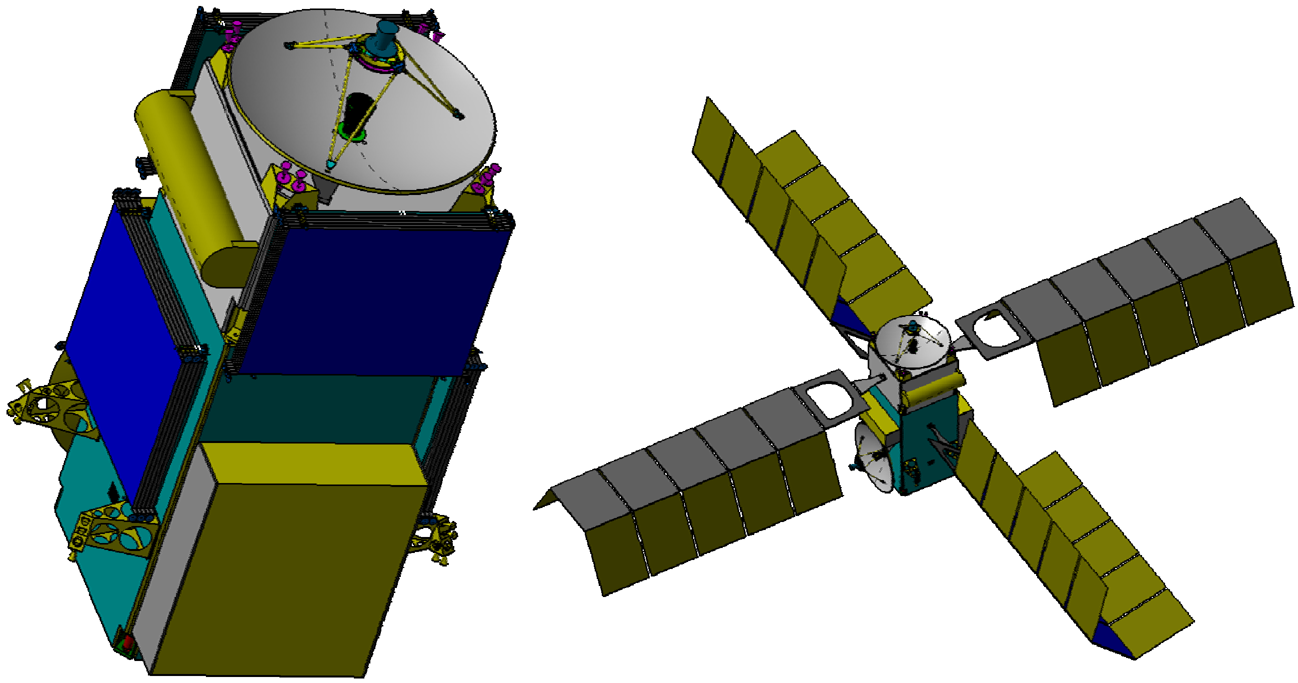

Figure 5-1: The JME spacecraft composite in launch (L) and transfer (R) configuration

The composite will also use the high gain antennas of both spacecraft, to be able to operate during all orientations, without the need of a steerable HGA. This will require a master-slave operation system capable of using systems on both spacecraft.

5.2 The Jupiter Europa Orbiter

The JEO will carry all payloads required for the remote sensing mission of Europa and might carry a microprobe (~1+5 kg), should a similar system this be feasible. The operational mission duration of the JEO is approximately 60 days. More details can be found in Table 5-1and Table 1-1.

