THE JOVIAN ENTRY PROBE
A feasibility study of a minimum resource Jovian Entry Probe

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ABSTRACT

In the framework of the Technology Reference Studies, ESA's Science Payload and Advanced Concepts Office (SCI-A) has initiated a Concurrent Design Facility study to investigate the critical technologies and design issues related to a ballistic Jovian entry probe, with the aim of performing atmospheric measurements during descent and to survive to an ambient atmospheric pressure up to 100 bar.

For this study, the probe's objective was the in-situ measurement of the Jovian atmospheric composition to complement and extend data from the NASA Galileo probe. To this aim an entry probe was designed to penetrate the denser layers of the atmosphere, e.g. up to a pressure of 100 bar (Galileo deepest measurement was at 20 bar pressure), targeting a cloudy zone in contrast with the Galileo's regions, which was a so-called hot spot.

The goal of this study was to derive a 'minimum' entry probe design, to assess design, mass, size and telecommunications requirements and to identify the required enabling technologies, as well as to assess the impacts of such a probe on a potential combined atmospheric/magnetospheric mission to Jupiter. The design of the spacecraft accompanying the probe was beyond the scope of this study.

1. INTRODUCTION

The Jovian Entry Probe study was performed in the context of the Technology Reference Studies (TRS), an initiative of ESA's SCI-A department. The goal of the TRS's is to identify and, when possible, develop critical technologies required for future scientific missions. This is done through the study of several challenging and scientifically relevant mission concepts, which are not part of the current ESA science programme, and focus on medium term enabling technology requirements.

The JEP study is part of the Jovian Technology Reference Studies, which are intended to help identifying enabling technologies for future minimum resource missions to the Jovian system or similar challenging environments. These studies are also intended to support the scientific community in the field of Jovian exploration.

Presently two studies have been completed and a new one has been initiated:

- Jovian Minisat Explorer: Focussing on the exploration of Europa (this included a Europa polar orbiter and a Jovian equatorial relay S/C, implications of radioactive power sources, as well as small Europa impactors) [finished]
- Jovian Entry Probe: Study of the Jovian atmosphere with one or more entry probes, up to 100 bar [finished]
- Jovian System Explorer: Study of the Jovian magnetosphere (one or more magnetospheric S/C) [ongoing]

This paper focuses on the Jovian Entry Probe (JEP) study, which was performed by ESA's Concurrent Design Facility (CDF). This particular study aimed to understand the requirements for a minimum resource probe capable of entering the Jovian atmosphere up to a pressure level of 100 bar.

The following requirements and constraints applied to the study:

- Carry the probe to Jupiter and release it at the correct time
- Perform entry and descent into the Jovian atmosphere at near equatorial latitude (with an option of non-equatorial descent up to -30deg/+30 deg, if possible)
- Measure atmospheric properties in-situ down to a depth corresponding to 100 bar using a given Strawman payload
- Transmit the data in real time to the accompanying Orbiter
- Achieve a final orbit for magnetospheric measurements with the Orbiter
- Achieve multi-probe mission, if mass allows
- Use of highly integrated payload: 12 kg; 30 W; 5 l; 353 bps

- Launch vehicle: Soyuz Fregat 2-1b from Kourou
- Preferred launch dates: 2016 or 2023
- Avoidance of Jovian ring when defining probe approach, while not exceeding maximum allowable distance during comms
- Design shall be compliant with Beagle 2 Enquiry Board recommendations and Huygens Lessons Learned
- Maximum heat flux during entry: 500 MW/m^2 (assumed as maximum capability for present TPS technology)

2. MISSION DESIGN DRIVERS

This mission concept is driven by four main drivers: The Jovian atmosphere, the high entry velocity, launch mass restrictions and communications.

The main issue with the atmosphere is related to the uncertainties regarding the aerothermal phenomena. These uncertainties strongly complicate the design of the heat shield, since they impose significant margins to be added to the design, to compensate for these uncertainties. As a consequence, this leads to a likely over-dimensioned thermal protection system: depending on the entry latitude the resulting TPS mass fraction is in the order of 50% to 70%.

The entry velocity cannot be reduced below ~47 km/s. At these velocities and due to the previously mentioned limitations, the aerodynamic phenomena in the atmosphere cannot be properly computed, leading to uncertainties in the calculation of the heat fluxes. Further, the very high thermodynamic fluxes are at the limit of present TPS technology capabilities. The very high deceleration loads (in excess of 1700 m/s^2) additionally require dedicated qualification of the probe's components.

