IAC-04-Q.2.a.02

SYSTEM CONCEPTS AND ENABLING TECHNOLOGIES FOR AN ESA LOW-COST MISSION TO JUPITER/EUROPA

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ABSTRACT

The European Space Agency is currently studying the Jovian Minisat Explorer (JME), as part of its Technology Reference Studies (TRS). TRS are model science-driven studies contributing in the ESA strategic development plan of technologies that will enable future scientific missions.
The JME focuses on the exploration of the Jovian system and particularly the exploration of its moon Europa. The Jupiter Minisat Orbiter (JMO) study, which is the subject of the present paper, concerns the first mission phase of JME that counts up to three missions spaced in time by 6 years using pairs of minisats. The scientific objectives are the investigation of Europa's global topography, the composition of its (sub)surface and the demonstration of existence of a subsurface ocean below Europa's icy crust.
The present paper describes the candidate JMO system concept, based on a Europa Orbiter (JEO) supported by a communications relay satellite (JRS), and its associated technology development plan. It summarizes an analysis performed in 2004 jointly by ESA and the EADS-Astrium Company in the frame of an industrial technical assistance to ESA.
It addresses the interplanetary transfer, the hostile radiation environment, the power generation issue, the communication system, as well as the need for high autonomy on-board.

1 INTRODUCTION

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 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 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 paper addresses one of them called JMO [1], standing for Jupiter Minisat Orbiter. This mission has to be seen as the first phase of a larger concept aiming at the Jovian system exploration, JME. JME is composed of up to three phases spaced in time by 6 years, using pairs of minisats. The science objective of these minisats is targeted towards Europa with regard to astro-biology and the presence of surface ice on this Jupiter moon, although other moons could be of interest. One of these two satellites, the Jovian Europa Orbiter (JEO) will perform in-orbit remote sensing measurements for an expected duration of 60 days, whereas the second one, the Jovian Relay Satellite (JRS) will be put in an orbit around Jupiter outside its main radiation belts, permitting to relay the JEO science data to Earth. Jupiter science observations from JRS are also seen as an added value to the mission.

The work presented here was performed within the frame of a technical assistance to ESA in support of an assessment study of the JMO.

Our presentation first addresses the **interplanetary transfer** analysis carried out in combination with propulsion systems and spaceship staging trade-offs. Chemical propulsion is considered either alone or associated with solar electrical propulsion. The constraining mission requirements are a launch by Soyuz-Fregat and a trip to Jupiter not longer than 6 years, fixed for cost efficiency purposes.

The Jovian hostile **radiation** environment is the second critical point ; in the Europa vicinity, surviving a few Mrads dose after 2 months of science experiments is indeed a real challenge. Our document shows the method for assessing the radiation levels, and the mitigation strategy.

At a distance of 5AU from Sun, and anticipating solar cell degradation as high as 38%, the use of solar electrical **power generation** rather than radio-isotope might seem unrealistic. We however demonstrate that this option is reachable within reasonable technological steps and with acceptable panel sizes.

Next, we discuss the need for a **communications** relay satellite, the choice between Ka-band and optical links, and the communications architecture designed both for commanding the two satellites and for science data download towards Earth, collected at 40kbps around Europa.

System **autonomy** is then presented. Autonomy is mandatory when a quick reaction is required whereas any signal takes more than 50 minutes to travel between Earth and spacecraft. It is also a mean to reduce the ground station work load.

Planetary protection is also an issue of prime importance as the objective is to keep Europa uncontaminated in order not to compromise further science investigations.

The resulting **spacecraft conceptual design** is described, with some details on the avionics and the propulsion system. The presentation ends with a synthesis of **requirements for new technologies,** and a tentative schedule for JMO developments.

2 INTERPLANETARY TRANSFER

2.1 Requirements and drivers

The objective is to define an interplanetary scenario that will place the two JMO minisatellites in their operational Jovian orbits using a Soyuz-Fregat launch vehicle in its updated variant, 2B, from Kourou, with an assumed launch capacity of 3000kg in geostationary transfer orbit [3]. The Orbiter (JEO) is placed in a low orbit around Europa, whereas the relay satellite (JRS) remains in an orbit around Jupiter. Such scenario has to be optimised according to the following criteria:

- interplanetary transfer duration; <6 years up to Jupiter arrival fixed as a requirement;
- radiation doses during transfer around Jupiter;
- propellant mass minimisation;
- intersatellite communications constraints.

To perform such optimisation, the following parameters were considered:

- interplanetary route with use of gravity-assist manoeuvres;
- all chemical propulsion system versus hybrid solar electrical-chemical propulsion system;
- number of modules: a dedicated propulsion stage is therefore considered in addition to the two minisatellites;
- operational orbits orbital parameters.

2.2 All chemical propulsion

Direct high thrust transfers up to Jupiter require too high ΔV for the available launch capacity and therefore are discarded. Multi gravity assists (GA) options, around Earth and Venus to provide aphelion raising, permit to save propellant mass.

The most ΔV efficient case is the VGA-EGA-EGA route, shown in Figure 1. That was the route followed by Galileo (launched in Oct. 1989) [2].

