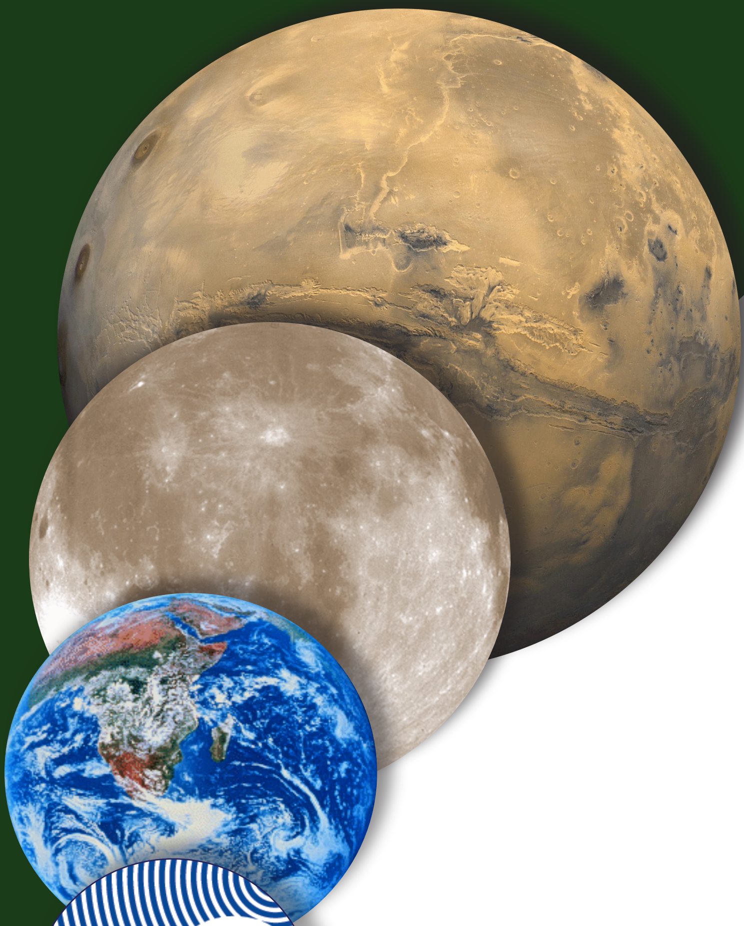
INTEGRATED EXPLORATION ARCHITECTURE



Strategy and Architecture Office

INTEGRATED EXPLORATION ARCHITECTURE

Draft

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TABLE OF CONTENTS

1 INTRODUCTION

1.1 Purpose

The overall objective of the architecture analysis is to define an integrated architecture for exploration of Moon and Mars responding to the objectives and requirements of European stakeholders and to integrate this architecture within the international context focusing on the next 15 years. This reference architecture is defined as a strategic tool to identify European strategic interests and priorities, define technology roadmaps, and to inform discussions at an international level on future exploration architectures and associated needs and opportunities for international coordination and collaboration.

Issue 1 of the document provides a first draft version of the Integrated Reference Architecture. The document will grow and deepen with the still ongoing architecture work focusing on the consolidation of this reference.

1.2 Definitions, Abbreviations and Symbols

1.2.1 DEFINITION OF TERMS

Launch	A “launch” consists of one or more mission elements that are brought to space on a single launch system.
Flight	Several launches make up a “flight”, being one major part to fulfil one or more certain requirements.
Mission	Architectures are split into “missions”. Each “mission” or “mission class” fulfils a set of requirements, coming either from stakeholder objectives or from internal architectural requirements. A “mission” can include several flights and a large number of elements, and it generally spans over a long period of time.
Architecture	A number of missions make up the integrated exploration “architecture” which fulfils as many stakeholder objectives and requirements as possible. This benefit of the “architecture” will be used to evaluate comparable architecture designs.

1.2.2 ACRONYMS & ABBREVIATIONS

ADn	Applicable document n
CDF	Concurrent Design Facility
CNSA	China National Space Administration
CSTS	Crew Space Transportation System
DI	Direct Injection
EML	Earth-Moon Libration Point (also known as Lagrange Point)
ESA	European Space Agency
ESOC	European Space Operations Centre
HME	Directorate of Human Spaceflight, Microgravity and Exploration Programmes
I/F	Interface
I/S	Infrastructure
LEO	Low Earth Orbit

LLO	Low Lunar Orbit
LMO	Low Mars Orbit
LOI	Lunar Orbit Insertion
LSS	Lunar Space Station
MOI	Mars Orbit Insertion
NASA	National Aeronautics and Space Administration
NEO	Near Earth Objects
P/L	payload
RDn	Reference Document n
SEL	Sun-Earth Libration Point (also known as Lagrange Point)
SR	Sample Return
TBC	to be confirmed
TBD	to be determined
TEI	Tran Earth Injection
TLI	Trans Lunar Injection
TMI	Trans Mars Injection

SI units will be used throughout this document.

1.2.3 HIGH-LEVEL ARCHITECTURE CLASSIFICATION

From the high-level classes of architecture requirements as outlined in [AD1], several top-level architecture solutions can be derived that will generally outline the architectural approach. Those requirements classes are:

- R-1: Robotic orbital operations
- R-2: Human orbital operations
- R-3: Robotic surface operations
- R-4: Human surface operations

A total of seven missions have been defined as a basis for future architecture analysis as shown in Figure 1. Each of the four first-level architecture solutions (M-1 to M-4) is driven by one or more of the requirements classes, while the three second-level missions (M-5 to M-7) satisfy derived requirements. The seven mission classes for the design studies are:

- M-1: Robotic Missions
- M-2: Surface Sortie Missions
- M-3: Orbital Operations
- M-4: Surface Operations
- M-5: Orbital I/F Construction
- M-6: Surface I/F Construction
- M-7: Communication, Navigation, Space Weather

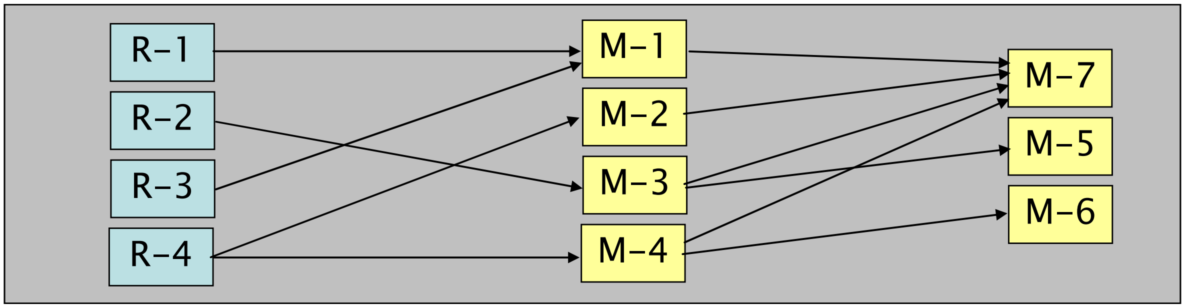


Figure 1: First- and second-level architecture solutions for the top-level requirements classes

These mission classes can be used for a requirements mapping to the stakeholder objectives and the derived scientific, political and economic requirements. With [RD1] and [AD1] it can be shown that each stakeholder group's requirements can only be fully satisfied by the full set of architectural solutions, and that all requirements can be fulfilled that way, so that the above mentioned distinction presents a complete set of missions for the overall architecture. This emphasizes once more the interdisciplinary benefit and necessity of space exploration.

1.3 Related Documents

1.3.1 APPLICABLE DOCUMENTS

[AD1] High Level Architecture Requirements for European Space Exploration, Issue 6, HME-HS/STU/RQ/BC/2007-05001, 12 April 2008.

1.3.2 REFERENCE DOCUMENTS

[RD1] Integrated Objectives for European Space Exploration, Issue 6, HME-HS/STU/RQ/WC/2007-03017.

[RD2] Architecture Trade Report, HME-HS/STU/TN/JS/2008-.

[RD3] Red Team Architecture for Moon exploration Report, CDF Study Report, to be issued.

[RD4] Blue Team Architecture for Moon exploration Report, CDF Study Report, to be issued.

[RD5] Lunar Frozen Orbits, David Folta and David Quinn, NASA Goddard Space Flight Center, AIAA 2006-6749

[RD6] The European launcher option for exploration, David Iranzo-Greus and al., Astrium Space Transportation, CNES and SNECAM, IAC-06-D2.7./A3.7.07

[RD7] ESAS report

[RD8-14] Contractors D4 documents

[RD15] D9.1 – LEO Manned Facility In-space Architecture Element Design. RR404168 AVA. Rheinmetall Italia SPA.

2 EXPLORATION ROADMAP

In order to define and analyze potential European contributions to the global space exploration initiative, ESA has developed a long-term, international space exploration roadmap, based on a current understanding of international space exploration plans and ESA's exploration objectives and technical capabilities. The roadmap assumes development of exploration capabilities and systems in a phased approach, leading ultimately to the implementation of the first international human mission to Mars. The four phases are:

- Phase 1, through 2020. This period will see the advancement of human operations in LEO based on extensive utilisation of the International Space Station (ISS), or potential new orbital infrastructures. At the same time, the development of a new generation of crew space transportation systems, designed for access to both LEO and low lunar orbit (LLO), will secure human access and frequent flight opportunities to space. Early robotic preparatory missions towards the Moon (the International Lunar Network) and Mars will pave the way for future human exploration and demonstrate key capabilities such as planetary descent and landing, surface mobility, in-situ resource utilisation (ISRU), and perform valuable in-situ science. Privately developed orbital transportation systems are likely to evolve as a first commercial service to space activities. In space tourism, it can be expected that over time different competing companies will establish operations and expand the market of suborbital flights.

- Phase 2, early-to-mid 2020s. This period could see extended human operations in LEO based on the transition to new orbital infrastructures replacing ISS, while first human missions to the Moon commence. During this period, further orbital infrastructures beyond LEO (e.g. in LLO) might be constructed as an element of a transportation architecture. Such infrastructure could facilitate the assembly of vehicles, crew exchange, docking operations, lunar landings and sustained surface operations, while also enabling research for interplanetary mission preparation. The first Mars Sample Return mission will be implemented early in this phase and its findings will drive further Mars exploration. Commercial access to LEO will be an established part of space activities. It will probably also see orbital structures set up by private enterprises that will be used for private businesses, such as tourism, commercialised microgravity research and media and entertainment activities. Space tourism might be expanded to lunar orbits.

- Phase 3, late 2020's or early 2030s. Assuming a global consensus for international cooperation and a strong rationale for sustained, long-term presence on the Moon, Phase 3 will introduce extended lunar surface installations for fixed and mobile habitation and research. Initial activities towards the preparation of an international human mission to Mars may commence. Commercial services will likely be an integrated part of space activities, including not only transportation services but also others like communication systems, logistics, in-space maintenance and repair. Additional private sectors that focus on public audiences, e.g. media, entertainment and education might use space activities as part of their business portfolio. A space economy is evolving with commercial players from various private sectors.

- Phase 4, mid-to-late 2030s. Based on the essential knowledge gained from and capabilities developed for continued lunar surface activities, Phase 4 will see the implementation of the first human Mission to Mars. Commercial enterprises are operating in LEO. Continuation of lunar surface activities will depend on the long-term exploitation objectives of institutional and private actors.

The chart below illustrates the long-term scenario described above.

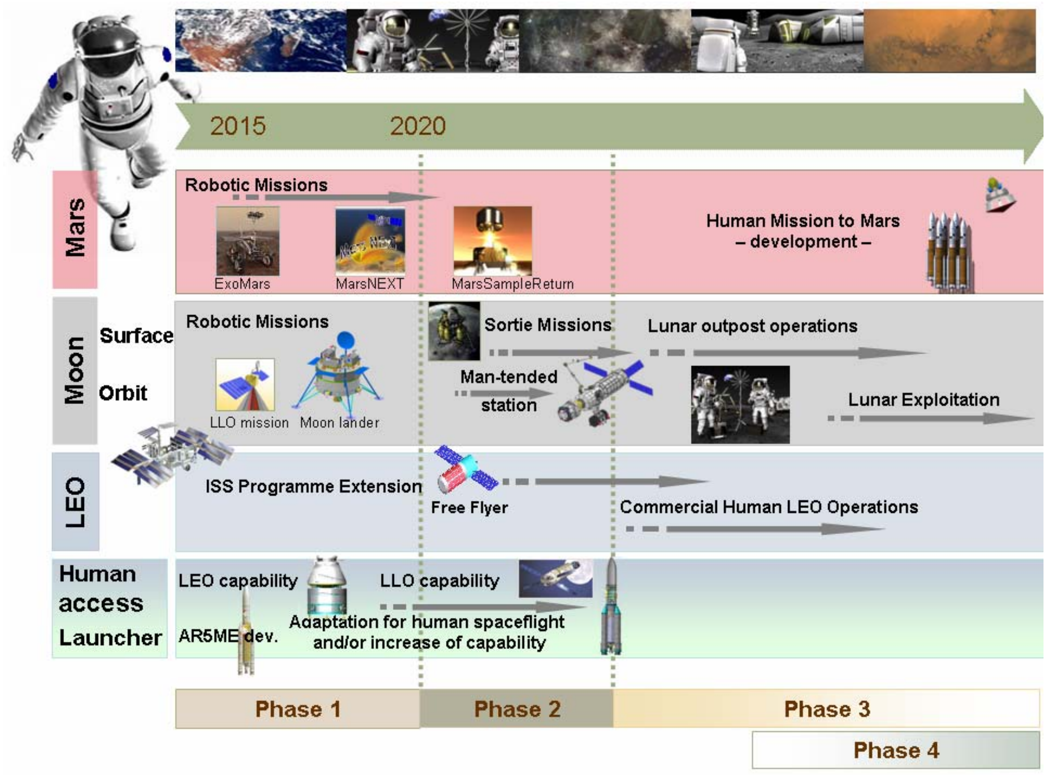


Figure 2 – Long term Space Exploration scenario

3 EXPLORATION ARCHITECTURE

3.0 Overview

A high level summary of how the proposed reference architecture supports the implementation of the exploration roadmap scenario described in the previous section is given in the tables on the next pages and depicted in the following figures.

The following chapters provide some more insight on the evolution of the architecture through the four exploration phases.