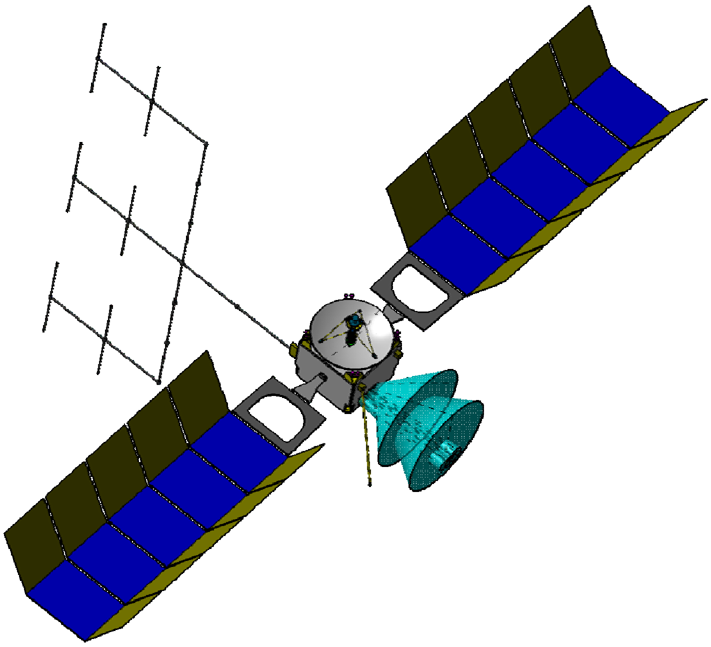

Figure 5-2: The Jovian Europa Orbiter (radar does not reflect ELRR design)

As explained before, the main challenges of the JEO are the very high radiation levels (in excess of 5 Mrad (4 mm Al)), the low solar flux (1/25th of the flux at Earth), short lifetime due to the strong orbit perturbations caused by Jupiter and the long distance between the Jovian system and Earth. The high radiation exposure calls for a combination of radiation hardened electronics and shielding: Radiation hardened electronics up to 1 Mrad are currently foreseen, the additional radiation will be attenuated by placing the spacecraft electronic components in a shielded box whenever possible. Spot shielding will be used for the remaining electronics.

The following figure shows the functional architecture of the JEO spacecraft:

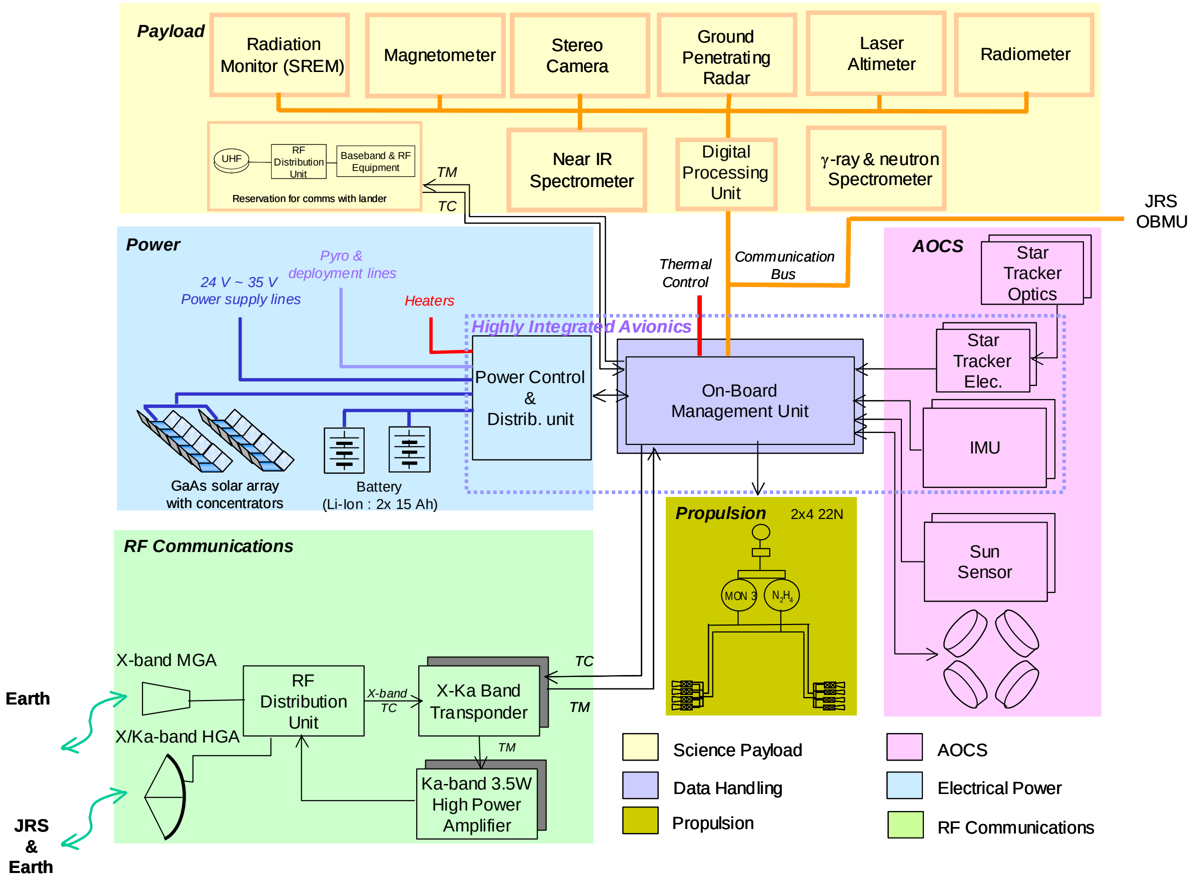

Figure 5-3: Schematic of the JEO system [1]

Figure 5-2 clearly shows the measure that has been foreseen to mitigate the low solar flux. The use of solar concentrators: highly reflective panels at the edge of the solar array that increase the total flux on the photovoltaic cells, to obtain an acceptable solar array size (~15 m^2 for 232 W EOL). These figures are based on current triple junction GaAs cells, assuming that LILT GaAs solar cells can be developed, capable of withstanding the encountered electron and proton fluence. This is currently being investigated in a dedicated study. Should the development of these cells prove to be unfeasible, an alternative power source, such as RTG's, will have to be considered.
The solar array is pointed towards the Sun by a Solar Array Drive Mechanism and around Europa, by a complementary satellite yaw manoeuvre for guaranteeing an optimal capture of the Sun flux, provided it doesn't affect science operations. During eclipses, the required power is supplied by a two 15 Ah Li-Ion batteries. Such sizing is driven by the requirement for science during eclipses by Jupiter (3.5h). Battery charge management is performed by the Power Control and Distribution Unit by shunting non-needed solar array sections.

The Data Handling architecture is organised around an integrated, internally redundant On-Board Management Unit (OBMU). The JEO data handling mainly works in slave state when stacked on top of the JRS and in independent state once the composite is separated. In slave state, the JEO OBMU directly receives its instructions from the JRS OBMU through the communication bus linking the two spacecraft. In independent state, the command and control functional chain is in charge of all activities, ranging from telecommands and telemetry to memory management, health monitoring and all AOCS functions. The On-Board Management Unit, which is part of the Highly Integrated Avionics package, is based on a powerful microprocessor and includes 50 Gbits of RAM memory.

The limited power and the short lifetime dictate the use of a relay spacecraft. Only in this way will the gathered data be secured, before JEO impacts on Europa: as will be explained in the next section, it is impossible to send all data to Earth in real-time. The Europa orbiter will require a data storage capability of approximately 50 Gbit, to store data that cannot be uplinked to the JRS directly. A 1.5 m high gain antenna (HGA) is used to communicate with the relay spacecraft and even Earth, when the spacecraft-Earth alignment allows for it. The communication links with Earth will only allow for very limited telemetry rates, just enough to send (and receive) housekeeping telemetry or very limited science data. RF communications are performed in X and Ka Bands. X-band is dedicated to ground telecommands either by a direct link (7 GHz) or via JRS (8 GHz). Ka-band (32 GHz) is dedicated to both housekeeping and science telemetry, in accordance with ESA standards. An additional MGA is used as backup. On one hand TM/TC with Earth is performed at a data rate of 2kbps. On the other hand, science telemetry is performed with JRS at a data rate of 2.3Mbps. New technology developments are required on the JEO communications system on high efficiency SSPA (30% targeted), and high data rate emitter.

