

The Role of Electric Propulsion in a Flexible Architecture for Space Exploration

IEPC-2011-210

*Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011*

C. Casaregola¹, D. Dignani², P. Pergola¹, A. Ruggiero² and M. Andrenucci³
Alta S.p.A., Pisa, 56121, Italy

Abstract: Lessons learned and the remarkable achievements from years of hard-won experience with the International Space Station are directly applicable to the design, development, operations and management of future exploration missions. Moreover, the development of enabling technologies and the improvement of in-space assembly capability beyond LEO are essential steps for future space exploration. Based on this and compliant with the NASA flexible path guidelines, Alta is proposing the design of a EP-based flexible architecture. Main elements of this architecture are a service module and inflatable structures. The service module is powered by a hybrid propulsion system that provides the vehicle with much more flexibility thus allowing a wider range of mission classes and objectives to be accomplished. Expandable structures are deployed after launch providing a significant volume to be equipped with cargoes and various experiments to be performed beyond LEO. Moreover, due to a modular configuration, these inflatable modules could also serve as building blocks of a future space station beyond LEO including some functional elements deriving from ISS disposal.

I. Introduction

HUMAN and robotic explorations both contribute to the expansion of scientific knowledge and expertise in further exploration. They also produce important tangible benefits to society, such as technological innovation for a better tenor of living, development of competitive commercial industries, national capabilities and new business opportunities. Moreover, to chart a path for human expansion into the solar system, space exploration is also the matter of setting up a rational logistic infrastructure as required to make it affordable, safe and sustainable. As “*we explore to reach goals not destinations*”¹, destinations should derive from goals, and then the definition of suitable architectures and missions may be weighed against those goals.

During last decades, the in-flight experience of the International Space Station (ISS) and a number of robotic missions have been successfully accomplished with new technologies aimed at expanding capabilities for future exploration and many lessons were learned in terms of docking operations, routinary module assembly, resupplying, refueling, long-term manned operations, permanent scientific research in microgravity conditions and international cooperation for space activities.

Based on these remarkable achievements, a number of designs have been assessed²⁻⁵ for much more ambitious targets such as human operations and long permanence beyond Low Earth Orbit (LEO). However, all these studies rely on the capability to transfer significant amounts of equipment to the final destination. To this end, the development of innovative propulsion technologies, mainly based on Electric Propulsion (EP) technology, and the improvement of in-space assembly capability beyond LEO are essential steps.

¹ Project Manager, c.casaregola@alta-space.com, p.pergola@alta-space.com.

² Project Engineer, d.dignani@alta-space.com, a.ruggiero@alta-space.com,

³ CEO; Professor, Department of Aerospace Engineering, University of Pisa; m.andrenucci@alta-space.com.

II. A Flexible Path for Exploration

Following the recent debates in major international space agencies on a sustainable path for space exploration, several scenarios were investigated to assess viable exploration strategies. Although Mars is undeniably the most scientifically interesting destination in the inner solar system and therefore the ultimate destination for all scenarios considered, some questions arise about the most sustainable and affordable way to Mars. One of the envisaged scenarios – the so called *flexible path* - is based on visiting a series of locations and objects in the inner solar system never visited before while traveling greater and greater distances from Earth (Fig. 1). This would allow humans to learn how to live and operate in free space beyond LEO and protective radiation belts for hundreds of days. Besides, this new approach aimed at reaching multiple destinations – Moon, Earth-Moon Lagrangian points (EML_i), Sun-Earth Lagrangian points (SEL_i), Near-Earth Objects (NEOs), Deimos, Phobos and then Mars - would help to demonstrate critical technologies, to reduce costs, to expand capabilities and thus taking steps towards Mars.

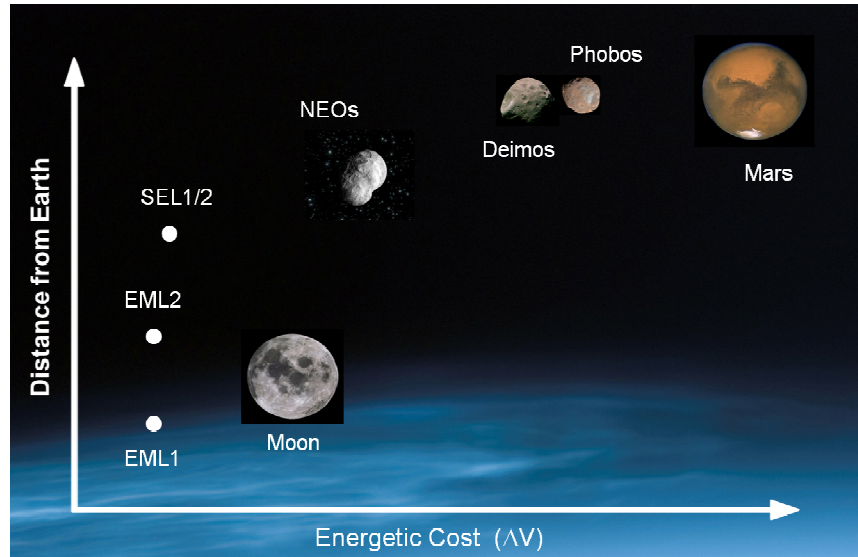


Figure 1. Multiple destinations along the Flexible Path

Indeed, flexible path missions assume the development of certain enabling technologies in several areas such as automated/autonomous rendezvous and docking, in-orbit propellant transfer and storage, lightweight/inflatable modules, advanced in-space propulsion, aero-assist/entry, descent and landing and closed loop life support.

