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# THE INTERSTELLAR HELIOPAUSE PROBE

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**ABSTRACT**

The Interstellar Heliopause Probe (IHP) is one of four Technology Reference Studies (TRS) introduced by the Planetary Exploration Studies Section of the Science Payload & Advanced Concepts Office (SCI-A) at ESA. The overall purpose of the TRSs is to focus the development of strategically important technologies of likely relevance to future science missions. This is accomplished through the study of several technologically demanding and scientifically interesting missions, which are currently not part of the ESA science programme. The TRS baseline uses small satellites (~ 200kg), with highly miniaturized and highly integrated payload suites. By using multiple low resource spacecraft in a phased approach, the risk and cost, compared to a single, high resource mission can be reduced.

Equipped with a Highly Integrated Payload Suite the IHP will answer scientific questions concerning the nature of the interstellar medium, how the interstellar medium affects our solar system and how the solar system impacts the interstellar medium.

This paper will present an update to the results of the studies being performed on this mission. The current mission baseline and alternative propulsion systems will be described and the spacecraft design and other enabling technologies will be discussed.

## 1. INTRODUCTION

Technology Reference Studies (TRS)[1] have been introduced as a tool to identify future technology needs and enable strategic technology development. TRSs are characteristically challenging missions in which critical technologies have yet to be identified. By introducing the TRSs the Science Payload & Advanced Concepts Office (SCI-A) ensures long-term technology developments within the science directorate to facilitate future science missions.

The interstellar medium is one of the frontiers of future space exploration and extreme challenges are imposed on a mission to reach the required distance for in-situ measurements of this medium. In the Interstellar Heliopause Probe (IHP) TRS a feasible mission concept is being developed, enabling a mission to investigate the outer heliosphere, the interstellar medium and the interface region between them.

Several missions to the heliopause have already been proposed. In the early 1980’s the ”Thousand Astronomical Units” (TAU) mission[2] was proposed based on a 1 MW nuclear powered electrical propulsion system. Later missions such as the Heliopause Explorer[3], and the Interstellar Probe[4,5] where studied using solar sails. All these studies have slightly different mission profiles in order to obtain the required distance from the Sun. The goal of the IHP TRS is to identify requirements for future technology developments that will enable such a mission, making it possible to reach a distance of 200 AU within 25 years transfer time.

## 2. SCIENTIFIC OBJECTIVES

The Heliosphere contains the plasma that originates from the Sun. This region is formed and structured by the Local Interstellar Medium (LISM), the solar wind and the relative motion of the Sun with respect to the LISM.

The heliopause separates the solar plasma from the interstellar plasma and can be considered to be the boundary between the interstellar medium and the heliosphere. The heliopause is located between the solar wind termination shock and bow shock in the LISM (Figure 1). These two shock surfaces terminate the undisturbed supersonic flows of the solar wind and LISM respectively and represent the inner and outer boundary of the heliospheric interface. In this region the IHP will make in-situ measurements to answer the questions:

- *What is the nature of the interstellar medium?*
- *How does the interstellar medium affect the solar system?*
- *How does the solar system impact the interstellar medium?*

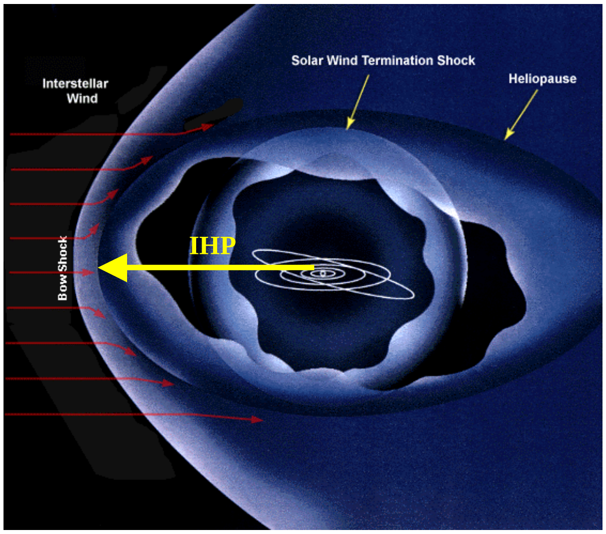

Figure 1: The heliosphere in the LISM

In order to answer these questions the IHP needs to make in-situ measurements continuously while travelling from the outer heliosphere and into the interstellar medium. Each of these regions will have different scientific interest.