The current design foresees the use of 2x4 22 N thrusters (I_{SP} = 308 s) rather than a high thrust main engine. This approach has been selected to facilitate the accommodation of the JEO on the JRS for the composite configuration, resulting in a very compact JEO design, saving structural mass. Furthermore the lower thrust level will also impose lower stress on the deployed JEO structure. This approach also offers an operational advantage: the thrusters can be tested during the cruise phase, which would be impossible for a main engine encased in the composite.

AOCS is performed by a chemical dual-mode propulsion system using 4 redundant 22N thrusters and operating with MON-3 and N2H4 propellants. During transfer and mission operational phases, the satellite is three-axis controlled according to a classic gyro-stellar architecture. The only actuator used for orientation and pointing of the satellite is a set of four 1 Nms reaction wheels mounted in a tetrahedral configuration (one ensuring redundancy). Chemical propulsion is used for wheels off-loading. Attitude sensing is performed by a self-redundant inertial measurement unit (IMU) and a redundant narrow-field star tracker. The IMU and the electronic part of the star tracker are part of the highly integrated avionics package. A coarse sun sensor is used to detect exit from eclipse without any a priori knowledge of the position along the orbit being needed, and to ensure solar array pointing towards the Sun. An innovative horizon sensor for accurate positioning around Europa will be required. Considerable developments are required to ensure compatibility of the star tracker and horizon sensor with the high radiation environment.

An additional complication applies to JEO: as the orbiter will impact on Europa, the JME will have to comply with the COSPAR requirements on planetary protection for Europa, imposing limitations on the usable materials as well as complex assembly and integration operations, which will be a design and cost driver.

5.3 The Jupiter Relay Satellite

The JRS has several tasks:

- Provide the propulsive manoeuvres from the highly elliptical Earth orbit to the JOI for the composite and subsequent manoeuvres to place the JRS in its final orbit around Jupiter
- Relay science and telemetry data from JEO and JRS to Earth and back
- Carry all subsystems that are not required on JEO, as it is exposed to much less radiation
- Carry a payload suite to study the Jovian system

The JRS will perform most of the spacecraft composite's propulsive manoeuvres and will finally assume a highly elliptical orbit around Jupiter, outside its main radiation belt. This will allow the JRS to survive for two years once it reaches its final orbit. As a result of the large propulsive manoeuvres, the JRS is considerably larger than the JEO, as can be seen in Figure 5-1 (JEO is the small cube placed on top of the elongated JRS). Figure 5-4 shows a cutaway view of the JRS.

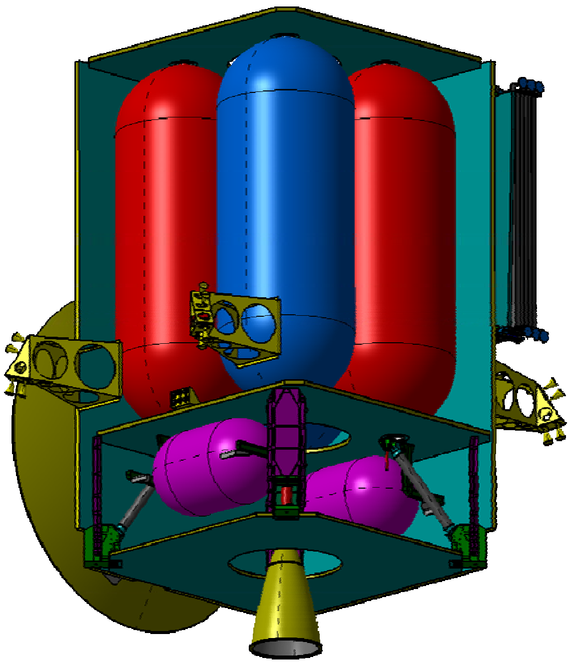

Figure 5-4: Cutaway view of the Jovian Relay Spacecraft

The JRS will only require modest additional shielding to survive for two years, since the radiation hardened electronics (1 Mrad) will offer adequate protection in the less severe environment. Even if the JRS requires more power than the JEO due to the comms system, the same solar panel surface will suffice (~15 m^2 for 300 W EOL), as the panels will suffer less degradation in 2 years, than the JEO in 60 days. Again, this assumes that the required solar cells can be developed.