Based on this, technology demonstration missions are necessary and fundamental precursor steps to allow humans a long permanence beyond LEO.

III. Proposed Architecture

A. Mission Objectives

Compliant with these flexible path guidelines, Alta is proposing the design of a EP-based flexible architecture as stepping stone for future space exploration. Main strategic objective of such a architecture is to improve servicing capabilities beyond LEO by means of testing innovative technologies. Conceived as flagship technology demonstrator, the proposed architecture will enable in-flight demonstration of the following technologies:

- High power advanced propulsion systems
- Inflatable structures beyond LEO and outside the magnetosphere
- Autonomous/automated rendezvous and docking beyond LEO
- Propellants storage and transfer

In addition, the proposed architecture would also allow next generation systems developed on ISS experience and existing elements of the ISS infrastructure meant to be disposed in a far future to be proved on a harsher environment. In fact, it could also serve for ISS resupplying and refueling, multi-purpose research laboratory beyond LEO, space tug from ISS to Earth-Moon Lagrangian points and support of human and robotic survey missions to the Moon and beyond.

B. Concept Design

Main elements of the EP-based flexible architecture are a service module and an inflatable structure (Fig. 2). The service module is derived from the European Automated Transfer Vehicle (ATV), it has a length of 6.412 m and a maximum diameter of 4.5 m.

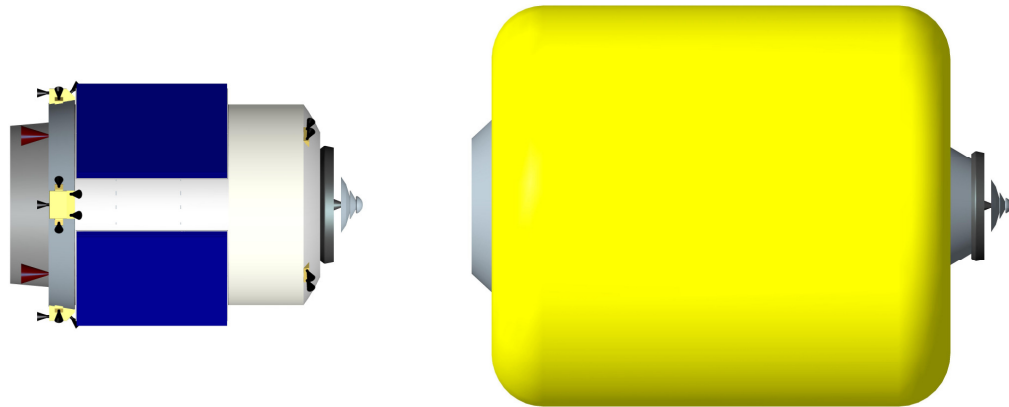


Figure 2. The Service Module (on the left) and the inflatable module (in scale).

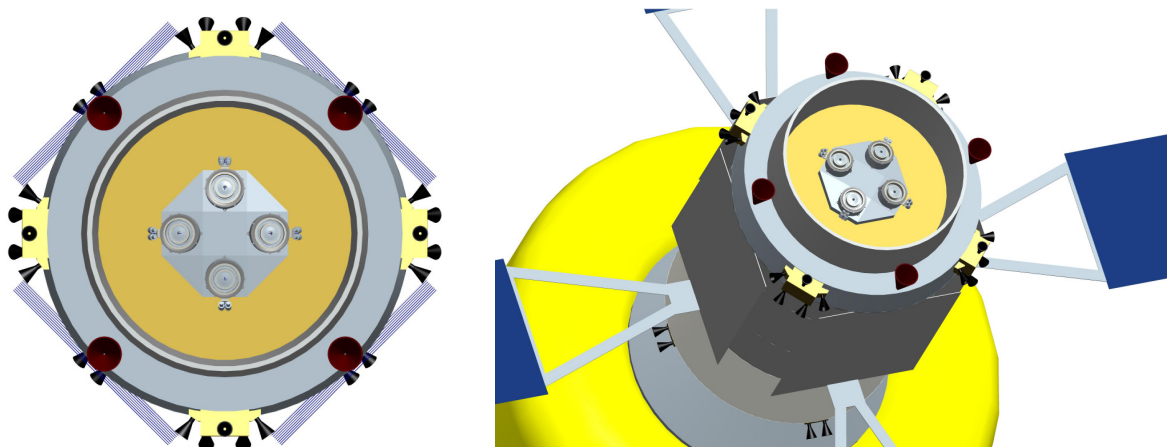


Figure 3. Details of the hybrid propulsion system on the Service Module.

It is powered by a hybrid propulsion system (Fig. 3) that provides the vehicle with much more flexibility thus allowing a wider range of mission classes and objectives to be accomplished.

