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## Human Exploration of Cis-Lunar Space via Assets Tele-Operated from EML-2 (HECATE)

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**Abstract.** This paper presents the preliminary design of the international space mission HECATE (Human Exploration of Cis-lunar space via Assets Tele-operated from EML-2), aimed at exploring the far side of the Moon via tele-robotic activities during the 2020s. The exploration is realized by astronauts from HOPE (Human Orbiting Protected Environment), a space habitat in a halo orbit around the Earth-Moon Lagrange Point 2, a critical staging location for future robotic and human deep space missions. Inside the habitat, astronauts have access to tele-robotic hardware and instruments, used to tele-operate rovers and scientific equipment on the surface of the Moon. Plans to resupply and maintain HOPE for future missions, using a solar electric

tug, are given. Ultimately, HOPE represents an energetically favorable intermediate locations for missions to Mars, Near-Earth Asteroids, and beyond.

### 1 Introduction

The next giant leap for mankind is a long-duration mission to the Moon. This mission does not only address priority lunar science objectives but it also represents a milestone towards the exploration to farther planets. A key element of this future mission is the partnership of human and robotic components as well as tele-presence, the tele-operation of robotic assets on the lunar surface by astronauts in orbit in cis-lunar space. Tele-presence could significantly enhance the ability of humans and

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robots to explore together, allowing in the future the exploration of the most challenging locations in the Solar System and preparing sustainable exploration using local resources, as outlined in the Global Exploration Roadmap [29].

In the context of a future human-robot partnership for future space missions, the European Space Agency has defined the Human-Enhanced Robotic Architecture and Capability for Lunar Exploration and Science (HERACLES) as a frame for multiple international space agencies to study and define an architecture for lunar exploration [34].

Of primary importance for a long-duration mission to the Moon based on human-robotic interaction, is the design of a stable and safe habitat where astronauts can operate instruments and equipment for the tele-operations of the assets on the ground.

This paper presents a human mission for the tele-robotic exploration of the far side of the Moon, HECATE (Human Exploration of Cis-lunar Space via Assets Tele-operated from EML-2), focusing in particular on the design of the space habitat.

## 2 Mission Overview

Mission HECATE delivers a habitat (HOPE, Human Orbiting Protected Environment) in a halo orbit around the second Earth-Moon Lagrangian point (EML-2) during the years 2022-2024 to help a crew of three astronauts:

- perform tele-robotic exploration on the lunar surface;
- conduct human-assisted scientific experiment and sample return of lunar surface material;
- realize 3D printing;
- deploy and test components of a low frequency telescope;
- execute site reconnaissance for future human exploration of the Moon.

HOPE can also be utilized as a platform for future deep space exploration. The mission timeline is summarized in Table 1.

In January 2022 the first space station module, Brave, is launched from Kennedy Space Center using a Falcon Heavy launcher [13]. The upper stage of the Falcon Heavy performs the necessary maneuver to inject the

module into a Weak Stability Boundary (WSB) trajectory [18]. After 4 months from launch, Brave is scheduled to arrive in EML-2.

In January 2023, a Space Launch System (SLS) Block 1 (cargo), [11], is adopted to deliver an interconnection/expansion module, Companion, to HOPE. It takes Companion 4 months to arrive at destination using a WSB transfer. Brave and Companion are expected to perform the necessary rendezvous and docking procedures autonomously. Until the crew arrives, HOPE remains dormant, except for standard operational checks.

In February 2024, an SLS Block 1B (cargo) carries a Bigelow B330 inflatable module [2], Tortuga, following a similar trajectory to those of Brave and Companion.

In March 2024, a Falcon Heavy is used to deliver a set of lunar robotic assets to the surface of the Moon via a direct transfer. The payload of Falcon Heavy consists of three landers, La Niña, La Pinta and La Santa Maria (Section 5), carrying a total of four rovers to three different locations on the far side of the Moon. The rovers are Messaggero (a humanoid rover), Oktagon 1 and Oktagon 2 (two 8-wheeled rovers) and Nozomi (a rover with 3D printing capabilities), or “MOON” for short (Section 6).

In April 2024 a crew of 3 astronauts departs from Kennedy Space Center on board of the Orion Multi-Purpose Crew Vehicle (MPCV), [10], launched into a Low Earth Orbit (LEO) by the NASA SLS Block 1 B. This launch vehicle is assumed flight proven at the proposed launch date. The upper stage of the Block 1 B performs the Trans-lunar Injection (TLI) such that the crew vehicle is placed in a prograde lunar flyby trajectory. Upon arrival at a lunar altitude of approximately 100 km, a propulsive maneuver is performed and the crew vehicle is placed on a trajectory to reach the station. Upon arrival at HOPE, approximately 10 days after launch, an orbit injection maneuver is performed. Successively, Orion docks to HOPE and the astronauts assist with the rendezvous, docking and inflation of Tortuga.

The astronauts arrive at HOPE 2 days before the beginning of the 14-days long lunar day and a total of 40 days are available to perform the necessary operations on the Moon and the scientific experiments on the space station. The crew performs tele-operated activities on the surface of the Moon utilizing the “MOON” rovers and the hardware described in Section 7. All the activities accomplish unique goals thanks to the exploitation of the human-robotic partnership between astronauts and assets on the lunar surface. Pre-planned activities,

Departure date	Arrival date	Launch vehicle	Payload	Transfer type
January 2022	April 2022	Falcon Heavy	Brave	WSB
January 2023	April 2023	SLS Block 1 (cargo)	Companion	WSB
February 2024	May 2024	SLS Block 1B (cargo)	Tortuga	WSB
March 2024	March 2024	Falcon Heavy	“MOON” Rovers	Direct
18 April 2024	28 April 2024	SLS Block 1 (crew)	Orion (crew)	Lunar Flyby
8 June 2024	June 2024	N/A (return to Earth)	Orion (crew)	Lunar Flyby

TABLE 1. Summary of HECATE’s launch sequence.

like traverse route for the rovers, are available. However, based on the observations and results obtained during the operations, and in coordination with the Mission Control Center, the crew has the possibility to modify those plan in order to accomplish the scientific objectives (Section 8).

