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# Propulsion architecture enabling an interstellar medium exploration mission to 200 astronomical units in 25 years

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**KEYWORDS:** Interplanetary trajectory, launcher, cryogenic propulsion, electric propulsion, storable propulsion, gravity assist, optimisation, on-board power, radio link, bandwidth, power source.

## ABSTRACT:

This paper analyses the possibility to propel a significant scientific payload to 200 AU in less than 25 years. The expected scientific reward of this kind of mission is very high: analysis of the interstellar medium, Kuiper Belt objects exploration, general relativity test. On the other hand, the required infinite speed of 40 km/s is considered as almost impossible. However, a clever combination of in-orbit cryogenic propulsion, electric propulsion and propulsive gravity assist may help to reach this goal.

## 1. INTRODUCTION

In 2021, the Johns Hopkins University Applied Physics Laboratory proposed an interstellar medium exploration mission using a SLS launcher and propulsive Jupiter Gravity Assist. The resulting infinite speed (i.e. heliocentric hyperbolic excess velocity)  $V_{\infty}$  would reach 14 to 16 km/s for a 478 kg payload similar to New Horizons probe. This mission profile presented a major problem: the cost of SLS. Would today's technologies allow us to design a more affordable deep-space mission much faster than any other similar mission, allowing to reach 200 AU in 20 years? This question was addressed by a small independent working group combining experts from space transportation commission of 3AF (Association Aéronautique et Astronautique de France), CEA, CNES, ONERA and Nantes Université. A broad spectrum of the challenges to tackle for such a small mission were discussed, including science objectives, interplanetary mission analysis, on-board power, deep space communication, spacecraft architecture and propulsion. The study aims at proposing an architecture compatible with Ariane 6 launcher capabilities. After a brief explanation of the interest of such a deep-space mission and general description of the assumptions leading to mass allocation to the different sub-

systems, the paper will mostly address propulsion and related iterations with mission analysis.

## 2. GENERAL MISSION ARCHITECTURE

The first step was to analyze the concept proposed by the Johns Hopkins University. The SLS combined with chemical upper stage, was able to launch a sizable mass (~3 tons) toward Jupiter. Instead of using a passive Jupiter swing-by, a propulsive one was used. A solid propellant engine provided a  $\Delta V$  of 3 km/s, thus allowing a much higher increase of infinite velocity. A payload almost similar to New Horizons was considered for the study.

To provide the same type of capability with Ariane 64, the new European heavy launcher, it was necessary to provide a much higher  $\Delta V$  with orbital propulsion (cryogenic stage and electric propulsion), retaining the idea of propulsive swing-by for the final boost. Thus, the following mission architecture was proposed: under the fairing, a cryogenic stage would complete the launcher work by providing an added  $\Delta V$  close to the Earth-Moon orbit; a solar electrical stage would then create an impulse towards the Jupiter system; and finally a storable chemical propulsion stage would perform the last main boost of the probe around Jupiter.

## 3. EARTH DEPARTURE STRATEGY

The first step of the study was to select the best orbit/payload combination provided by the Ariane 64 launcher for departure from Earth. We have considered the following launch strategies:

- Twin launches, LEO, and in-orbit assembly (same speed as single launch to LEO).
- Single launch LEO
- Sub-GTO
- GTO
- Direct Solar System escape

The following table provides the performances in each case [R2].

Case (single launch)	Ariane 64 Payload mass	Orbit insertion velocity
LEO	20 000 kg	7 755 m/s
Sub-GTO	12 950 kg	9 890 m/s

GTO	11 500 kg	10 194 m/s
Direct Escape	6 900 kg	11 248 m/s

This performance set was combined with the performance of an orbital cryogenic stage under fairing to optimise the payload / escape velocity combination. The twin LEO launch was eliminated as unnecessary, as well as direct escape.

Case	Orbital cryo-propulsion module propellant mass	Payload mass
LEO	13 500 kg	4 630 kg
Sub-GTO	9 000 kg	2 805 kg
GTO	7 300 kg	2 700 kg

The following table provides the resultant velocity after the cryo propulsion orbital stage operation.