The following figure shows the functional architecture of the JRS spacecraft:

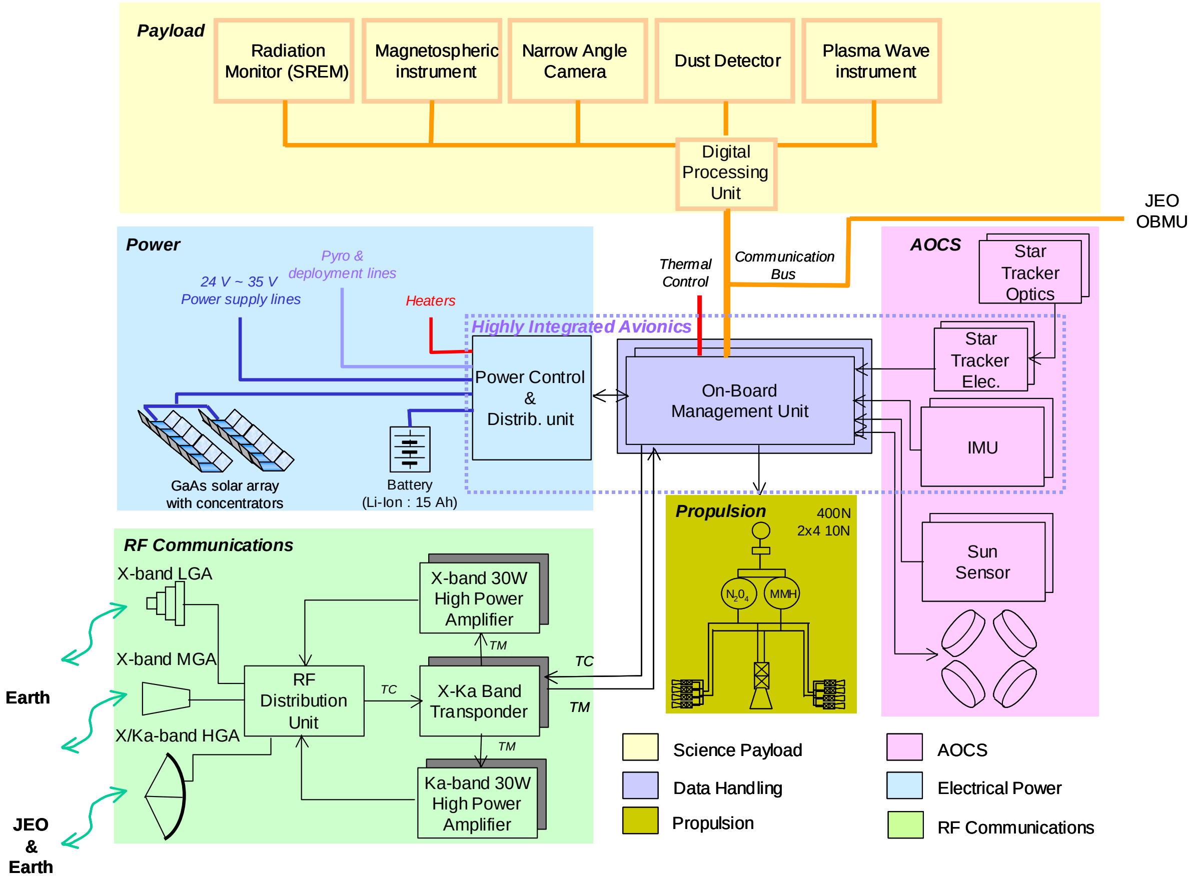

Figure 5-5: Schematic of the JRS system [1]

The solar arrays require to be pointed towards the Sun by a Solar Array Drive Mechanism during interplanetary cruise and while performing Jupiter science operations while Jupiter pointed. During eclipses, which are only expected in the vicinity of Earth and possibly during gravity assists, the required power is supplied by a 15 Ah Li-Ion batteries. Battery charge management is performed by the same PCDU used on JEO. The resulting 28 V regulated power bus is distributed to all spacecraft users by solid state switches located in this unit. The PCDU is also responsible for Pyro commands generation. The PCDU is integrated in the Highly Integrated Avionics package.