After the crew has spent 40 days on board of HOPE, Orion undocks from the space station beginning its journey back to Earth. In June 2024, Orion arrives at Earth, reenters the atmosphere and splashes down in the Pacific Ocean.

HOPE is left operational in EML-2 and kept available for use for future exploration and technology demonstration missions. As described in Section 3, sustainable plans to resupply HOPE have been laid out. HOPE’s capabilities to be modular and expandable combined with its highly Earth-Moon energetic orbital location give the station the potential to become a “refueling depot” for missions heading beyond the Earth’s sphere of influence. Furthermore, HOPE represents a safe haven between LEO and deep space; it represents an orbiting infrastructure accessible to humans to perform experiments on sample returns from various celestial bodies (such as Mars and Europa) to ensure that planetary protection procedures are respected.

### 3 Mission Analysis

The  $\Delta V$  and time of flight required for each transfer of Table 1 are summarized in Table 2.

The departure dates are chosen so as to minimize the  $\Delta V$  required to realize each transfer and taking into account eclipse condition in EML-2 and illumination conditions of the far side of the Moon [44].

The chosen orbit for HOPE is a halo orbit around EML-2 with  $A_z$  amplitude of 8000 km [21]. This orbit has an orbital period of approximately 14 days and provides a permanent communication link with Earth. Moreover, the orbit of choice allows continuous cover-

age of the lunar far side surface which greatly facilitates the tele-robotic operations performed by the crew when on HOPE. In order to maintain HOPE in EML-2, a station keeping control is required throughout the entire mission duration. The  $\Delta V$  needed for station keeping is approximately 50 m/s per year [23], resulting in 1900 kg of propellant required for the Attitude and Orbit Control System (AOCS) per year for the considered mass of HOPE (Section 4), [44].

HOPE is planned to be resupplied with propellant and cargo using a reusable tug equipped with Solar Electric Propulsion (SEP). The tug performs a transfer between a Geostationary Equatorial Orbit (GEO) and EML-2 [44]. A module is required to deliver the cargo to GEO, where the tug docks with it and transfers to the station. The initial launch of the tug with the cargo is going to be done as an auxiliary payload of an Ariane 5 launch in Geostationary Transfer Orbit (GTO), [39]. The electric engine is then used to move the cargo to EML-2. The thrust considered for the electric engine is  $T = 0.6$  N and the specific impulse is  $I_{sp} = 2800$  s. Table 3 describes  $\Delta V$ , mass and time of flight for each phase of the transfer considering an initial mass in GTO of 5500 kg and 2500 kg of cargo delivered to HOPE. The total resupply mission from GEO to EML-2 and back to GEO takes 300 days.

### 4 Space Station

A space station in cis-lunar space is fundamental not only to realize tele-robotic exploration of the Moon but also to support many additional activities: gathering of resources, in-orbit servicing for deep space destinations such as Mars and study and development of new technologies for future space exploration.

For mission HECATE, the habitat HOPE have a modular, expandable and versatile design capable of satisfying two major scientific requests: Enhancement of Moon Exploration (EME) and Fundamental Deep

Transfer type	$\Delta V$ [m/s] (one way)	ToF [days]
Direct transfer	4435	6
Lunar Flyby (LFB) transfer	3480	10
Weak Stability Boundary (WSB)	3200	80-120
Lunar surface to EML-2	2530	5-7
Return from EML-2 to Earth via LFB	390	10

TABLE 2. Earth to EML-2 halo transfers.

Transfer	$m_0$ [kg]	$\Delta v$ [km/s]	ToF [days]	$m_{fuel}$ [kg]	$m_f$ [kg]
GTO - GEO	5500	2.11	330	410	5090
GEO - EML2	5090	2.13	210	380	4710
EML2 - GEO	2210	2.13	90	165	2015

TABLE 3. Data for HOPE's resupply using SEP.  $m_0$  is the initial mass,  $m_{fuel}$  is the propellant mass and  $m_f$  is the final mass.

Space Research (FDSR).

In terms of EME the space station has been designed to fulfill the following tasks:

- Provide a stable and reliable platform for low-latency tele-robotic control of the lunar rovers and surface equipment. The short distance between the space station and the lunar surface permits a close to real time operation, with control latencies of around 400 ms [35]. The low latency time allows to conduct sample examination and soil operation in an accurate, robust and time efficient way, maximizing the effectiveness of the mission.
- Simplify and increase the reliability of multiple sample returns to the space station. Scientific experiments on the samples collected on the surface of the Moon are performed directly on the station, rather than sending the samples back to Earth. This aspect is crucial for an extensive scientific research of important compounds in the lunar soil. Moreover the sample return to the space station is remarkably less expensive than a direct return to the Earth, which introduces limitations and difficulties due to the re-entry phase [19].

As regards the FDSR, the most important aspects are:

- HOPE represents a deep space radiation laboratory, where space medicine experiments such as ALTEA [38] can be performed. Moreover, HOPE allows to develop, qualify and improve new materials and strategies for deep space radiation protection.

- HOPE allows to investigate and test new solutions for multi-functional materials for space environment design. This class of new materials provides efficient structural, thermal and radiation protection capabilities [24].

HOPE is composed of three modules: Brave, Companion and Tortuga (Figure 1).