Case	Payload mass	Burn-out velocity
LEO	4 630 kg	12 514 m/s
Sub-GTO	2 805 kg	15 050 m/s
GTO	2 700 kg	14 966 m/s

The sub-GTO case has been selected because it provided the largest burn-out velocity.

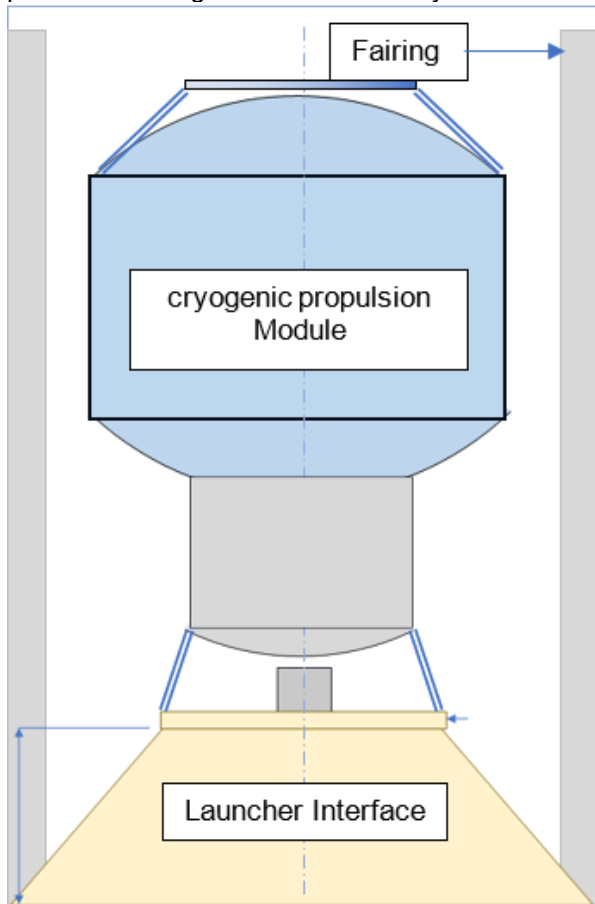


Figure 1. Cryogenic propulsion module

#### 4. CRYOGENIC STAGE DESCRIPTION

The orbital stage technology involves an advanced thermal insulation combining evacuated

honeycomb envelope and outer superinsulation. The evacuated honeycomb is especially efficient on the ground while the outer superinsulation reduces the heat flux to  $\sim 1 \text{ W/m}^2$  in orbital conditions.

The propulsion is ensured by four 10 kN expander cycle engines.

The LH2 mass is 1 324 kg (21,12 m<sup>3</sup> tank); the LH2 propellant tank is 3.4 m in diameter and 2.96 m in height. The LOX tank shares a common bulkhead with the LH2 tank. It contains 7 676 kg of LOX (Mixture Ratio = 5.8).

The stage dry mass is 1 250 kg. The provided  $\Delta V$  is 5 160 m/s.

The stage interface is the 2 624 mm adapter. The overall stage height is 5.89 m (Fig. 1).

The overall  $\Delta V$  is performed in two parts: a first burn provides a highly elliptical orbit 250 x 194 600 km.

A second burn provides the insertion on a hyperbolic trajectory ( $V_\infty = 10\,300 \text{ m/s}$  with respect to Earth) as seen in Fig 2.

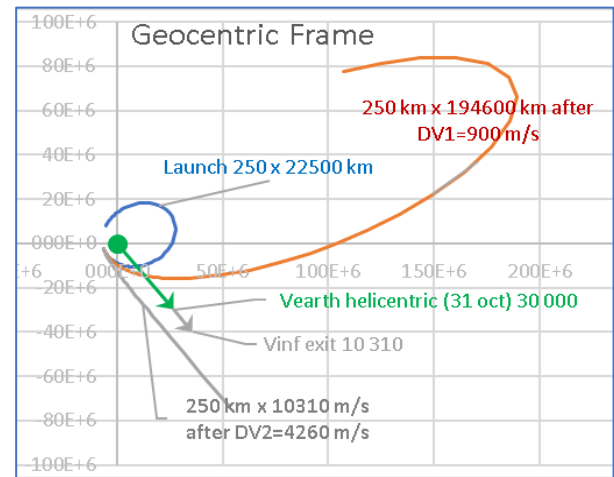


Figure 2. Two burn injection strategy.