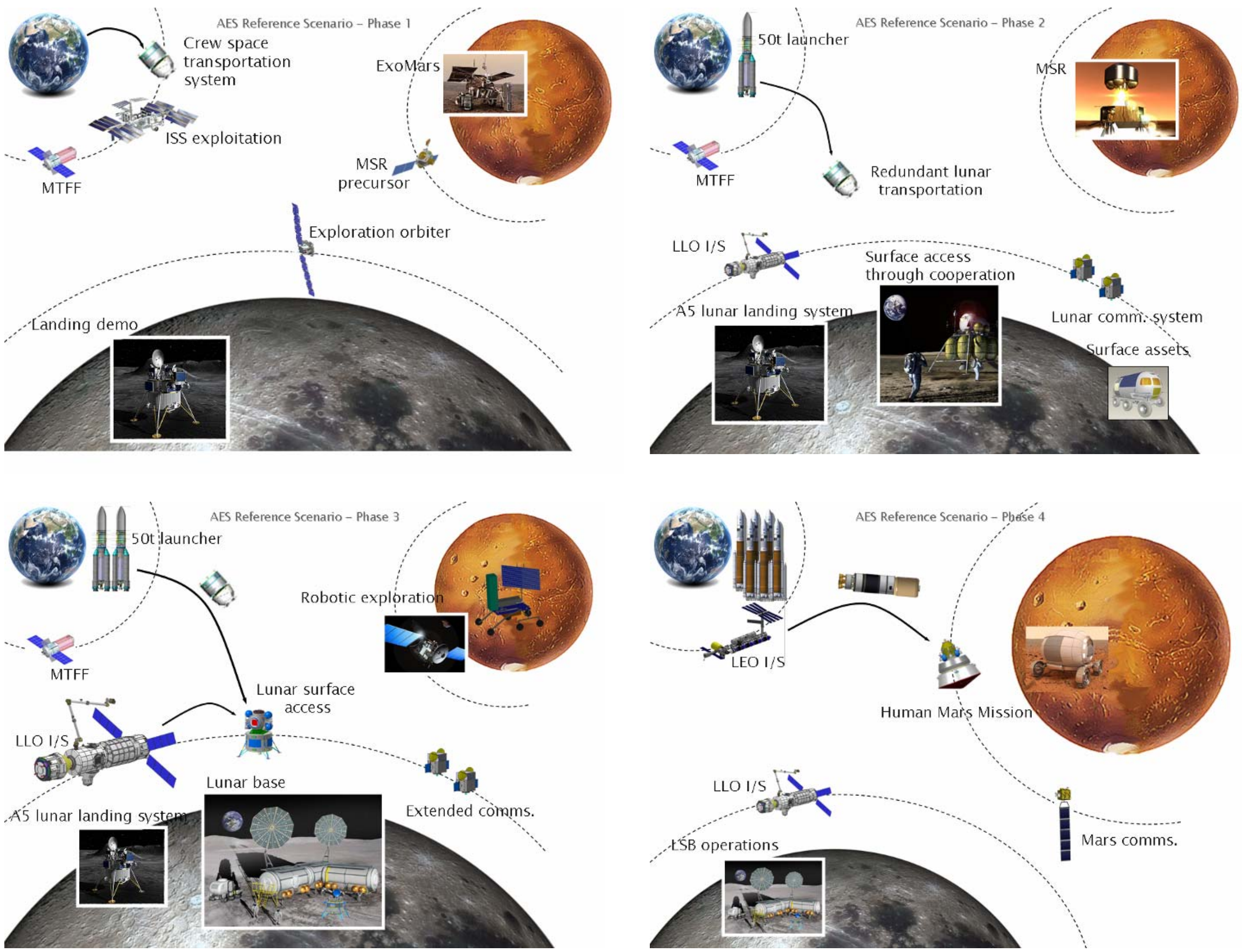


Figure 3 – Reference architecture through the four phases

	Phase 1 ISS / Robotic precursor	**Phase 2** Human Moon sorties / MSR	**Phase 3** Crewed Lunar Outpost	**Phase 4** Human Mars mission
M-1: Robotic Missions	• **Robotic lunar landing system:** 1st mission for technology maturation and demonstration Approach to development and demonstration still needs further assessment.(*) • **Lunar orbiter for exploration:** High resolution terrain and resources mapping and imaging of landing sites might significantly reduce risk in lander system (TBC) • **Robotic Mars:** ExoMars and MSR precusor in order to learn more about Mars environment (*) Link to on-going science mission such as ILN to be assessed	• **A5-based lunar landing system:** Extensive use to support human moon return preparation and science. Phase 2 P/Ls: deep driller, sample return,… Support human sortie missions • **Mars Sample Return:** MSR findings and operations will prepare and decide further robotic Mars activities	• **A5-based lunar lander:** Logistics and surface support to human surface base and extended sorties • **Robotic Mars:** Post-MSR robotic exploration of Mars and human landing preparation	
M-2: Surface Sortie Missions		• **Human surface access:** European astronauts to Moon through NASA collaboration	• **Extended sortie missions:** Global extended sorties vs. crewed outpost	• **Human Mars Mission:** Various options have been considered showing that an heavy lift launch capability is a must together with advanced in-space propulsion.
M-3: Orbital Operations	• **ISS exploitation:** Science, demonstration of exploration capabilities • **Human access to LEO:** Development of new generation crew space transportation system	• **Continuation of LEO operations:** LEO man-tended infrastructure enabling EU autonomous scenario after ISS • **Redundant transportation and LLO infrastructure (*):** LLO I/S developments to support transportation architecture. Architecture access limited to LLO. (*) Medium launcher developm.:Launcher (>50t) and EDS development for LLO access (assuming crew transportation vehicle availability)	• **LLO I/S operations:** Man tended LLO station to support transportation architecture to LLO and surface (Staging-post, safe-haven, rescue functions) • **Orbital servicing:** Servicing of high-value assets (telescopes, transportation vehicles). Need for an orbital infrastructure to support is not consolidated.	

	Phase 1 ISS / Robotic precursor	**Phase 2** Human Moon sorties / MSR	**Phase 3** Crewed Lunar Outpost	**Phase 4** Human Mars mission
M-4: Surface Operations		• **A5-based lunar landing system:** Logistics and surface support to NASA sortie missions	• **Human surface support:** Logistics support through A5-based lander system(s) and/or larger lander development based on heavy launcher (>50t) • **EU astronauts to LSB:** Own sorties and/or collaborative LSB operations	
M-5: Orbital I/F Construction	• **LEO man-tended infrastructure for science:** Depending on ISS utilization, installation of a free-flying element in order to allow for science and applied research	• **LLO I/S installation:** LLO I/S to support sustained operations and initial base build-up	• **LLO I/S enhancement** Exploitation of I/S for lunar exploration support and human Mars preparation. Potential evolution scenario with added refueling capability.	
M-6: Surface I/F Construction		• **Surface assets:** Habitation to support sortie missions (fixed or mobile)	• **Human surface elements for long duration missions:** (habitat module, pressurized rover, power plant,…)	
M-7: Communication, Navigation, Space Weather	• **Communication support:** Demonstration of advanced capabilities with operational application.	• **Lunar Comm. System:** Basic comm. for lunar surface operations (EML) Cooperation with NASA and/or private sector engagement	• **Extended lunar comms./nav**	• **Basic Mars comms.:** Support of robotic missions and first human landing

3.1 Phase 1

3.1.1 ROBOTIC MISSIONS

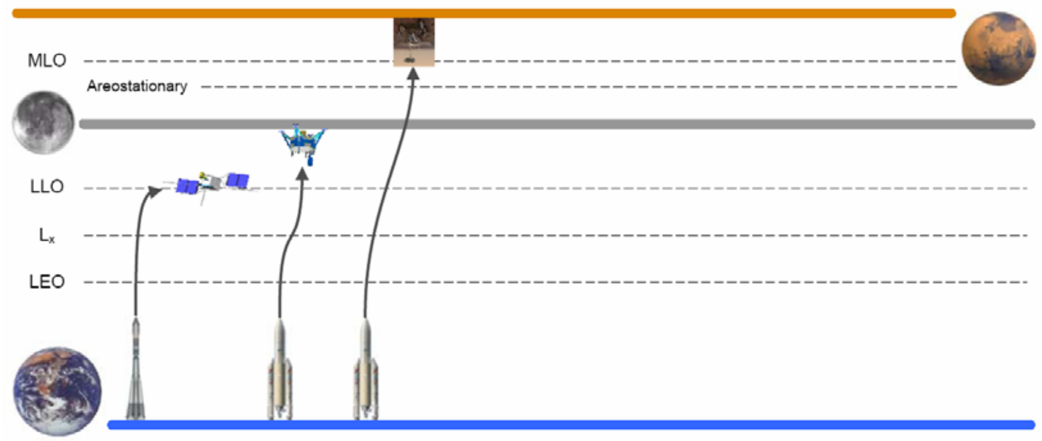


Figure 4 – Phase 1 Robotic missions

The Exploration Lunar Orbiter is the first element to be launched in phase 1 of the Exploration architecture. The primary objective of the lunar orbiter is to provide further information on the Moon environment in view of later missions. The provision of high accuracy maps of the lunar surface is primordial for further-on soft precision landing missions and to define future safe paths for rovers. Such an orbiter could also provide essential data for the selection of future man-landing site through illumination and resources mapping as well as lunar dust environment characterization. Further information regarding the lunar gravitational field for low circular orbit could also be gathered with the Exploration Orbiter. It could thus validate the existence of near circular frozen orbits that could be used later during human exploration to reduce the cost of orbit maintenance.

These exploration objectives are in-line with the fulfillment of three scientific requirements derived from [AD1], which are:

- Investigation of lunar dust environment
- Performing high-resolution crater altimetry
- Performing a resource mapping of lunar surface

The solution proposed is essentially made by a satellite which has to carry in Low Lunar Orbit the payloads needed to perform such experiments; these payloads are essentially constituted by a cooled long-wave infrared spectrometer, which is the most suitable instrument to take information about dust micrometry and composition, a high-resolution stereo camera, to satisfy the second requirement about crater altimetry, a low-frequency radar sounder, and some other spectrometers were selected as suitable to detect the presence of particular substances in and below lunar ground, and therefore they could be used to satisfy the third requirement.

Furthermore, the orbiter holds also a telecommunication payload necessary to maintain the contact with Earth ground stations. Therefore, the Orbiter may be used as a relay for surface elements, for which it would be easier to send data towards Earth via Orbiter than directly. This function would be useful in the early phases while the Communication satellites would not be available yet.

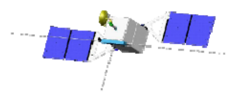
Element	Exploration Lunar orbiter	
Objective	Provide data on Lunar environment	
Timeline	2015-2016	
Characteristics	Total mass of 1700kg Soyuz LTO launch Polar circular orbit at a 100km altitude Lifetime 5 years Payload mass up to 125kg X-band steerable antenna	

Table 1 - Exploration Lunar orbiter

Currently, several moon orbiters are already operating around the Moon (JAXA Selene mission launched in September 2007, CNSA Chang'e 1 mission launched in October 2007) and others are expected to follow soon (Chandrayaan expected in 2008 and LRO expected in 2008). Therefore, any follow-on orbiter shall either provide significant instruments performance improvement with respect to the similar ones housed in previous missions or investigated different aspects of the Lunar environment.

Mission	SELENE	CHANG'E 1	CHANDRAYAAN	LRO	ESA IN-SPACE
Objectives	Study the origins of the Moon and its geologic evolution Obtain information about the lunar surface environment Perform radio science on lunar orbit	Three-dimensional images of the lunar surface. Map the distribution of various elements on the lunar surface. Probing the features of lunar soil and evaluate its depth. Probing the space environment.	High resolution mapping in 3D. Distribution of various elements covering the entire lunar surface.	Global topography. Characterization of deep space radiation in lunar orbit. Lighting environment in polar regions. High resolution mapping.	Investigation of the lunar dust environment. Perform high resolution altimetry of lunar craters. Perform a mapping of lunar resources
Instruments					
Terrain Camera	10 m/pixel	120 m/pixel	5 m/pixel	X	X
X-Ray Spectrometer	X	X	X		
Lunar Magnetometer	X				
Multi-Band Imager	20 m/pixel visible 62 m/pixel infrared	X	X		
Laser Altimeter	X	X	X	X	X
Lunar Radar Sounder	X				X
Gamma-ray Spectrometer	X	X	X		X
Charged Particle Spectrometer	X				X
Plasma Analyzer	X				
Upper Atmosphere and Plasma Imager	X				
Microwave Radiometer		30 m max penetration depth		X	
High Energy Particle Detector		X			
Solar Wind Detector		X			
Solar X-Ray Monitor			X		
Moon Impact Probe			X		
SAR			X	X	
Radiation Dose Monitor			X	X	
Neutron Detector				X	X
Electron Reflectometer					X
Infrared Spectrometer					X

Figure 5 – Moon orbiter objectives and instruments compared to current or planned missions.

A robotic lunar landing system is essential to fulfill science objectives and to future human scenario on the moon surface and within current launch capability.

Human lunar exploration requires access to the lunar surface for crew and cargo. While a large payload performance is a pre-requisite for crew access and initial outpost build-up, a variety of missions do not necessitate such capacity. Therefore a cargo lander system can be a key element of a lunar exploration architecture.

A lunar lander using the full Ariane 5 ME capability to Lunar Transfer Orbit could deliver up to about 1.7 tons of gross payload mass to the lunar surface depending on the launcher version considered. Such a payload capacity allows the Ariane 5 based lander to be utilized in a broad range of lunar exploration scenarios, even though they may have quite distinct mission objectives. The cargo lander could form a significant contribution as a major element in an international lunar exploration architecture while providing a versatile and flexible system for utilization in a broad range of lunar missions based on European own interests and objectives.

In order to develop such a vehicle several capabilities including soft precision landing, hazard avoidance, night-time survival on the lunar surface are required together with an engine class not available currently in Europe.

While the lunar cargo lander needs to be operational in the timeframe of the human return to the moon in 2018-2020, a demo mission could mitigate the risks associated to the new capabilities required for the full system while providing ground truth data on the lunar surface environment and test mobility concepts in-situ. Furthermore, it would be a potential candidate of a European contribution to a network of landers. Finally such a demo mission should be conceived such as to minimize the delta cost development of the full A5 cargo lander.

Several payload package concepts have been identified for the demo lander:

- Environmental Characterization / Monitoring
- Life support
- Materials exposure
- Robotic systems
- Comms/nav
- Commercial/Education

Although the primary focus of this demo lander shall be on technology demonstration and preparation for the human exploration some science opportunities might be provided for geophysics, life science and Earth observation.

The demonstration of critical technologies and operational aspects for soft precision landing together with the improved knowledge of the lunar surface environment could also reduce the technology risk for a crew lander depending on the timeframe of the first foreseen flight.

Several lunar lander demo are possible with different cost to payload efficiency. A small demo lander launched on Soyuz could deliver on the Moon surface a payload smaller than 100 kg. A shared Ariane 5 launch could improve the payload performance up to 250 kg. Finally a full scale Ariane 5 demo lander could bring up to 1.3 ton of payload on the lunar surface. The demonstration mission need to be further consolidated with respect to the minimum set of objectives to be fulfilled, the financial constraint and the level of international cooperation in such a mission.

Element	Demo lunar lander	
Objectives	o Technology demonstration for soft precision landing o Ground truth data of lunar surface environment o Demonstration of surface mobility o Reduce risk and development cost of A5 cargo lander	
Timeline	2017-2018	
Characteristics	Soyuz version with about 50kg payload Shared A5 with about 215 kg payload Full A5 with up to 1.7t of payload	

Table 2 – Demo lunar lander

No specific communication support is currently foreseen for moon phase 1 robotic missions. The exploration orbiter presented before could act as a relay for surface elements. However, communication orbiter foreseen to support Human activities in phase 2 could be anticipated to support a network of landers on the moon surface and combined with a shared Ariane 5 lander in a single launch.

Exomars

During Phase 1, the Exomars mission to Mars is already planned and on-going within the Aurora exploration programme to demonstrate key technologies, to search for signs of past and present life and to learn more about Mars environment. The primary objectives of the Exomars mission are the development of the following technologies:

- Entry, Descent and Landing (EDL) of a large payload on the surface of Mars,
- Surface mobility via a Rover having several kilometres of mobility range,
- Access to sub-surface via a Drill to acquire samples down to 2 metres,
- Automatic sample preparation and distribution for analyses of scientific instruments.

The ExoMars mission's scientific objectives, in order of priority, are:

- To search for signs of past and present life on Mars;
- To characterise the water/geochemical environment as a function of depth in the shallow subsurface;
- To study the surface environment and identify hazards to future human missions;
- To investigate the planet's subsurface and deep interior to better understand the evolution and habitability of Mars.

The ExoMars Spacecraft will be designed and qualified for both Ariane 5 and Proton launchers. Launch is planned in late November 2013. The mission profile employs a direct injection into fast interplanetary trajectory (T2 type) to Mars resulting in a cruise phase duration of about 10 months.

The composite of the Descent Module and the Carrier Module is injected into orbit around Mars. This has the benefit of providing a smaller landing ellipse for a more precise landing on Mars and it allows choosing the moment for entering the Mars atmosphere at favourable time in particular with respect to Dust storms.

When the decision to begin descent is taken, the spacecraft composite performs a manoeuvre to de-orbit and the Descent Module subsequently separates from the Carrier Module to descend into the atmosphere of the planet. The Descent Module carries all the equipment needed to decelerate and land safely the large payload consisting of a mobile Rover and a stationary Lander. The Rover carries the Pasteur Payload scientific instruments along with a sub-surface drill and sample processing system, while the Lander carries the Geophysics and Environmental Humboldt Payload instruments.