Brave and Companion provide an initial combined free volume of 152 m<sup>3</sup>, that is a volume per astronaut of 50 m<sup>3</sup>. This is double the minimum value imposed by the NASA Standard 3000 [20]. The final configuration (Brave, Companion and Tortuga) provides an internal volume of 356 m<sup>3</sup> thanks to the use of the Bigelow Aerospace inflatable module, B330 (Tortuga).

#### 4.1 Command Module (Brave)

A representation of Brave is given in Figure 2. Brave is based on an adapted cryogenic composite fuel tank developed by NASA and Boeing. This strategy has been adopted in the past for the Skylab mission, that used a converted Saturn V propellant tank as a habitable space station, [25]. Using this structure has different advantages: it is already launch qualified, it provides a considerable amount of habitable volume, it is capable of withstanding the internal pressure necessary for manned missions and it has a relatively low cost [25]. Brave is based on the most recent advancement in Composite Cryotank Technology, which allows a structural mass of 1445 kg and a Technology Readiness Level (TRL) of 6 [22, 30]. Brave has a total length of 10 meters and a diameter of 5 meters, with an internal

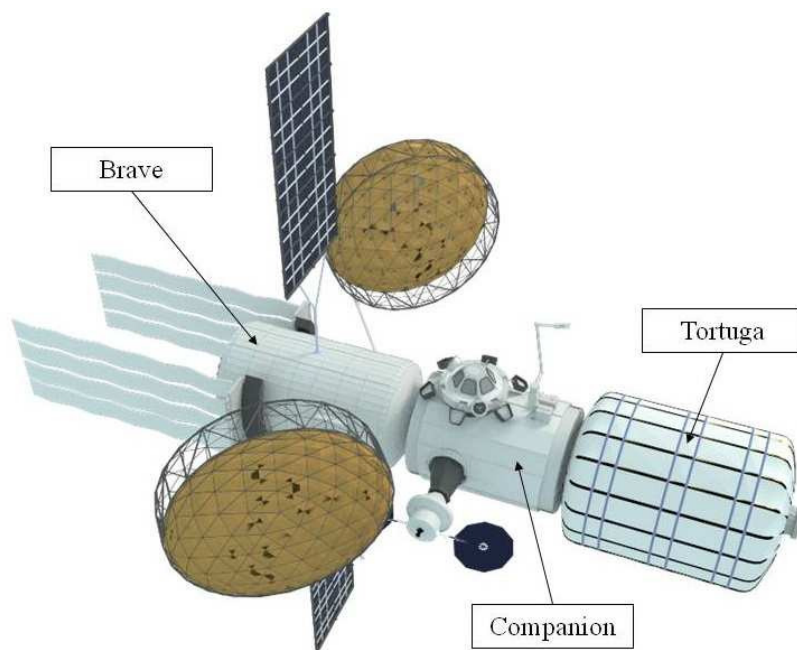


FIGURE 1. HOPE space station.

volume capable of housing many crucial subsystems. The total launch mass is of 14200 kg [44]. Brave is provided with a low impact docking port, where Orion can dock to, as well as a module adapter for further expansion of the station.

In EML-2 particular attention has to be paid to the radiation protection. An accurate design of the radiation shield has been performed for Brave, due to its peculiar structure in composite material. The amount of radiation absorbed in interplanetary space is over 20 kSv per year. The NASA standard states that a maximum of 1 Sv and 1.5 Sv can be absorbed during the entire astronaut life by female and male respectively. A design constraint has been fixed to a total radiation level of 0.5 Sv per year. Careful material selection and structure design is required to meet this constraint. For this purpose a detailed campaign of analyses has been performed using ESA Spennis tool [28]. In order to be conservative against the great amount of uncertainties, a worst case scenario is simulated. A period of maximum solar activity is selected and the radiation dose is computed using isotopic particles source and isotopic shield.

The external main structure of Brave is composed of a Boeing Fluted Core Sandwich wall [37]. Without

any additional protection the radiation dose per year would be approximately 0.8 Sv, which is unsatisfactory. Furthermore the structure must be protected also by the possible threat of micrometeorites.

The debris shield is made by a layup of Nextel and Kevlar for a total thickness of 4 mm. Nextel is a ceramic material and has also a good content of aluminum, which has been expected to further increase the radiation shielding properties. In order to slow down both solar particles and cosmic radiation low atomic number material must be used [26]. The internal empty volume of the sandwich allows to introduce an additional protection made by polyethylene for maximum thickness up to 3 cm. By performing a parametric study the optimal result has been obtained with a total thickness of 2.5 cm. In the worst case scenario a total of 0.448 Sv per year are absorbed by the crew. The protection could be further enhanced using up to 3 cm of polyethylene foam. However, this configuration would not allow the use of the Falcon Heavy launcher, due to payload mass limitation, making the SLS the only viable option. Further studies in this field are required, in order to deliver the safest and lightest radiation protection for the crew.

## 4.2 Service Module (Companion)

Companion is the space station service module (Figure 1 and Figure 3), providing the Environment and Control Life Support System (ECLSS) for up to 3 crew members, the toilet service, the exercise machines for the astronauts and access to different space station areas. The use of an inflatable air lock based on BEAM design allows astronauts to perform EVAs [3]. Companion includes a Cupola where robotic operation can be performed using a robotic arm, based on the design of the International Space Station (ISS) Canadarm, [5], or tele-operating the rovers on the lunar surface. Companion is designed to be attached to the inflatable airlock for EVA, the B330 inflatable module (Tortuga), an emergency Orion capsule (if one were to be launched and used by the crew) and, finally, a docking hatch where the lunar ascent module can dock. The structure of Companion is similar to that of the ISS Node-3 [7]; an additional mass is considered to adapt it to the mission constraint, considering also the radiation protection. The liftoff mass of this module is approximately 27800 kg [44].