The relatively modest launcher provides the upper limit for the launch mass, while the fulfilment of the mission requirements provides the lower limit. This clearly poses a limit to the maximum TPS mass and therefore to the maximum entry velocity.

The high temperature and pressures in the atmosphere at lower altitudes further complicate the design of the entry probe, since the design needs to offer adequate protection against these conditions.

The strong attenuation of radio signals by the atmosphere below the 20 bar level impose stringent design requirements for the communication systems on both the probe and the orbiter. Furthermore, the trajectory of the carrier S/C will have to allow for a continuous communication with the probe during the deployment and relay phase.

3. MISSION ARCHITECTURE

The mission composite (Orbiter + Entry Probe) shall be launched by Soyuz-Fregat 2-1b into a highly elliptic orbit (HEO). The spacecraft is then inserted into a hyperbolic Jupiter transfer orbit by its own propulsion system with a two-burn sequence. The launcher performance into the optimal HEO is 2346 kg including adapter.
The Jupiter transfer trajectory is of the VEEGA type; including a Venus swing-by and two Earth swing-by's aiming at Jupiter impact for release of the entry probe. No mid-course manoeuvre is required except for navigation corrections.
Two cases have been considered: single probe or two probes onboard of the same Orbiter.

During cruise the probe is attached to the Orbiter S/C and uses the Orbiter's power supply to perform periodic instrument checkout and possibly software updates.

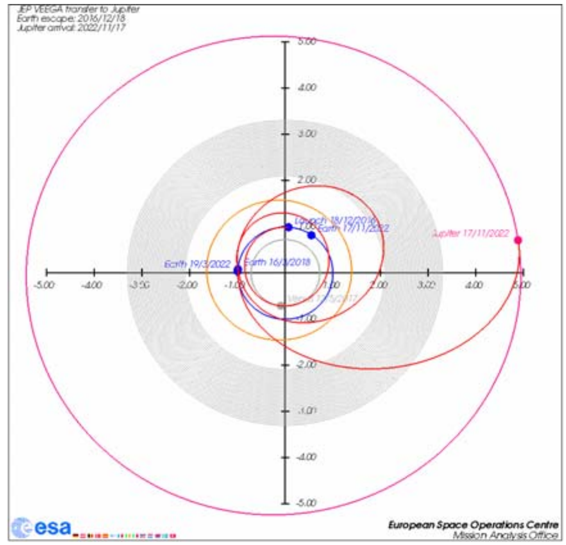

Figure 1: The VEEGA Transfer Trajectory

Sufficiently before Jupiter arrival, the Orbiter deploys the entry probe (in short sequence, should two probes be considered) and performs a deflection Manoeuvre (ODM) to get into a safe non-entry trajectory.
The time of probe release compared to the entry time sizes the delta-V cost of the ODM and the error on the Flight Path Angle (FPA) at entry which is constrained by probe TPS design. The selected release time is 90 days before entry with a delta-V cost of 89 m/s and a FPA error at entry of less than 1 deg.

During the coast phase, the probe is uncontrolled and unguided. It uses its own power system to perform communications with the Orbiter, and timer switches are used to activate automatic sequences.
While the probe coasts to its entry point, the Orbiter performs a Ganymede swing-by to reduce its incoming velocity and therefore reduce the delta-V cost of the Jupiter Orbit Insertion (JOI). The Insertion Orbit is the orbit from which the relay with the probe(s) is performed during their entry and descent. This is a 4x200 Jovian Radii (Rj) equatorial orbit around Jupiter (for near equatorial entry and descent). The perijove radius is a compromise between distance for probe relay (the closer, the lower the required power) and radiation protection (the closer, the higher the dose). The apogee corresponds to the required final orbit of 15x200 Rj. The JOI manoeuvre takes place 1 hour before perijove arrival, requires 570 m/s and its duration is about 0.5 hours.

The start of the probe entry phase is defined as the point where the probe reaches 450 km altitude above 1 bar (the 1 bar level is used as a reference zero level for altitude measurement). During this phase the probe relays flight instrumentation data (used for trajectory reconstruction) to the Orbiter with the exception of the period of blackout caused by the plasma sheath around the probe.

Due to Jupiter's massive gravity field, the spacecraft will accelerate considerably as it approaches perijove. The consequence for the entry probe is that the inertial velocity at entry will amount to around 60 km/s with only a weak dependency on the hyperbolic entry velocity. As Jupiter's rotation period is less than 10 hours, the equatorial atmospheric rotation speed is almost 12.6 km/s. Therefore, the actual atmospheric entry velocity depends strongly on the entry location. For a prograde, near-equatorial entry, the relative entry velocity is thus 47 km/s.