2.1 The Outer Heliosphere

The Solar System was formed approximately 4.6 billion years ago. Still, the origin and the evolution of the solar system are fairly unknown. Collisions play a central role in the formation and evolution of planetary systems. The present interplanetary dust population is a result of collision processes occurring in the solar system. By studying interplanetary and interstellar dust the IHP will help to understand the origin and nature of our solar system and hence other planetary systems.

2.2 The interface region

The location of the termination shock and the heliopause are yet to be known exactly. Determining the location of these areas as they vary with solar and interstellar pressure is one of the key objectives of the IHP.

Anomalous cosmic rays are particles accelerated in the termination shock. How these particles are accelerated is not yet fully understood. Hence, getting a better understanding of this process is also an important scientific goal for the IHP.

2.3 The Interstellar Medium

The Sun is thought to be located near the edge of a low-density interstellar cloud (~0.3 $cm^{-3}$). In order to establish an understanding of the LISM's nature, a series of measurements should be made in this region. The IHP will facilitate the derivation of the physical properties of the LISM and investigate astrophysical processes such as acceleration by supernova shock waves, interstellar radio heating and dynamics of the interstellar medium.

## 3. PAYLOAD

A common building block of all the TRSs in the Planetary Exploration Studies Section of SCI-A is the Highly Integrated Payload Suite (HIPS) concept[6]. A HIPS reduces the overall resources (i.e. mass, power and volume) by sharing common structures and payload functionalities, such as power supply and processors, and by using miniaturized sensors and components, such as stacks, 3D electronics, etc.

By performing the measurements described in Table 1 the IHP will be able to meet the scientific objectives. The mass of this payload, excluding the secondary instruments, is about 22 kg and the power requirement is less than 15 W. Due to sequential operation of the instruments the continuous payload power demand could be less than 10 W.

## 4. PROPULSION SYSTEM

To keep total cost of the mission reasonable the IHP shall be compatible with a launch on a Souyz Fregat 2B launch vehicle from Korou. This allows for a total launch mass approaching 2000 kg to a low energy Earth escape orbit.

| **P/L** | **Purpose** | **Mass (kg)** | **Power (W)** |
|---|---|---|---|
| Plasma Analyser | Elemental and isotopic composition of plasma and the associated energy levels at temporal composition | 2.0 | 1 |
| Plasma radio wave experiment | Plasma and radio waves experiment | 5.5 | 2.5 |
| Magnetometer | Magnetic field measurements in very low fields | 3.2 | 2.5 |
| Neutral and charged atom detector | Energy levels, composition, mass, angular and energy distribution of neutral atoms | 0.5 | 1 |
| Energetic particle detector | Energy levels of cosmic rays | 1.8 | 1.2 |
| Dust analyser | Energy levels, mass and composition of dust particles | 1.0 | 0.5 |
| UV-photometer | Hydrogen density | 0.3 | 0.3 |
| FIR spectral imager* | Measurement of the radial distribution of dust and the cosmic infrared background | (0.3) | (0.2) |
| VIS-NIR imager* | Determine the radial distribution of Small Kuiper belt objects and TNO | (1.0) | (0.5) |
| *DPU + CPS* | *Data processing and power supply* | *2* | *3.5* |
| *Structures* | *Optical bench and mounting structures* | *2* | - |
| *System Margin (20 %)* | | *3.7* | *2.6* |
| **Total** | | **22.0** | **14.9** |

Table 1: Tentative payload for IHP. *) Instruments are only secondary and are hence currently not part of the overall mass and power estimate

To reach the interstellar medium in the shortest possible time the spacecraft will have to be launched in the direction of the heliosphere nose, which is located at 7.5° latitude and 254.5° longitude in the ecliptic coordinate frame.

Three different propulsion systems where identified as potential candidates for the IHP TRS, chemical propulsion, Nuclear Electric Propulsion (NEP) and solar sailing. Each of these propulsion systems were investigated in order to find the most feasible alternative with the given requirements and constraints.

A major factor for all propulsion system types considered is the desire to achieve the transfer to the heliopause within some maximum mission duration, typically 15-25 years.