## 4.3 Inflatable Module B330 (Tortuga)

The last module to arrive in EML-2 is the inflatable B330 from the private company Bigelow Aerospace, Tortuga (Figure 4). Tortuga has an estimated mass of 20000 kg for a total habitable volume of 330 m<sup>3</sup> [44].

It is assumed that the B330 technology is going to be flight proven in 2024. Current findings indicate that inflatable habitats offer good levels of protection for crew, from both radiation and micrometeorites. Tortuga provides additional space for more crew members, space for science and engineering experiments, and a dedicated area for the tele-operation of the lunar rovers (Figure 5).

## 4.4 Interior Design

The interior design of HOPE is realized according to NASA-STD-3001 Space Flight Human-System Standard [31]. The organization of the space (vicinity and/or separation of specific activities) is designed to ensure the well-being of the crew members, their physical and psychological health and the efficient transit between the three modules. Storage racks are designed based on International Standard Payload Racks [27]. This standardized system provides an easy-arranged interior design and the accessibility to every equipment. In Brave

and Companion the racks are located on the four sides of the modules, creating a rectangular free space core.

The idea of creating an artificial orientation, in order to provide a vertical feeling of “up” (ceiling) and “down” (floor) is a main guideline of functional interior planning. This sensation is increased by locating the main activities, such as working and exercising and hygiene facilities on opposite sides of the modules, to give a sensation of right and left spaces. The space on the floor and ceiling is used for member-use storage and some access demanding equipment (water or air supply).

**Brave.** The interior design of Brave is shown in Figure 2. Brave is designed for the private needs of the crew and for some of the group activities. At the end of the module (which corresponds with the end of the whole station) there are 3 quarters (volume 4.14 m<sup>3</sup>) for each astronaut; they are visible on the left-hand side of Figure 2. These private areas include individual equipment and storage areas (personal hygiene, sleeping bag, leisure clothing and private medical care). Additionally they can be used as shelters against Solar Particle Events. The radiation protection is provided by equipment such as water tanks, waste tanks and storage items which are located next to private modules.

To ensure an optimal acoustic isolation (a big issue for mental health), the private quarters are separated from the galley and group-activity space by wardroom with additional stowage and equipment sector. The common area takes most of the habitable volume (over 45 m<sup>3</sup>). The galley is used for dining, group meeting and station operations control. It is equipped with food processing system, water supply and collapsible furniture. When the galley is not in use, the mobile furniture might be shifted to change the volume to an open space. A complement to this working area is provided by communication and control equipment located on two opposite walls. The galley contributes to the integration of the crew members, thanks to the group and working activities.

**Companion.** The interior design of Companion is based on the ISS Node 3 Tranquility, [32], and it is shown in Figure 3. Similarly to Brave, most of the storage and technical control equipment are placed on the “floor” and “ceiling” of the module. The remaining space on either side of the module is designed for exercise equipment and Waste Management Supplies. The activities connected with these areas are related to dirt and smell issues. Due to this problem they are isolated in this module and share space only with stowage, technical equipment and ECLSS. The remaining space in



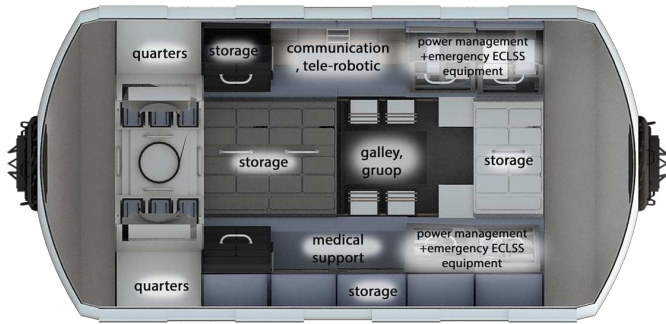


FIGURE 2. *Brave internal view.*

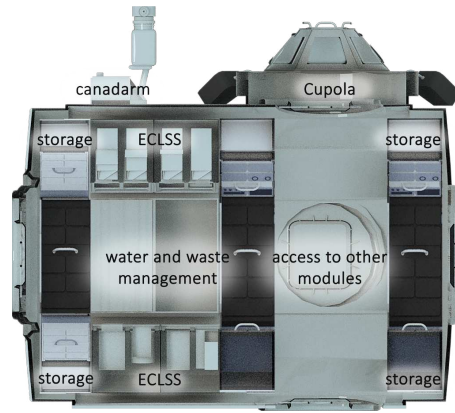


FIGURE 3. *Companion internal view.*

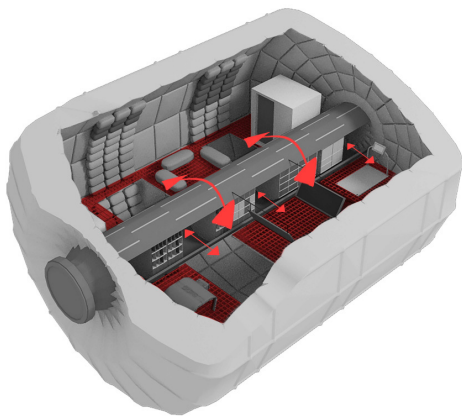


FIGURE 4. *Tortuga.*

Companion is an open space which provides access to Orion, the Cupola and other possible modules.