The science data relay phase occurs after the front heat shield and back cover have been released and the main parachute has been deployed. At this point all instruments will take measurements from the Jovian atmosphere and send them back to the Orbiter. The relay phase ends after the one hour communications window when the probe has reached 100 bar depth in the Jovian atmosphere. At this point the probe's mission is complete.

During the relay, the Orbiter needs a relatively slow, constant-rate slew manoeuvre (rate ca. 17 deg per hour), to keep its high-gain antenna trained upon the current probe location.

It is noted here that Direct-To-Earth communication from the probe is only possible during the early phases of entry. This is due to the low Earth elevation with respect to Jupiter's local horizon in the analysed 2022 arrival case; the very high rotation speed of Jupiter only allows for a short visibility time of the probe.

After the relay phase, the Orbiter will reach its final orbit for magnetospheric measurements, which has a line of apsides aligned with the sun direction. This is achieved by the combination of a propulsive manoeuvre of 500 m/s at apojove to increase the altitude of perijove and a Jovian satellite tour (a sequence of five Ganymede swing-by's) to rotate the line of apsides as needed.

Manoeuvre	1 probe Mission Delta-V (m/s)	2 probe Mission Delta-V (m/s)
Satellite tour/Apojove raise	30	30
Perijove raise (PRM)	500	500
Jupiter orbit insertion (JOI) 1 hr before perijove	570	570
Orbit deflection man. 70d before entry	N/A	120
Hyperbolic probe release	N/A	0
ODM 90d before entry	89	42
Probe release from hyperbolic	0	0
Mid-course manoeuvre	0	0
VEEGA	30	30
Escape from HEO	626	626
Inclination change	82	82
GTO to HEO	692	692
Total incl gravity loss Final total incl margin	2668 2801	2740 2878

Table 1: ΔV budget for baseline and option 1

The mission delta-V budget is shown in table 1 for a single probe and a two-probe mission. The table is based on the 2016 launch window, which is the worst case between the selected target launch dates.

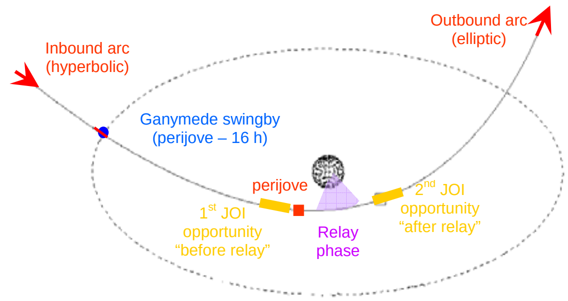

Figure 2: Swing-by augmented JOI

4. ALTERNATIVE OPTIONS

4.1 Two probes

A two probe mission would be preferable to enable different entry points and more data collection, and to allow for redundancy. Nonetheless, due to launcher mass constraints, the case of two probes is only considered feasible if the deepest altitude to each is reduced to 40 bar. In this case the two probes are deployed into approach orbits of different inclinations, leading to a difference in the entry and descent locations, the first probe aiming at a latitude of 3.6 deg N, the second at a latitude of 6.8 deg S. The relative entry velocity for both probes is slightly higher than 47 km/s.

4.2 Off-equatorial entry

The preferred probe entry latitude is non-equatorial between 30 deg N and 30 deg S. Entry at high latitude would require an approach from an inclined trajectory and an increase in delta-V to retarget the Orbiter for an equatorial insertion.

For the high-latitude probe, the inclination can be fairly low, which will limit the rise in relative entry velocity but would require a steeper entry. Or, the inclination can be larger, in which case a larger increase in relative velocity is incurred, but the entry angle could be kept relatively shallow.

This effect is due to the fact that the perijoves of the arrival hyperbolae are all close to equator and that shallower angles can only be achieved close to the perijove.

As an example, for a descent latitude of 15 deg South, the lowest inclination possible is 25 deg, leading to an entry FPA of -16 deg and an entry velocity around 49 km/s, while the larger inclination leads to –10 deg FPA and an entry velocity of about 50 km/s. In any case, heat fluxes occur in excess of 500 MW/m^2, exceeding available TPS capabilities. In addition, the high-latitude probe would require the communication relay to be conducted at an oblique angle with respect to the equatorial Orbiter. For these reasons, non-equatorial entry has been considered as non-affordable.