Good launch opportunities, summarized in Table 1, occur between 2010 and 2030, and are driven by the Earth-Venus synodic period,. Transfer durations in the order of 6 years imposes ΔVs' in the range 1900m/s to 2400m/s.

Launch Date	Total DV	Duration	Launch Date	Total DV	Duration
19-Jul-10	2290 m/s	6.4 yrs	8-Feb-20	2770 m/s	6.2 yrs
31-Jul-11	2380 m/s	6.2 yrs	16-May-23	2140 m/s	6.2 yrs
21-Apr-12	1890 m/s	6.4 yrs	26-Oct-24	2560 m/s	7.2 yrs
7-Oct-13	2300 m/s	6.2 yrs	13- Aug-26	2210 m/s	6.1 yrs
1-Jan-17	2180 m/s	6.0 yrs	20-Nov-29	2580 m/s	7.4 yrs
25-Jun-18	2240 m/s	9.1 yrs			

Table 1: ΔVs and durations as function of launch dates for interplanetary transfer using all chemical propulsion

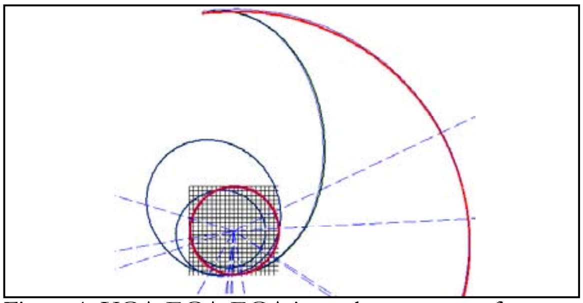

Figure 1: VGA-EGA-EGA interplanetary transfer

2.3 Hybrid electrical/chemical propulsion

Solar Electrical Propulsion (SEP) is considered in addition to chemical propulsion. Due to the power demand of such propulsion mode, the strategy is to use it only for Earth departure, where adequate power can be collected with solar arrays of acceptable sizes. SEP is combined with a Lunar GA (LGA) to provide a low energy Earth escape, and one or several EGAs' to provide aphelion raising.

After LGA, return to Earth occurs typically 15 months later after an intermediate deep space ΔV to increase Earth approach speed. After a second gravity assist at Earth, aphelion is raised considerably. With one EGA the transfer duration is 3.7 years but requires 6000m/s with a 200mN thrust per ton, whereas it is 5.7 years with 2 EGAs', and only 2200m/s with same thrust to mass ratio.

A study of ΔV sensitivity to acceleration capacity (thrust to mass), presented in Figure 2, allows trade-off of ΔV with propulsion system mass. After aphelion raising by chemical propulsion the composite spacecraft mass is <2000kg. Moreover, Europe is developing SEP Xenon thrusters providing 150mN to 200mN thrusts with Isp>4000s, for telecommunications satellites and for the Bepi Colombo mission to Mercury. Comparing the propellant mass gain of having more thrusters with the mass penalty due to SEP hardware equipment showed that one thruster is optimal. During this analysis, it has also been demonstrated that the solar array as sized for power requirements around Jupiter is sufficient for the SEP needs around Earth.

Launch opportunities occur each 13 months with ΔV varying between 2800m/s and 3300m/s, for a Xenon mass variation between 170kg and 190kg. This proves that SEP permits to have a system concept more flexible with respect to the launch date than the all chemical propulsion option.

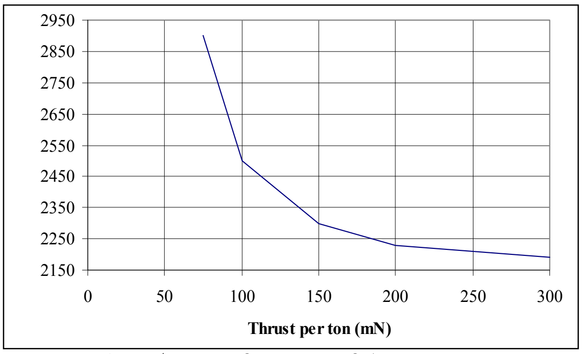

Figure 2: SEP ΔVs' as function of thrust to mass ratio in an LGA-EGA-EGA scenario

2.4 Capture at Jupiter

The capture at Jupiter is performed by chemical propulsion. An impulsive ΔV can perform a direct injection, but a Callisto or Ganymede GA followed by a pericentre ΔV is more efficient. This ΔV depends on the arrival velocity, as shown in Figure 3. GA with Io was the option for Galileo.

The resulting capture orbit is a 900000km by 20million km orbit. After capture, it has been found more mass efficient to put the two satellites on different trajectories.