4.1 Chemical Propulsion

The chemical propulsion system could use one or two Earth gravity assists to reach Jupiter and then employ a close solar flyby with a propulsive manoeuvre to achieve the required Solar system excess hyperbolic speed. The two Earth gravity assist route is used in conjunction with a preceding Lunar or Venus gravity assist. A Lunar-Earth-Earth-Jupiter-Sun (LEEJS) trajectory is shown in Figure 2. The solar approach would have to be as close as 4 solar radii to obtain the Delta-V required to reach the distance to the heliopause. However, even at this close distance to the Sun current chemical propulsion systems would not have sufficient specific impulse to provide more than approximately 50 kg of useful mass (i.e. mass of spacecraft excl. propulsion system).

With new developments in high thrust propulsion systems such as nuclear thermal propulsion this trajectory could become feasible. However, the thermal requirements for such a mission would be extremely challenging and hence this alternative was discarded as an option for IHP.

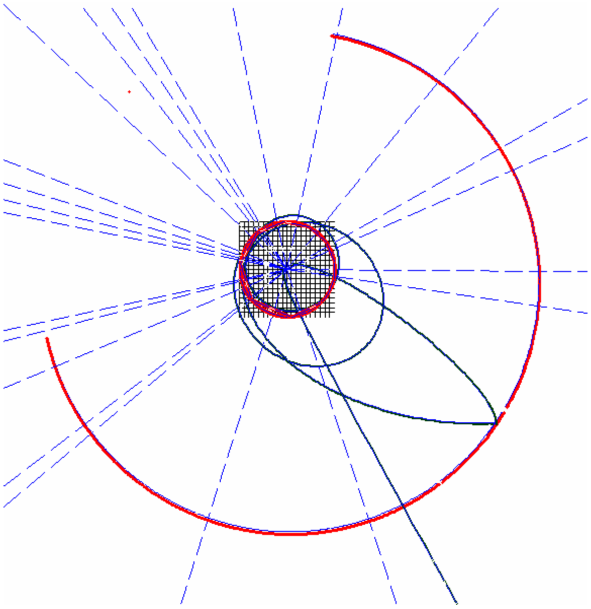

Figure 2: Chemical propulsion trajectory with close solar flyby (LEEJS)

4.2 Nuclear Electric Propulsion (NEP)

The second propulsion system identified as an option was NEP. The best launch scenario would then be an LEEJ gravity assist sequence. The number of gravity assists would be limited due to the cruise time constraint to 200AU. More gravity assists reduces the $\Delta V$ needed to achieve a high energy Jupiter crossing orbit, but requires a greater $\Delta V$ after passing Jupiter because the remaining cruise time is reduced.

An example of such a transfer is shown in Figure 3. After a close Jupiter fly-by, achieving a moderate Solar system excess hyperbolic speed, an extended low thrust phase is required to achieve the transfer in the required timescale.

The thrust required for a NEP mission is dependent on the time that the thrusters are on (thrust time). The longer the thrust time the less thrust is required. For instance a 20-year thrust sequence after JGA will require a thrust of between 53-68 mN/tonne and a 10-year thrust after JGA will require about 77-95 mN/tonne. The specific impulse that was investigated was between 5000 s and 20000 s.

The thrust and specific impulse necessary for this option would require a large amount of power (i.e. between 5 kW and 20 kW). To produce such power at distances beyond Jupiter orbit requires power systems that are currently not available. In a best-case scenario with a 20-year thrust time the required specific power for these systems would be in excess of 10 W/kg. Current Radioisotope Power Systems (RPS) are not capable of providing specific power of this magnitude. Even if high specific power RPS were developed, the required amount of radioisotope material would be too great to make NEP a viable power system solution for IHP. The only alternative remaining would be to use a nuclear reactor. If a nuclear reactor were developed, the required specific power could be possible to obtain. However the total power system mass is severely constrained due to the extremely large Delta-V required and cannot be more than approximately 500 kg for IHP. To develop a nuclear reactor capable of meeting the IHP requirements and constraints will therefore be extremely challenging, as the nuclear reactor is difficult to scale down in mass while keeping the specific power high. Therefore even a 20 kW reactor would have a mass in excess of the maximum available mass for the IHP.