4.3 Release from orbit

Release from capture orbit requires a higher delta-V and gives an allowable probe mass of approximately 230 kg while it doesn't reduce the probe's entry speed enough to enable a lighter probe (46-47 km/s for capture vs 47.4 km/s for hyperbolic). Furthermore, the communications between the probe and the orbiter become much harder, as there cannot be a continuous one hour communication window, due to the eclipses caused by Jupiter. As there were no other clear advantages for the release from capture orbit, this option was discarded.

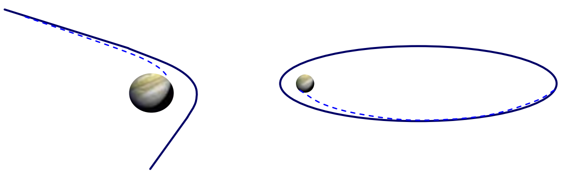

Figure 3: Hyperbolic release vs. from orbit

5. AERODYNAMICS

The assumed probe shape is similar to the Galileo probe design, containing a front shield with a half cone angle of 45°, as shown in Figure 4:

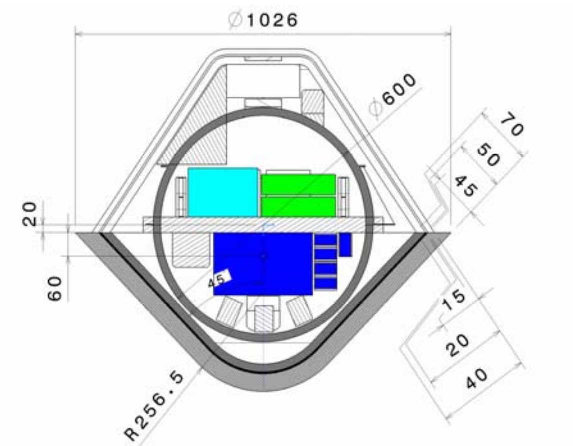

Figure 4: Probe geometry

The equatorial entry parameters are the following:

- Entry Altitude: 450 km
- Entry Velocity: 47.4 km/s
- Entry Angle: -7.5˚

5.1. Equatorial entry

Two entry mass cases, 310 kg and 280 kg, have been studied depending on the final altitude respectively pressure level (100 bar and 40 bar). Figure 5 presents the entry and descent trajectories.

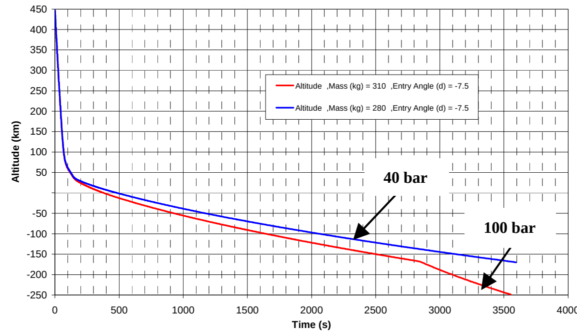

Figure 5: Altitude vs Time for equatorial entry

Relatively similar acceleration profiles are obtained for both cases with a peak around 1 700 m/s^2 at 69 s after the entry point (Figure 6). The smaller peaks correspond to the pilot chute deployment, release of the pilot / back cover / deployment of the main chute and the release of the front heat-shield.

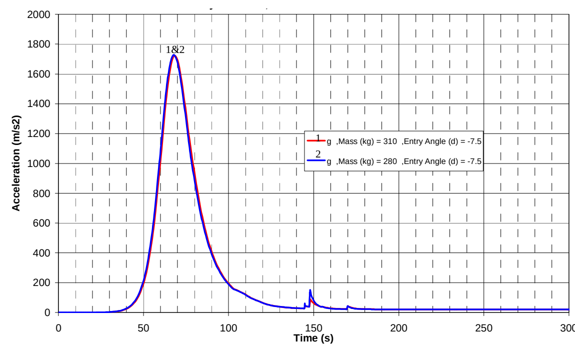

Figure 6: Acceleration vs Time for equatorial entry

The radiative heat fluxes at the stagnation point in both options are presented in Figure 7.