Element	Exomars	
Objectives	o Technology demonstration for Entry, Descent and Landing (EDL) o Demonstration of surface mobility o Access to sub-surface via a Drill o Automatic sample preparation and distribution	
Timeline	2013	
Characteristics	Ariane 5 launch (Proton back-up) Carrier Module (CM) and Descent Module Composite (DMC) Carrier Module (CM) performs MOI DMC is a blunt-shape entry capsule mounted on the upper side of the Carrier Module. DMC design includes a heatshield, parachute system, descent thrusters, reaction control system and the Lander. The Lander features the vented airbags and the required support and egress system Descent Module Composite (DMC) deploys the Lander, which accommodates the Rover Module (RM) and the Geophysical and Environmental Payload (GEP) instruments. The ExoMars Rover is a highly autonomous six-wheeled terrain vehicle.	

Table 3 - Exomars

3.1.2 CREW ORBITAL MISSIONS

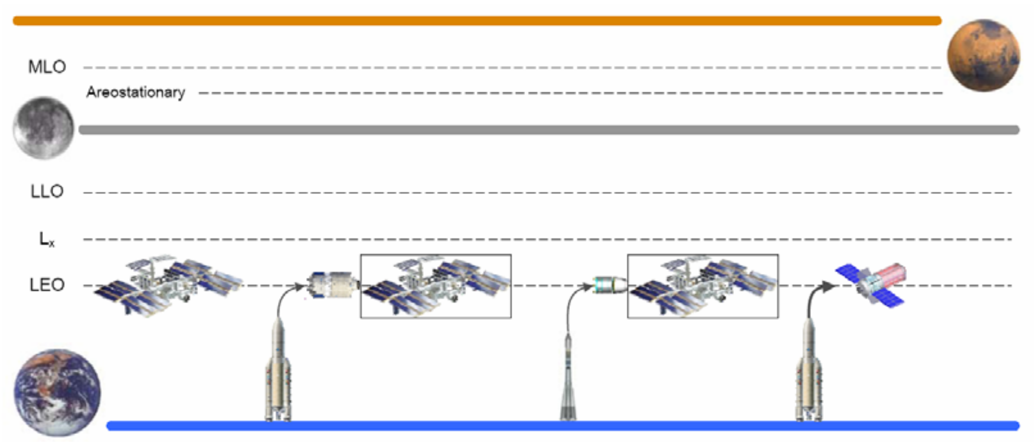


Figure 6 – Phase 1 crew orbital missions

The International Space Station (ISS) constitutes a partnership among the nations of Canada, Europe, Japan, Russia and the United States (US) to cooperate on the design, development, operation and utilization of a permanently occupied civil space station. Assembly began with the first element launched in November 1998, and the ISS has been permanently crewed since November 2000. The on-orbit assembly is scheduled to be complete by the end of 2010.

The ISS is an important destination and laboratory for exploration-focused research. Research into the effects of microgravity on the human body, and reliable counter-measures for these effects, is ongoing and will continue for the foreseeable future. In addition, ISS affords a unique facility to perform technology demonstrations.

Based on ISS elements design life the current plans call far a completion of program operations in 2016. Nonetheless, past operating experience with both human-rated and robotic spacecraft clearly indicates that systems are capable of performing safely and effectively for well beyond their original design lifetime. Service life can be extended dependent on actual operating experience, and the selected approach to maintenance and refurbishment.

In order to secure access to orbital research facility, it is assumed here that the lifetime of ISS is extended up to 2020. Before ISS decommission, demonstration and utilisation flights of the crew transportation system for LEO and ISS access are foreseen. Later on, a man-tended free flyer platform that can be visited by the crew transportation vehicle is introduced as a minimum orbital infrastructure to ensure continuity of research in space.

The development of crew space transportation capability is essential to secure an appropriate role in the future international human spaceflight and exploration programme which is based on an adequate balance of cooperation and autonomy.

The development of crew transportation capability needs to address two key objectives:

- To secure access to existing (ISS) and future orbital research infrastructures in LEO,
- To enable participation in human exploration.

The crew space transportation system has therefore to be defined such as to enable missions to and beyond LEO.

This next generation crew transportation vehicle could be sized to accommodate up to 6 crew in a ISS lifetime extension scenario or a reduced crew of 3 to a smaller scale future orbital research infrastructure in LEO such as a man-tended free-flyer where logistics would have to be brought with the crew.

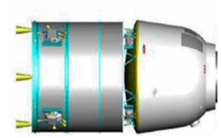
Element	Crew transportation vehicle	
Objective	Secure crew access to existing and future orbital research infrastructures in LEO, Enable participation in human exploration.	
Timeline	2018-2025+	
Characteristics	Total mass of LLO version < 13t Service module of 5.5t Crew capsule of 7.5t Launch by new man-rated launcher Crew of up to 5-6 to LEO Crew of 3 to LLO.	

Table 4 - Crew transportation vehicle

The minimum configuration for a future orbital research facility in LEO is addressed hereunder. This facility shall satisfy the top level functional requirement related to research applications to enable Microgravity and life support research. The proposed LEO Micro-g Infrastructure is a man tended research facility for experiment under a microgravity environment. The required micro-g level is 10^{-6}. To satisfy this requirement the LEO I/F should fly above 450 km altitude.

The LEO facility configuration is composed of two elements, a service module and a laboratory module. The Laboratory Module house the payloads and can sustain manned crew visiting for at least one week, and the Resource Module provides all the necessary services (power, communication, propulsion, AOCS,..). The orbital facility is able to house 2000 kg of Payloads in standard ATV type racks.

In order to carry out only research applications, 2-3 crew members are considered. Remembering that payloads can run autonomously and that crew visits are periodic, lasting 15-30 days every 6-12 months (TBC),

Launched by an Ariane 5 ME launcher in a 450 km altitude orbit, the LEO I/F will start the payloads operational phase. For about 6 months the orbit will be allowed to decay to avoid disturbing the microgravity environment. The resulting orbit altitude after 6 months will still be compatible with the microgravity environment (for residual drag). Orbit decay in 6 months is about 25 km (no impact on micro-g quality). Annual delta-V for orbit maintenance is 72 m/s.

Periodically (6-12 months) the LEO I/F will be visited by a manned CSTS for maintenance and payloads refurbishment, prior the next payloads operational phase.

The LEO Station is temporarily manned, i.e. only during Payload (P/L) and Spacecraft Subsystem (S/S) servicing. Payload (P/L) processing is performed in an automatic mode during unmanned free flights. During servicing there are nominally up to 3 astronauts working in the LEO facility.

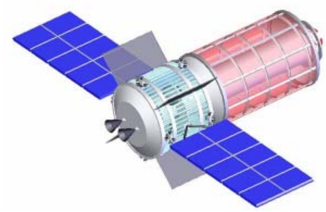
Element	LEO Man-tended facility	
Objective	Secure access to orbital research facility	
Timeline	2018-2020	
Characteristics	Total mass of 20540 kg Length 11m x 4.5 diameter Ariane 5 ME launch in a 450 km circular orbit Support crew of 2-3 astronauts for 15 days stays 75 m^3 of pressurized volume House 2 tons of payloads Lifetime 10 years	

Table 5 - LEO Man-tended facility

In addition, the LEO Station should have the potential to grow from a man-tended vehicle to a building block for a larger research station with minor modification and adaptation.

3.2 Phase 2

3.2.1 ROBOTIC MISSIONS

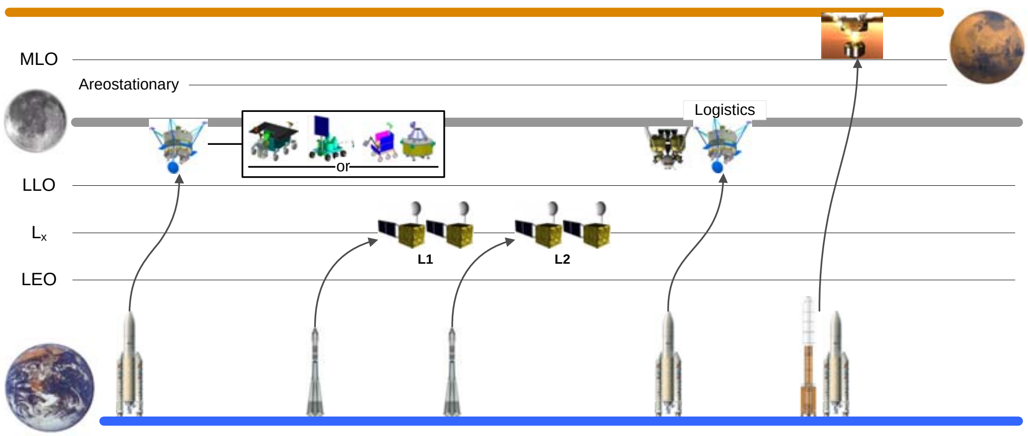


Figure 7 – Phase 2 robotic missions

As previously mentioned the Ariane 5 cargo lander could form a significant contribution as a major element in an international lunar exploration architecture while providing a versatile and flexible system for utilization in a broad range of lunar missions based on European own interests and objectives.

Using the Ariane 5 ME, which would have a launch capability for a direct Lunar Transfer Orbit injection of about 9700 kg, the lunar lander system could deliver up to 1.7 tons to the lunar surface.

The mission profile of the lunar lander system is described hereafter. The Ariane 5 upper stage delivers the lander into the Lunar Transfer Orbit, where a small correction maneuver could be necessary, which will be performed after separation from the upper stage by the lander itself and also the Lunar Orbit injection maneuvers, which position the lander into a 100 km lunar circular orbit. After several orbits for the precise determination of the orbit data and the monitoring of the landing site, the lander begins the descent and landing maneuvers.

While a large payload performance is a pre-requisite for crew access and initial outpost build-up, this is not always necessary for a variety of missions or mission options. Therefore a logistics lander system can be a key element of a lunar exploration architecture.

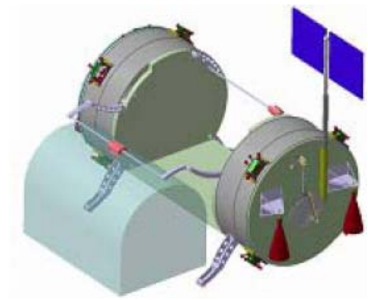
Element	A5 cargo lander	 
Objective	Science and technology demonstration; Delivery of regular logistics to a lunar base; Provision of consumables for extended surface exploration range and duration; Delivery of surface assets to support and accelerate lunar outpost build-up	
Timeline	2020-2025	
Characteristics	Direct LTO injection by Ariane 5, performs LOI, descent and landing Payload performance of 1.3t with A5ECA and 1.7t with A5ME Storable propulsion Thrust range from 12kN (LOI, Descent) to 3kN (Landing) Soft precision landing with hazard avoidance	

Table 6 - A5 cargo lander

The possible scenario options for the cargo lunar lander include:

- Science utilization, technology demonstration and potential human landing preparation in an early lunar robotic exploration program;
- Delivery of regular logistics to a lunar base;
- Provision of consumables for extended surface exploration range and duration;
- Delivery of surface assets, be they stationary or with mobility, in order to support and accelerate lunar outpost build-up or for science and technology demonstration in sustained human operations

If used in support of extended lunar sortie missions, it would be adequate to provide a crew of four astronauts with consumables that would last for approximately one month. A pre-deployed logistics lander can thus significantly increase both exploration range and astronaut time on the surface for any surface activity, especially when involving crew mobility systems.

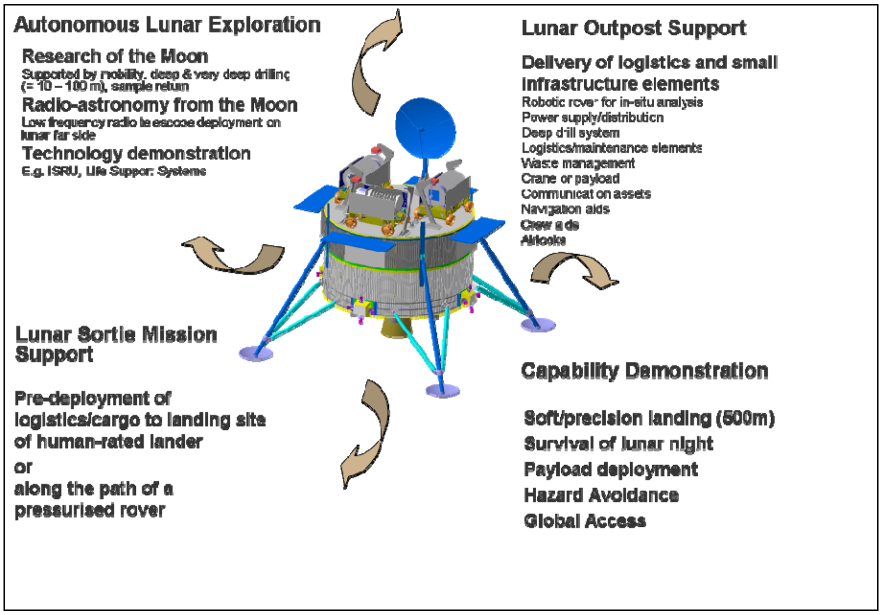


Figure 8 – The A5 cargo Lunar Lander versatility

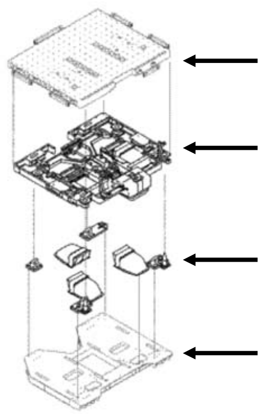
To a lunar outpost at a fixed location, currently foreseen to be set up in the early 2020s, an automated lunar lander can enable the acceleration of outpost build-up through the early deployment of smaller systems such as power supply and distribution, communications and navigation aids, EVA support and surface mobility elements, as well as through extending early surface stay duration through the deployment of life support and crew consumables.

Indeed, the availability of such a logistic vehicle would simplify the operations of the large crew lander and extend crew surface activities by providing a dissimilar redundancy in the critical delivery of supplies to the crew and thus improving the overall mission assurance.

Ariane 5 based logistic lander should be designed with a cargo accommodation system flexible enough to interface with the large range of possible payloads.

<u>Interfaces</u>

A clean interface plate will be attached to the top of the lander, in which a common interface system will be located. This interface could be based on the Columbus External Platform Adapter (CEPA), attached to the interface plate with a Flight Releasable Attachment Mechanism (FRAM). This system would allow for easy off loading of the lander cargo by robotic means. Details of the proposed system can be found in the table here after.



Total mass: 81 kg

Dimensions: 1.2 x 1 m

<u>Consumables Cargo Carrier</u>

Different types of consumables should be carried to the Moon surface to maintain an outpost. They can be categorised as follows:

- Food (pressurised)
- Water
- Gases
- Equipment (spare parts, medical equipment, experiments, etc)

In the case of water and gases, the most efficient way of transportation is dedicated tanks attached to a FRAM. In the case of pressurised cargo (food and equipment), a dedicated cargo container has to be developed. Due to the limited cargo capabilities of the lander, the mass should be minimised. An initial concept for such a cargo container could be based on a propellant tank equipped with a clamp band mechanism providing sealing capabilities. Once off loaded from the lander and placed in the airlock, the crew could manually operate the clamp band mechanism to access the payload. Details of a system like this can be found in the table below:

	Tank:	EADS Propellant Tank (OST 22/X)
	Mass:	36 kg
	Diameter:	1.1 m
	Volume:	0.7 m^3
	Mechanism mass:	6.3 kg
	System mass:	42.3 kg

Cargo manifest

Brut cargo capability of the logistic lander is estimated to 1.7 Ton. Interfaces and cargo containers should be subtracted from this amount.

As an example, a configuration including 3 cargo containers is proposed. Such a system would have a net cargo capability of 1330 kg (and $2.1m^3$). The payload of the three containers can be subdivided as follows:

Container	Payload	Net mass [kg]	Volume [m^3]
Container 1	Food	476	0.48
Container 2	Water	508	0.51
Container 3	Equipment and gasses	344	0.30
	Total	1330 kg	1.28 m^3

This cargo should be enough to maintain a crew of 4 on the surface of the moon for more than one month. Other logistics will be required to maintain the outpost itself, i.e. ISRU feedstock, large replacement units, etc.