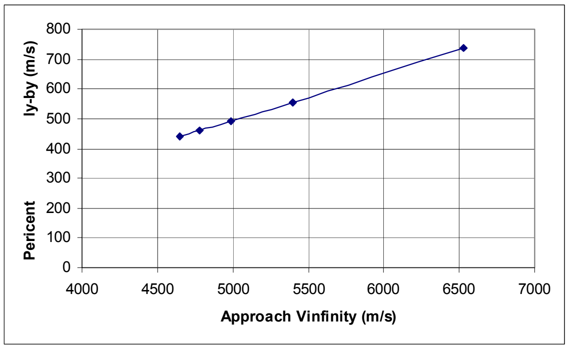

Figure 3: injection ΔV as function of approach velocity after a Ganymede GA

2.5 JEO Jupiter tour and insertion

The main issues for JEO are transfer time, ΔV and radiation. The pericentre burn required for Europa orbit insertion depends on the approach excess hyperbolic speed to the moon. Therefore, insertion ΔV is reduced if GAs' and intermediate ΔVs' can be used to achieve a low eccentricity Jupiter orbit with a similar semi-major axis as Europa. The trade-off resulted in a sequence of 4 Ganymede GAs', followed by 7 Europa GAs', for a total duration of 550days. Intermediate ΔVs' amount to a total of 350m/s.

Finally, JEO is inserted on a polar circular orbit around Europa, at 200km altitude, by means of a

ΔV equal to 920m/s. Such altitude was selected with respect to the following constraints:

- power required on the science instruments for a given observation accuracy rapidly increases with altitude;
- altitude also influences the eclipse duration, which should be limited to reduce battery charging needs;
- the higher the altitude, the quicker the orbit decay (this trend starts from ~150 km upwards; below it is not the case).

Orbit altitude control is moreover baselined as it only requires ~20m/s for 60 days. Without any orbit control, typically when its mission ends, JEO impacts the Europa surface after 60days.

2.6 JRS Jupiter tour and insertion

Similarly to JEO, the issues for JRS are transfer time, ΔV and radiation. But communications with JEO play an important role in the final orbit selection. An operational orbit resonant with Europa permits to envisage communications slots at regular time intervals and shortest distance. A 3:1 resonant orbit instead of a 2:1 resonant one was selected, as it implies higher distances to Jupiter, which means lower radiation. The orbit is equatorial with apojove at 26.3Rj (Rj=Jupiter radius=71,400km) and perijove at 12.7Rj. The orbital period is 10.6days.

Such orbit is reached by means of 4 Ganymede GAs', 1 Callisto GA and a final Ganymede GA. The required ΔV is 280m/s, and the tour duration 450days.

2.7 Staging analysis

The staging analysis is first intended to optimize the total mass by defining the number of modules composing the spacecraft, and the propulsion system assigned to each of them. Complexity and cost are other criteria taken into consideration.

Staging optimisation included the following options:

- addition of boosters for Earth aphelion raising;
- high thrust chemical or SEP for Earth escape;
- additional Carrier module to perform Jupiter insertion, and possibly to bring JRS or JEO to its operational orbit.

The trade-off conclusions are the following:

- There exist solutions compatible with launch mass capacity for both all chemical propulsion and chemical+electrical propulsions;
- the mass optimum architecture with solar electrical propulsion is 140kg lower in mass than the mass optimum architecture with all chemical propulsion;
- options with Carrier module are heavier;
- boosters are only worth using with electrical propulsion because of the Isp improvement in the apogee raising phase (320s for boosters instead of 290s for small thrusters).

3 SYSTEM CONCEPTS

3.1 System concept drivers

Table 2 gives an overview of the JMO system drivers, and the decision rationale for each of them. The main criteria for decision were the cost, the reliability and the science return. Although new technologies are mandatory to enable such mission, particular care was taken to limit their number, in order to increase the chances for realizing it within two decades from now.

	Elements to be traded	Decision rationale
Mission with one or two satellites	Need for JRS to relay science data between JEO and Earth	Two satellites required. Launch mass does not permit to embark enough power on JEO to directly transmit the required amount of data in 60 days
Inter-planetary transfer	Chemical propulsion or hybrid chemical-electrical propulsion	Chemical propulsion selected for robustness and cost reasons
Staging	Number of stages and type of propulsion system	2 stages selected for simplicity (=> robustness & cost) & launch mass Dual mode on JEO using 4x22N thrusters for deltaVs , Isp=308s
Radiation	JEO equipment tolerance	H/W tolerant to 1Mrad together with additional satellite shielding (10mm on JEO), based on a technological feasibility estimation
	Solar cell tolerance to radiations	Off-the-shelf GaAs cells have acceptable degradation levels
Power systems	Solar arrays or RTGs	Solar arrays selected because of ecological problems due to Earth fly-bys and lack of RTG availability. JEO Europa orbit local solar time=60°
Commu-nication archi-tecture	Permanent links between JEO and JRS versus dedicated slots	JRS orbit selection permitting communications at shortest distance
	Mobile or fixed antenna on both JRS and JEO	Fixed antenna selected for robustness and cost purposes
	JEO direct communi-cation with Earth for ranging and TM/TC (excluding science TM)	JEO TM/TC communication with Earth, identical to JRS
Wavelength for commu-nications	Ka-band, X-band or optical links Data rates	Ka-band at 30kbps to Earth and 2300kbps at 250000km from JEO to JRS. Optical links not bringing advantages accounting for mid-term perspectives

Table 2: JMO system concept trade-offs overview

3.2 Radiation

Radiation, caused by Jupiter electrons emission, is the most critical issue of the JMO mission.