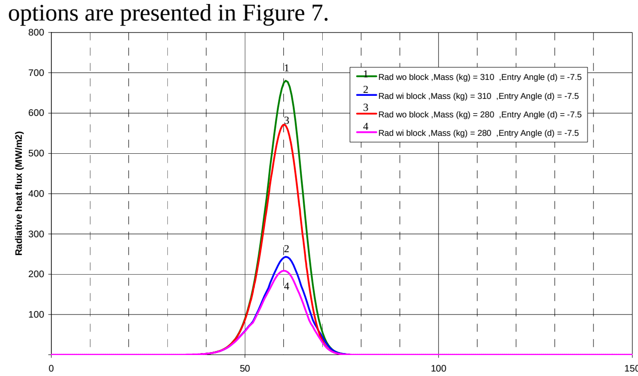

Figure 7: Heat Fluxes vs Time for an equatorial entry

The heat flux distribution along the front shield, at the stagnation point, mid-cone, edge and base point is presented in Figure 8 for the 100 bar option.

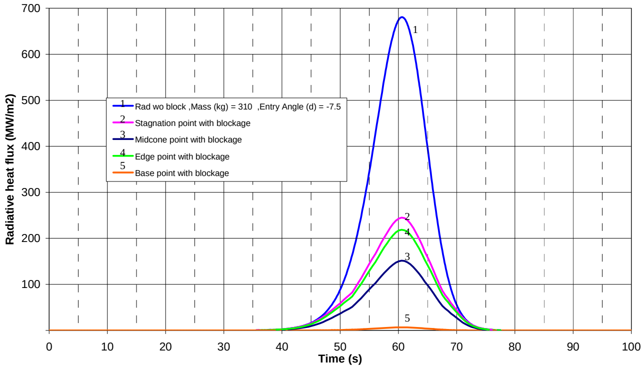

Figure 8: Heat Fluxes vs Time over the front shield surface for a Final pressure of 100 bar

Only 3-dof analyses were performed, therefore the probe stability during entry and descent could not be confirmed. The distance between the CoG location and the back cover/front shield interface is -38.7 mm which is about 3.8% of the base diameter and therefore lower than 4.5%, which was the requirement for the Galileo probe. This point would need to be addressed in further detail.

5.2. Non-equatorial entry

For a non-equatorial entry, the entry mass was assumed to be 500 kg in all cases. The used dimensions of the probe are 1.30m for the base diameter with a nose radius of 0.65m. The radiative heat fluxes are presented in Figure 9. Due to the very high level of the radiative heat fluxes (>1 GW/m2 even with blockage), the non-equatorial entry mission is beyond present technology capabilities.

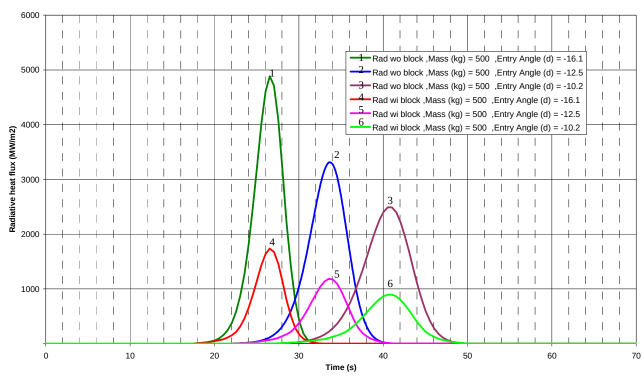

Figure 9:Heat Fluxes vsTime for non equatorial entry

6. THERMAL PROTECTION SYSTEM

One of the major feasibility drivers of the overall mission is the design of the thermal protection system and the availability of a suitable material capable to withstand the very high radiative and convective heat fluxes. A significant effort of the study was dedicated to the screening of potential heatshield concepts. As a result, a Galileo-like shield based on Carbon-Phenolic ablator still appears as the most promising solution.

The material considered as reference in this study is part of a family whose characteristics are close to the one used for the Galileo mission. The present availability of the material could not be confirmed. In any case, a dedicated development would be required for Europe.

Analysis has shown that if the ablator is applied using the SEPCORE concept (Figure 10), a mass reduction of about 25% can be achieved compared to a conventional ablator with a cold structure concept. This is mainly due to the fact that the ablator is mounted on a hot structure, which is insulated against the inner compartment using lightweight insulation, possibly fibres. Considerable mass savings are obtained due to reduced ablator thickness and the use of a more efficient insulation.