**Tortuga.** The interior of Tortuga is organized as a single open space. The only separations are wall-panels for the private leisure areas and an open-work “floor” separating top store from lower store. According to the Bigelow B330 inflatable module system specification, along the main axis of the module there is a core, used in Tortuga to hold the technical equipment. The access paths to every part of the module lead around the core, in two transit segments determined by floor’s holes. The top store is used for group activities, (it could, for example, hold a second galley, if the number of crew members were to increase), leisure and entertainment and to tele-operate equipment on the surface of the Moon. The rest of the space is used for the storage of the exoskeleton and

the equipment required for Human-Robotic operations on the lunar surface (Figure 5 and Section 7). The lower store is designed for private quarters and storage. Personal areas are located at the ends of the module. They are isolated from shared space with small storage-bags covering walls.

#### 4.5 ECLSS

The ECLSS of HOPE must be able to:

- control temperature, pressure, humidity and ventilation;
- revitalize the atmosphere (removal of carbon dioxide, monitoring of oxygen and other gases level, ventilation);
- recover and manage water and waste;
- guarantee the safety of the crew (radiation shielding, fire detection).
- guarantee physical and psychological support.

All these capabilities must be performed for the entire duration of the mission without failures. Thus the ECLSS has to provide service for 80 days (that is, mission time multiplied by a safety factor of 2). Furthermore, the system has to be available to be used in future missions. In order to satisfy these points, a system based on the the ISS ECLSS is used for HOPE. Appropriate modification needs to be applied to the ISS ECLSS in order to account for the different radiative environment (absence of the Earth’s magnetic field protection) and to introduce new technologies. Furthermore the longer resupply times for a station in EML-2



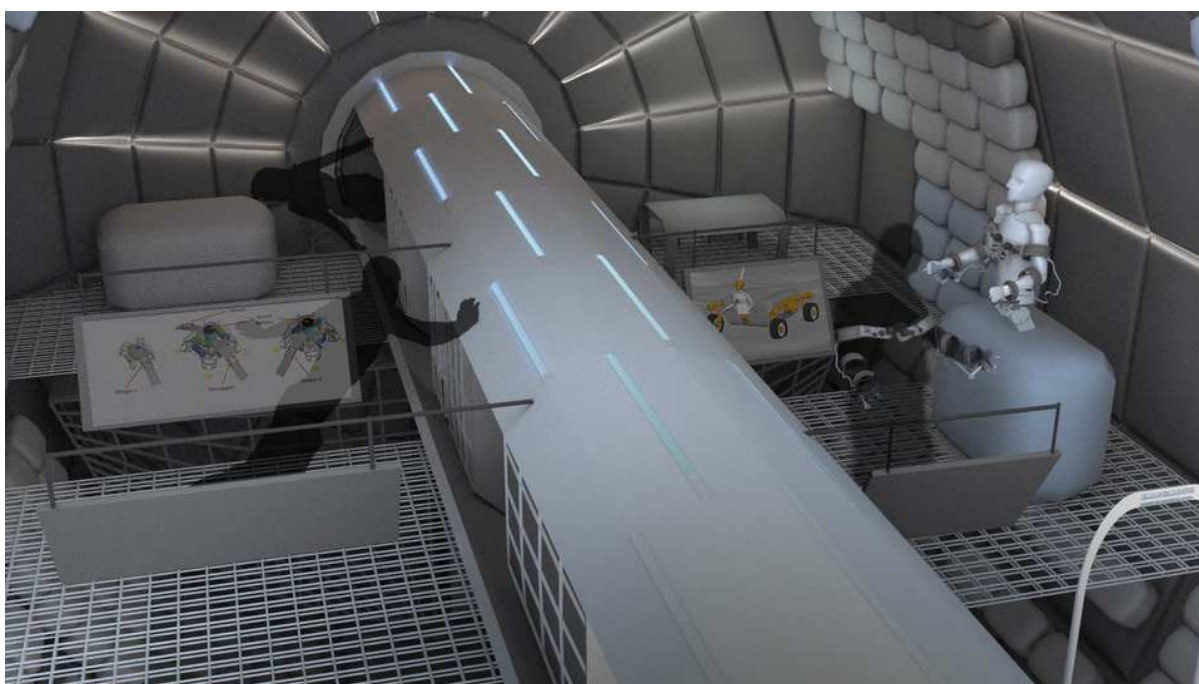


FIGURE 5. *Tortuga internal view.*

with respect to a station in Low Earth Orbit have to be considered. Therefore, a new generation of items designed for long deep space mission are necessary. A key feature of the ECLSS of HOPE is the capability of recycling a high percentage of waste, so as to make the station almost autonomous and to reduce the number of resupply missions. In the following a list of the main ECLSS components is given [44].

**Water reclamation system.** This is a key element of the ECLSS of HOPE. It provides clean water by reclaiming waste-water (crew-member urine and humidity condensate) [45]. By doing so, the mass of water and consumables that would need to be launched from Earth can be greatly reduced. The system works by recycling pretreated urine and flush water, coming from the Waste and Hygiene Compartments, to produce purified water, using the Urine Processor Assembly (UPA). In addition, the Water Processing Assembly (WPA) processes UPA distillate and produces iodinated water, delivered through a potable water bus to the Oxygen Generation System.

**Oxygen generation system.** The Oxygen Generation System (OGS) produces oxygen for breathing air for the crew and to replace the oxygen lost during airlock depressurization and carbon dioxide venting or due to

module leakage [45]. The OGS uses water from the WPA; it electrolyses the water to produce oxygen (delivered to the cabin atmosphere) and hydrogen (vented over-board or used by the Carbon dioxide removal assembly). In addition, storage tanks system for the oxygen and nitrogen gases are located on the Airlock to compensate for leak in the system.