To assess the Jovian radiation levels around Jupiter, the Divine-Garrett model was considered as the reference model for the JMO study. This model seems to be more pessimistic, and thus leads to more conservative solutions, than a new model like the Galileo Interim Radiation Electron (GIRE) that could replace it in the near future.

Results, as shown in Figures 4 & 5, demonstrate that off-the-shelf hardened devices, withstanding typically 200krad as a maximum, are not well suited for a JMO mission. The 1st enabling technology for JMO is therefore to consider that new equipments can be built which are tolerant to 1Mrad. A substantial development effort will be required for such objective.

Based on that assumption, a typical 10mm aluminium shielding is required on JEO, and 4mm on JRS. This is presented in Table 3 together with fluences computation, assuming 500µm cover glass over the solar cells, and 50% margin.

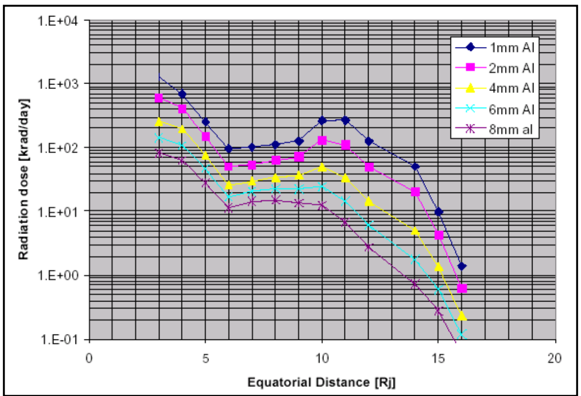

Figure 4: Daily ionizing dose as a function of distance from Jupiter for varying shielding thicknesses

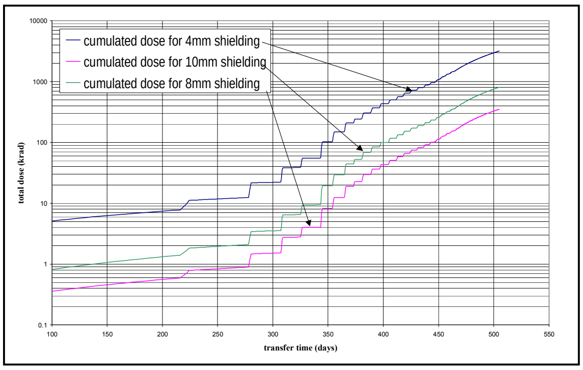

Figure 5: JEO total ionizing dose during 1.5-year Jupiter tour for varying shielding thicknesses

	Radiation dose (krad)		Fluence on cells (1MeV e-/cm²)	
	JEO	JRS	JEO	JRS
Jupiter tour	350	74	9.0e14	2.2 e13
orbit	420	450 per year	1.15e15	1.4 e14 per year

Table 3: JEO and JRS total doses and fluences

3.3 Power

An early decision not to go for radioisotopes, motivated by launch safety constraints and lack of existing hardware in Europe, has permitted to study a concept with solar power generation.

Solar cells

Due to low solar flux input (50W/m²), triple-junction GaAs cells are preferred to Si cells for their higher efficiency. Such cells however will operate in low intensity and low temperature (LILT) conditions. In Europe, the LILT technology only exists for Si cells [4], and was applied for the Rosetta probe, launched in 03/02/2004 from Kourou. The 2nd enabling technology is thus the development of GaAs LILT cells.

In addition, and according to manufacturers data, the efficiency decrease of off-the-shelf GaAs cells covered with 500µm coverglass, and for a fluence of 3e15 1MeV-equivalent electrons/cm², is 38%. That value, combined with an initial electrical power conversion efficiency of 34% at -100°C, was found to be acceptable in the system design. However, early verification of cell behaviour with respect to high fluences will be required.

Solar concentrators

Due to the low Sun flux intensity and the mass constraints, techniques enabling to collect more flux on the cells were investigated. The most efficient was found to be a concept similar to the one used for the concentrators implemented on the Boeing HS-702 telecommunications satellite. The principle of these concentrators, considered as the 3rd enabling technology, is depicted in Figure 6. Light incident on inclined flat panels mounted on both sides of the panel covered with cells is specularly reflected on that one.

The concentrators surfacic mass is assumed to be 150g/m², where solar panels featuring cells and coverglass weight 4kg/m². Without concentrator, the panel mass efficiency is 2.2W/kg, for JEO in end-of-life (EOL) conditions. The theoretical maximum with concentrators leads to 4.7W/kg. The baseline is actually to consider concentrators tilted by 60°, thus with same width as the solar panel, and a specularity ratio of 0.8 at EOL accounting for any degradation. This gives:

- JEO EOL: 3.9W/kg & 15.8 W/m²;
- JRS EOL: 4.9W/kg & 21.2 W/m².

Early testings of the specularity ratio will be however required to confirm the assumption, as the impact on the system may be very high.