Furthermore, the capability of the lunar lander would be sufficient to meet all identified European lunar exploration objectives [AD1] which do not require human lunar surface operation.

Typical fully-automated mission scenarios include:

- Deployment of around 100 elements of a low-frequency radio telescope on the lunar far side using a small rover (including deployment of 1 seismic element);
- Deployment of a deep driller (10 m depth) element to collect samples for dating and later return to Earth (including deployment of 1 seismic sensor);
- Deployment of a very deep driller (tens of meter depth) element for collection and later sample return of paelaeoregolith samples;
- Deployment of three small rovers to search for terrestrial material among the lunar regolith, and return the samples to Earth;
- Sample return of 1kg collected by deployment of two small rovers (including deployment of 1 seismic sensor).

Typical potential payloads of such a cargo lander are briefly described in the tables hereafter.

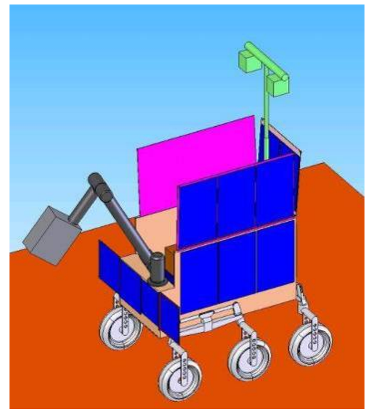
Element	Small rover	
Objective	Mobility platform to support science objectives	
Timeline	2016-2017	
Characteristics	40kg available for payload Total mass 190kg (including payload) surface mobility of some hundreds meters for each battery discharge, can collect and manipulate surface samples can deploy payloads on the lunar surface stowed dimensions 700 x 500 x 400 mm communication via Lander or communication relay orbiter	

Table 7 - Small rover

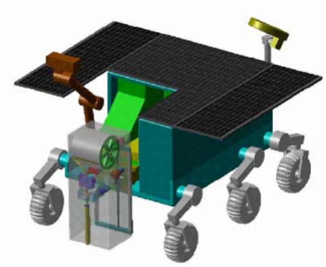
Element	Deep driller	
Objective	Perform deep drilling (up to 10m) on the Moon surface	
Timeline	2020-2025	
Characteristics	Total mass 415 kg Operate a deep drill System and collect samples down to 10 meter depth. Horizontal mobility of some hundreds of meters / few kilometers. Survive the moon night communication via Lander or communication relay orbiter stowed dimensions 1800 x 1700 x 900 mm	

Table 8 - Deep driller

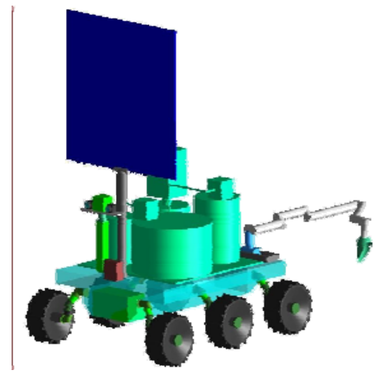
Element	ISRU demo	
Objective	The ISRU Demo Rover has the objective to demonstrate the technology necessary to produce oxygen on lunar surface.	
Timeline	2020-2025	
Characteristics	Total mass of 725 kg Autonomous site identification Oxygen storage capacity of 15 kg Production rate 5 kg/month Design Lifetime 3 months Stowed envelope volume 2,5 m x 2 m x 1,8 m	

Table 9 - ISRU demo

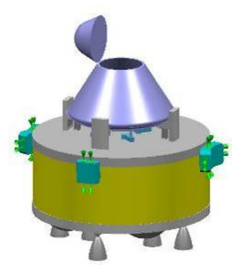
Element	Sample return vehicle	
Objective	Transport back to earth lunar samples of a mass of about 1 kg	
Timeline	2020-2025	
Characteristics	Total mass of about 1100 kg Storable propellant for the orbit and attitude manoeuvres Six 500 N thrusters perform the ascend and Earth Transfer Orbit injection manoeuvres The 100 kg Reentry capsule will perform an aerobraking manoeuvre in earth atmosphere and landing with a parachute A small robotic arm shall load the sample container into the Earth Return Capsule	

Table 10 - Sample return vehicle

Moon Communication

A key requirement in early lunar operations is the provision of adequate communications and navigation support at high data-rates, not only as a pre-requisite for human surface coverage, but also for large amounts of science data produced by robotic probes.

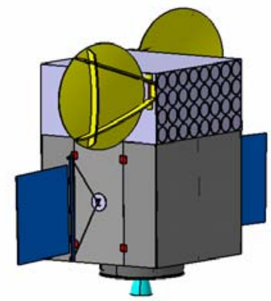
Element	Communication/Navigation orbiter	
Objective	Provide communication and navigation support to human missions and large scale robotic surface activities	
Timeline	2020-2025	
Characteristics	Total mass of 1600 kg Dual Soyuz launch into GTO and weak stability boundary transfer to EML Service module for propulsion subsystem Dedicated payload module on top with one navigation antenna and two communications antenna and associated electronics Lifetime 10 years	

Table 11 - Communication/Navigation orbiter

The in-space communications and navigation architecture element aims at providing the necessary framework for the navigation, and communication with the various mission elements on the surface of the Moon.

A single spacecraft is used to accommodate both the communications and navigation payload for the in-space architecture segment in order to save cost by using a recurrent design and provide redundancy for the communications system.

The communications and navigation architecture is implemented in a phased approach:

In early phase 2, two spacecraft are launched on a shared Soyuz-Fregat one into orbit around the Earth-Moon L1 point and one into orbit around L2 providing complete communication coverage for the lunar surface.

In early phase 3, communication and navigation coverage is required over the entire lunar surface. This is provided by 3 communications/ navigation spacecraft orbiting the Earth-Moon L1 point and another 3 spacecraft orbiting the Earth Moon L2 point.

The deployment of the communications and navigation spacecraft in Lagrange orbits was selected as it provides a long term scalable communication and navigation architecture. Full coverage can be provided by 6 spacecraft without the need for highly steerable antennas on the surface elements although there is a large link distance (~64,000km) to the surface elements. The constellation architecture allows multiple widely separated surface elements to access communication and navigation resources simultaneously. The stable orbit environment at L2 allows maintenance of the spacecraft for a long operational lifetime with limited resource, it allows high accuracy navigation.

The concept of the communications payload is based on the concept of several users (or one mobile user) positioned on one lunar hemisphere (either Earth-facing or Lunar farside). A set of fixed overlapping beams could be designed on the payload to access different parts of the lunar surface, very similar to modern communications spacecraft in geostationary orbit. Given the low number of initial users and eventual expansion of lunar surface activity, a low number of beams, less than 7, is recommended. Some steerability of beams will be necessary, in order to compensate for the motion of the spacecraft in the halo orbit. This would also shift beams slightly during the halo. Surface architecture should be aware of this and ensure that all beam frequencies are available on the surface transponders.

The backlink to Earth would use a combination of the traffic from each of the beams and multiplex it back to a single Earth station. A global Earth beam could allow multiple ground stations to receive the data, depending on the size of the ground facilities. The transmit power and sizing of the backlink antenna would have to be suitable to allow high bandwidth and steerability during the halo orbit. It is likely that the antenna on the spacecraft at the farside L2 point will need to be slightly larger, or the transmit power slightly higher. Otherwise the two spacecraft should be essentially identical.

The navigation payload on board the satellite has similar characteristics to those used for global navigation satellite systems on earth, e.g. Galileo. Hence, it will transmit navigation signals (spreading codes modulated on one or more carrier frequencies) which can be received by an unlimited number of user terminals on the moon's surface, provided that LOS connectivity is guaranteed. The positioning of a receiver is then based on trilateration. Therefore, additional Transmit Stations are required on the surface of the moon.

Two satellites in a Halo Orbit around L1 will serve as an augmentation system for surface based transmitters of similar Navigation Signals. Only very few ground based transmitters (such as Pseudolites) are required as the reception of signals from at least 4 different Transmitters (including those form SVs) is needed. Global coverage of 55 % is provided with an availability of more than 90 % as the visibility to the satellites is generally very good, due to their high elevation angles. Hence, continuity of service of 80% for any 15 seconds is achievable. The accuracy is dependent on the placement of ground based transmitters and is potentially in the region of 2-5 m.

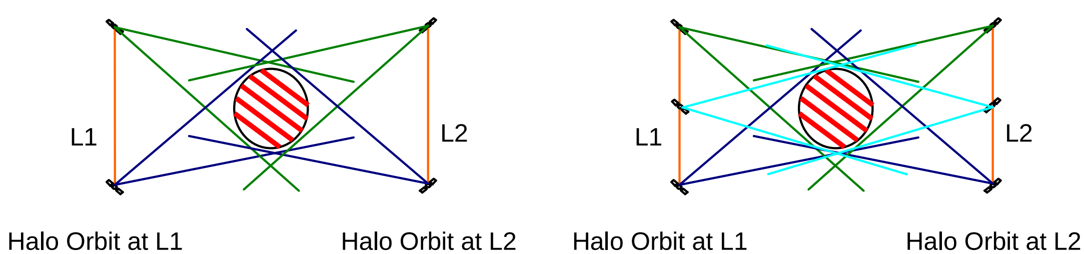


Figure 9 - Navigation Service Coverage on Surface

With three satellites around L1 and L2, a purely space based navigation system with global coverage is realised (see right image), assuming that the User terminals are equipped with high standard frequency oscillators (e.g. atomic clocks). This is a minimalist architecture if no additional transmit stations are used. However, these stable clocks are dispensable if further Pseudolites are used on the surface. Thus availability, continuity and accuracy can be enhanced. If the measurement technique is using the carrier phase of the signals instead of the nav. code, cm-level accuracy is achievable with this architecture.

The navigation and communications payloads are accommodated on a single spacecraft. The spacecraft service module is based on the structure used for Mars Express and houses the propulsion system for the transfer to the Lunar Lagrange point orbits and the spacecraft subsystems. The navigation and communications payload are accommodated in a separate module mounted on top of the service module. The payload module consists of one navigation antenna two communications antennas and the supporting electronics.

Mars sample return:

Mars Sample Return mission is foreseen within phase 2 around 2020-2022. The current high level reference architecture of this mission as defined by the International Mars Exploration Working Group (IMEWG) is described hereafter.

The present mission architecture includes an Atlas V launched Lander element, which includes a static Surface Platform, the sample collecting Rover and a Mars Ascent Vehicle (MAV) to carry the sample container from the Mars surface to the Mars orbit. A second launch, possibly with an Ariane 5 ECA, would then carry the Orbiter element which includes the Rendezvous and Sample Capture System and the Earth Re-Entry Capsule (ERC).

A profile of the MSR mission as conceived today can be seen in the following pictures:

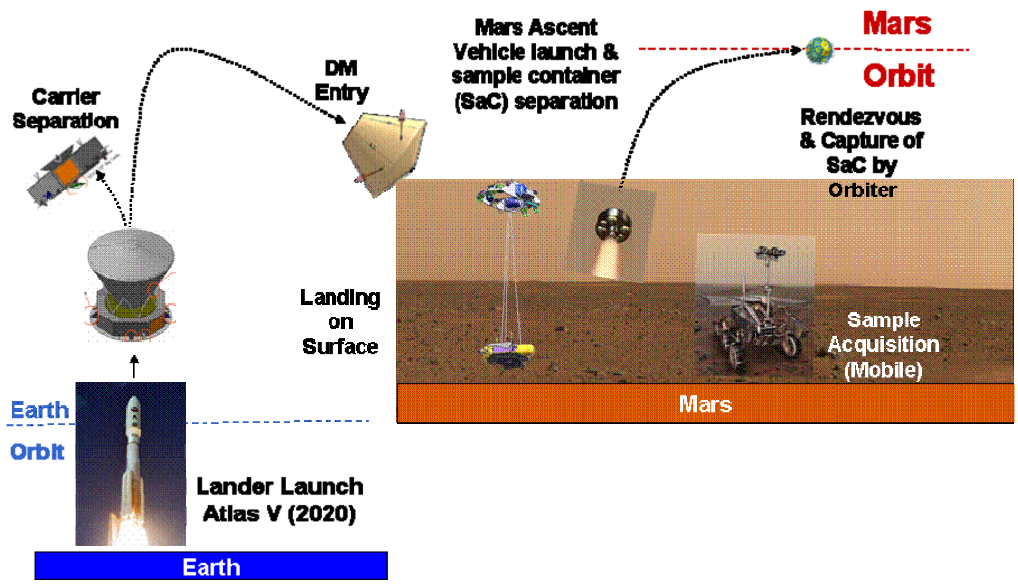


Figure 10 – MSR Lander sequence

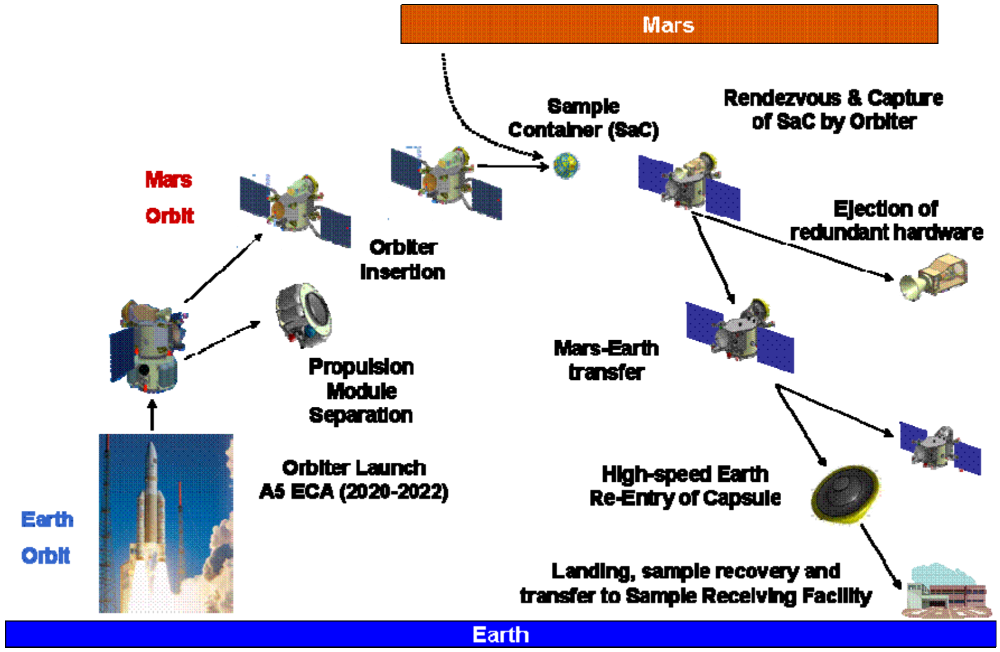


Figure 11 - ***MSR Orbiter sequence***

The Lander will perform a Mars entry from hyperbolic arrival trajectory. Entry Descent and Landing will be based on the system developed for the Mars Science Laboratory (MSL) and will allow landing accuracy in the order of 5 km. After landing, the sample collecting rover will egress and visit a given number of sites within and at the border of the landing ellipse returning each time to the Surface platform where samples are stored. A maximum permanence of one Earth year is assumed on the Mars surface.

By the time all the samples have been collected the MSR Orbiter has arrived to Mars and placed into its nominal orbit. All the required samples are placed in a Sample Container (SaC) which is transferred and stowed on the MAV, and launched into Mars orbit. The Orbiter then performs a series of manoeuvres to rendezvous with the SaC, and then performs the capture of the SaC.

After the SaC is secured inside the ERC, any unnecessary hardware may be ejected in Mars orbit and the Orbiter performs an Earth return manoeuvre, placing itself on a Mars-Earth trajectory.

On approach to Earth, the ERC is released from the Orbiter which ultimately performs an Earth avoidance manoeuvre while the ERC re-enters the Earth's atmosphere and lands.