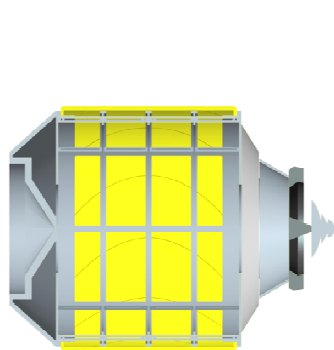


Figure 4. Inflatable module at launch (section).

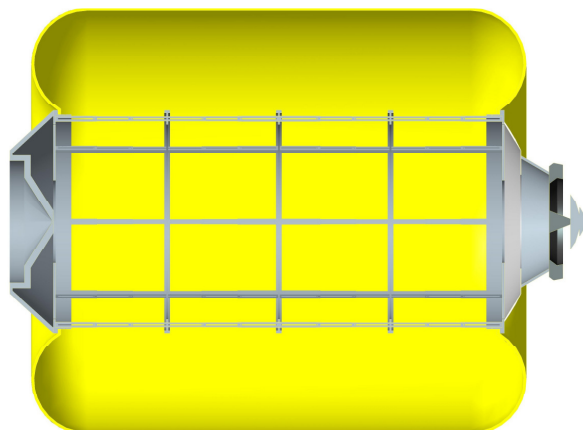


Figure 5. Inflatable module deployed (section).

The chemical propulsion system is totally derived from the ATV and it is composed by four main engines providing 490 N thrust plus twenty-eight smaller 220 N thrusters for attitude control⁶.

An Electric Propulsion system is integrated in the service module. In particular, two 25 kW Hall thrusters firing simultaneously are able to provide a nominal 2.5 N thrust at a specific impulse (Isp) of 2500 s. Due to redundancy reasons and to extend the operational lifetime of the platform, two additional thrusters are included; the total impulse provided by the EP system is therefore $4.5 \cdot 10^8$ Ns.

The inflatable module at launch is stowed and offers an internal volume of about 40 m³ available for cargo (Fig. 4). At launch, the inflatable module has a length of 3.13 m and a diameter of 4.15 m. Once in orbit, the module is inflated and becomes 8 m length with a max diameter of 7.7 m (Fig. 5). Therefore, it offers an available pressurized volume of about 388 m³ that can be equipped by the ISS crew with additional cargo or with various experiments to be performed beyond LEO or constitute building blocks of a space station in EML₁.

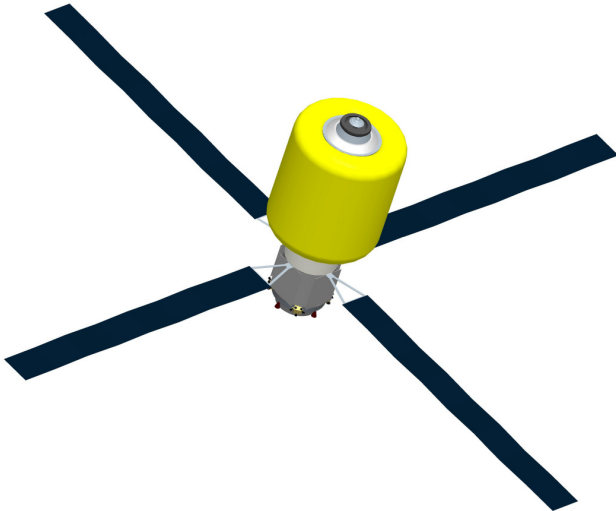


Figure 6. Deployed configuration of the proposed architecture.

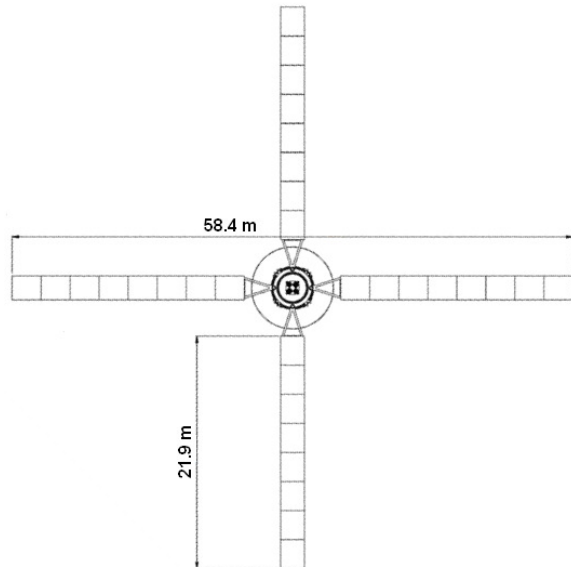


Figure 7. Max dimensions of the deployed configuration.

Solar arrays are deployable and composed of four wings able to provide a total on-board power of about 60 kWe at Begin Of Life (BOL) (Fig. 6). State-of-the-art triple junction cells GaInP2/GaAs/Ge with an efficiency of about 29% at BOL were selected. Each deployed wing is about 22 x 2.25 m² for a total wingspan of 58.4 m (Fig. 7). As the ISS approach phase is performed by means of chemical thrusters only, during this phase the solar arrays are partially deployed. This allow the spacecraft to better perform the ISS docking maneuvers. Besides, the service module and inflatable module assembly at launch is compatible with Ariane V launcher (Fig. 8) and with other state-of-the-art heavy launchers.