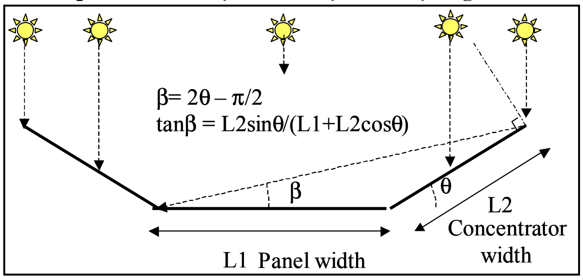

Figure 6: JMO solar flux concentrator principle

3.4 Communications

Communication architecture drivers

The trade-off objective is to determine the preferred JMO communication architecture in terms of wave-lengths (RF & optical) and associated equipments, possible communication links between JEO, JRS and Earth, and types of antenna. The trade-off drivers were the following:

- Data: data rate & volume;
- JEO-JRS relative geometry: distances, pointing, occultations;
- Antenna size limitation: Soyuz-Fregat, pointing accuracy;
- Ground station: available frequencies, G/T (for 34m ESA DSN), EIRP for TC;
- RF emission/reception auto-compatibility;
- ranging: position accuracy vs correction ΔV;
- Robustness (to avoid sat. to be 'lost in space');
- Cost: technologies, common equipments on JEO & JRS, ground operations;
- Mass: limit numbers of equipments.

Wavelength selection

Optical links present a big potential for future missions [5]. In Europe, it has been successfully tested between the Artemis geostationnary satellite and the Spot4 low Earth orbiting satellite. Presently however, such technology is not mature enough, doesn't show decisive advantages in terms of mass power and volume for the mid-term, and would add too much complexity.

RF is therefore selected, and Ka-band preferred to X-band, as it requires less power for same data rates.

Communication links

The JMO system communication links are sketched in Figure 7. Links can be permanent or temporary. A permanent communication link of JEO with JRS during science observations would impose a high gain antenna (HGA) mounted on 2 axes. This means a complex mechanism, although this exists on Rosetta. Moreover, the data rate capacity is very low in regions where the distance between the two satellites is maximum. On the other side, a permanent link on JRS would impose either to upload all science data before sending them to Earth, or to have 2 HGAs'.

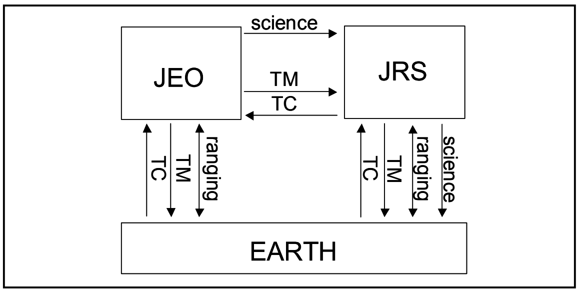

Figure 7: Communications links configuration

Having temporary slots and fixed antenna on both satellites is thus the selected option. The best strategy for this is to have a JRS orbit synchronised with Europa, and to perform communications when JRS is at its perijove, as depicted in Figure 8. JEO & JRS are baselined with identical 1.5m parabolic HGA. JEO features a 3.5W solid-state power amplifier, enabling a data rate of 2.3Mbps at 250000km. Science data collected by JEO during 10.6 days at 40kbps (required value) are thus transmitted to JRS in less than 6h. Such strategy requires the 4th enabling technology:

- high data rate Ka-band receiver on JRS;
- 30% efficiency SSPA on JEO, to optimize power resources, where the current state-of-the-art is 15% [6].

On JRS, the 1.5m HGA permits to consider emitting data towards Earth at 30kbps with 45W RF power. Assuming 8h communication windows a day with Earth, 300 days are enough to transmit the whole science data estimated at 250Gbits.

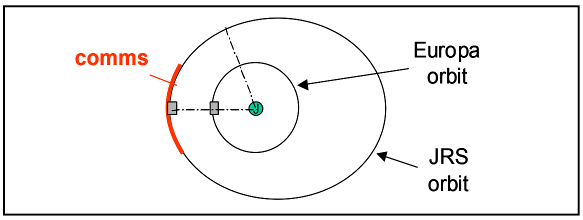

Figure 8: JEO-JRS communication slot

3.5 System Autonomy

System autonomy is mandatory due to the very long mission duration, and because it's not possible to react interactively from ground at such distances from Earth.

During interplanetary cruise, a daily beacon monitor track is performed to establish that no on-board event has been detected that requires ground interaction until the next regularly (interval in the order of two weeks) scheduled telemetry pass.

The design shall be flexible enough to autonomously handle unexpected situations onboard in the following most critical phases of the mission:

- Jupiter and Europa insertions, where a failure could lead to spacecraft loss;
- All gravity assists where inaccurate trajectories would lead to a prohibitive propellant cost;
- Europa fly-bys and orbit around Europa where JEO collision with moon should be avoided before end of mission.

Applied techniques shall be sized with the needs, and the possibilities of validating them on ground shall be guaranteed at an acceptable cost.

3.6 Planetary Protection

COSPAR rules [7] impose a probability of a Europan ocean contamination<1.10^{-4}.

After orbit insertion, it is a fact that JEO hasn't enough capacity to avoid a final Europa surface collision. Therefore, to mitigate contamination risks a two step approach is proposed:

1^{st} step: Jovian radiations are considered to clean the JEO satellite external surfaces of any biological element. Indeed, with a total time in orbit of 120days before final collision with Europa surface, 10Mrad are received behind 4mm Al.