**Carbon dioxide removal assembly (CDRA).** This system is designed to remove carbon dioxide from the space station. It works by causing the hydrogen produced by the OGS to react with the carbon dioxide removed from the cabin atmosphere, to produce water and methane [45]. Due to the lack of experience in managing and storing safely methane on-board, methane is ejected from the station. The water produced in the process is instead fed to the WPA for processing. A number of lithium-hydroxide canisters are available on-orbit to support carbon dioxide removal in case of complete CDRA failure.

**Pressure, temperature and humidity control.** Each module of HOPE is equipped with a fan and with heat exchanger and pressure sensors linked to tanks to control temperature, humidity and pressure inside the station.

**Air Contamination Control (ACC).** This system is composed of a Trace Contaminants Control Assembly

(TCCA) and a Major Constituent Analyser (MCA), [6]. The TCCA checks the cabin air for concentration of trace contaminants; it does so by using a charcoal bed (for the removal of high molecular weight contaminants), a high temperature catalytic oxidizer (for low molecular weight contaminants) and a lithium-hydroxide sorbing bed, [6]. The MCA is a mass spectrometer; it is used to monitor the partial pressures of oxygen, carbon dioxide, hydrogen, methane, nitrogen and water vapour in the atmosphere of the cabin [6].

#### 4.6 Private Sector Involvement

The emergence and rapid growth of private companies into the space sector has shown that there is a significant opportunity for further expansion. SpaceX is a clear example of successful private sector cooperation with space agencies. Bigelow Aerospace are also forging relationships with traditional space exploration, using the ISS to test their technologies. The ISS pioneered multinational cooperation in space exploration; the next step is the further integration of the private sector. HOPE provides a perfect stepping stone for this cooperation. It is a proving ground for private sector proprietary technologies, which not only require testing, but also benefit from the extensive experience of space agencies. Furthermore, the association with trusted space agencies will give private companies and their technologies a level of recognition they would otherwise be unable to achieve. The private sector are constantly seeking new areas to expand their operations, and HOPE can provide an opportunity for cooperation.

## 5 Landers

In order to realize the objectives of the mission, three landers are required, one for each of the landing sites defined in Section 8. The first lander, La Pinta, delivers Nozomi, a construction rover, and Messaggero, a humanoid rover, to the north region of the Schrodinger Crater. The second lander, La Niña, delivers Oktagon 1, an 8-wheels scientific rover, to the east region of the Schrodinger Crater. The third lander, La Santa Maria, delivers Oktagon 2, the second 8-wheels scientific rover to the Daedalus Crater.

Due to the nature of the mission, the landers have to provide high autonomous landing accuracy and autonomous Hazard Detection and Avoidance (HDA). According to [33] and to the lander types categorization given by [17], the best lander type to provide high

accuracy and soft landing for unknown terrain is the legged lander type; therefore this has been chosen as the baseline for the landers of HECATE.

The baseline structure bus for the lander body is a typical octagonal pallet lander with four legs that incorporate crushable honeycomb for shock attenuation after the touchdown. The electronic systems are placed together with the thermal control subsystem at the side of the lander. The rovers are attached to a deployable ramp and secured within the lander by pyrotechnic bolts. The rovers are deployed to the lunar surface by the deployable ramp that unfolds and lowers softly to the lunar surface after the discharge of the pyrotechnic bolts. All the landers consist of a Lunar Descent Module (LDM). La Pinta and La Niña also carry a Lunar Ascent Module (LAM) which includes the sample return capsule. Table 4 shows preliminary estimation of the mass budget for all of the landers assuming a  $\Delta V$  for lunar landing of 1.72 km/s, [44].

The propulsion makes use of a liquid bi-propellant,  $N_2O_4/MMH$ , divided among two tanks for the fuel and four tanks for the oxidizer for La Pinta and La Niña, and one fuel tank and one oxidizer tank for La Santa Maria. The Main Engine Assembly (MEA) is mounted at the bottom of the lander and aligned symmetrically so the thrust vector runs through the center of gravity. The total thrust level in vacuum provided by the MEA and the number of clustered thrusters of each of the lander are: 14 kN (4.5 kN x 4) for La Pinta, 6 kN (1.5 kN x 4) for La Niña and 4 kN (1 kN x 4) for La Santa Maria. Helium gas is used as suppressant.

## 6 Rovers

Mission HECATE lands four vehicles on the surface of the Moon: Messaggero, Oktagon 1, Oktagon 2 and Nozomi.

There are two main factors that influence the vehicle design choice: lunar regolith and lunar gravity (about one sixth of Earth's gravitational acceleration). Lunar regolith is the layer of loose material covering the surface of the Moon; it causes challenging driving conditions. It includes glassy, spheroidal particles which are drops of melted lunar material formed from meteorite impacts [41]. The spheroidal nature of the particles reduces the friction by making slipping easier. To overcome this problem, careful attention has to be paid to the tread on the tyres. It should maximise the grip and friction to reduce slip when drive is applied [36]. The

La Pinta		La Niña		La Santa Maria	
Wet mass	7270	Wet mass	3220	Wet mass	1558
Propellant mass	4700	Propellant mass	2085	Propellant mass	1009
Total payload mass	1200	Total payload mass	620	Total payload mass	300
- Nozomi	550	- Oktagon 1	220	- Oktagon 2	220
- Messaggero	250	- Ascend module	400	- Telescope	80
- Ascend module	400				

TABLE 4. Mass break-down for the landers (masses are in kg).

porosity of the soil is another interesting lunar property. Due to the small gravitational acceleration it is unlikely for the particles to form a dense structure.

In the following subsections the design of the “MOON” rovers, realized taking into account the effect described above, is described.