All propellant tanks are allocated in the service module between the thrusters and the avionic bay. The chemical propulsion system is supplied by eight 1030 liters titanium propellant tanks able to hold up to seven tonnes of propellant - monomethylhydrazine (MMH) and Mixed Oxides of Nitrogen (MON) - and by two 390 liters high pressure carbon-fiber helium tanks. Twelve 132 liters carbon-fiber tanks able to hold up to 300 kg of xenon each are also included⁷.

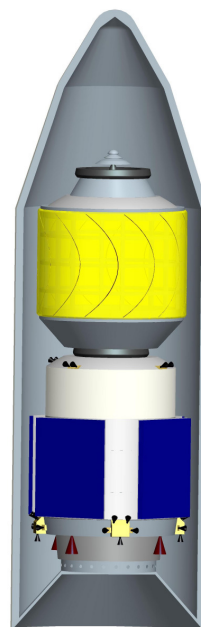


Figure 8. Configuration at launch under Ariane V long fairing.

The avionics is completely inherited by the ATV with ISS autonomous docking capability. Also the docking systems are inherited by the ATV flight experience and compatible with the ISS port⁸. They are both on the service module and on the inflatable modules thus allowing a modular design.

A preliminary mass budget is shown in Table 1.

Table 1. Preliminary Mass Budget of the proposed architecture

Subsystems	Estimated Mass (kg)	Contingency (%)	Estimated Mass w/Contingency (kg)
Structure&Mechanisms	1.200	20	1.440
Inflatable Module	3.500	20	4.200
Electrical Power	750	20	900
Propulsion & Propellant Management	1.200	20	1.440
Communications and Tracking	80	20	96
Avionics, Guidance, Navigation & Control	170	20	204
Thermal	200	20	240
Cargo for ISS	1.500		1.500
Estimated Dry Mass	8.600		10.020
Propellant for Chemical Propulsion	6.000		6.000
Propellant for Electric Propulsion	3.600		3.600
Estimated Wet Mass	18.200		19.620

C. Application Scenarios

Main application scenarios of the proposed architecture are hereafter listed:

- *ISS resupplying and refueling*

After launch and before performing operations beyond LEO, the proposed architecture could serve as logistic servicing for the ISS (pressurized and unpressurized cargoes, ISS orbit re-boosting and refueling). In this phase, payloads already available on the ISS can be mounted on the inflatable module to be tested on a harsher environment, e.g. beyond protective radiation belts.

- *Testing of enabling technologies for future space exploration activities*

One of the major goals of this EP-based flexible architecture is to improve servicing capabilities beyond LEO for future space exploration activities. Therefore it has been conceived as an advanced spaceship in which some innovative and key technologies are built-in such as high power Electric Propulsion, high efficiency power systems and high performance materials and structures.

The in-flight demonstration of such technologies will provide important data for future developments. Moreover, autonomous operations beyond LEO are mandatory if more complex architectures are needed for future space exploration. The proposed modular architecture could therefore also serve as test bed for autonomous operations aimed at building new facilities in the Earth-Moon Lagrangian point L1 composed of expandable structures.

- *Multi-purpose research laboratory beyond LEO*

Due to the expandable module to be deployed after launch, the proposed architecture offers a significant volume to be equipped with various experiments. In particular, these modules could serve as test bed of habitable modules and life support systems and also enable biomedical and space radiation research. Results of such experiments would address fundamental questions about the capability of long-duration human operations beyond LEO. In addition, multiple dockings with the ISS for refueling operations would allow ISS crew members to displace and set up new experiments for various target orbits.

- *Support of human and robotic survey missions*

Equipped with dedicated cargo, the modular spacecraft could also serve as support to supply manned and robotic missions to the Moon, Near-Earth Objects (NEOs) and beyond.

- *Crew Space Transportation System*

In a longer run, a second generation architecture properly powered by nuclear power could serve as manned spaceship for missions to the Moon and beyond.

IV. Mission Profiles and Concept of Operations

Based on the main application scenarios previously discussed, some mission profiles are hereafter shown. For brevity reasons, only mission analysis details of the *Space-Hub* scenario are presented.

D. Multi-Purpose Research Laboratory beyond LEO

An Ariane V launch delivers the assembly at a circular 400 km orbit, then early operations phase starts. After preliminary checks in orbit, solar arrays are partially deployed to provide the necessary power to the overall platform. The expandable module is inflated and then ISS approaching maneuvers start by means of chemical propulsion only.

Once docked, 1500 kg ISS cargo is delivered (water, oxygen, propellant for ISS, dry cargo) and ISS re-boost performed. Before departing from the ISS, the ISS crew can set-up experiments to be performed beyond Van Allen belts in the available volume of the inflatable module. To reach a 25000 x 25000 km orbit, a $\Delta V=3700$ m/s and 327 days are needed from LEO. Then, after the operational time spent in orbit, the platform spirals down to ISS for docking operations. Experiments performed could be dismantled and new ones mounted again.

After the separation from the ISS and before performing a second journey beyond the protective radiation belts, a docking maneuver with a fuel depot launched in LEO for refueling operations is performed.