3.2.2 CREW ORBITAL MISSIONS

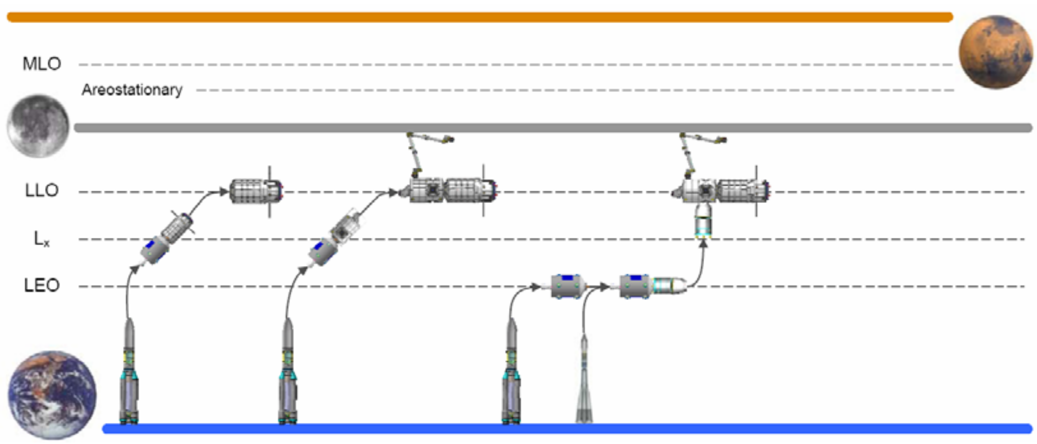


Figure 12 – Phase 2 crew orbital missions

During Phase 2, the low lunar orbit capability of the new crew space transportation system introduced in phase 1 is demonstrated and used to visit a man tended Low lunar orbit infrastructure.

To reach low lunar orbit with the crew space transportation system described in §3.1.2, the development of a heavy lift launcher with a low Earth Orbit performance of 50t is assumed. Indeed it was shown during the first phase of this study [RD4] that using currently existing launchers of Ariane 5 class (about 20 tons in LEO) requires a large number of launches and proximity operations (rendezvous and docking) to reach LLO even with a minimalist crew space transportation vehicle similar to the current Soyuz vehicle. Figure 13 shows that up to four launches are required to reach LLO and eight to reach the lunar surface assuming that long-term cryogenic storage could be improved by then.

As the number of A5 class launcher becomes too important, the launcher production rate and launch sequence could become problematic (cf. below) especially when dealing with cryogenic transfer stages. Because of the number of operations (launches and rendez-vous and docking) involved for one flight the overall probability of mission success is low (around 60% for a 6 launch configuration assuming a challenging 95% reliability of the overall rendez-vous and docking operations).

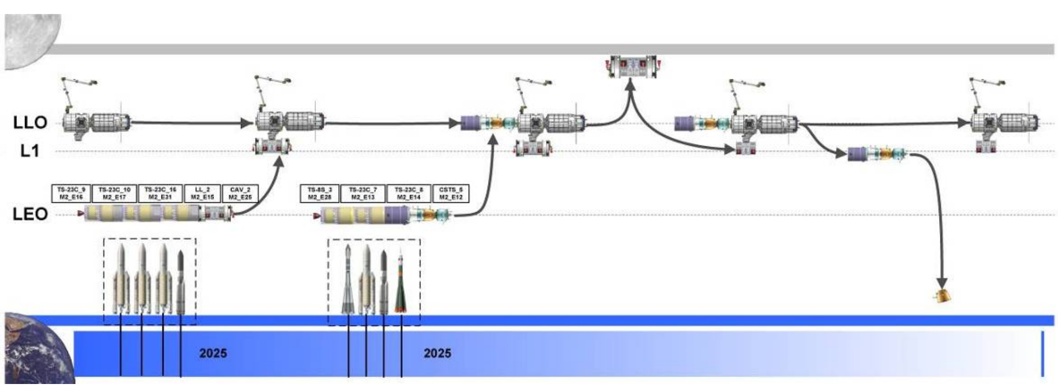


Figure 13 – Moon crew surface transportation scenario with existing launchers [RD4]

Therefore, the only sustainable way to reach LLO with the new crew space transportation vehicle is through the development of a heavy lift launcher with a capability of about 50t. Such a launcher could be used to deliver in LEO a propulsion stage that would rendez-vous with the crew space transportation vehicle and deliver it into LLO by performing both the trans-lunar injection and the Lunar Orbit Injection.

Since this scenario involves only two launches and one rendez-vous, cryogenic propulsion could be used to reach LLO therefore maximizing the available payload performance into LLO for the crew space transportation system. Once in LLO, the Trans-Earth Injection to return to Earth would be performed in this scenario by the service module of the crew vehicle using storable propulsion.

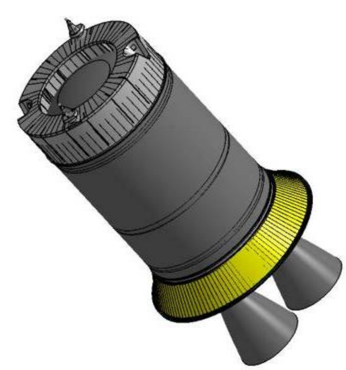
Element	Cryogenic propulsion transfer stage 50t	
Objective	Perform trans-lunar manoeuvres	
Timeline	2020-2025	
Characteristics	Total mass of 50t Cryogenic Lox/Lh2 propulsion 2 x 180 kN thrust Isp 460s Lifetime: 1 month Single docking capability (either with another EDS or payload)	

Table 12 – Propulsion transfer stage 50t

The design of a specific heavy lift launch vehicle was out of the scope of the study but the 50t capability to LEO is proposed here as a heavy lift class compatible with enhanced versions of Ariane 5 re-using as much as possible current stages configurations without extensive redesign based on the outcomes of a study performed by the major contractors of the Ariane 5 system together with CNES [RD6]. An output from the study is the preliminary definition of the fairing volume that would be required for exploration systems as described hereafter.

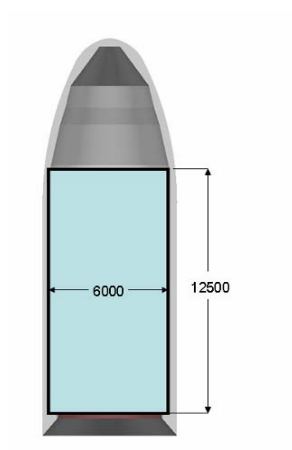


Figure 14 – 50t heavy lift launcher fairing specifications

To support the crew transportation vehicle missions to LLO, a man-tended orbital infrastructure in LLO is introduced. The LLO orbital infrastructure adds robustness and safety to the mission scenario by providing additional habitable volume for up to 30 days stays, services such as attitude control, power and communications to the crew transportation vehicle and finally any-time return capability from LLO to Earth. Furthermore, this orbital infrastructure could act as a staging post between international partners meeting in LLO. It has the potential to enhance mission safety and performance, and could enable different mission profiles than the ones currently foreseen by International partners. For example, Crew rotations on the surface could be extended well beyond six months, if the U.S. Orion vehicle could dock with an LLO station and depend on that station for power, orbital maintenance, and thermal control.

The facility enables crew and cargo transfers between vehicles, checkout, maintenance and eventually reconfiguration of vehicles.

The LLO orbital infrastructure can also act as a safe-haven for the crew in case of loss of engine on the crew transportation vehicle during Moon orbit insertion [RD4] or latter-on for the crew on the surface.

The minimum configuration of the LLO orbital infrastructure is composed of a resource module and a node-habitation module.

The main functions of the LLO orbital infrastructure resource module are to provide resources to other modules and to provide attitude control and re-boost capability. It also provides some pressurized volume to accommodate the crew as well as to allow the stowage of resources/consumables for life support (oxygen, nitrogen, water, food, etc.) and to accommodate the on-board systems.

The Service Module consists of three principal components:

- The payload compartment (pressurized);
- The service compartment (unpressurized)
- The Solar Generation System (SGS)

The module consists of a rigid, cylindrical section with a transfer zone, to allow the crew to move from/to other modules, an automatic docking equipment to host and service the Node (IBDM).

The Node-habitation module is part of the Phase 2 LLO Core Space Station with the main function of providing docking capabilities for transfer stages, landers and ascent vehicles. Beyond accommodating system avionics racks, the Node will also provide habitable volume for the crew. It is foreseen to have dedicated racks to provide ECLSS functions and other racks related to Crew functions support, namely the former Waste & Hygiene Compartment racks.

The Node element has been conceived as a pressurized module made of a cylindrical segment core closed at the ends by two conical segments.

The Cylinder is divided in two main sections:

- Radial Berthing Ports section

- Node Racks section

The internal volume shall be adequate for the basic needs of a 3 crew members during sortie missions. The LLO orbital infrastructure Node will be designed to have six attachment ports, two axial and 4 radials, equipped with the IBDM docking/berthing systems. The minimum passageway for an astronaut in IVA (800 mm diameter) will be provided. The Node shall be also capable of providing avionics functions and supporting rejection of thermal loads.

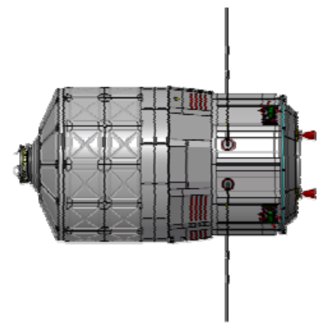
Element	LLO orbital infrastructure – Resource module	
Objective	provide resources to other modules and provide attitude control and re-boost capability	
Timeline	2020-2025	
Characteristics	Mass at launch about 14000 kg • Overall length of about 10 m • External diameter of 4.5 m • 10 m³ of habitable volume • 4 solar arrays with an overall surface of 40 m², equivalent to an installed power of about 10 kW. • 3 tons of propellants for LSS station-keeping and initial rendez-vous.	

Table 13 – LLO orbital infrastructure Ressource module

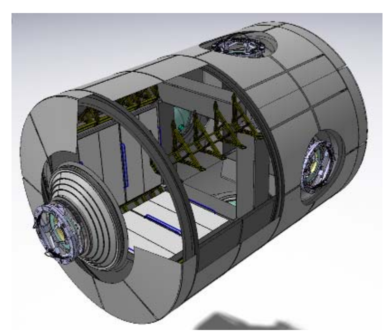
Element	LLO orbital infrastructure – Node-habitation module	
Objective	Provide docking capabilities for Transfer Stages, Landers and Ascent Vehicles, Crew Rescue Systems Provide interfaces for the Manipulator Arm Provide habitable volumes for the crew	
Timeline	2020-2025	
Characteristics	Node Mass at launch about 13000 kg Overall length of about 7 m External diameter of 4.4 m 23 m³ of habitable volume Designed to host up to six attachment ports, two axial and 4 radials, equipped with the IBDM docking/berthing systems	

Table 14 – LLO orbital infrastructure – Node-habitation module

A storable propulsion module with rendez-vous and docking capability could also be located at the LLO orbital infrastructure in order to provide any time return capability to the crew transportation vehicle in case of contingency or to rescue a vehicle (crew transportation vehicle or ascent stage) stranded in LLO to the orbital infrastructure safe-haven.

Each of the main elements of the lunar orbital infrastructure can be deployed using a single 50t class heavy lift launch vehicle on a direct lunar transfer orbit injection together with a 8t storable propulsion stage that will perform the lunar orbit insertion as depicted on Figure 12.

Element	8t storable Transfer stage	
Objective	Perform LOI for LLO orbital infrastructure modules delivery	
Timeline	2020-2025	
Characteristics	Storable propellant MON/MMH Total thrust: 3 x 8 kN Isp 317s Length 4.7m x Diameter 3.3 m Operative life: ~2 months Overall mass 8000kg	

Table 15 - 8t Transfer stage

A low circular polar orbit is selected for the lunar orbital infrastructure in order to allow global access to the surface and especially to Polar regions that might be suitable to the establishment of an inhabited lunar base.

The orbit maintenance for a purely circular 100 km altitude polar orbit around the Moon is quite expensive in term of propellant consumption. Therefore, it is foreseen to use so-called frozen orbits [RD5] to reduce the LLO orbital infrastructure associated logistics. Frozen orbits are specific orbits around the Moon where the orbital parameters are naturally stable over time thus requiring very low orbit maintenance. The LLO orbital infrastructure will thus be deployed on a quasi-circular polar orbit with an aposelenium altitude of 203 km and a periselenium altitude of about 43 km. The argument of the periselenium is fixed at 270 deg, i.e. the periselenium is directly over the South Pole. The result of a numerical integration using detailed lunar gravity field models and fine perturbation models shows the stability of such an orbit over more than five years without any orbit maintenance. The excentricity of such frozen orbit is small at around 0.04 and thus will not modify significantly the relative dynamics for a rendez-vous toward the orbital infrastructure. Therefore no additional specific constraint on rendez-vous operations and hardware is expected from such quasi-circular orbits. The exact orbital parameters of such frozen orbits might be slightly modified with improved modelling of the lunar gravitational field but their existence is attractive to reduce the logistics needs of an orbital infrastructure in LLO.

The logistic to the Lunar orbital infrastructure can be performed with a vehicle directly injected into LTO by an Ariane 5 launcher and providing about 4 tons of gross payload in LLO. Only one such logistic mission would be required every 18 months to sustain the facility.

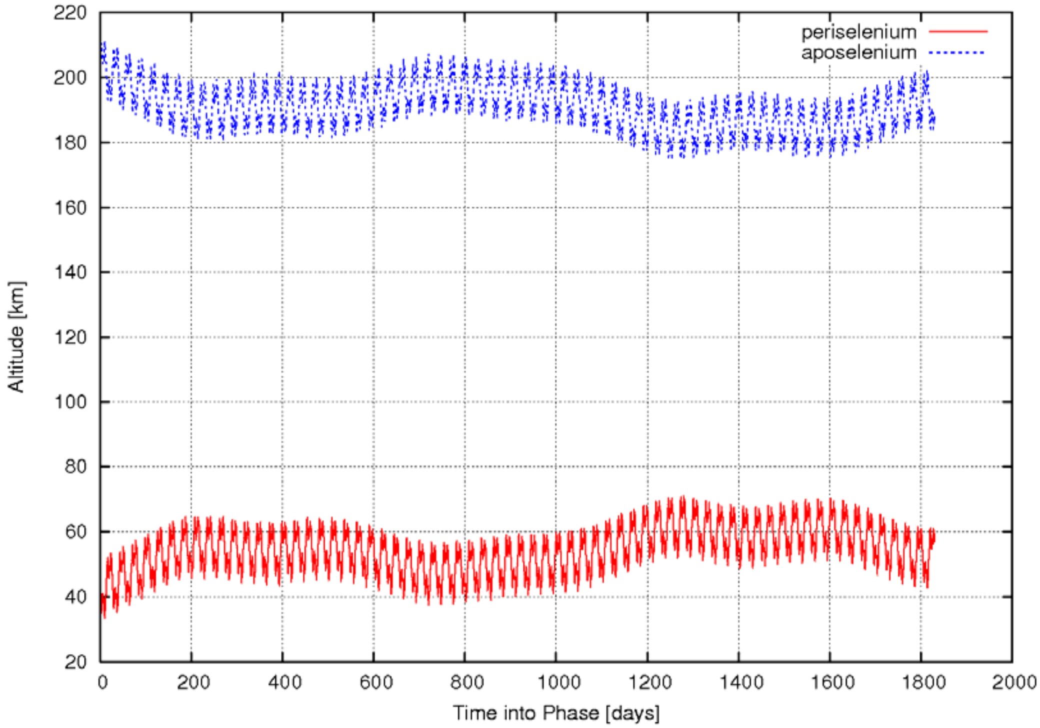


Figure 15 – Stability of quasi-circular polar low lunar orbit over 5 years

3.2.3 CREW SURFACE MISSIONS

During phase 2, the transportation architecture proposed here does not allow to reach the surface but this could be granted through cooperation with NASA plans for at least sortie missions in this timeframe. NASA completed its Exploration Systems Architecture Study (ESAS) in 2005, which outlined as its highest priority NASA's intent to safely transport a crew of four astronauts to and from the lunar surface around 2018. To meet this objective NASA identified the architecture that will constitute the next generation of human space transportation [RD7]. Elements of this transportation architecture include the following:

- Orion crew exploration vehicle.
- Ares I crew launch vehicle and Ares V cargo launch vehicle.
- Altair lunar lander (and ascent return vehicle).

