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# Architecture for exploration & gravity study at edge of Solar System

This paper arises from the pre-assessment study of FOCAL mission proposed by Italian researchers to place a probe beyond 550 AU, where the gravity lens of the Sun phenomenon can be exploited for radio-astronomy purposes. The aim of the study is to explore the feasibility of this mission in a reasonable time, which is set to be around 50 years.
The envisaged solution combines a chemical upper stage with a low-thrust phase. The former is used to put the spacecraft on a direct trajectory to Jupiter, the latter starts soon after the escape from Jupiter's SOI and should last for a decade. Nuclear electric propulsion (NEP) has been selected as the baseline in the second phase, after a trade-off supported by a preliminary numerical analysis among solar sails and SEP.
Basing on the actual technology, 3.2 light days distance from Earth is quite demanding for the link budget, and it is a core requirement for the sizing of the spacecraft at its scientific phase. FOCAL scientific requirements ask for around 100 dB in gain at the Hydrogen natural frequency: 56 dB coming from the Sun's lens and the rest from the antenna.
A trade-off between power, mass budget and data rate brought to an antenna diameter of 6 meters, a mass around 169 kg and a data rate of 4kbit/s in downlink at 550 AU and 1kbit/s at 1000 AU. A traditional rigid deployable antenna has been selected instead of an inflatable technology, due to the low TRL of this alternative and uncertainties on its resistance in a very harsh environment (still unknown) for very long time.
According to the ASTRO-FOCAL concept, the selected directrix for the escaping trajectory points in the opposite direction of the galactic centre position on the celestial sphere. Thus, a significant out-of-ecliptic velocity has to be gained. The mission design plans to use a single flyby of Jupiter for achieving both the correct orbital plane and sufficient velocity to set the spacecraft on the solar system escape orbit. Flyby is performed on March 6th 2039 and the Jovian hyperbolic passage has a pericenter altitude of about 167,000 Km. Departure from the sphere of influence of Earth occurs on September 28th 2037 on a trajectory for a direct ascent to Jupiter. The departure window lasts for about 10 days. The energy for this departure is to be provided by a single or multi-stage cryogenic upper stage. The optimization of the internal solar system mission design has been assessed using a custom developed multi-objective genetic algorithm. Planning a multi-gravity assist solar system tour proved to be unadvisable for the long time-of-flight it would require, which would reduce the useful life of the nuclear reactor, that is a limiting factor for the low-thrust phase.
An optimization analysis has been implemented in order to find out the main propulsive parameters required by the low thrust phase. After a preliminary trade-off among the available technologies, three High Power Gridded Ion Thrusters have been considered: HiPEP (NASA GRC), NEXIS (NASA JPL) and DS4G (ESA). The class of these thrusters refers to a power range of 30-100 kW, specific impulse of 7,000-11,000 s, thruster efficiency higher than 75% and a life range of 7-10 years. Significant results have been obtained in the case of a simple step on the thrust profile: the "minimum weight"solution has been found with a constant thrust of 0.45 N and a specific impulse of 8800 s, given for 15.25 years (after the Jupiter GA) by a single HiPEP switched on. Power required is 26.6 kW and it is supplied by a nuclear fission reactor through a thermo-ionic conversion, preferable to the most promising Brayton. Nuclear power system has been designed according to updated literature and assuming a lifetime of about 15 years. Finally the scientific phase beyond 550 AU and the cruise to Jupiter is powered by a set of RTGs.
This proposed solution aims to reach the targeted 550 AU in 55 years. A sensitivity analysis has been made, making it possible to reduce the time of travel down to 45 years, but involving necessarily multiple launches and relative docking manoeuvres in LEO. The selected launcher is the Space Launch System (SLS) Block II,

whose first launch is scheduled for 2032.
The resulting architecture is exploitable for many other high delta-v missions to the edge of the solar system, being interested in the Local Interstellar Medium, distant Kuiper Belt Objects or inner Oort cloud objects. To increase the scientific return in the mid-term (soon after 16 years), a medium-size payload (50 kg) is planned to be added, leading an increase of the 14% on the overall mass to launch, still without affecting the actual baseline architecture.
In this paper the configuration alternatives will be presented along with the discussion on the subsystems sizing and the trade-offs. These have been performed as a function of the technological level, focusing on the enabling technologies.

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