Mission Design for a Manned Lunar Base

Hanane Ait-Lakbir, Jonathan de Laval, Alexander Fehr, Birger Vaksdal
{*HananeAL, JdL, AFehr, Vaksdal*}@KTH.se

KTH Royal Institute of Technology, SE-100 44 Stockholm

Abstract

According to latest information, the International Space Station is only to be utilised until the year 2024. After that, it will most likely be discontinued and de-orbited. A possible follow-on project could be the colonisation of the Moon, involving all major space agencies and thus facilitating international cooperation. The manned lunar outpost could serve two basic purposes, the execution of versatile research paving the way for subsequent commercial resource utilisation and a preparation for future deep space missions. Hence, this report gives an overview of a respective mission design, taking logistics, communication, navigation, off-nominal cases and financial aspects into consideration. Furthermore, essential findings regarding the base itself, human aspects including life support systems, on-site mobility and crew work are considered. In this feasibility study, special attention is paid to state-of-the-art technology and cost-efficiency. However, the mission design is on a conceptual level because such an undertaking is very comprehensive and complex. The major outcome of the analysis performed is that a human outpost on the Moon is not only technically but also financially feasible. This becomes particularly apparent when one assess current technologies and looks at today's budget of the major space agencies.

Nomenclature

ISS : International Space Station
LEO : low earth orbit
LLO : low lunar orbit

ϕ : latitude of a position on Earth
λ : longitude of a position on Earth
$r_{\oplus}$: mean radius of the Earth
r_{Moon} : mean radius of the Moon
i : inclination of an orbit

1 Introduction

> Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is. [1]

Ever since, mankind is fascinated by the universe and thus curious about exploring it. Consequently, the colonisation of the Moon is a recurrent topic in science-fiction literature and has been seriously considered by space organisations worldwide, such as ESA and NASA.

During the Apollo programme, twelve men have been on the Moon's surface, the last steps were taken in December 1972 during the Apollo 17 mission. Since then, the Moon has not been visited again but the aforementioned project is not abandoned. Space probes are sent every year in order to continue exploring the lunar surface. Moreover, the ISS is said to be discontinued around the year 2024. A manned outpost on the Moon is then an excellent alternative to retain a human presence in space and to conduct research that is currently carried out on the ISS, for instance on life science. Furthermore, the lunar base can serve as a preparation for future deep space missions, such as one to Mars. Since the red planet's development and position are comparable to the Earth's, a Mars study can considerably increase the knowledge about our planet.

The purpose of this report is to describe how a lunar base mission could look like considering state of the art technology and cost-efficiency.

2 Project Scope

Since the proposed undertaking is quite comprehensive and complex, the scope of this report is limited to a conceptual level. In the project assignment, certain requirements on the lunar base and the space vehicles are posed. These are summed up in the following list.

Lunar Base

- nominal lifetime of at least 10 years
- capability of hosting up to 6 astronauts
- permanent crew must be sent by the end of the year 2024

Space Vehicles

- planned or state of the art vehicles should be used
- assumptions for trans-lunar payloads and a lunar lander have to be made

This report deals with three major aspects of the lunar base mission.

The starting point of the reflection is the architecture of the mission. The first questions raised are related to the primary mission requirements. Should the base be mobile or not? Where should the base be built on the Moon, if it is fixed? What are the main parts of the mission and what are their interdependencies? What should be done and in which order?

The second point of the report is about the logistics of such a mission. For this, some ways to transport materials from the Earth to the Moon should be chosen. To do so, currently available or planned technologies are presented that can accomplish the mission. Also, a brief inventory of needed materials is described which enables to balance the masses and thus judges the feasibility of the mission. Furthermore, resupply of the lunar base is addressed, in particular the crew rotation, the material needs and the expected frequency of the resupply missions.

Last but not least, costs and funding of the project are discussed. This mainly comprises an overall financial estimate and how to acquire potential investors.

3 Related Work

A lot of research has already been conducted on manned lunar missions and a permanent human outpost on the Moon. It is impossible to reflect on all the works done but some served as guidelines or inspirations of what seems feasible for the project. In comparison to previous works, this project not only aims at designing a state-of-the-art mission for a future human outpost on the Moon but also accounts for the cost-effectiveness of such an undertaking. Still, considering the project scope, only a conceptual overview of a respective mission can be given.

In the project, the main reference was "*The Lunar Base Handbook*" by P. Eckart [2] which is quite extensive and well-structured but does not take state-of-the-art technology into consideration. This, however, can be very helpful or necessary as to maximise payload ratios and minimise costs.

In order to accomplish the project, collaboration with three other groups was necessary:

- *base construction and lay-out* group [3]
- *human aspects incl. life support systems* group [4]
- *on-site mobility and crew work* group [5]

4 Analysis

In the following section, the different aspects of the project will be presented: the mission architecture, choice of the location, involved subsystems, logistics and off-nominal scenarios.