The discussion in this section will therefore be restricted to potential surface assets enhancing sortie missions such as pressurized rovers.

For sortie missions the following mission operations and associated activities have been identified:

- Geological fieldwork:
    - Observations (e.g. verbally recorded data)
    - Assistance through telerobotic robotic survey
    - Collection (and caching) of samples, including drilling

- Mapping of lunar resources:
    - Ground truth confirmation of orbital measurements.

The lightest approach involves simple surface sortie missions of up to 14 days, where full habitation is provided by the lander element and no pre-deployed surface elements are strictly required. The mobility at each site is severely limited by the rover capability and contingency requirements. This could potentially improved by delivery of a redundant mobility element on a logistics lander, which could also enable further science through dedicated equipment delivery. However, the sortie scenario is highly hardware-intensive since no reusability of surface systems is possible.

Super-Sortie scenarios involve a pre-deployed pressurized rover for extended surface mobility as well as logistics delivery with an Ariane 5 based landing system. They therefore offer significantly increased surface exploration range and duration, enabling higher science return.

A pressurized rover sized for a crew of 2 as described in the table hereunder could extend the range of operations that can be performed with a conventional sortie mission. The more basic mission profile for such a single pressurized rover is to perform a looping route around the crew landing site, where the pressurized rover comes finally to the point of departure, where the crew transfers into the ascent module. At the multiple exploration sites on the course, sample collection, analysis and drilling can be done. The crew transfers to the ascent module at the mission end.

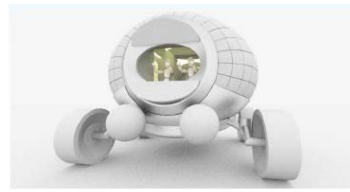
Element	Pressurized rover	
Objective	Provide long-range mobility for human surface exploration	
Timeline	2020-2025	
Characteristics	Size of crew 2 crew egress and ingress airlocks and suitlocks Overall length, width, height (deployed configuration) L = 6.55 m, W = 4.95 m, H = 4.31 m Empty mass approx. 6200 kg Loaded mass approx. 7600 kg Surface mission duration 42 days Cruising speed 10 km/h Maximum traverse gradient 20° Minimum ground clearance on level ground 800 mm	

Table 16 – Lunar Pressurized rover

The duration and overall capability of the mission may be enhanced through the provision of logistics support via the A5 cargo lander. The pressurized rover may be remotely operated to move (un-manned) to support future cooperative lunar operations at a different landing site.

3.3 Phase 3

3.3.1 ROBOTIC MISSIONS

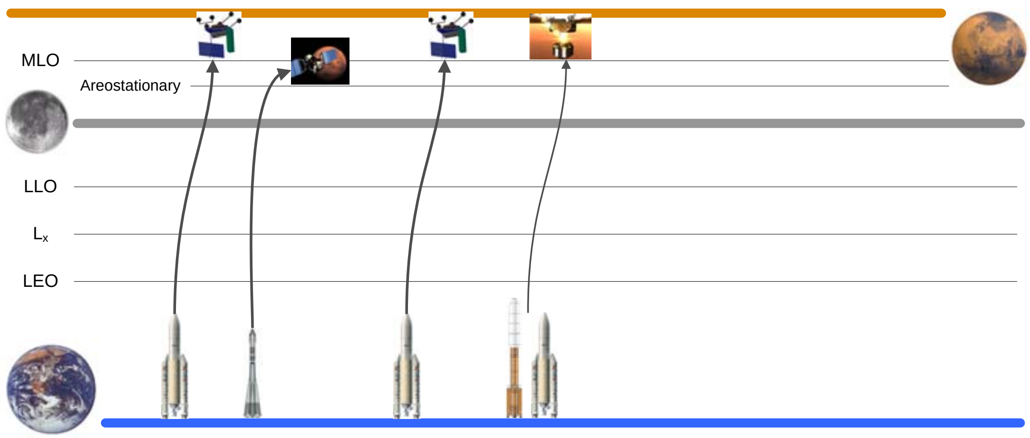


Figure 16 – Phase 3 robotic missions

The Mars robotic exploration architecture beyond the first MSR mission is oriented toward the further preparation of the first human mission. Further robotic missions are required to prepare for human missions; landing site selection and characterization, resource and environment mapping, pre-deployment of assets and technology demonstration (i.e. ISRU, navigation and communications). Scientific objectives described in [AD1] are also taken into account when designing these missions.

The main components of this robotic architecture are the following:

- a set of seismic stations, that can be seen as lightweight, long-duration payloads to be carried on surface elements.

- a set of robotic "deep drilling" rovers, that are sent to sites on the Martian surface that appear the most "interesting" in terms of the overall science return and could be candidate for future Human landing. Besides a "Standard Payload Package", that is placed on all of them, also an "Additional Payload" is considered for each rover that can perform various "special" functions (like e.g. an ISRU demonstration)

- a set of orbiters to provide further resource mapping and detailed topological maps.

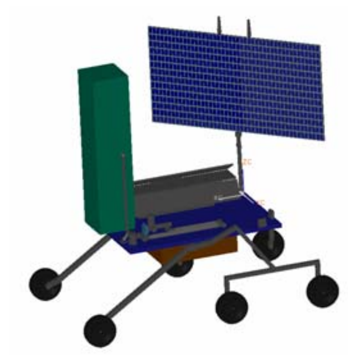
Element	Mars Deep Driller Rover	
Objectives	Perform deep drilling up to 40m on Mars surface scientific in-situ soil prospecting sample management scientific in-situ sample analysis scientific in-situ dust environment measurement	
Timeline	2024-2030	
Characteristics	Total mass of about 510 kg (10m version) Deep Drilling (10 m or 40 m) functionality 6-wheeled mobility platform with steering capability long-range, long-duration, high autonomy rover autonomous site identification sample storage capacity of 1 kg stowed envelope volume < 2.5 m x 2 m x 2 m	

Table 17 - Mars Deep Driller Rover

Potential landing sites associated to the science objectives described in [AD1] have been identified in a preliminary assessment:

- 10-m class drillers:

  - Mawrth Vallis (24°N, 20°W)
    - phyllosilicate site
    - ancient outflow channel
  - Nilli Fossae Crater (18°N, 78°E)
    - ancient crater lake with two inlet and one outlet valleys
    - large fan delta deposit, with phyllosilicate minerals
  - Holden Crater (26°S, 34°W)
    - deep hole in S highlands, cuts Uzboi Vallis (ancient outflow channel)
    - after the crater's formation, Uzboi flowed again, breaching the crater wall and depositing layered sediments containing signs of phyllosilicates

- 40-m class driller: Northern polar area

Such deep drilling missions could be followed by a second Mars Sample Return mission with enhanced capability that could possibly collect some of the samples that have been previously placed in a “cache” and considered as most promising.

The deep drillers could be delivered to the Mars surface using a Mars Science Laboratory-like delivery, i.e. using a “SkyCrane Lander”, where the rover is below the lander, and near the end of the powered descent the rover is lowered on a tether until it touches the ground; at that point, the tether is severed and the lander flies away and crashes. An alternative concept could be to develop a soft landing platform based on full A5 capability that could deliver up to about 1 ton onto the surface of Mars. Such concept would require the use of four 10kN class bi-propellant engines.

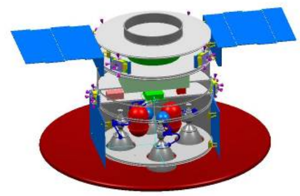
Element	A5 Mars robotic lander	
Objectives	Soft landing payload delivery on Mars surface	
Timeline	2025+	
Characteristics	Launch mass 4950kg (A5 Launch) Direct Entry Ablative heatshield 2 parachutes + 4 thrusters (12kN) Payload 1000kg	

Table 18 - A5 Mars robotic lander

The main characteristics of the Deep Driller rover are described hereafter. The rover-like mobility is combined with a Deep Drilling (10 m or 40 m) functionality; the mobility performance is “ExoMars-like”; power is provided using solar panels. A “Standard Payload Package” is used for performing the necessary observations, measurements and sample analyses; besides this, also an “Additional Payload” is included.

The lander could also host further payloads for environment monitoring and also technology demonstration such as an ISRU demonstration mission. Since the atmosphere of Mars is rich in carbon dioxide, the idea is to process it and to extract from it the oxygen that could be used to support the human presence at least for consumables and potentially for propellant. The first ISRU demonstration plant can be quite small with a production capability of 1 kg/day.

Prior to the first Mars Sample Return mission, a significant amount of orbital work should have been performed in order to assess the most appropriate site(s) for collecting a useful scientific sample. This is likely to have included at least:

• Topographical mapping.

• High resolution imaging (possibly in the form of stereo imaging in conjunction with determining topography).

• Spectral mapping for identification of interesting mineralogy for determining the best sample site(s).

The orbiters following the first Mars Sample Return missions may therefore be more driven by the possibility of landing humans on Mars so other important factors may be:

• Martian weather monitoring.

• Martian weather prediction.

• Space weather monitoring.

• Suitability of sites for human habitation.

• In-situ resources.

In order to fulfil these objectives an atmospheric science orbiter may be most useful, which could also be used to determine global methane abundances. It may also be worth considering that provision of ground penetrating radar may not have been fully implemented and may be useful in finding habitable sites or searching for usable in situ resources. For example a ground penetrating radar may be able to determine the depth and extent of cave systems (such as those seen by Mars Odyssey) which may be used for safe habitation or may be able to identify new cave systems. A similar system may be able to locate layers of underground ice for in-situ use.

A suitable set of instruments may include:

• High resolution IR spectrometer.

• Microwave sounding unit.

• Ground penetrating radar.

• Medium resolution imaging system.

• Radio occultation experiment.

3.3.2 CREW SURFACE ACCESS

In phase 3, the transportation scenario to reach LLO described in §3.2.2 is extended such as to reach the lunar surface with a minimum crew of 2 astronauts. The proposed scenario is based on an incremental approach building on assets previously developed and deployed in phase 2.

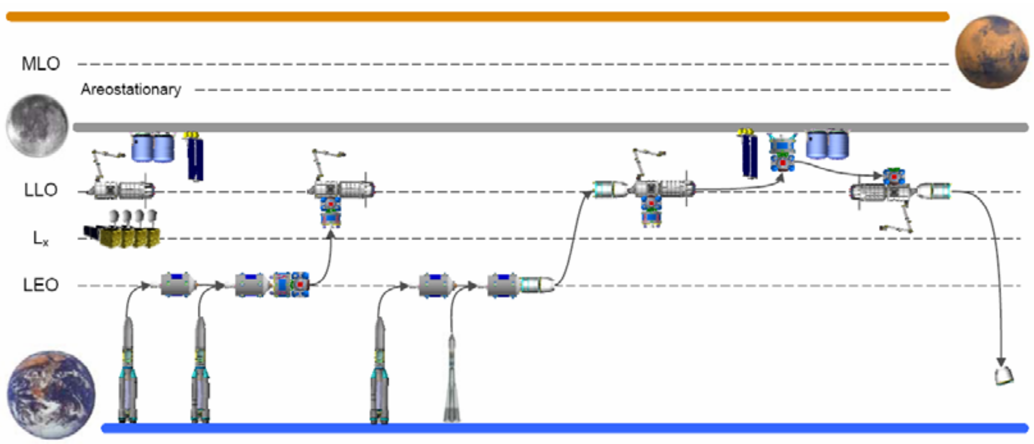


Figure 17 – Crew surface access reference scenario

The heavy lift launcher introduced earlier as the minimum configuration to deliver the propulsion stage that will bring the crew transportation vehicle into LLO, is used in a 2-launch scenario to deliver the crew descent/ascent vehicle into lunar orbit. By pre-deploying the storable crew ascent and descent logistic into LTO, this scenario relax the constraints on the sequence of launches involving cryogenic propulsion transfer stages into a multiple launch scenario.

The ascent and decent crew lunar vehicles have a combined total mass of about 26t to be injected into LLO. A first heavy lift launcher is used to deliver a 50t EDS into LEO and is followed within a month by a second heavy lift launch that delivers the ascent/descent crew vehicles together with a 24t cryogenic propulsion stage. The large EDS perform a rendez-vous and docking with the smaller propulsion stage. Then, the 50t cryogenic propulsion stage performs most of the TLI burn before separating from the ascent/decent stack. The smaller propulsion stage then performs the remaining maneuver to deliver the ascent/descent crew vehicles into LLO.

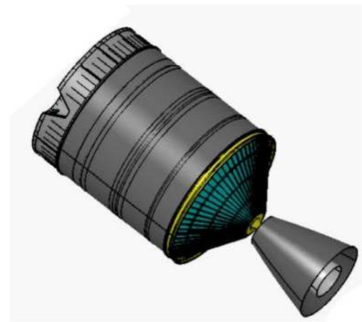
Element	24t cryogenic propulsion stage	
Objective	Perform trans-lunar manoeuvres	
Timeline	2025+	
Characteristics	Total mass 24t Cryogenic Lox/LH_2 propulsion Isp 460s Thrust 180kN Lifetime 1 month Docking interface with large 50t propulsion stage	

Table 19 - 24t cryogenic propulsion stage

Once in LLO, the ascent and descent vehicles have to perform a rendez-vous with the LLO orbital infrastructure and can wait several months in orbit supported by the LLO orbital infrastructure for basic services such as power and attitude control.

The crew transportation vehicle can then be delivered to LLO using the same scenario as described previously in section §3.2.2. The crew vehicle then docks to the LLO station and 2 astronauts out of the crew of 3 can then transfer to the ascent/descent vehicle while the third one remain within the orbital infrastructure.

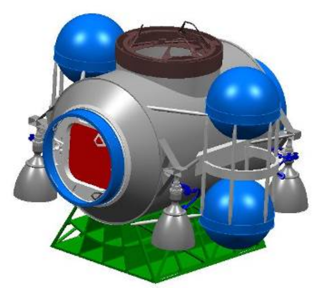
Element	Lunar crew ascent stage	
Objective	Provide crew of 2 habitation during descent and ascent Bring back crew from lunar surface to orbital infrastructure	
Timeline	2025+	
Characteristics	Crew of 2 Habitable volume ~10m Storable propulsion 4x12kN engines Isp ~325s Interface to LLO orbital infrastructure Total mass 7.5t	

Table 20 – Lunar crew ascent stage

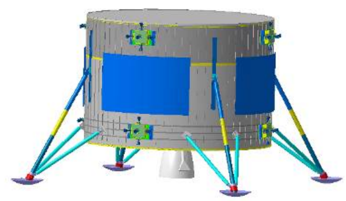
Element	Large Lunar Descent stage	
Objective	Perform lunar descent and landing from LLO orbital infrastructure	
Timeline	2025+	
Characteristics	Payload to the surface up to 7.5t Storable propulsion 70kN engine Platform height from surface: 4.5m Total mass 18.6t	

Table 21 - Large Lunar Descent stage

The descent vehicle then perform the descent and landing maneuver using storable propulsion to bring the crew to the lunar surface. Once the astronauts surface mission is completed the ascent vehicle bring the crew back to the LLO orbital infrastructure where they can transfer to the crew transportation vehicle to come back to Earth.

The utilization of the LLO polar orbiting infrastructure imposes some constraints on the overall mission opportunities based on the following facts. A launch opportunity from Earth towards a specific polar LLO (with a fixed RAAN) exists only every fourteen days at a minimum cost. The LLO station could be accessed at anytime by crews at a polar outpost, and once every fourteen days from other locations. In a nominal scenario, the LLO station enables a return to Earth only once every fourteen days at a minimum cost. Adding the any-time return capability for contingency situations requires an additional velocity increment of up to 550 m/s. This additional capability could be eventually stored at the orbital infrastructure.