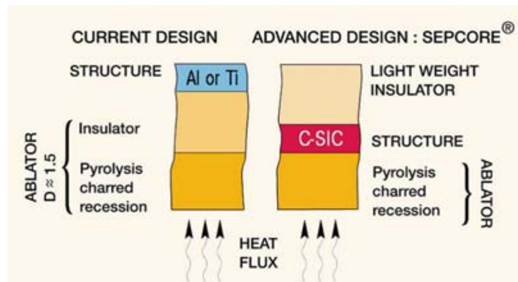

Figure 10: Classical vs SEPCORE TPS

Alternative options to be considered in later project phases are heatshields based on either Carbon-Carbon or Carbon-SiC ablators.
The TPS design is shown in the following figure:

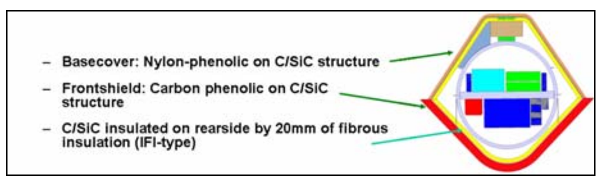

Figure 11: TPS schematic

Due to the uncertainties on the aerothermodynamic fluxes and loads as well as the TPS material characteristics in such entry environment, a robust margin philosophy has been applied (> 40% overall).

7. DESCENT SYSTEM

In the nominal case, the end of mission will occur when the probe reaches a depth corresponding to 100 bar. Due to communications constraints this will have to be achieved in less than one hour, otherwise measurements performed at low altitudes cannot be relayed back to the Orbiter. Therefore the requirement for the parachute system is to provide a flight time of around one hour to the final altitude. In addition, the parachute shall safely separate the probe from the heat shield by increasing the area of the separated elements, obtaining a ballistic coefficient that is sufficiently different (factor 2).
A minimum parachute designed to provide the above separation leads to a flight time in excess of 1 hour to achieve 100 bar altitude. Therefore, the parachute system

needs to include a release mechanism so that the probe can accelerate in the last part of the descent (see Figure 12)

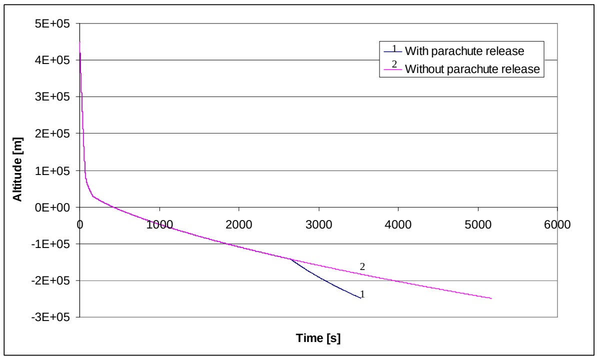

Figure 12: The descent trajectory

The descent system consists of a pilot parachute attached to the back cover with a diameter of 1.47m and a C_d of 0.52. The pilot is deployed at Mach 1.1 by a mortar, triggered by an accelerometer, g switches and a timer as backup. A main chute with a diameter of 2.28 m is deployed by the back cover once it is separated.

The descent module together with the front shield will continue the descent under the main chute for another 20 sec, allowing for stabilisation before a timer triggers the front shield release. The descent module will then continue its descent under the main parachute with the scientific payload operational. The main parachute is finally released after 47 min.

Conical ribbon technology was selected for the parachute due to its superior performances at high dynamic pressures (opening of the parachute occurs at q=12 kPa) and structural integrity. Furthermore, this type of parachute fulfils the stability requirement, although a small penalty has to be paid in terms of drag coefficient.
Dacron is proposed as the material for the canopy construction and Kevlar for the lines. At the time of release, the atmosphere temperature will still be sufficiently below the material performance limits.

8. COMMUNICATIONS

The following communication architecture is foreseen:

- *Coast phase:* data transmission to the orbiter occurs via a back cover antenna. Carrier recovery and Doppler tracking can be achieved by VLBI (Very Large Base Interferometry). To reduce the power consumption, a 3 hours total transmission time is assumed during the whole cruise phase at a data rate of 8 Kbps
- *Entry phase:* during this phase (~3 minutes) no transmission will be possible (black-out) due to attenuation by the plasma cloud
- *Parachute deployment and descent till 0.2h from entry:* after the back cover separation and parachute deployment, the Descent Module (DM) helix antenna will start to transmit. The TM signal will be received by the orbiter and VLBI until 0.2h after the entry. After that the Earth will be below the 'Jovian horizon' and VLBI can not detect the probe's carrier signal anymore
- *Descent, from 0.2h after the entry till 100 bar pressure altitude:* data transmission between probe and orbiter will take place via the DM patch array antenna. A minimum net data rate of 353 bps is required

A variable power system is foreseen to cope with the very strong atmospheric attenuation (up to ~24 dB at 100 bar). The maximum power consumption of one link is 225 W. Link redundancy (as in Galileo and Huygens), would imply unacceptable power consumption. Therefore, only cold redundancy has been assumed.