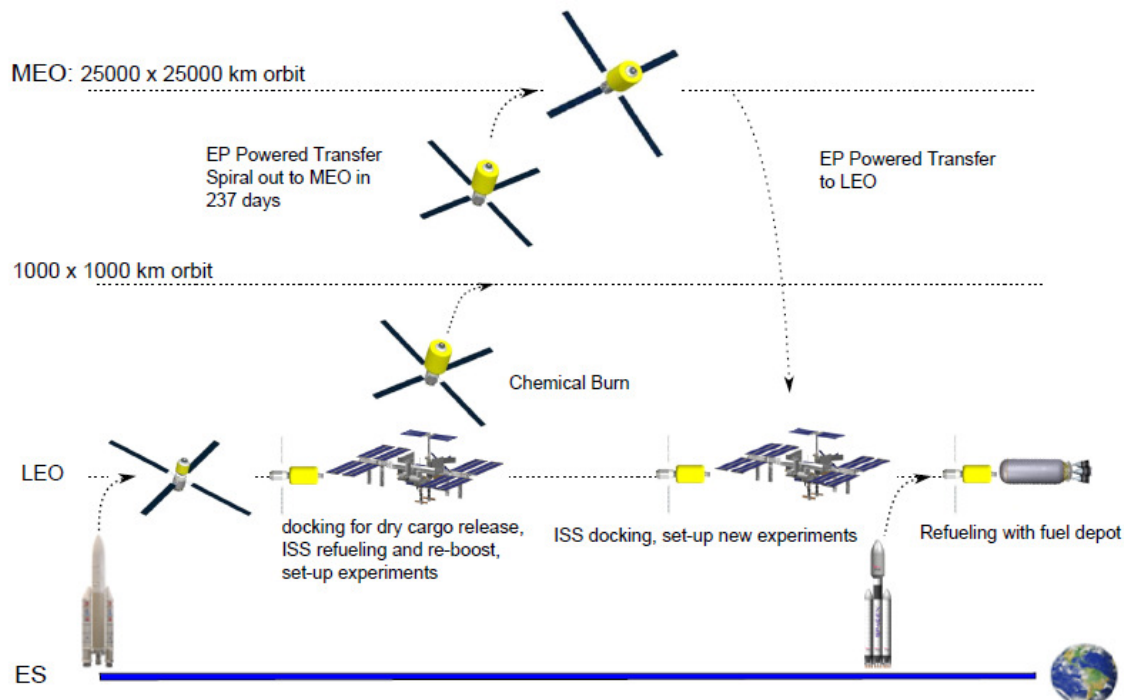


Figure 9. Mission Profile for the multi-purpose research laboratory beyond LEO

E. Space Hub in Earth-Moon L1

The capability to assemble in space and to operate for weeks at time would result a necessary cornerstone before human occupation of lunar surface as well as human voyages beyond the Earth-Moon system. Therefore, the deployment of in-space infrastructures such as a space harbor in EML1 would represent an essential step for such a vision providing an advantageous logistic hub for a more efficient exploration.

Once launched in LEO and then docked at the ISS for cargo delivery and ISS refueling and re-boost, the platform reaches the Earth-Moon Lagrangian point L1 in less than 1 year. Docking operations with the “NODE-1” previously launched are performed, then the service module undocks the inflatable module-NODE-1 assembly to