The JRS data handling architecture is identical to the JEO architecture, without the dual mode configuration and is also part of the highly integrated avionics package.

RF communications are performed in X and Ka Bands. X-band is dedicated to ground telecommands (7 GHz), to telecommands sent to JEO (8 GHz) and for telemetry in early operations (LEOP). Ka-band (32 GHz) is dedicated to both housekeeping and science telemetry, in accordance with ESA standards. A 1.5m diameter HGA is used for communication, whereas an LGA and an MGA are used during LEOP operations. The MGA is also intended for backup telecommand reception at large distances from Earth. TM/TC with Earth is performed at a data rate of 2kbps, while science telemetry with JEO and Earth is achieved at data rates of 2.3Mbps and 30kbps respectively. As for the JEO, new technology developments are required on the JRS communications system on high data rate receiver. A down converter from 32GHz to 7GHz on the telemetry receiving channel permits to use the same transponder on JRS as on JEO.

The propulsion system of the JRS (and for the entire composite) is based on a 400 N main engine operating with N_2O_4 and MMH propellants (I_{sp}= 320 s), equivalent to the performance of a European S400 series engine. It would be advantageous to target a performance of >323 seconds. This would increase mass margin by at least 24kg. The baseline architecture uses 8 pairs of thrusters to provide thrust in all axes and pure torques.

During transfer and mission operational phases, the satellite is three-axis controlled according to a classic gyro-stellar architecture. The only actuator used for orientation and pointing of the satellite is a set of four 1 Nms reaction wheels mounted in a tetrahedral configuration (one ensuring redundancy). 8 redundant 10N thrusters are used for wheels off-loading. This configuration permits pure torque generation in order to minimize the perturbations on the interplanetary trajectory (most interplanetary spacecraft use only 8 thrusters (4 pairs) for manoeuvres and attitude control, but this does produce cross-couplings, and there is only one axis for pure thrust.). Attitude sensing is performed by a self-redundant IMU and a redundant narrow-field star tracker. As for JEO, the IMU and the electronics part of the star tracker belong to the highly integrated avionics package. A coarse sun sensor is used to detect exit from eclipse without any a priori knowledge of the position along the orbit being needed, and to ensure solar array pointing towards the Sun. The same challenges apply for the JRS star tracker as for the JEO system.

The relay spacecraft will have a memory storage capability of approximately 256 Gbit. This will allow for the storage of JEO and JRS data obtained during the operational phase of the mission. Unfavourable alignment with Earth will preclude continuous data transmission: even the foreseen data rate of 30kbps to Earth through a 1.5 m HGA will require up to 290 days to send the JEO data gathered during its 60 day mission. Since the JRS will have its own payload suite, additional storage is required: as the scientific interest will be focussed on the Europa science data, the JRS science data transmission will have lower priority than the JEO data. Multiple scenarios can be envisaged for relaying the data to Earth: either all JEO data is first sent before sending any JRS measurements, or a priority ratio is established: e.g. 80% of JEO data and 20% of JRS data. In this way it would take approximately 20% more time to send down all JEO data, but this would give the JRS payload PI’s data to work with in the first year.

The JME mass budget is summarised in Table 5-1. More characteristics can be found in Table 1-1.