2^{nd} step: for JEO radiation protected equipments, specific integration processes on ground in a class-100 room are required. Bioburden reduction can be performed by various means: dry heating, radiation sterilization, or Hydrogen Peroxide Gas Plasma. Before mounting on the platform, these equipments are eventually sealed in a box to avoid any Earth backward contamination.

Consequently to that approach, collision risks during fly-bys and at insertion impose a reliable and accurate autonomous navigation, with avoidance manœuvres in case of major failures.

4 SATELLITE CONCEPTUAL DESIGN

4.1 Science Payload

A preliminary assessment of strawman science instrument packages for JEO & JRS, was performed to determine requirements for new technologies together with the scientific interest potential of such a mission in terms of amount of data collected, accuracy and types of instruments that can be implemented on-board [8][9]. Having an interactive process between the science instruments and the system design in such feasibility study permits to rapidly identify the possibilities.

A highly integrated payload approach for JEO & JRS was considered to optimise the masses. Tables 4 & 5 illustrate the capacities of the built scenario, and are ready for a deeper scientific expertise. On JEO, the ground penetrating radar is assumed to operate alternatively with the other instruments.

Instruments	Mass (kg)	Power (W)		Data rate (kb/s)
Ground penetrating radar	11.5		25	28
Stereo Camera	0.6	1.2		5
Visible-Near Infrared spectrometer	2.0	2		13
Radiometer	2	1		0.1
Magnetometer	1.4	0.5		0.3
Laser Altimeter	2	2.5		3.0
Radiation Monitor	1.5	1		1.1
γ and Neutron spectrometer	3.1	1		To be defined
Digital processing unit	2.5	4.0	4.0	
Structures & Shielding	6.2			
Margins (20%)	6.6	2.6	5.8	
Total	39.4	15.8	34.8	25 to 30

Table 4: JEO preliminary science instruments package

Instruments	Mass (kg)	Power (W)	Data rate (kb/s)
Radiation Monitor	1.5	1	1.1
Plasma wave instrument	3.5	1.6	3.8
Narrow camera	1.5	1	9.1
Magnetometer	1.4	1.0	0.3
Dust detector	1	1	0.02
Digital processing unit	2.5	4.0	
Structures & Shielding	4.3		
Margins (20%)	3.1	1.9	
Total	18.8	11.5	14

Table 5: JRS preliminary science instruments package

Thanks to JRS arrival on its orbit 100 days before JEO, and to its lifetime going beyond JEO science data transmission to Earth, a Jupiter science mission can easily be envisaged. Moreover, power for science is not an issue on-board JRS since power resources can be used alternatively for communication and science.

4.2 JMO design drivers

Table 6 presents an overview of the spacecraft design trade-offs carried out in the frame of the JMO study. The propulsion system and the highly integrated avionics are further discussed in sections 4.3 & 4.4.

Function	Elements to be traded	Design selection
Command & Data Handling System	Strategy during interplanetary transfer	JRS as master and JEO as slave
	Reliability	redundancy strategy, protection to radiation, functions sharing between the different CPUs
	Mass memory	50Gbits for JEO & 256Gbits for JRS
Attitude & Orbit Control System	Equipments high integration for shielding mass optimization	Shielded Highly Integrated Avionics box including all radiation sensitive electronics
	Power optimization	Low power bus
	Autonomous navigation	Navigation camera
	Mass optimization	Attitude control with wheels (1Nms)
	JEO nadir pointing accuracy	Need for a Europa horizon sensor to be further investigated
	Recurrency optimization	Same avionics on both JEO & JRS
Propulsion System	Large DeltaV	500N main engine on JRS
	Gravity losses vs hardware mass	22N Leros thrusters on JEO, Isp=308s. No main engine.
	JEO accommodation on top JRS	
	Cost	Off-the-shelf E2000+ tanks on JRS
Thermal Control System	Highly varying fluxes from Venus vicinity to Jupiter	Standard thermal control. Need for fluid loops to be further investigated
	Limited power resources	Need for local RHUs to be further investigated
Power System	Low Solar input flux	Solar array with concentrators
	Solar cells degradation by radiations	LILT triple-junction GaAs, 500µm coverglass
	Recurrency optimization	Same solar arrays on JEO & JRS
	High fluxes in Venus vicinity	Si cells + 25% OSR on JRS solar array back side used at distance from Sun<1AU
Commu-nications System	Data rates with low power resources	Ka-band selection for science data transmission
	Reliability	fixed HGA preferred
	Recurrency optimization	Same transponder & HGA on JEO & JRS
	Possibility to use JRS HGA or JEO HGA during cruise	Impact on JRS/JEO electrical interface

Table 6: JMO design trade-offs overview

4.3 JMO propulsion system

The JRS propulsion system, shown in Figure 9, is used for Earth departure, interplanetary transfer, Jupiter capture, JRS Jupiter tour and station keeping. It is a conventional 4-tank MMH/NTO bi-propellant system, using EADS Eurostar 2000+ (Hotbird 2) tanks with a capacity of 393l each. and an EADS 500N main engine, under development in Germany.