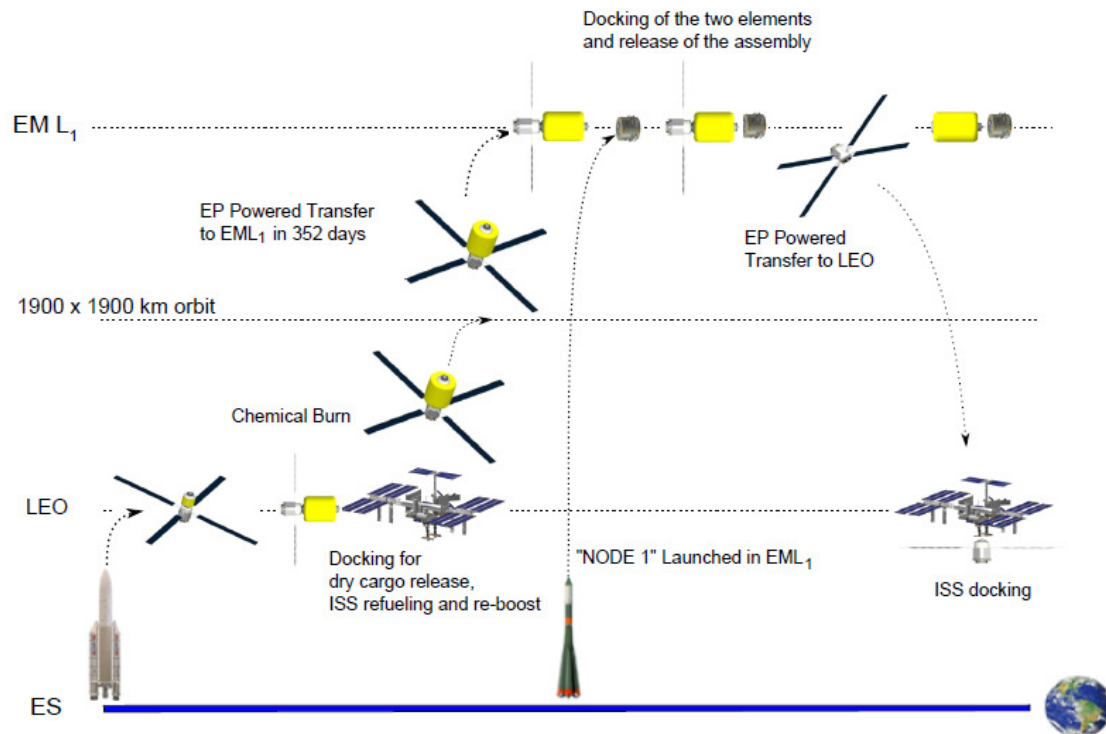


Figure 10. Mission Profile for the Space Hub in Earth-Moon L1 – Phase A

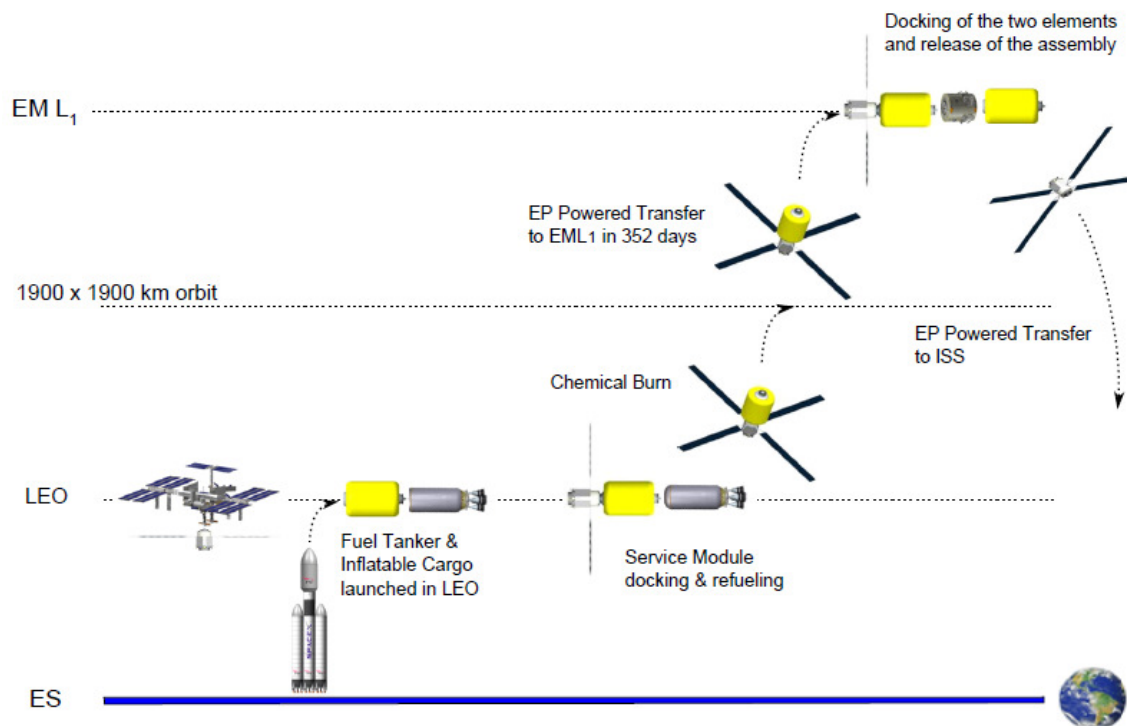


Figure 11. Mission Profile for the Space Hub in Earth-Moon L1 – Phase B

return to the ISS. If available, propellant from the ISS is used to refuel the service module, otherwise the launch with an additional inflatable module will also provide a fuel depot for refueling operations. Then, after docking with an additional inflatable module launched from the Earth surface and refueling operations, the platform performs again its orbit raising to EML1. Following the docking operations with the initial space hub assembly in EML1, another inflatable module is added to the NODE-1. Then the service module returns to ISS for additional voyages.

Details of transfer from the Geostationary Orbit (GEO) to EML1 are shown in Fig. 12 and Fig. 13. A final 12000 km amplitude Halo orbit was chosen as target orbit for the envisaged Space Hub and the overall transfer from the circular 1900 km orbit to EML1 is composed of two phases and takes 352 days. The first phase is the orbit raising from the circular 1900 km orbit up to GEO with a tangential thrust vector. This phase takes about 219 days with a delta-V of 3877 m/s. The second phase is the optimized GEO to Halo minimum mass transfer (Fig. 12). It requires a delta-V of 1322 m/s and takes about 133 days where only 110 days require the electric thruster switched on before the manifold insertion. A propellant mass of about 560 kg is consumed during this phase (Fig. 13).