5.4 Overall mass budget

The present analysis has shown that the budgets are very sensitive to variations in the mission variables, such as the actual radiation dose, orbital parameters, science operation duration and especially payload mass. The current launcher margin includes a system margin of 20% along with a component margin of 5%-20%, depending on the technology readiness level of the component. The payload mass has been maximised; i.e. the excess launcher capacity after applying the relevant margins has been allocated to the payload. Marginal increases of P/L or of the S/C subsystems could jeopardise the entire mission. The current mass budget is shown in Table 5-1:

Table 5-1: The JME mass budget including margins (status November 04)

Item	Mass including margin (kg)
JEO platform mass	373
JEO science instruments capacity	30
JEO dry mass	**403**
JEO propellant mass	253
JEO wet mass	**656**
JRS platform mass	580
JRS science instruments capacity	14
JRS dry mass	**594**
JRS propellant mass	1680
JRS wet mass	**2274**
Total JME mass	**2930**
Adapter mass	70
Total launch mass	**3000**
Launcher capacity	3000
Margin w.r.t. launcher capacity	0

This table shows that the payload capability of the two spacecraft is lower than the specified HIPS payloads (34.4 kg vs. 30 kg and 15 .7 kg vs. 14 kg). However, possibilities have been identified to increase the payload capacity of the JME. One option is the use of hybrid propulsion: solar electric propulsion (SEP) combined with a conventional chemical propulsion system. By using the large solar array area required for operation in the Jovian system (low solar flux) in the inner solar system, enough power is available to operate an SEP system without the need for additional solar arrays. Initial analysis has shown that this could lead to a mass saving around 100 kg. Another option is the development of a main engine with a higher I_{SP}.

6 THE CHALLENGES

The JME Technology Reference Study is intended to identify the technologies required for a mission to the Jovian system or other outer planets. It is clear that a similar mission stretches the limits of our current technology and serious development efforts are required to enable a mission to the Jovian system. The development of these technologies and techniques will have to start within the next few years to make sure that such a mission can be achieved within the presented timeframe. Currently the following issues have been identified:

Radiation: The spacecraft electronics need protection against the radiation levels in excess of 3 Mrad. To avoid an excessive shielding mass, radiation hardened electronics will be required in the order of 1 Mrad. This will require extensive development in this field, making it the main challenge identified in this study. An effort is also required to identify the best suited radiation material, as well as the design and qualification of the shielding structure. The design of an integrated avionics box capable of operating up to a 1 Mrad dose at low mass will also be a must.

Power generation: The 5.2 AU distance from the Sun results in 1/25th of the solar flux. Therefore solar power generators need to be compatible with low intensity, low temperature (GaAs LILT cells are foreseen) and very high fluence (possibly three orders of magnitude higher than current GaAs cells allow). This will require a new and costly development. In order to increase the efficiency of the solar arrays, solar concentrators will be required (see section 5.2). Presently a patent exists on this technology, deposited by Boeing, an issue that will need to be addressed in future. Should these developments prove to be unfeasible, RTG technology will have to be taken into consideration. The implications of an RTG system on the design are being assessed.

Material compatibility: Another issue that needs to be addressed is the behaviour of the selected spacecraft materials in this extreme radiation environment. The selected materials shall also be compatible with the cleanliness requirements dictated by the COSPAR planetary protection rules.

Thermal: The spacecraft must be compatible with both the hot (Venus fly-by) and the cold case (Jovian system). The use of active heat transfer (fluid loop) as well as RHU's might be required.

Low resource: Even if LILT cells and solar concentrators will be available, the available power will be quite limited. Therefore efficient low resource systems will be required for all subsystems: from communication systems to the payload. One promising way is be the development of highly integrated payloads and spacecraft subsystems, which will limit both required mass and power.

Payload: The payload design is based on the HIPS approach, which seems the only approach that makes a small spacecraft approach feasible. This will require considerable developments, both from a technical point of view as from a programmatic point of view. Apart from the development of the required technology, a strong coordination will be required between the institutes responsible for the different payloads. Another challenge lies in the development of the radar antenna, to make sure that a successful deployment can be obtained.