The frequency band selection is a trade-off between the conflicting factors of atmospheric attenuation and synchrotron radiation of Jupiter. The high atmospheric absorption is due to ammonia, water, sulphide and phosphine in the Jovian atmosphere (polar molecules). The synchrotron radiation originates in the Jovian magnetic field and depends on the geometry of the orbiter antenna orientation.
Frequencies below S-band (2GHz) need to be considered to limit attenuation. Therefore, the reuse of the Huygens frequency band (S-band) is not possible. On the other side, below 1.3GHz, the synchrotron radiation is expected to increase, overcoming the positive effect on signal attenuation. As a result of this trade-off, a 1.3GHz system (L-Band) has been selected for this mission.

All considered mission cases give a positive margin for a minimum data rate of 370 bps (353 bps + 5% margin), a maximum power of 100W and an antenna size on the Orbiter of 4m for the 100 bar cases. This antenna size will cause considerable accommodation problems for the carrier and needs to be properly understood if this concept is selected for further study. Because of the high attenuation, deeper altitudes into Jovian atmosphere would imply a significant increase of resources to maintain the link budget margins and is therefore considered unfeasible with the selected configuration.

9. DESCENT MODULE CONFIGURATION

A trade-off has been performed between several different structural concepts for the Descent Module (DM). In the end a spherical titanium sealed vessel was selected, with an internal pressure of 1 bar. The option of a fully internally pressurised DM (100 bar) has been rejected due to expected leakage during long cruise to Jupiter, the structural loads and the handling risks.
Under uniform external pressure, a thin-walled sphere buckles at a fraction of the pressure that would cause the same vessel to fail under uniform internal pressure. Therefore, the vessel has been stiffened with circular ring frames. These frames are also used to support the equipment shelf and serve as an attachment for the interface brackets of the DM to the front shield.

The DM features a single internal equipment shelf that hosts the entire internal equipment. In particular, the vessel contains the science payload, the CMDU, PCDU, Comms transponders and amplifiers, batteries as well as the L-Band patch and helix antenna on the outside. A volume reduction exercise of this equipment has been performed to decrease the required dimensions of the DM.

Figure 13: Exploded view of the probe+the DM

For stability during the descent of the DM into the Jovian atmosphere, vanes are added on the DM. Inlets and windows are added for the Strawman payload, as it is needed for its operation.
As the overall dimensions and mass of the probe result from the dimensions of the DM (which is sized by the equipment volume), the probe mass cannot be reduced below a certain threshold unless high electronics integration is pursued, something that should be kept in mind for further studies.

10. BUDGETS

10.1 100 bar probe mass budget

The minimum configuration mass budget is shown in the following table:

Structure	30.7
Thermal control	145.7
Mechanisms	9.3
Comms	6.8
Data handling	11.5
GNC	1.6
Power	18.1
Harness	10.1
Instruments	10.4
DLS	6.3
Total dry mass	250.5
20% system margin	50.1
Total mass with margin	300.6

Table 2: 100 bar probe mass budget (mass in kg)

10.2 Mission options comparison

The following table shows the available launch mass margin for the analysed mission options:

	Baseline	Two 40-bar probes	Larger P/L	Two S/C	From orbit
Total dV with margin	2801	2878	2801	2641	3002
Orbiter 1 dry (kg)	700	700	700	700	700
Orbiter 2 dry (kg)	--	--	--	700	--
Tot prop mass (kg)	1236	1409	1268	1903	1644
Probe 1 dry (kg)	300	268	350	--	300
Probe 2 dry (kg)	--	268	--	--	--
Total launch mass (kg)	2236	2646	2318	3304	2944
Launch margin SF 2-1b	24%	10%	21%	-12%	2%

Table 3: Mission architecture comparison with launch margin

The "larger P/L" option concerns a single probe with increased payload mass as a result of:

- 100% increase of the P/L mass
- 100% increase of the P/L volume
- 50% increase of the P/L power
- 50% increase of the P/L data rate

This option was analysed to assess the sensitivity of the probe design to changes in the payload.

Note, that all dry masses include 20% system margin.

10.3 Power budget

The following table shows the power requirements of the probe as a function of the different phases: passive coast (90 days prior to entry), check-out during coast (3 hours total) and the entry and descent phase (1.25 hours, including check-out).

The relevant power architecture is based on two different types of primary battery, $LiSOCl_2$ for the timers during coasting and $LiSO_2$ for the PCDU. This approach gives the minimum system mass.