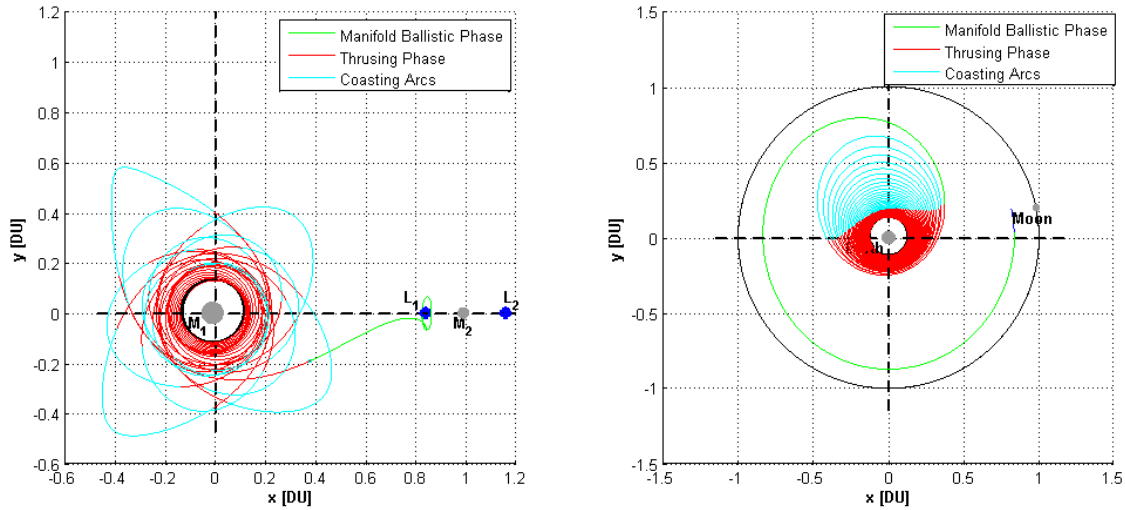


Figure 12. GEO-to-Halo minimum mass transfer in the Earth-Moon rotating frame (left) and in the geocentric inertial one.

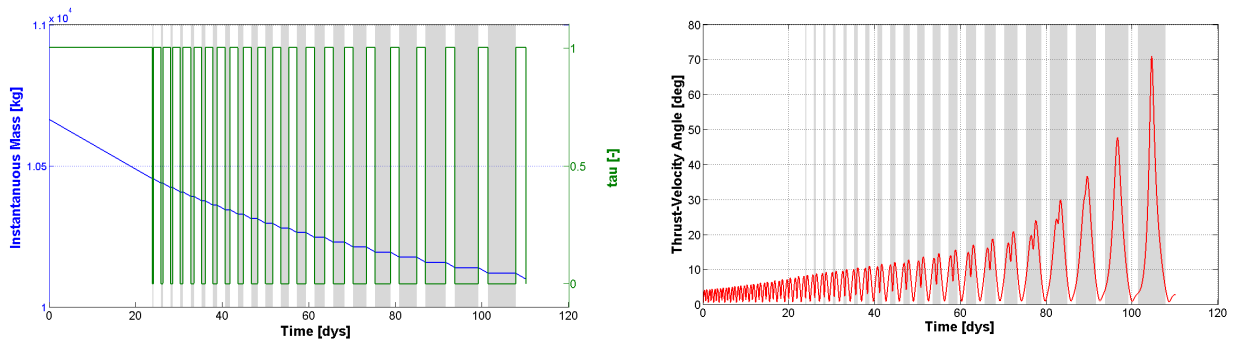


Figure 13. Mass consumption (on the left) and optimized thrust laws for the GEO-to-Halo transfer. Overshadowed zones indicate coasting arcs.

F. Support to Human and Robotic Survey Missions

As for previous mission profiles, after launch the platform performs the ISS docking. In this mission scenario, the platform is only able to deliver the on-board cargo to the ISS crew, no ISS re-boost is foreseen. Then the platform is loaded by the crew with new cargo for the support missions for example in Low Lunar Orbit (LLO) or at NEOs. The chemical propellant available on-board is therefore needed to perform a higher orbit raising from LEO up to a 1000 x 4000 km orbit. This allows the EP delta-V and transfer time to be reduced. Then an EP powered orbit raising up to LLO is performed that takes about 1 year. Once in LLO, cargo for human/robotic survey missions is

released and a new one is mounted on the platform, then the platform can perform the orbit change from LLO to EML1 for docking operations with an existing Space Hub.

After refueling operations, cargo dismantled/mounted, an hybrid transfer from EML1 to a NEO can be performed. As target case, asteroid 1989 UQ was chosen as it also represents the baseline target for ESA Marco Polo mission⁹. This transfer takes about 292 days with a total propellant mass consumption (bi-propellant plus Xenon) of about 6453 kg (34% of initial mass). At NEO arrival, cargo is released and the platform can return to the EML1 station. From here, new journeys to asteroids/LLO or alternatively, a return to the ISS in LEO can be performed.