The transportation architecture describes here allow a step-wise approach to Moon exploration by providing first an access to LLO and is then capable of reaching the lunar surface. The key features of this architecture are a 50t class heavy lift launcher selected as the minimum performance launcher able to deliver the propulsion transfer stage needed to bring the crew space transportation system in LLO and an orbital infrastructure in LLO introduced in order to support the crew missions beyond LEO and bring cooperation opportunities with international partners. The orbital infrastructure in LLO provides a staging post for the descent/ascent vehicles that relies on storable propulsion in order to relax the launch sequence constraints inherent to an architecture relying on medium sized heavy lift launchers (50t class) and cryogenic propulsion for lunar transfer.

This LLO orbital infrastructure has several potential evolution scenario beyond the core configuration depicted here. The addition of fuel depot and refueling capability to the station would allow the descent and ascent stage to be delivered in a single 50t class launch with a direct LTO injection. The descent stage would be partially fueled to perform the LOI and rendezvous to the LLO orbital infrastructure. Then the descent stage would be refueled at the LLO orbital infrastructure to be able to perform the descent and landing maneuvers. This scenario has the benefits to increase the performance efficiency by performing direct LTO mission to the moon instead of going through rendez-vous in LEO, to allow descent/ascent vehicles delivery to LLO with a single relatively small heavy lift launcher (50t class) and to open potential commercial involvement through the supply of propellant to the orbital infrastructure. The capability of the fuel depot for the lander re-fuelling application case shall be about 15t.

Further on, the utilization of a re-usable lander stored at the orbital infrastructure would permit mass savings for the surface base logistics. Such station would become a cargo-staging location; cargo transported to LLO could be delivered to the lunar surface via an automated lander that simply travels to and from an outpost to LLO. ISRU based propellant could also be latter on envisioned to even further decrease the logistic cost to the surface base in a long-term sustained presence scenario.

3.3.3 CREW SURFACE MISSIONS

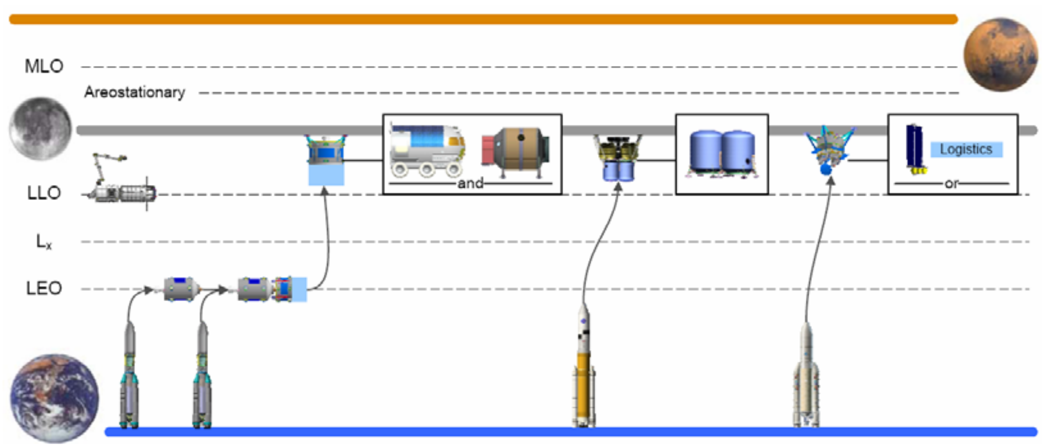


Figure 18 – Phase 3 Lunar surface delivery capabilities

For phase 3 surface operations, two lunar exploration campaign options were identified (1) outpost (several short visits to same location) and (2) fixed lunar base, on top of the classical sortie mission already described for phase 2.

The outpost scenario is designed to support a crew of two astronauts visiting a particular site of interest more than once for short time duration (typically 14 days). The interest in this site might be linked to highly valuable science to be done around the same location that would require more than a single sortie mission or the construction, operations and maintenance of some high value assets such as telescopes or very deep driller that would need to be located for scientific reasons far from the main base. As an example, the low frequency radiotelescope would be ideally located near the equator on the far side of the Moon far from the currently foreseen location of a human base.

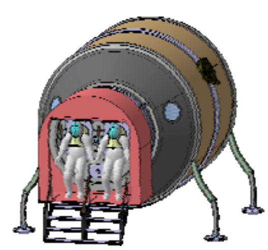
Element	Mini-habitation module	
Objective	Support crew of two for short duration missions (14 days)	
Timeline	2020-2025	
Characteristics	Total mass including margin: 6960 kg Dimension: 4.2 m ext. diameter, 6.8 m length (stowed) Includes an airlock to allow docking of 2 EVA rear-entry suits and an internal hatch for pressurized volume isolation Internal pressurized volume of 40 m3	

Table 22 - Mini-habitation module

The outpost habitat could deployed by the cargo version of the crew lander described in §3.3.2 which has a capability of about 7 tons. Additional supporting assets such as very deep driller or additional power plant could be delivered by the A5 cargo lander. Spare parts, maintenance equipment and logistic to refurbish the outpost would also be brought to the surface using the A5 cargo lander. The crew would use the taxi lander described earlier to reach the outpost, perform their activities on the surface with the support of the mini-habitation module during 14 days and then return to the lunar orbital infrastructure.

Finally, such outpost could also be used to extend the further the range of pressurized rover by providing safe-haven on the surface to deal with contingency cases.

The base location, contrarily to the outpost, is selected primarily for engineering reasons offering the more favorable illumination conditions to facilitate the support of astronauts for extended stays of up to several months. Based on the current knowledge of the Moon environment, the most likely candidate for the establishment a base is the rim of the Shackleton crater that lies at the lunar South Pole, at 89.54° South latitude and 0° East longitude, and has a diameter of 19 kilometers. Such a base could host up to four crews for long stays of a few months. The following activities have been identified as major outpost tasks, based on analysis of the European stakeholder objectives as defined in [AD1]:

- Life and physical sciences experiments;
- Geological fieldwork;
- Laboratory analysis of collected samples;
- Construction and commissioning of a large cosmic ray telescope;
- ISRU processing
- Various support tasks associated with the base.

Furthermore, establishing a sustained human presence in a base on the Moon has a critical role for preparation of further exploration. It is an opportunity to learn how to support astronaut crews living far from home in harsh environments for long duration and to operate effectively on another planet.

A lunar base is composed of several elements among which are habitation modules that constitute the core of the base and provide pressurized habitable volume, ECLSS, consumables storage, radiation shelter and airlocks-suitlocks for ingress-outgress.

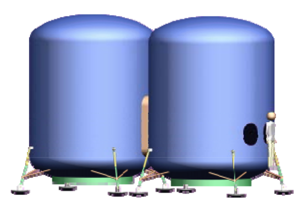
Element	Lunar Base Modules	
Objective	Support astronauts to survive on Lunar Surface for extended stays (several months)	
Timeline	2020-2025	
Characteristics	habitat module (“Hab”) and a service module (“SM”) layout: vertical cylinders with end domes, 2 floors each + storage space in bulkheads houses a crew of 3 for 3 months mass: ca. 13.1t each (plus surface mobility), hull dimensions: ∅4.1m, h=5.2m provides crew with storm shelter in case of SPEs and over 16.1m³ habitable volume per person (requirement: 15m³) 1 airlock plus 3 suitlocks Max required power 30kW	

Table 23 - Lunar Base Modules

The power plant is a critical element required to provide electrical power both in daylight and during night periods to surface elements with large power requirements such as the habitation modules. The baseline solution for the power plant is based on the following technologies:

- Solar cells: a steerable solar array is used to provide the required electrical power during the daylight periods.
- Regenerative fuel cells: used to provide electrical power during the lunar night.

In this concept part of the power generated by the solar array is used for water electrolysis in order to provide the reactants to the fuel cell. The plant includes the consumable storage unit. Once it has been placed in its operative site, it must be connected to the element to be powered; this connection can be performed by means of a docking/berthing operation or by means of an external robotic element.

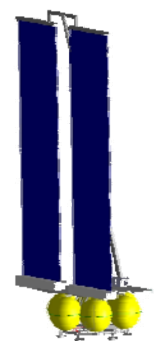
Element	Large solar power plant	
Objective	Provide power to outpost/base	
Timeline	2020-2025	
Characteristics	Mass of 1500 kg provide 10kW during daylight provide 3kW during night Stowed dimensions 3.5m diameter by 3.5m height	

Table 24 - Large solar power plant

Nuclear power plants such as the one depicted below could also be envisioned to provide continuous power whatever the illumination conditions.

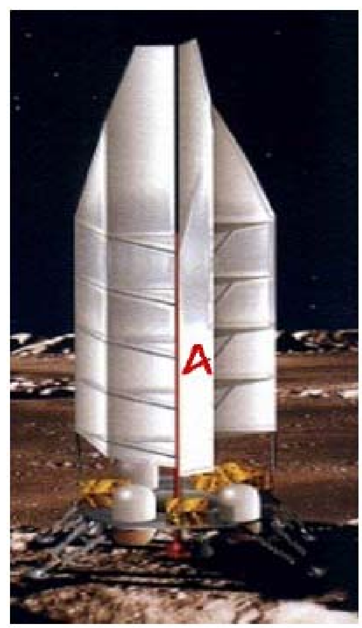
Element	Nuclear Power plant	
Objective	Provide power to outpost/base	
Timeline	2020-2025	
Characteristics	Mass of 3000 kg Provision of 50 kW Power Plant distance to the consumers: up to 1km or less if buried lifetime duration: 7 to 10 years	

Table 25 - Nuclear Power plant

Utility rovers, payloads trucks are also required to unload the payloads of the landers, deliver the elements to their destination, and connect the interfaces between elements.

Navigation pseudolites would also be set-up around the base such as to provide an accurate position determination around the base with the contribution of the communication/ navigation constellation described earlier.

The preparation of specific landing zones equipped with navigation beacons would also facilitate the landing of crew and cargo next to the base.

The logistics that are required to support a continuous presence of four crewmembers in the lunar base have been preliminarily estimated. The logistics comprised the life support supplies such as air, water and food supply as well as the equipment, tanks to store them, the maintenance needs such as hand tools, spare parts and test equipment and finally the crew systems supplies such as clothing, medical kit, hygiene and recreational equipment. For a typical year of operations the total amount of logistics to be delivered to the base is estimated to be about 13100 kg with the following mass and volume breakdown.

Type of Supply	Mass	Unit	Volume	Unit
Life Support	7880	kg	9.6	m^3
Maintenance	3000	kg	10.8	m^3
Crew Systems	2220	kg	13.2	m^3
Total	**13100**	**kg**	**33,6**	**m^3**

Table 26 – Base logistics demand for one year of operations

Thus, almost the full capability of an Altair lander is needed every year to sustain the base with logistics. It is therefore obvious that if the logistics can be provided by alternative and smaller systems such as the previously described A5 cargo lander a more flexible and robust approach to logistics could be implemented to sustain the base without relying on a single yearly delivery while also enabling more astronauts opportunities by substituting cargo missions with crewed ones.

3.4 Phase 4

3.4.1 MARS HUMAN MISSION

The ultimate goal of the ESA's Aurora program being to land humans on Mars, exploration architectures have been studied to attain this objective. Several options have been considered and are briefly described here with a focus on the findings related to Mars human missions. No particular reference scenario has been selected since the challenges and level of technology improvement required for such a mission do not allow it.

Two major different types of mission to Mars are distinguished based on the underlying orbital mechanics. Opposition class missions are characterized by long inbound and outbound transits (~300 days each way) and short surface duration stays (~40days). They are associated to high-propulsive requirements and large variation energy requirements across mission opportunities. Conjunction class missions are characterized by relatively short transits (~180 days) and long stay at Mars (~500 days). They are associated to lower propulsive requirements and small variation energy requirements across mission opportunities. Since, conjunction class missions allow spending the majority of the mission at Mars and require less energy, they have been selected as baseline during this study even if the total duration of the mission is then higher, i.e about 2.5 years. Opportunities for such conjunction missions exist only about every 2 years from Earth. Outside these specific windows of opportunities, the propulsive requirements for performing a mission toward Mars are prohibitive. In a similar way, if a contingency occurs during the stay at Mars, no return opportunity to Earth exists before the end of the planned 500 days. A key challenge of a Human mission to Mars is thus already enlighten by the required capability to sustain human life in a hostile environment for such a long duration without re-supply or abort opportunity.

All scenarios studied in this study are based on a split scenario in which elements of the architecture such as power plants, habitats and pressurized rovers are deployed automatically prior to the arrival of humans. This approach has the benefit to allow splitting the total mass to be delivered to the surface into different landers and thus limiting the size of such a lander to reasonable dimensions (i.e. fitting within an 8.8m diameter fairing). Furthermore, the initial automated missions can serve as qualification flights for the transfer stages and Mars descent vehicle prior to the crew flight.

The size of the crew for the Mars human mission has been limited for the purpose of the study to four astronauts even if a crew size of six would be better from a scientific return point of view.

The main elements that are required to support the crew during its missions are the transit habitat module, the surface habitat module and associated exploration tools such as pressurized rovers. The transit habitat module supports the crew during their inbound transit, in-orbit stay around Mars and outbound transit. It is a key element of a Mars architecture since it has to sustain the life of the crew for up to 2.5 years (depending on contingency situations) in a deep space environment. The characteristics of an inflatable design of such a transit habitation module are given in the table hereunder. The inflatable design is interesting from a mass saving point of view, especially since the transit habitation has to be delivered to Mars and brought back to Earth vicinity. However, it raises some issues regarding the outfitting of such module and the level of radiation protection achievable. The single hull configuration might also be problematic in contingency cases such as local depressurization.

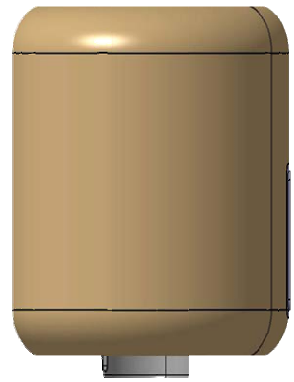
Element	Mars transit habitation Module	
Objective	Sustain crew of four for up to 2.5 years in a deep space environment	
Timeline	2035+	
Characteristics	Total dry mass of 23t Habitat Module is 8.5 m long with a diameter of 7.2m The primary structure is composed by a central rigid core and an inflatable shell provide a total pressurised volume of 300 cubic meter provide storage for 16t of consumables provide a protection from Galactic Cosmic Rays of at least 10 g/cm2 in any direction; provide a storm shelter for Solar Particle Events with a protection of 15 g/cm2; provide exercise facility for the crew to ensure countermeasure for the microgravity environment; provide audio, video and data exchange capability with the ground segment.	

Table 27 - Mars transit habitation Module

The Mars surface habitat has a similar role than the transit habitat. It sustains the crew during its stay on the surface and provides interfaces (airlock and suitports) to perform surface activities. The suitlocks are the normal way of egression to avoid dust and contamination issues inside the modules while the airlock provides a redundant escape route and the possibility to move cargo in and out. The surface habitat requires power from independent power plants throughout their surface lifetime. A nuclear power plant was selected as a baseline to provide electrical power to the whole base. It can assure required power level of 50 kWe for a long time period, without maintenance intervention and fuel supply. An ISRU plant capable of producing oxygen, water and buffer gas has also be envisioned in order to provide life support consumables to the Mars surface habitat and pressurized rover.

A pressurized rover is an indispensable exploration tool allowing astronauts to explore the surroundings of the surface habitat landing location. Several designs of such elements have been studied focusing on a configuration carrying two crewmembers for a duration of 15-20 days. The pressurized rover can support scientific exploratory sorties from the main habitat for geological and astrobiology fieldwork and also support deep drilling activities and in-situ analysis of sample.