The JEO propulsion system, shown in Figure 10, is used for JEO Jupiter tour, Europa orbit insertion and station keeping. It is a dual-mode system using N_2H_4 as fuel, and MON-3 (N_2O_4) as oxidiser. It features two 72l fuel tanks, one 85l oxidant tank, and four redunded ARC UK Ltd 22N thrusters (Leros 20H), with Isp of 308s, under development in UK.

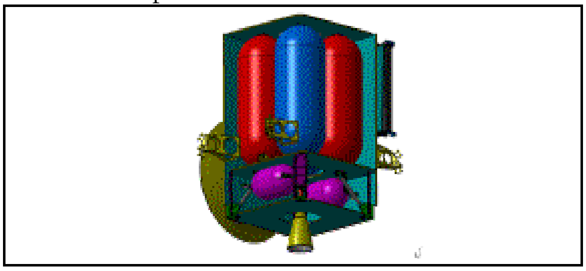

Figure 9: JRS propulsion system

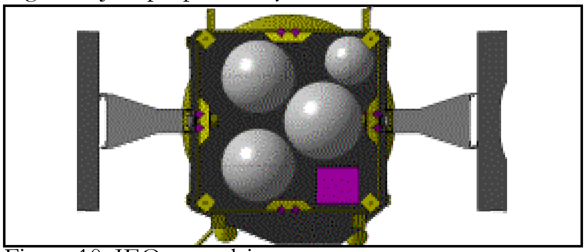

Figure 10: JEO propulsion system

4.4 JMO avionics

Having a highly integrated avionics has a double advantage for JMO: it reduces the mass and the hardware volume. Reducing the volume enables to limit the room to be shielded against radiation, and thus the shielding material mass.

The reference data handling architecture selected for both JEO and JRS is the Bepi Colombo computer. Functional enhancements are considered, such as integration of the star tracker electronics, the navigation camera electronics and the inertial measurement unit. In addition, the Power control & distribution unit board becomes part of the avionics box. A technological enhancement is also considered with the replacement of the standard 1553 bus by a low power 1553 (preferred for compatibility) or CANBus, or even Spacewire.

The avionics box functions and interfaces are summarized in Figure 11.

The estimated size of the avionics box is 800x200x250mm based on Double Europe format (233x160x20mm) boards. For JEO, assuming a wall thickness of 7mm, the aluminium shielding box weights 15.5kg.

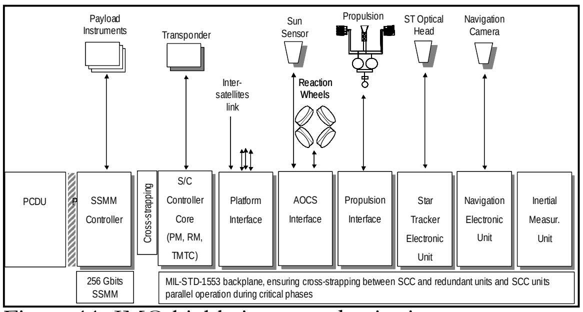

Figure 11: JMO highly integrated avionics

4.5 JMO configuration

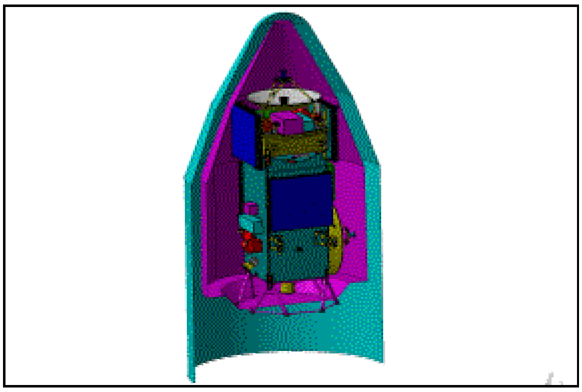
Figure 12: JMO in launch configuration with JEO mounted on top JRS

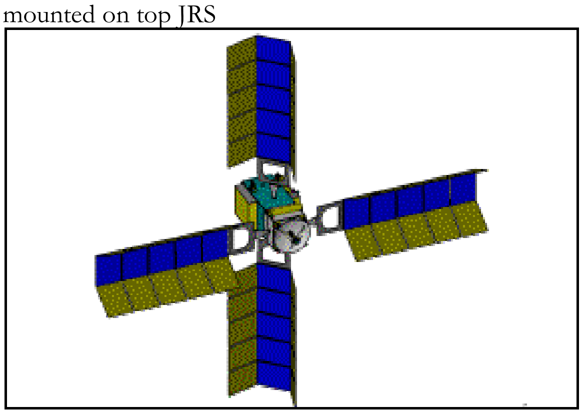
Figure 13: JMO in cruise configuration with solar panels and concentrators deployed

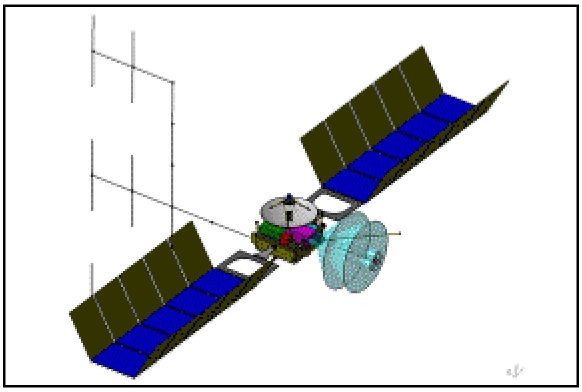
Figure 14: JEO in cruise configuration with ground penetrating radar deployed

4.6 JMO budgets

Table 7 is a summary of the satellite subsystems masses, without payload.
The JMO system mass budget, presented in Table 8, shows the science payload maximum mass capacity with maximum launch mass.