#### 5. SOLAR ELECTRIC PROPULSION STAGE

The initial concept was derived from a classical orbit transfer Hall Effect Thruster (HET) propulsion module used for telecommunication satellites (20 kW to power four 5 kW HET (PPS@5000)).

However, it is not possible to adapt the trajectory constraints to the solar power decrease with Sun distance. It was necessary to design a much more powerful unit.

Eight PPS@5000 are combined to produce a combined thrust of 2.05 N (at 1 AU) with a solar array power of 45 kW (two wings of 10 panels each, 4 x 3 m with thinned solar cells, weighing less than 10 kg/kW). The propellant is Xenon (900 kg mass). The full power duration is relatively short (2 200 hours) but it enables to reach the Jupiter vicinity in 0.7 terrestrial year (most of the firing occurs at reduced power, decreasing to 1.3 kW at thruster's cut-off). The Mars orbit is crossed in no more than 2.2 months. The total  $\Delta V$  is 6 982 m/s (Fig. 3 & 4).

The payload of this stage is limited to 806 kg. It is sufficient to accommodate the probe itself and the on-board bipropellant (dual mode) propulsion module.

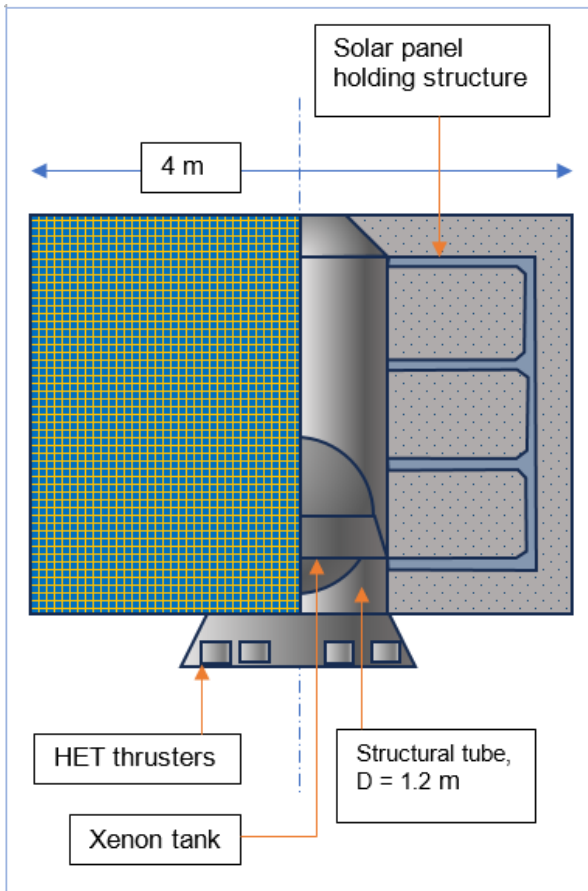


Figure 3. Stowed electric propulsion stage. Left: solar panel side, right: cutaway.