Coast Phase	*90 days*		
DHS		0.3 W	
GNC		0 W	
Comms		0 W	
		648 Wh	
Check out during coast	*3h total*		
DHS		22 W	
Payload		5 W	
Comms		50 W	
		231 Wh	
Entry + descent	*1h 15*	**Average**	**Max**
Comms		104 W	225 W
DHS		22 W	22 W
Payload		28 W	29 W
GNC		22 W	22 W
		220 Wh	298 W
Total Wh (30% margin)		1429 Wh	
Total Pmax (30% margin)			388 W

Table 4: Power budget per phase

11. CONCLUSION

The study has shown that, for the given payload, a minimum Jupiter entry probe of about 300 kg can be designed reaching a depth corresponding to a pressure of 100 bars.

A smaller probe (about 10 % lighter) could be achieved if the requirement is relaxed to an altitude corresponding to a pressure of 20-40 bar. In this case, the mission mass capability would allow for two identical probes on one carrier (~700 kg dry mass) launched by a Soyuz-Fregat. Therefore, the requirement of atmospheric deep sampling needs to be traded against sampling in two different shallower atmosphere locations. On the other hand, lower altitudes corresponding to pressures in excess of 100 bar quickly become unfeasible because of the very high atmospheric attenuation and the associated low link margin or high communication power. Due to the very low resources and the atmospheric attenuation, communications are a major problem, driving the probe & S/C design. Furthermore, the distance between probe and relay S/C is limited to the ~4 Rj range to limit the required power to reach the carrier spacecraft.

Entry from a hyperbolic approach trajectory takes place 90 days after release. Only near equatorial latitudes can be targeted, as the study has shown that for higher latitudes the entry heat fluxes exceed the present capabilities of ablative thermal protection systems.

Jupiter entry probes face extreme aerothermodynamic challenges: the identification of adequate TPS is very challenging, therefore the probe design includes a generous margin for Thermal Protection System (TPS) design. This is mainly due to the large uncertainty that exists in the calculation of heat fluxes and performance of TPS in this thermal load range. Such uncertainties come from the fact that design and qualification will have to rely only on partial representation of the physical phenomena and on a reduced environment (testing in a representative environment is considered unfeasible, leading to large uncertainties in theoretical models).

High complexity and extreme test conditions are major cost drivers. The TPS design and qualification is the most critical issue of the mission. Therefore, a careful margin philosophy is required and the option of flying two identical probes may help reducing the mission risk. Next to this, highly integrated electronics will be required to minimise the required resource allocation.

12. ACKNOWLEDGEMENTS

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11. KEY LITERATURE

Bagenal, F. et al, "Jupiter, The Planet, Satellites and Magnetosphere", Cambridge University Press, 2004

Huygens Science, Payload and Mission, SP-1177, 1997

Park, C., Overview of Radiation Problems in Planetary Entry, Proceeding of the International Workshop on Radiation of High Temperature Gases in Atmosphere Entry, ESA-SP-583.

Matsuyama, S., Ohnishi, N., Sasoh, A. and Sawada, K., Numerical simulation of Galileo Probe Entry Flow field with Radiation and Ablation, J. Thermophysics and Heat Transfer, Vol 19, No 1, Jan-March 2005.

Moss, J.N., Jones, J.J. and Simmonds, A.L., Radiative Heat flux Penetration through a Blown Shock Layer for Jupiter Entry, AIAA 78-908, 1978.

Sutton, K., Jones, J. and Powell, R.W., Effect of Probe Configuration on Radiative Heating During Jovian Entry, AIAA 76-471, 1976.

Williams, S.D. and Curry, D.M., Thermal Protection Materials – Thermophysical Property Data, NASA Reference Publication 1289, 1992

Park, C. and Tauber, M.E., Heatshield Problems of Planetary Entry, a Review, AIAA 99-3415, 1999

Laub, B. and Venkatapathy, E., Thermal Protection System Technology and Facility Needs for Demanding Future Planetary Missions, NASA Ames, 1st International Workshop on Planetary Probe Atmospheric Entry and Descent, October 2003

Moss, J.N., Jones, J.J., Galileo Probe Forebody Flow field prediction during Jupiter Entry, AIAA 82-0874

State of Affairs for Jupiter Deep Entry Probes, 3rd IPPW, by Balint, Young, Venkatapathy, Spilker and Kolawa., June 2005

CDF Study Report JEP Jupiter Entry Probe, CDF-43(A), December 2005