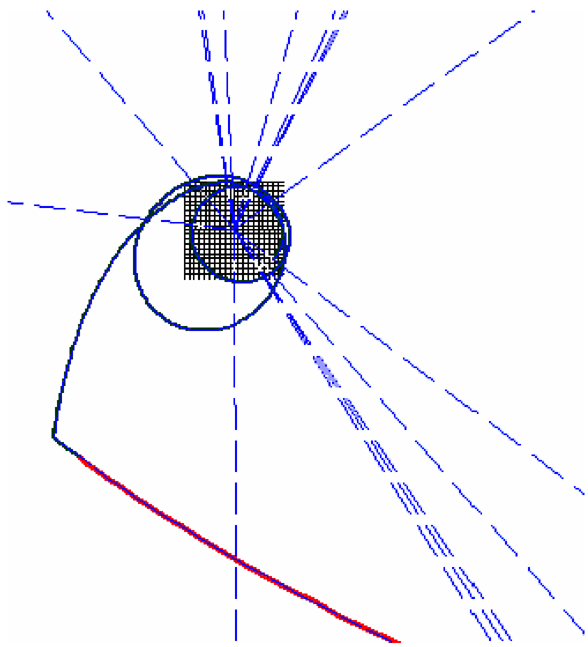

Figure 3: EEJ gravity assist trajectory using Nuclear Electric Propulsion.

Another issue with the NEP option is the thrust time. The power system would have to be even larger for thrust times of less than 20 years as a higher thrust is needed. Current electrical propulsion systems are quite far from obtaining 20-year continuous thrust lifetime and even a 10-year lifetime will require substantial development.

Based on this careful assessment the NEP option was considered to be infeasible with the current TRS constraints.

4.3 Solar sailing

The third, and currently most feasible propulsion technology given the constraints and requirements of the study is solar sailing. Hence this is the baseline propulsion system for the IHP. There are many different solar sail configurations and currently two are being investigated for IHP; a square sail and a spinning disk sail.

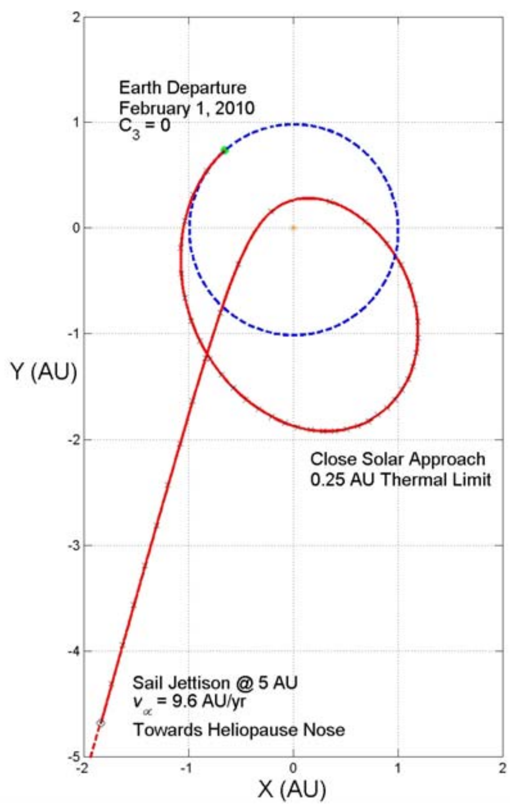


Figure 4: Trajectory for IHP with a characteristic acceleration of 1.5 mm/s$^2$

Solar sails utilize the momentum of photons to obtain a very low acceleration. However, since no propellant is being used the propulsion system is very effective although very large structures are needed. For the square sail scenario a sail size of about 260 m x 260 m and a sail thickness of 2 μm is needed. At 1 AU this sail size will give us a characteristic acceleration of 0.85 mm/s$^2$, which will greatly increase as the probe travels closer to the Sun. Hence, all the solar sail alternatives for the IHP have to capitalize on this effect by first travelling closer to the Sun to get the required acceleration to reach 200 AU in 25 years.