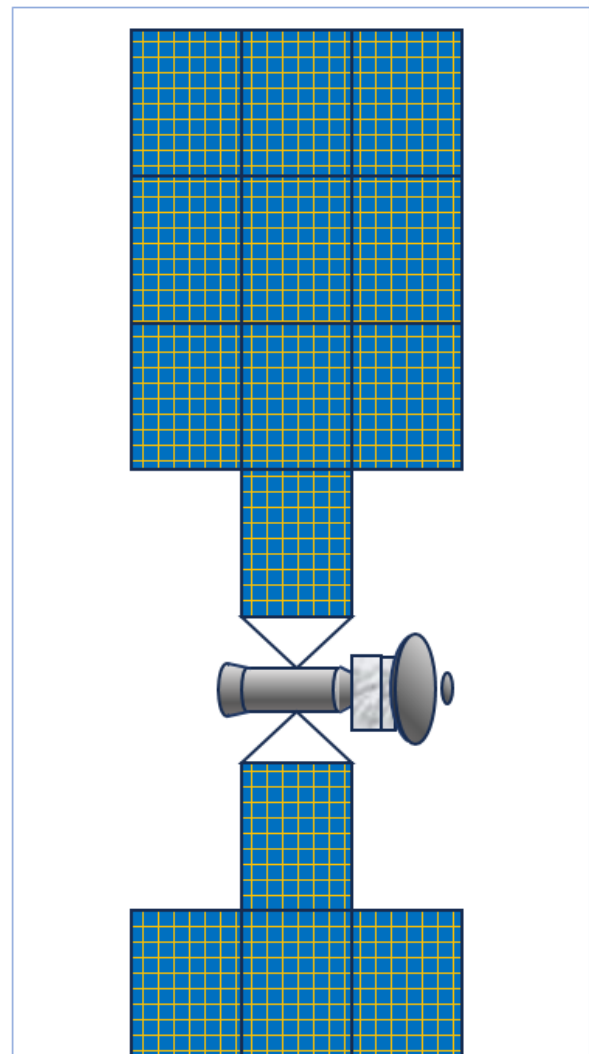


Figure 4. Deployed electric propulsion module

## 6. INTERSTELLAR MEDIUM PROBE

The probe includes a dual mode propulsion system using three propellant tanks of identical dimensions: (600 mm diameter and 785 mm in length), two for hydrazine and one for NTO. The propellant mass is 220 kg for NTO and 298.8 kg for hydrazine (including 30 kg for Reaction Control System operation) for a total of 508 kg. The dry mass of the propulsion system is 74 kg. The three tanks are housed in a box, 2 m in length and 620 mm wide, 820 mm in height (Fig 5). The main thrusters are four 22 N dual mode engines,  $I_{sp} = 310$  s and the Reaction Control is ensured by 12 x 1 N hydrazine catalytic thrusters. The pitch and yaw controls are performed by off-pulsing of the 4 x 22 N thrusters. The roll control is performed by the 1 N hydrazine thrusters.

The firing duration of the main thruster is 4.6 hours and the  $\Delta V$  provided by the operation 2 806 m/s.

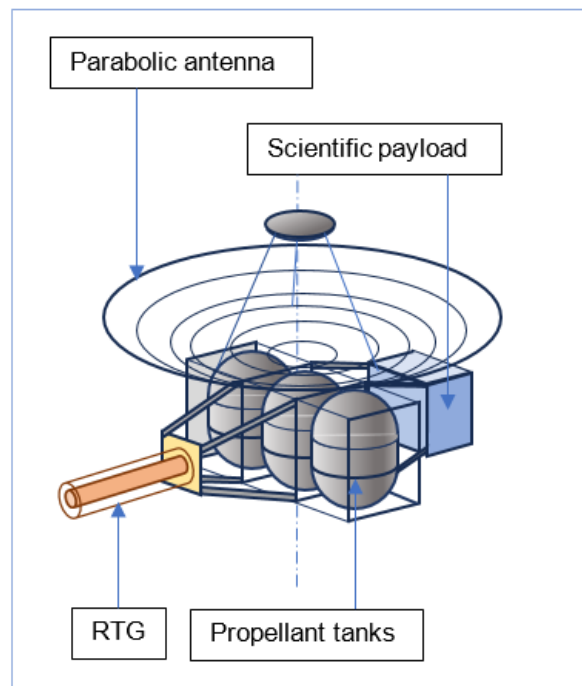


Figure 5 Perspective view of interstellar probe.

A slightly more complicated design has been considered and then discarded: using a 490 N Apogee Boost Motor (ABM) helps to decrease the thrust arc duration to 3 018 s and increase the Isp to 315 s. It results in a few months reduction of the overall mission duration. However, this is counter balanced by the introduction of a thrust vector control. The ABM must be mounted on a gimbal and oriented by two electromechanical actuators, the hydrazine engines thrust is insufficient to provide the pitch and yaw control.

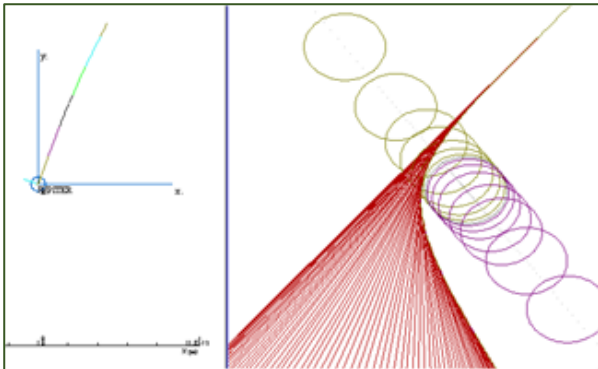


Figure 6 : Jupiter planet encounter (with thrust vector in red, tangent to the local trajectory)

Fig 7 shows the probe covered with superinsulation.