### 6.1 Exploration Rovers - Oktagon 1 and 2

The wheels of the lunar rovers Lunokhods [12] and LRV [14] were made from metal mesh and had favourable characteristics when used on lunar soil. The “MOON” rovers uses similar wheels to those of Lunokhods. To minimise surface pressure there are two options: many small wheels (a characteristic similar to robots with tracks) or a few large diameter wheels [36]. Oktagon 1 and Oktagon 2 are Eight Wheeled Exploration Rovers (EWER). The suspension of this kind of rover is similar to that of Lunokhods. However, their design improves upon the original by implementing proper turning capability instead of relying on skid-steering. This is achieved by having four independent bogies, each with two wheels whose relative angles can be controlled. Independent suspension is desirable because when the rover is tele-operated the user often wants the capability to drive at the minimum speed of human walking pace (approximately 5 km/h). This is a relatively high speed for lunar locomotion and generates lots of unpredictable dynamic impacts. Independent suspension is better able to absorb these impacts and facilitates more accurate control of the rover.

During the exploration various gradients of terrain are going to be encountered. EWER should be capable of traversing a slope of up to 30 degrees; since the stability depends on the center of mass it is desirable for both rovers to be as low to the ground as possible.

The rovers are expected to return samples to HOPE. Therefore it is unnecessary for them to have many

onboard testing equipment, thus reducing the weight and complexity of the rover. The estimated mass per rover is 220 kg. The design of the rovers accounts for transportation by considering the form taken when in storage. A single use mechanism is used to take the robot from a small size to operation mode by using a mechanism consisting of springs and pawls of solenoids [44].

The torque required to drive and turn the rover is calculated with the estimation that Oktagon needs to transport up to 10 kg of samples. Calculations have shown that to move at speeds up to 5 km/h, each drive needs an approximate power of 50 W. Therefore, the total power when all eight drives are at maximum is 400W. Typical small Radioisotope Thermoelectric Generators (RTG) can produce 1200 Wh/day [16]. RTGs are suitable because the rovers are not planned to be in the proximity of humans. That means that with maximum sample capacity, on the steepest slope the robot is designed to operate for up to three hours per day. This is a worst case scenario. However, the onboard drill has some power use when taking samples so the amount of material collected affects the operational time of the robot.

### 6.2 Humanoid Rover - Messaggero

Messaggero is a humanoid rover. Examples of existing humanoid mounted rovers include ESA's Centaur [8] and NASA's Robonaut [15]. Robonaut is unlike other space robotic systems in that it is designed for tasks requiring dexterity, not to move bulky objects. Its humanoid shape allows it to use tools designed for human astronauts allowing it to work side by side with its organic counterparts. The torso can be attached to a wheeled platform such as Centaur 1 to allow movement over long distances. ESA's Centaur shares the same name as the wheeled platform but is an entirely sepa-

rate project. It is also capable of high precision tasks. This human robotic interaction is seen as a vital part of space exploration for long term projects.

### 6.3 Construction Rover - Nozomi

Recently ESA has proposed constructing a base with lunar soil on the Moon [4]. The “printer” consists of a robot that acquires lunar regolith and converts it into a material suitable for onboard nozzles to print with. It does this by placing layer upon layer over a long period of time, slowly building the desired structure.

The technology needed to build structures using additive manufacturing in a non-terrestrial environment is still in its infancy with much further development needed. For HECATE, it is proposed that a prototype construction robot, Nozomi, is deployed as an early stage feasibility test.

## 7 Human-Robotic Interaction

To achieve HECATE mission goals, human-robotic interaction hardware and software are available to the astronauts inside HOPE. All robots part of the HECATE mission are designed to be autonomous and capable of operating on their own. However, at times it may be beneficial for a human operator to take control through a tele-operation and human-robotic interaction. For example, a collection of rocks have been found but the payload capacity of the robot is such that only one can be carried.

Artificial intelligence is progressing but currently a trained human has a better understanding of complicated scenarios where a wide variety of tasks must be performed. The main benefits of human-robotic interaction include less risk to humans, lower costs and the ability to have a presence in multiple locations simultaneously.

Current technology requires an operator to make some physical input to a controller. In return, the system may provide feedback to the operator to assist his actions. Four technologies have been chosen from many to be included on HOPE: Gesture Tracking, Exoskeleton, Virtual Reality and Auditory Feedback. They have been selected not only because they are suitable for the job but also because HECATE mission should further and improve their development.

Gesture tracking is used for simple control motions of the “MOON” rovers, such as basic locomotion maneuvers. The main advantage of this method is the minimal

amount of setup for the operator. No devices must be prepared or attached so the operator can multi-task and only apply commands when required. The hardware is similar to that of Microsoft’s Kinect platform, consisting of a camera and IR structured light depth camera.

The Exoskeleton located inside Tortuga is used for more complex operations involving Messaggero (the humanoid rover). The astronaut wears hardware that tracks the full six degree of freedom (6DOF) movements of his arm and sends commands to the robotic arm to replicate the action. Sensors on the robotic arm is used to provide tactile feedback to the operator back in Tortuga.

The virtual reality environment has a direct practical use in operations involving Messaggero, but crucially it is designed to increase the psychological and physical well-being of the astronauts. Perhaps this is not essential for the HECATE mission but in the future space voyages are going to take a long time; a round trip to Mars is predicted to last at least two and a half years. Proving the viability of the technology in missions like HECATE is important and HOPE offers a platform to research and improve the hardware.

Finally auditory feedback is available to provide information to the operator when controlling the robots during complicated task. Binaural feedback keeps the operator informed of the robot’s state and sound warnings when necessary.

## 8 Scientific Objectives

To realise the scientific objectives of mission HECATE, the “MOON” rovers are expected to land inside the Schrodinger basin and Daedulus Crater on the far side of the Moon.