Communications: New developments will be required to operate in both X- and Ka-band: high data rate (3 Mbps) KA-X transponders for both TC and TM, high efficiency Ka-band SSPA (3.5 W RF, 30% efficient)

AOCS: The instruments (e.g. the radar) will require accurate nadir and attitude pointing control. Current systems are not compatible with the expected radiation environment, which will pose a considerable technology challenge. Furthermore, a new planet edge detection system will be required, as Europa does not have (sufficient) CO_2 in its exosphere, to allow for conventional limb detection systems. Further complications arise due to the large disk of Jupiter, masking the limb of Europa during the JEO orbit.

Autonomy: The long mission duration and the hostile environment call for a highly autonomous mission capability. The costs of the mission operations for the long mission duration (7+ years for JEO and 9+ years for JRS) including extensive GAM's will be very high. Furthermore the exposure to the very high radiation will most likely cause a significant number of safe modes, upsets, etc. Having a robust autonomous system would preclude the necessity of expensive round the clock presence of spacecraft operators, with the exception of the most critical manoeuvres. This will require developments in software, optical navigation, manoeuvre scheduling as well as sun sensors compatible with large solar flux variation. Additional autonomy is required for the instruments: Both the commissioning and the operation will have to be monitored on board as much as possible, in view of the short science mission. The commissioning phase must be very short, to allow for an acceptable operational phase. Furthermore, it will not be possible to receive all data in real time, as most data gathered by JEO will reach Earth after the 60-day operational phase. Intervention in case of problems from ground would be too late by then, as the JEO will have already crashed onto Europa.

Planetary protection: COSPAR planetary protection requirements for Europa are of the highest level. As JEO will impact on Europa, this will impose serious complications for the JEO: it will limit the materials that can be used and will require complex and costly integration procedures. A means must be found to optimise the operations requiring the highest cleanliness demands and allow for integration in environments with less stringent cleanliness, without compromising the achieved decontamination. In-flight decontamination by the severe radiation in the Jovian system must also be exploited as much as possible.

Microprobe impact: Impacting at high initial velocity (in the order of several km/s) on planetary bodies without an atmosphere requires materials and subsystems capable of withstanding very high impact shocks (~ 10,000 - 100,000 g, strongly depending of deployment method). Unless an attitude control system can be accommodated, no preferential load axis can be assumed, requiring a design that is independent of the attitude. This approach will be required if a low mass microprobe system is to be used.

7 ACRONYMS

AIT	Assembly Integration and testing
Al	Aluminium
AOCS	Attitude and Orbit Control System
AU	Astronomical Unit (~150 Mkm)
CDF	Concurrent Design Facility
COSPAR	Committee on Space Research
ELRR	Europa Low Resource Radar
EOL	End Of Life
GA	Gravity Assist
GaAs	Gallium Arsenide
GAM	Gravity Assist Manoeuvre
GNS	Gamma and Neutron Spectrometer
GTO	Geostationary Transfer Orbit
GSE	Ground Segment Equipment
HGA	High Gain Antenna
HIPS	Highly Integrated Payload Suite
IMU	Inertial Management Unit
JEO	Jupiter Europa Orbiter
JOI	Jupiter Orbit Insertion
JRS	Jupiter Relay Spacecraft
JME	Jovian Minisat Explorer
LGA	Low Gain Antenna
LILT	Low Intensity Low Temperature
MGA	Medium Gain Antenna
OBMU	On-Board Management Unit
OSR	Optical Solar Reflectors
P/L	Payload
RHU	Radioisotope Heating Unit
R_J	Jupiter equatorial radius
ROM	Rough Order of Magnitude
RTG	Radioisotope Thermoelectric Generator
S/C	Spacecraft
SEP	Solar Electric Propulsion
SSPA	Solid State Power Amplifier
TBC	To Be Confirmed
TBD	To Be Determined
TC	Telecommand
TM	Telemetry
TRS	Technology Reference Study
VEEGA	Venus-Earth-Earth Gravity Assist
VIS-NIR	Visible and near-infrared

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