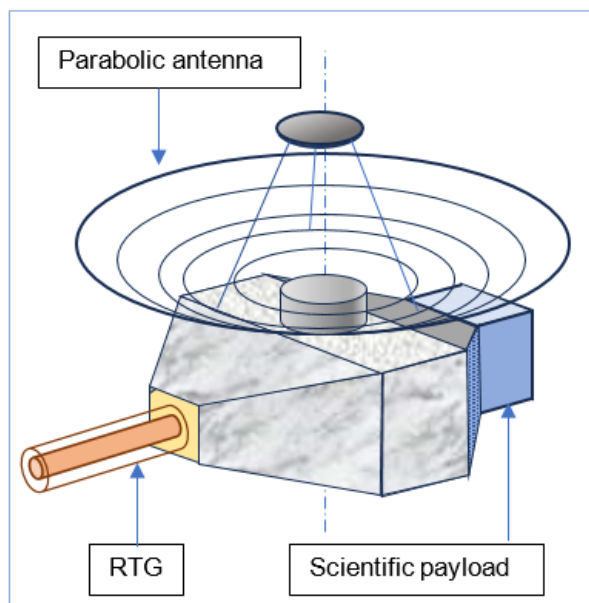


Figure 7 Perspective view of super insulated probe.

## 7. PROBE INSTRUMENTATION

The instrumentation suite is somewhat inspired from the one of New Horizons. Some instruments can work in spin stabilisation mode while other require a three axes stabilisation mode (telescope, Gravity Advanced Package, Doppler Spectro Imager). This is why the probe is designed to be able to operate in either mode.

- Telescope: it is intended to visualise the celestial bodies of Kuiper Belt (and Jupiter). With an aperture of 20 cm, it would be like LORRI of New Horizons.
- Doppler Spectro Imager (DSI), used only during the Jupiter encounter; it will allow to analyze the inner structure of the planet itself.
- Gravity Advanced Package (GAP) micro-accelerometer: main objective: verification of the general relativity in the Solar system.
- Radio and plasma Wave instrument: near DC electric field (LP-PWI), electric component of plasma waves (LP-PWI and RA-PWI), magnetic component of electromagnetic waves (SCM), radio emissions (RWI) as well as detailed characteristics of the thermal plasma (LP-PWI) including electric conductivity.
- Particle Package: ions, electrons, energetic neutral atoms, and neutral gas spectrometers.
- Dust Counter: concentration of dust particles in outer solar system.

Optional instruments may be added, bearing in mind that the mass budget is constrained.

- Multispectral Visible Imaging Camera (MVIC), and an infrared compositional mapping spectrometer called the Linear Etalon Imaging Spectral Array (LEISA).
- Radio Science Experiment (REX): a small printed circuit board containing sophisticated signal-processing electronics. Could be used to probe the Jupiter atmosphere.

## 8. SPACECRAFT OVERALL DESIGN

The spacecraft is contained under the fairing of Ariane 6 (overall design shown in Fig.8.).

## 9. PROBE POWER SOURCE

The power is provided by a RTG supplying 400 W of electrical power and dissipating 4 kW of thermal power. A part of thermal power is used directly to maintain the probe temperature without additional electrical power. The RTG is an improved version of New Horizons RTG, the Next Gen Mod. 2.[R5]. The expected operating life is 50 years. The RTG mass is 55 kg, its length 1.1 m.

## 10. TELECOMMUNICATIONS

Two types of telecommunications have been analysed:

- Laser communication
- S or X band parabolic antenna.

The Laser communication is a very promising technique, providing a data flow four to ten times higher than a RF link of same power. However, it requires an extremely fine three axes pointing, a difficult requirement for a 50-year mission.

The RF link (parabolic antenna) provides the advantage of being compatible with spin stabilisation, a purely passive solution.