### 8.1 The Schrodinger Basin

The US National Research Council (NRC) has identified eight scientific concepts and thirty-five prioritized goals for future human and robotic exploration of the Moon [42]. The Schrodinger basin is a geologically rich area and a sample return from this region would address many of objectives of the NRC.

It is located on the lunar far side (latitude  $-75^\circ$ , longitude  $132.5^\circ$ ) and it has a diameter of approximately 320 km; its floor, at its deepest points, is 4.5 km beneath the crater’s rim [40]. Schrodinger is the second youngest basin on the Moon and it is inside the oldest and largest lunar basin, the South Pole-Aitken. Because of this, a

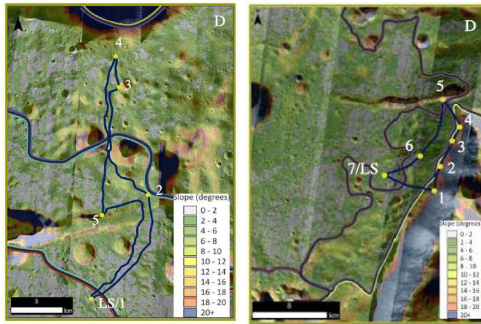


FIGURE 6. SBL1 (left) and SBL2 (right) traverse slope map, [40].

mission to Schrodinger would permit the rovers to recover samples from both basins, allowing to test of the lunar cataclysm hypothesis and to determine the age of the oldest lunar basin, meeting two of the highest NRC science priorities [42], [40]. Two of the three landing sites of the mission are located within the Schrodinger basin.

**Landing Site SBL1.** The first lunar mission is planned to land within the peak ring of Schrodinger, at approximately  $-73.35^\circ$  latitude and  $134.47^\circ$  longitude. This landing site is identified as Schrodinger Basin Landing Site 1, SBL1. Messenger and Nozomi land at SBL1. The considered traverse for Messenger in SBL1 is 37 km long and five main sites for sampling have been identified as represented in Figure 6, [40]. The traverse shown in Figure 6 is used as a baseline for the operations of Messenger. Astronauts teleoperating the rover from HOPE use data from an Alpha Particle X-Ray Spectrometer (APXS) to move Messenger to different locations on the surface of the Moon, depending on the data obtained. Operations of the APXS takes 4 hours with an additional 0.5 h to position the instrument, [40]. The high resolution visible light camera has been selected in order to obtain images of the surface and provide geological information on the collected samples.

**Landing Site SBL2.** The second landing site, Schrodinger Basin Landing Site 2 (SBL2) is located at latitude  $-75.50^\circ$  and longitude  $141.37^\circ$ . Oktagon 1 operates a baseline traverse in SBL2 as shown in Figure 6; the route is 28.8 km long and considers seven main sites for scientific exploration. The estimated traverse minimum time is 9.1 days [40]. As for Messenger, data from APXS and the on-board camera gives the astronauts information about the best place for sampling.

## 8.2 3D Printing

The landing in SBL1 is exploited also for technology demonstration of 3D printing of the lunar surface, a concept of particular interest for future long term human mission to the Moon. With the aid of tele-operated Messenger, a radiation sensor is placed under a layer of 3D printed regolith, to assess the radiation shielding properties of the 3D printed material. Nozomi has been designed also to print several specimens, returned to HOPE and then to Earth for structural analysis.

## 8.3 Telescope Deployment on Daedalus Crater

A unique science opportunity presented by operations on the far side of the Moon is the deployment of a low frequency radio telescope. The position on the far side takes advantage of the Moon acting as a shield for radio noise coming from the Earth. This reduction in noise allows the detection of extremely faint signals produced by neutral Hydrogen during the Cosmological Dark Ages.

A concept for a lunar surface antenna composed of numerous flat radio antennas that can be easily unfurled on the lunar surface has been developed [9]. The 3-armed, Y-shape flat polyimide film antenna design allows simple deployment by Oktagon2 of 3 antenna components. The best location for the positioning of the telescope has been identified as the Daedalus crater, located at latitude  $-5.9^\circ$  and longitude  $179.4^\circ$  [43, 1].

## 9 Mission Cost

A preliminary analysis of the cost of mission HECATE has been realized. Margins are employed to account for uncertainties in the design process. This can be due to insufficient data, low TRL and to increase safety. Margins are applied according to NASA/SP-2007-6105 to individual elements based on the level of uncertainty and criticality estimated by the designer and range from 5% to 25%. Additionally, a 20% margin is applied to the overall system budget. Margins apply to mass, power, volume and cost estimates. Operational cost is estimated at \$3.5B per year. The total cost of the mission is approximately 38B\$. Table 5 summarizes HECATE's costs.

## 10 Conclusions

This paper highlights the critical steps of a mission architecture that allows humans to explore the far side

Element (Number of elements)	Cost [M\$]
Launch Vehicles (5)	10270
Orion MPCV (1)	1300
Brave (1)	4120
Companion (1)	6410
Tortuga (1)	4000
“MOON” rovers (4)	750
Landers (3)	2470
Operational cost (2.5 years)	8750
Total cost	38070

TABLE 5. HECATE’s costs in \$FY15.

of the Moon as well as creating a space infrastructure, HOPE, that can be sustainably resupplied to enable further exploration of our Solar System. The emphasis of this paper is primarily on the space station, HOPE, and how its strategic location and role in the Earth-Moon system can be utilized for exploring the Moon and for deep space exploration. Along with a detailed description of HOPE, the mission analysis for HECATE’s architecture, the scientific values of exploring the Moon using tele-robotic operations, and the overall cost of the mission are discussed in this paper. Thus, this demonstrates that HECATE is a feasible and sustainable mission aimed at furthering the presence of humanity on the Moon, Mars, and beyond.

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