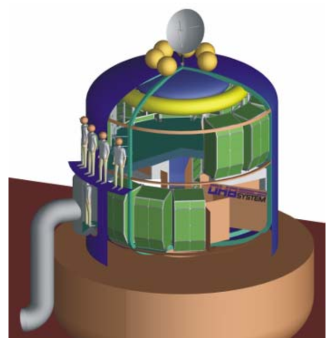
Element	Mars surface habitation Module	
Objective	Sustain crew of four for up to 400 days on the surface of Mars	
Timeline	2035+	
Characteristics	Total mass of 32t consists of a single module hull dimensions: ∅6.2m, h=6.2m layout: vertical cylinder with end domes, 2 floors + storage space in bulkheads, I/F tunnel to press. rover provides crew with storm shelter in case of SPEs provides some 20m³ habitable volume per person and some 44m³ pressurized volume per person provides crew with 1 airlock plus 4 suitlocks stays on the lander, no mobility / off-loading capability required houses 13 racks, of which 4 are ECLSS/EVA, 5 are science Power supply comes from external power plant	

Table 28 - Mars surface habitation Module

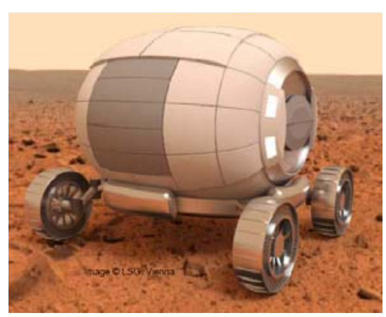
Element	Mars pressurized rover	
Objective	Sustain crew of two for sortie mission of 15-20 days on the surface of Mars	
Timeline	2035+	
Characteristics	Total mass of 9.6t Dimensions: 4.9x5.9x4.5m Pressurized volume 49 m^3 Range of up to 800 km Cruising speed 10 km/h Maximum traverse gradient 20°	

Table 29 - Mars pressurized rover

The Mars surface elements described hereabove have strong synergies with the Moon elements presented earlier in particular for power systems such as RTG, RHU and fuel Cells, life support systems, radiation protection and mitigation, extended mobility systems, surface operations and particularly human/robot partnership, ISRU operations…

The Human Mars ascent vehicle functionality is to transport a crew of four back from the surface to a circular 500 km Mars orbit and to sustain the crew during both descent and ascent. The selected configuration is a two stages design. The key figures of one configuration studied are recalled hereafter.

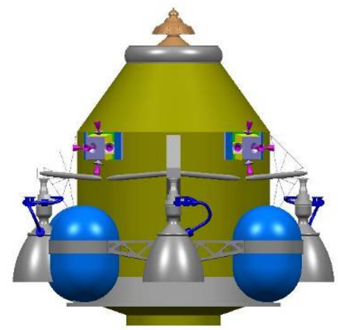
Element	Mars ascent vehicle	
Objective	Perform ascent from Mars surface toward a 500km circular mars orbit and sustain the crew during descent and ascent.	
Timeline	2035+	
Characteristics	Total mass 30t Crew of four Conical shap to fit within lander payload volume with a height of 6.4 m and a larger diameter of 7m. 2 stages configuration (only second stage shown) First stage thrust is about 132 kN Second stage thrust is 20 kN	

Table 30 - Mars crew ascent vehicle

The table below summarizes the mass properties of the various mission elements to be transported for two design reference points:

	Solar electric scenario	Nuclear scenario
Element	Mass (tons)	Mass (tons)
Transfer habitat	50	38
Surface habitat	32	31.9
Additional surface elements (rovers, power plant)	22.2	30
Mars crew ascender	29.3	31.5

Overall, the total mass to be landed on the Mars surface to support the Human mission is about 90tons and the mass to deliver to MLO and back toward Earth is in the 40-50ton range.

From the previous table it can be seen that the elements to be delivered to the surface by a mars descent vehicle can be split into three different deliveries of about 30t. Therefore, the human Mars Lander is designed to allow a soft landing for a payload mass of up to 32 t using storable propulsion. Such a configuration could fit within a maximum fairing envelop with an 8.8m diameter as foreseen for Ares V.

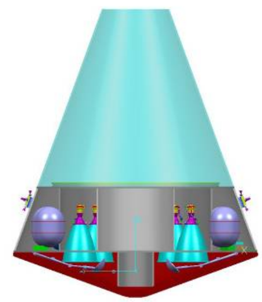
Element	Mars Descent stage	
Objective	Perform Mars descent and landing from Mars orbit	
Timeline	2035+	
Characteristics	Total mass 24t Ablative heat shield for Mars entry of 8.8m diameter 8 throtleable thrusters of 55kN Conic payload compartment with a base diameter of 7m, a top diameter of 2.4m and a height of 6.4m. Soft precision landing on Mars	

Table 31 - Mars Descent stage

The first transportation scenario studied focused on the use of solar electric propulsion for the main transfer to Mars with an assembly location in EML1. In this scenario, the elements to be transported toward Mars and the electrical transfer stage are delivered in EML1 using chemical propulsion. They are then assembled together in EML1 using if necessary the support of an orbital infrastructure. The aim of this scenario is to study the potential application of Earth-Moon libration for mission to Mars and to avoid long spiraling time within the Earth's Van Allen belt with electrical propulsion. A first mission of the electrical spaceship to deliver cargo to Mars is foreseen. The ship then returns to L1 where it is refurbished before the crew mission can start. Therefore this scenario allows a certain level of reusability in the transportation systems.

The first cargo mission shall deliver both the habitation module on Mars surface and the associated exploration tools (power plant, pressurized rover,…). Therefore it shall deliver to the low mars orbit a total payload mass of about 100t. The foreseen electrical tug is based on the clustering of up to 46 Xe-NASA 457 thrusters producing a total thrust of 100N with a specific impulse of 2929s. A total power of 2.5MW is required for the engines leading to a huge vehicle to be assembled in L1. The following graphics gives an idea of the dimensions involved before deployment of the solar arrays and integration of the payloads.

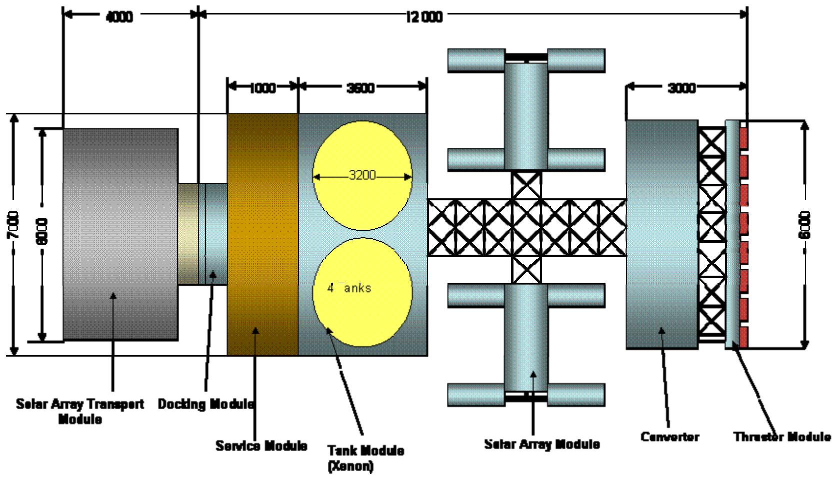


Figure 19 – Mars Electrical Transfer Vehicle

In total about 100t of propellant are required to perform the transfer from EML1 to LMO. Therefore up to 7 Ares V launchers are required to deliver the elements to be assembled in EML1 for this first mission.

For the crew mission, the total payload to be delivered to LMO is about 100t (transit habitation, crew ascent/descent vehicles) also but out of which the 50t tons of the transit habitat needs to be brought back to EML1. Therefore, the electrical tug needs to be refurbished and carry a larger amount of propellant. The total number of launch Ares V launchers required to deliver all elements to EML1 is about 10 since the additional required propellant for the crew mission outweighs the potentially re-used mass.

The total number of Ares V for such scenario is therefore more than 17 and clearly not attractive given also the technical challenges involved in the assembly of the huge electrical spaceship. Overall, the cost of delivering the elements first to EML1 with chemical propulsion is just prohibitive. A classical chemical scenario (no aerocapture) relying on cryogenic propulsion and using the same mass assumptions for the elements to be transported would lead to similar numbers with a less significant technology gap.

The second scenario relies on the use of nuclear thermal engines and aerocapture maneuvers for cargo flights to minimize the overall mass in LEO required. A split mission is also foreseen where two cargo flights involving 2 Ares V launch are followed by the human flight requiring also 2 Ares V launch on top of the man-rated launcher that deliver the crew.

The two cargo flights deliver both the surface elements and the crew Mars Ascent/Descent vehicle in MLO. For each flight a nuclear transfer stage as described hereafter is used to perform the trans-Mars injection starting from a nuclear safe orbit, while the Mars orbit insertion is performed via aerocapture. One Ares V is dedicated to the launch of two Mars descent vehicle and associated payload and the second one to the delivery of the nuclear transfer stage. Alternatively, two slightly upgraded 50t class launcher introduced earlier in the Moon architecture could be used to deliver each descent vehicle with its payload which would require an additional docking/assembly but would facilitate the launcher integration.

The Human flight is composed of two additional Ares V flight plus a man-rated launcher flight. The first AresV delivers the Mars nuclear transfer stage while the second flight delivers the Mars transfer habitation module and an additional transfer stage which provides the supplementary fuel necessary to perform the additional propulsive injections required by the manned mission: the MOI and the TEI. The man rated launcher brings the crew to the transfer habitation module together with the return capsule.

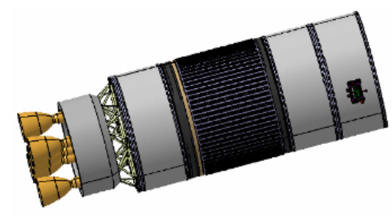
Element	Mars Nuclear Transfer stage	
Objective	Assure the propulsion required to perform the human mission to Mars	
Timeline	2035+	
Characteristics	Total mass 120t 10 m diameter x 29 m length Five Nuclear thermal engine using LH2 as propellant Isp 1000s Individual engine mass 2225kg Total thrust of 333.5 kN Active cryogenic cooling with Brayton refrigeration system	

Table 32 - Mars Nuclear Transfer stage

This advanced scenario allows a significant reduction in the total equivalent mass to be injected in LEO since it relies only on 6 Ares V launches. A comparable scenario with identical payloads relying only on chemical cryogenic propulsion and aerocapture would require 10 Ares V launch. However a significant number of enabling technologies are required to reach such values such as nuclear thermal propulsion, active cryo-cooler systems, aerocapture, advanced radiator concepts, large throtleable cryogenic engines, very high speed re-entry in Earth atmosphere, large scale inflatable structures…The reference values associated to each of these technologies used in the design of the overall mission are based on currently available information.

In conclusion, the implementation of a human mission to Mars requires major advances in research (e.g. radiation biology), knowledge of the Martian environment and technology (in fields such as propulsion, entry descent and landing, life support, human health management and structures). A key issue for the design of a future human mission to Mars is the selection of the propulsion system. Investments in advanced propulsion systems, albeit hardly existent today at international level, (e-g. nuclear) are therefore essential in enabling a human mission to Mars.

3.4.2 MARS COMMUNICATION

The phase 4 orbiter is a communications/Navigation spacecraft to support very high data rates during all phases of manned exploration of Mars. In addition, it shall continue to support robotic elements once manned sorties have begun. The advantage of the Mars scenario is that additional constellation (coverage) options exist which are not available in the lunar scenario, due to the presence of Earth generated gravity perturbations. In particular an areostationary orbit (equivalent to the Earth centric geostationary orbit) can be employed to fix assets over given positions on Mars.

Spacecraft in this phase are located in an areostationary orbit to provide 100% coverage of a large region on the planets surface, centred on a manned outpost. There will be two such spacecraft in phase 4 which also relay data from other orbiters and TransHab module (when required).

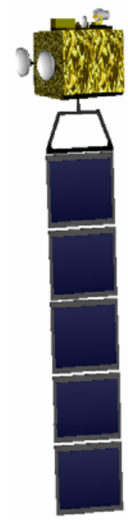
Element	Mars aerostationary communication orbiter	
Objective	Ensure high data-rate communication relay to support human activities in-orbit and on the surface.	
Timeline	2035+	
Characteristics	Launch mass 2700 kg Circular, equatorial orbit with altitude of 17030 km Lifetime 10 years Optical link for Mars-Earth communication with up to 10Mbps, X-band for proximity links to surface elements Ka-band for inter-satellite links (Transfer habitat, MLO orbiter, second aerostationary orbiter)	

Table 33 - Mars aerostationary communication orbiter

4 SPACE EXPLORATION CAPABILITIES

The integrated exploration architecture exposed in this document relies on a series of capabilities that should be developed as a high priority in order to enable this architecture. These capabilities are:

Habitation

Habitation is a pre-requisite for exploration. Capabilities need to be developed for orbital and surface systems:

- Human transportation
- Orbital stations
- Surface elements

The size of the habitats is the driver for the full transportation system. There is a clear need on defining habitation requirements and standards as well as design rules to provide the astronauts with a comfortable environment while reducing the total mass of the systems, especially for the surface elements for Moon and Mars.

Technology development required in the areas of:

- Material (structures, meteoroid and radiation protection…)
- Structures, i.e. inflatable
- Life support, close loop systems, live out of the ground (ISRU)
- Radiation protection
- Crew systems
- Crew Health management
- EVA equipment

Propulsion

Propulsion is a key capability for space exploration. New technologies and systems are required for human Mars exploration, launchers, and robotic exploration:

- 5-12 kN, throttle-able for robotic landers, CSTS, human moon ascent vehicle
- 50-70 kN throttle-able for human Moon lander
- 180 kN cryogenic engines with re-ignition capability after long ballistic phases for transfer stages
- ~240 kN throttle-able for human Mars lander
- 100s kN for human missions to Mars transportation (cryo)
- Several MN range required for Heavy Lift Launcher (cryo)

All the different propulsion technologies will be used for exploration but in particular it will be required to invest in development of new engines, cryo management and man rated systems. In the short term it has been identified the need of throttle-able storable bipropellant engine 5 -12 kN for CSTS, Moon and Mars Lander.

For later phases, technologies to be investigated in the area of propellant production, fuel depots, refueling, and mainly a clear decision should be taken on propulsion technology for human missions to Mars in particular with respect to nuclear propulsion.

Entry descent and landing

Soft precision landing is required to pre-deploy payload on the surface, maintain an outpost and reduce the mobility requirements. Improvements are required in the area of propulsion (see above), GNC, and decelerators.

With today's technologies, landing large payloads on the surface of Mars is on the edge of feasibility. Inflatable decelerators or high speed parachutes should be developed.

Energy management

In the exploration program there is a large variety of elements requiring a large range of energy, from few hundreds of watts of a moon orbiter to 50 kW for a Moon outpost. Furthermore, very different environments will be visited, from the Moon surface to interplanetary to the surface of Mars.

Therefore different technologies will have to be developed for energy production, storage control and distribution will have to be developed to cover these needs, ranging solar cell systems with batteries or fuel cells for production and storage to nuclear power plants for human missions.

Technology development is required in the areas of:

- High efficiency solar cells
- Regenerative Fuel Cells
- RTG, RHU
- Nuclear power plants
- Power distribution and control

Servicing

Due to the launch capability constraint, several elements will have to be assembled in orbit to perform human missions both to the Moon and Mars. These elements will have to be maintained and operated while they wait for the beginning of its operational life.

In order to provide all the required services, technology development is required in the areas of:

- Assembly services, new docking systems for large payloads
- Robotics
- Teleoperation
- Refueling
- Cryo management
- ISRU

Advanced communication and navigation

High data rate communications are mandatory for human exploration where high definition video and large systems monitoring will be required (10s Mbps from Mars). Continuous link with Earth will be as well required, leading to the deployment of several relay satellites. New technologies need to be developed and tested like large distance optical link communications.

In the case of robotic exploration, data rates will be more moderate (except for low frequency telescopes). In this case more simple communication networks will be able to fulfill the requirements.

Finally, the ground segment will requires enhancements to cope with the large number of missions (i.e. Mbps upload capability, number of stations,…), while coordination scheme has to be set up for all control centers involved in an international scenario (i.e. common standard for communications).

In terms of navigation, several rendezvous maneuvers are required in LEO, LLO, LMO, and autonomous systems based on LIDAR or cameras will have to be developed to work in the absence of GPS. Navigations aids for landing will be required for planetary landers.