The RF data rate at 200 AU with a 3-m diameter antenna, 8.5 GHz frequency and a 12 W RF power is 0.6 bps (bit per second). This corresponds to 2.16 kbytes in 8 hours. This may seem extremely low but is in line with other very long-distance telemetry rates. The data rate will increase to 3.7 bps (13.8 kbytes in 8 hours) with a RF power of 35 W and a 4-m diameter parabolic antenna, but this will come at the expense of the scientific payload mass.

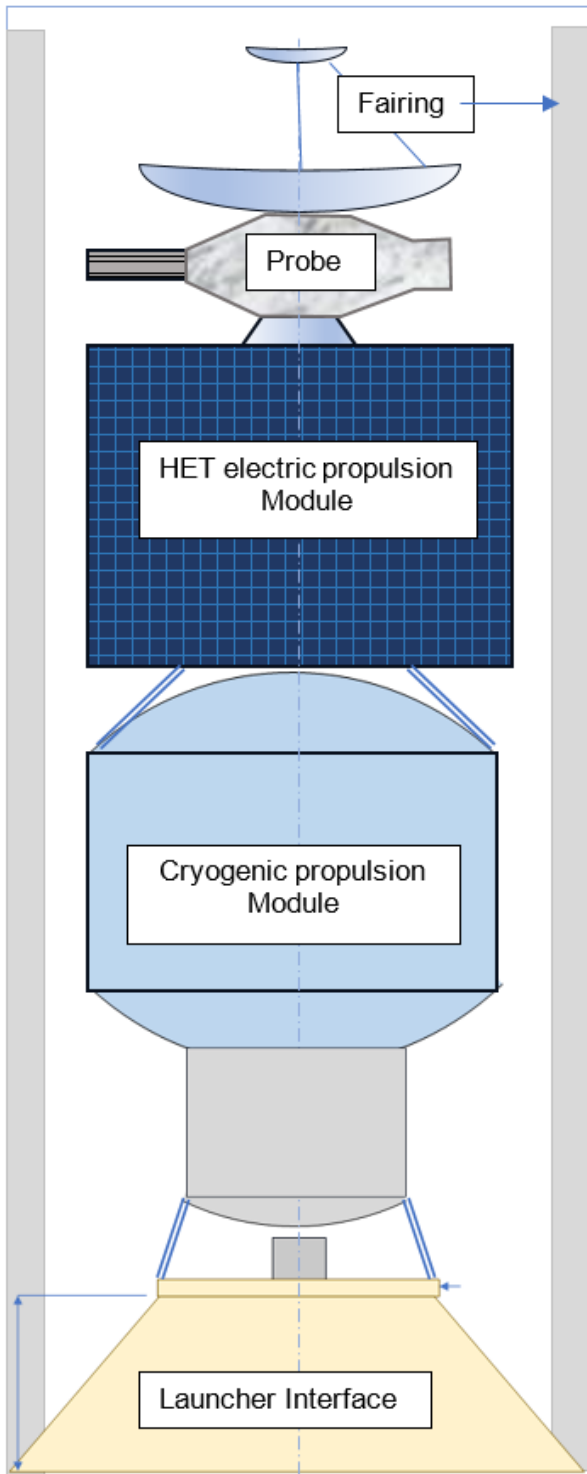


Figure 8: Spacecraft architecture

## 11. OTHER POTENTIAL APPLICATIONS

This kind of probe technology has the potential to perform rendezvous with extrasolar objects like 1I/Oumuamua. It may be too late to reach 1I/Oumuamua in a reasonable time, but other opportunities of extrasolar objects will occur and enable such type of mission.

## 12. CONCLUSION

Launching a probe at 40 km/s devoted to the exploration the interstellar medium seemed almost impossible. However, a careful examination of the problem showed that this is indeed possible, combining a sub-GTO launch with Ariane 64, a solar electric (HET) propulsion stage and a propulsive boost during Jupiter swing-by. The scientific payload will be used during the Jupiter swing-by. Its main purpose is to explore the interstellar medium and to verify fundamental physics questions (general relativity). In addition, this spacecraft design may be used to examine future extra-solar asteroids and comets like 1I/Oumuamua.

The cryogenic orbital stage may have also interesting uses like sending heavy landers toward Moon or Mars.

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