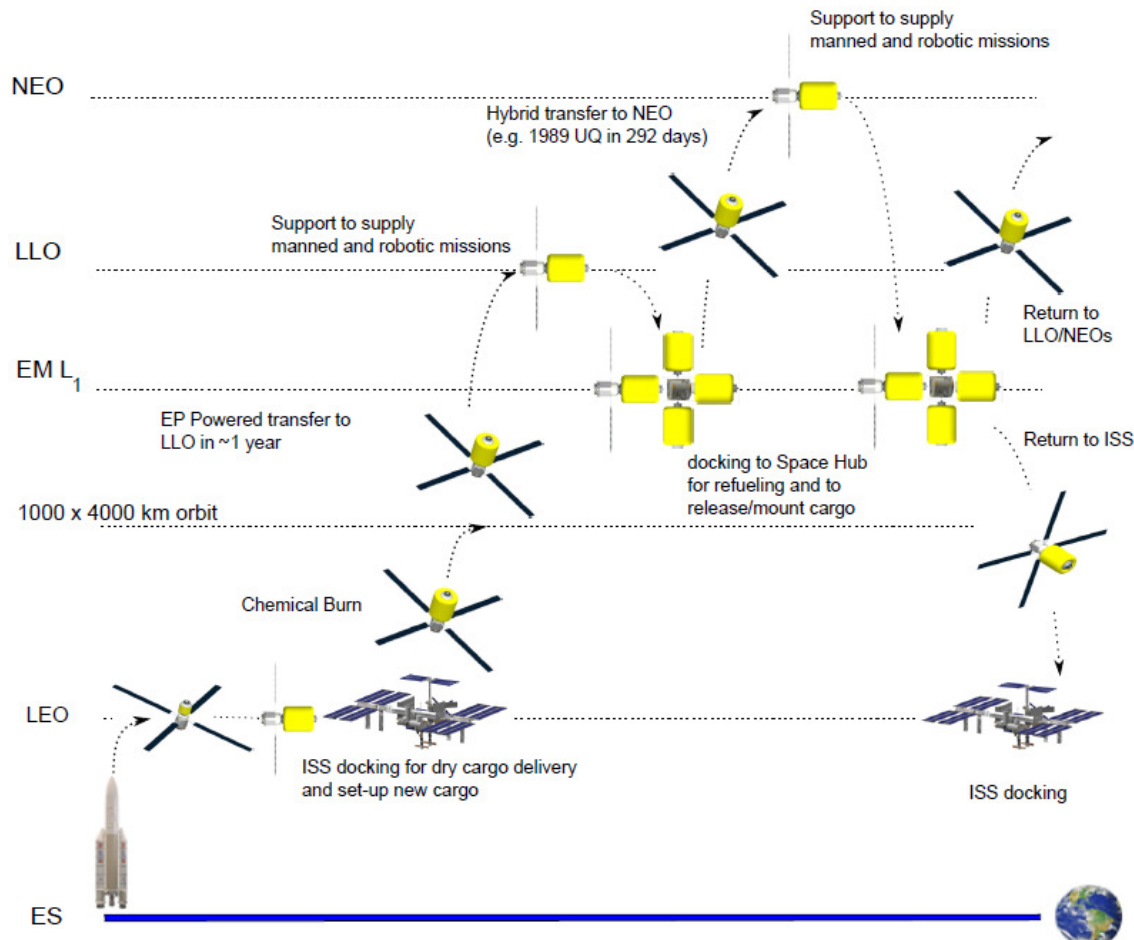


Figure 12. Mission profile for support to human/robotics survey missions

V. Conclusion

The development of enabling technologies is one of the essential steps for the performance enhancement needed by future space missions. In this study, an evolutionary approach to a flexible architecture for space exploration has been proposed in which two innovative technologies – high power Electric Propulsion and expandable structures – have been coupled. Furthermore, the concept design allows other important enabling technologies - such as the autonomous rendezvous and docking and in-space propellant storage and transfer - to be tested beyond LEO.

The proposed architecture is composed of a modular and re-usable service module and inflatable modules able to offer a significant volume to be equipped with experiments to be performed beyond LEO or cargo to be transferred to higher orbits. This configuration has been shown capable of delivering a significant payload and of performing various mission classes compliant with the flexible path for exploration. In fact, in addition to in-flight demonstration of critical innovative technologies aimed at improving servicing capabilities beyond LEO, the modular configuration of the proposed architecture also allows inflatable modules and some functional elements deriving from the ISS disposal to serve as building blocks of a future Space Hub in EML1 and as cargo to support human and robotic survey missions beyond the Moon.

References

- ¹"Review of US Human Spaceflight Plans Committee", October 2009.
- ²"Post-ISS Human Operations in free space", H. Thronson, September 2009, Future In-Space Operations working group telecon
- ³"The L1 Orbit used for servicing", B. W Barbee, June 2010, Future In-Space Operations working group telecon
- ⁴"Propellants Depots and a Reusable Cislunar Transportation Architecture", D. Bienhoff, May 2010, Future In-Space Operations working group telecon
- ⁵"Space Exploration Architecture Review High-Level Findings", ESA Strategy and Architecture Office, July 2008
- ⁶"The Automated Transfer Vehicle – ATV Overview", ATV Information Kit, ESA, February 2008
- ⁷"Composite overwrapped Pressure Vessels", ATK Space Systems Inc., Commerce, CA - USA; URL: http://www.psi-pci.com/Data_Sheets_Library/DS458.pdf
- ⁸M. Cislighi, C. Santini, "The Russian docking system and the Automated Transfer Vehicle: a safe integrated concept", 3rd IAASS Conference, Roma, 21-23 October 2008.
- ⁹"Marco Polo – Sample Return Mission to Near Earth Object", CDF Study Report, CDF-72(A), ESA-ESTEC, May 2008.