A spinning sail without rigidizing structure is lighter compared to the square sail option, which requires booms. Since the mass of the sail can be reduced in this configuration, a smaller sail could be used to obtain the same acceleration as the square sail. The current spinning disk sail scenario utilizes a sail with a radii of approximately 140 m and a sail thickness of 1 μm, this gives a characteristic acceleration of 1.5 mm/s$^2$. The trajectory for this configuration is shown in Figure 4.

## 5. IHP SPACECRAFT

Because most of the instruments described in Table 1 require a 4π field of view the IHP spacecraft is spinning. The subsystem mass breakdown of IHP is given in Table 2. These numbers were obtained assuming several technology developments such as within the power system, where a specific power of approximately 10 W/kg has been used.

| **System** | **Mass (kg)** |
|---|---|
| Science instruments | 22 |
| Attitude Determination and Control | 35 |
| Telemetry, tracking and command | 61 |
| On-board data handling | 12 |
| Thermal Control | 14 |
| Power | 42 |
| Mechanisms and structure | 27 |
| **Total mass** | 213 |

Table 2: Current subsystem mass breakdown

The spacecraft dry mass of the IHP is similar for both solar sail configurations. However, the sail masses differ significantly. The square sail is much heavier than the disk sail, mainly due to the mass of the boom structures and the thickness of the film (Table 3). The total solar sail mass includes the spin-up mechanisms using cold gas thrusters on thrust arm booms and the deployment mechanism, which is quite different for the two concepts. The overall mass including margin for both sails is well within the capabilities of a Souyz Fregat.

| Sail configuration | Spinning | Square |
|---|---|---|
| IHP Spacecraft Dry Mass | 213 kg | 213 kg |
| Solar Sail System Mass | 311 kg | 492 kg |
| System margin (20 %) | 104 kg | 141 kg |
| **Total launch mass** | **628 kg** | **846 kg** |

Table 3: Launch mass for different sail configurations

## 5. TECHNOLOGY DEVELOPMENT

The IHP TRS faces several challenges. However the purpose of the study is to identify these challenges and potentially develop technologies that will enable such a mission in the future.

### 5.1 Solar sail technology developments

The biggest challenge that a mission like the IHP will face is the development of an adequate propulsion system. The development of solar sails for the IHP will require great advances from current available technologies. Presently the largest sail deployed has been the ESA/DLR ground deployment test[7]. There have been other deployment demonstrations as well, such as a small spinning disk sail deployment[8] and the in-orbit solar sail deployment on the Progress vehicle[9].

Due to the close approach to the Sun the IHP will have very stringent thermal requirements. The minimum distance to the Sun is currently set at 0.25 AU, which implies that the solar sail will have to withstand a solar flux 16 times greater than at the Earth. The solar sail will be jettisoned at 5 AU, which means that the solar sail is used for a period of close to 5 years. Within those 5 years it is important that the sail keeps its optical properties, since the performance of the sail is directly dependent on the reflectivity of the sail material.

Solar sails will also require a reliable deployment mechanism. This will be dependent on the chosen sail configuration (i.e. disk or square sail). For the smallest sail option using a spinning disk sail the area of the sail is as large as 50 000 m$^2$, which will be very challenging to deploy without causing ruptures, damage to the coating, etc.

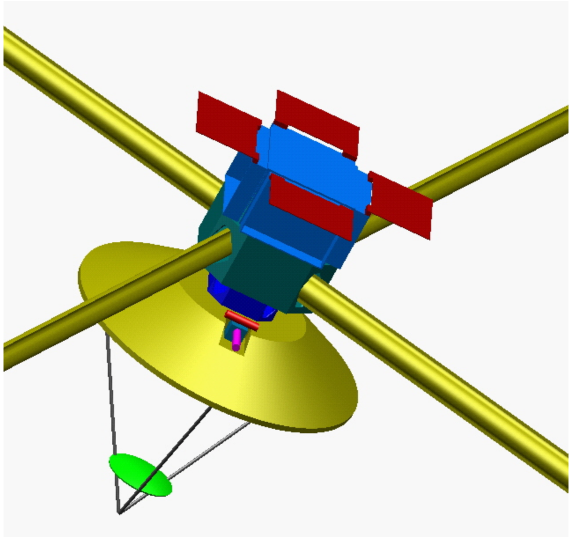

Figure 5: Potential configuration of the IHP

Designing an Attitude Determination and Control System (ADCS) for the spacecraft sailing phase will also be challenging. Several alternatives exist, such as gimballed boom between sail structure and spacecraft bus, tip vanes or thrusters on booms. A suitable alternative for this system must be identified and developed in order to enable a mission such as the IHP. This system will be dependent on whether a spinning or a three axis stabilized sail is chosen.