	JRS	JEO
Power	110kg	106kg
AOCS	8kg	8kg
Propulsion	135kg	40kg
CMDS	26kg	26kg
Communications	42kg	25kg
Structure	145kg	73kg
Thermal	10kg	6kg
Radiation shielding	8kg	27kg
Total	**484kg**	**311kg**

Table 7: JRS & JEO masses with maturity margins

JRS platform	580kg
JRS science instruments	14kg
JRS propellant	1679kg
JRS wet mass	**2274kg**
JEO platform	373kg
JEO science instruments	30kg
JEO propellant	254kg
JEO wet mass	**656kg**
Total Launch mass (without adapter)	**2930kg**
Launcher adapter	70kg
Launcher capacity	**3000kg**

Table 8: JMO system mass with 20% system margin

The limited power resources led to the optimisation of the consumptions. Assessment of these consumptions were based either on equipments under development or on potential improvements to occur in a short to mid-term.
Table 9 gives an overview of JEO & JRS power needs in worst cases. It appears that, due to differential cells degradations on both satellites, JEO & JRS can be designed with the same solar array of 14.7m^2 (excluding concentrator areas).
Most JRS payloads operate outside of communications windows with Earth. This means

that power available for communications becomes available for science.

	JRS	JEO
Power	10W	67W
AOCS	23W	23W
CMDS	29W	29W
Communications	123W	11W
Thermal	54W	28W
Harness losses	8W	5W
Payload	2W	30W
Total with 20% system margin	**359W**	**270W**

Table 9: JMO power budget with 20% system margin

5 DEVELOPMENT PLAN

The previous chapters show that the feasibility of a JMO mission depends on a limited number of new technologies summarized in Table 10.

Technology	Development activity
Electrical	
Rad-hard components	Specify, design & qualify 1Mrad tolerant components, common to payload, avionics & communications systems
Shielding material	Specify, design & qualify radiation shielding structure for electronic housing enclosures (avionics, payloads, communication system)
Rad-hard avionics box	Study & develop an integrated avionics box concept bread-board, specified to operate up to a 1Mrad dose and aiming at low total mass (electronics + radiation shielding enclosure)
Power	
GaAs cell for LILT & harsh radiation environment	Delta-qualify cells for the specified environment
Solar concentrators	Specify, design and qualify one solar panel with concentrators & deployment mechanisms (with ground test in solar simulator chamber)
RF communications	
High data rate receiver (3 Mbps)	Design & development of a bread-board transponder
High efficiency Ka SSPA (30% @ 3.5 W RF)	Design & development of a bread-board with specific components (e.g. FPGA)
Avionics	
Software architecture for high autonomy	Design and validation on numerical system simulator
Autonomous optical navigation & small correction manoeuvre scheduling	Camera Bread-board + RT system simulator with hardware in the loop. Specify, develop & validate algorithms for optical navigation within Jovian system.

Table 10: Technology development activities

Should a launch be considered in 2016, the development schedule could look like Table 11.

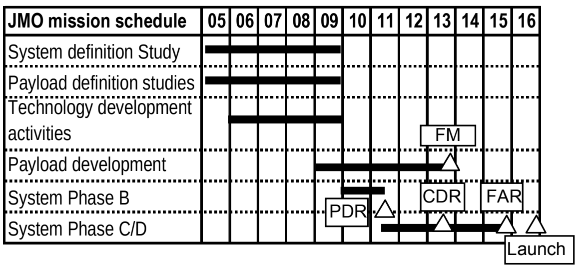

Table 11: JMO development plan

6 CONCLUSION

The feasibility of a valuable scientific mission to Jupiter/Europa with two mini-satellites, launched by Soyuz-Fregat from Kourou, and powered by solar generators is demonstrated by this technical assistance study. There is a good confidence in the final result due to:

- focus on a low cost, reliable, technically sensible mission ensuring good science return;
- a full coverage of the mission permitting to identify major system concept drivers;
- a preliminary payload assessment feeding the system with science considerations in its very early stage;
- the presentation of a coherent and sensible scenario;
- a rigorous margin philosophy guaranteeing flexibility in the scenario;
- a proposed system mixing conservative approaches and innovative solutions based on EADS-Astrium experience in scientific missions (Rosetta, Mars Express) and on its technical expertise;
- a limited number of enabling technologies.

JMO development plan remains however very challenging for the European community. A firm commitment is required on enabling technologies.

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