If the square sail configuration is used then there will be a need for further development of boom technologies. Current booms in Europe have a specific mass of ~100 g/m, this implies a large mass penalty compared to lower mass booms.

Using solar sails for a mission like IHP also requires development of a jettison mechanism that could safely jettison the sail from the spacecraft after 5 years with minimum risk for collision with the spacecraft structure.

### 5.2 Additional technology developments

#### 5.2.1 Power

The power system that will be used for the IHP will most likely utilize conversion of radioisotope thermal energy. Current Radioisotope Thermoelectric Generators (RTG) such as the General Purpose Heat Source (GPHS) RTG, have a specific power of about 5.1 W/kg and conversion efficiency of 6.6 %[10]. The solar sail principle greatly benefits from general mass reductions as the acceleration is based on conversion of momentum. An improvement to the specific power of current RPS will help reduce the solar sail size of the IHP. The current estimated specific power needed for IHP is 10 W/kg. Figure 6 shows how the specific power influences the solar sail size for the spinning disk sail configuration.

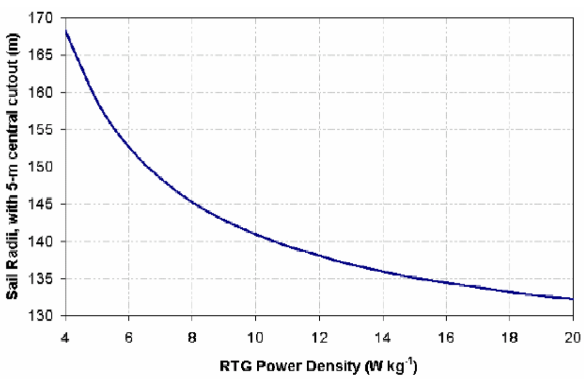


Figure 6: Solar sail size as a function of specific power

5.2.2 Communication

The communication system for the IHP will be limited to downlink an average data rate of approximately 200 bps at 200 AU. In the current IHP profile an RF communication system has been selected. However, both RF and optical communication systems are being assessed for the IHP in the ongoing study.

If optical communication is chosen, issues such as acquisition strategy will have to be solved. Current optical communication systems use a beacon strategy to communicate. Light takes 13 hours to travel a distance of 100 AU. Hence using a beacon is not a suitable acquisition strategy for the IHP. In addition to an acquisition strategy, lightweight components and long lifetime lasers will need to be developed in order to make the optical alternative feasible.

The other alternative for a communication system is RF communication. This requires a large antenna size and high power levels. This results in a high overall mass of the system (in excess of 60 kg total). The IHP will therefore greatly benefit from development of lightweight antenna structures and highly efficient power amplifiers.

5.2.3 Lifetime and autonomy

The long lifetime of the spacecraft sets strict requirements on all subsystems. Due to the long travel distance of 200 AU the lifetime of the IHP must be more than 25 years hence each of the subsystems will have to be designed for this duration.

Satisfying these long lifetime constraints will require innovative ways of making the spacecraft fault-tolerant and provide significant redundancy. Furthermore, as operations cost is traditionally a large portion of the overall mission cost a reduction of the manpower required to operate the spacecraft over such a long time period is of paramount importance. This will require, due to long transmission and response times, a large degree of onboard autonomy.

## 6. CONCLUSION

Technology Reference Studies have been introduced by ESA’s Science Payload & Advanced Concepts Office to identify critical technologies of likely relevance to future science missions. By studying challenging future mission concepts where enabling technologies have yet to be identified the individual TRSs can provide a guideline for future technology development activities.

The Interstellar Heliopause Probe (IHP) is one of these technology reference studies. It has identified a feasible propulsion option and identified several technologies and technology areas in which developments are required to enable such a mission profile. The ongoing study of the IHP will provide additional and consolidated requirements for these technologies, which also can benefit other missions such as outer planet missions, which are sharing very similar technologies.

## 7. ACKNOWLEDGEMENTS

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