4.1 Mission Architecture

In the proposed mission, the development of the lunar base can be divided into four principal stages (see figure 1). These stages can basically be understood as the consecutive steps of an evolution the base is undergoing. With each stage, the base is expanded. In the precursor phase, a preparatory reconnaissance mission of the Moon is performed by the aid of orbiters and robotic surface rovers. In the case at hand, this preparation relies on scientific publications and existing research data. In the subsequent pioneering phase, the minimum base is constructed and a stockpile of fuel, food and water is brought to the Moon. After that, the first crew is sent to the minimum equipped base to prepare future missions and conduct initial research. During the consolidation phase, the base is permanently occupied and will be largely extended, e. g. by a separate laboratory and additional scientific equipment. The final settlement phase is characterised by a fully operational base that provides all necessary equipment and facilities to fulfil the mission objectives. [2]

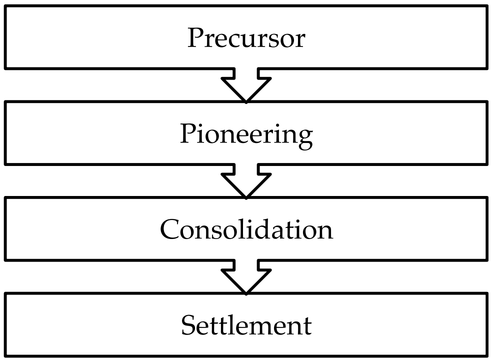


Figure 1: *Lunar Base Development Phases*

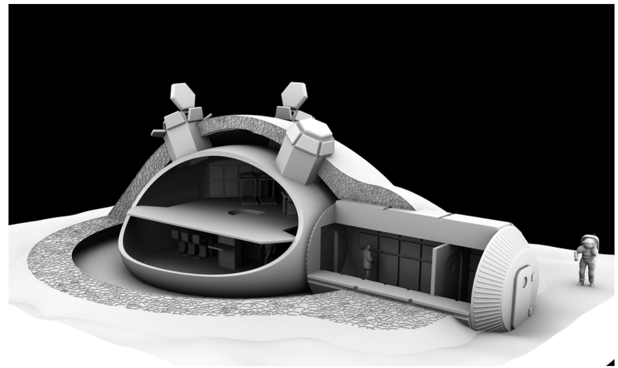


Figure 2: *Artist View of the 3D-printed Lunar Base [6]*

Details regarding the different lunar base development phases can be found in appendix A.1.

Moreover, two unwritten laws for drafting the lunar base should be followed relying on previous experiences [2]:

1. *The simplest concept is the best!*
2. *What you can do on Earth, you should plan to do on Earth and not in space!*

Following these rules typically leads to minimised costs and earliest accomplishment of the mission objectives.

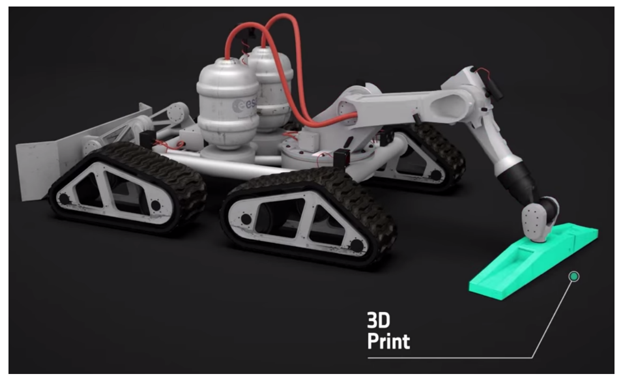


Figure 3: *Lunar 3D-printing Rover [6]*

4.2 Subsystems

As stated in the project assignment, the planned undertaking is divided into five major categories: base construction, life support systems, on-site mobility, crew work and overall coordination. As mentioned, this report focusses on the overall coordination. This section presents the other subsystems and their requirements and specifications for the logistics.

4.2.1 Base Construction and Lay-Out

The first system is the base which comprises all facilities that are necessary on the Moon. The base includes the habitat, the storage location, and, among others, the power supply system (see base illustration in figure 2).

As explained in [3], the base concept is to launch the main module of the habitat, an inflatable structure that will be deployed. Then, this temporary structure will be covered by a layer made of lunar regolith, which protects the structure from radiation and provides thermal control (see construction rover in figure 3).

4.2.2 Human Aspects incl. Life Support Systems

The second system of the lunar base project is the human aspects and the design of the life support system, which offers a habitable environment for up to 6 astronauts. As mentioned in [4], this involves the creation of a breathable atmosphere by producing dioxygen and disposing carbon dioxide, as well as the production of food and water, and the design of a thermal control system. The second point of interest is the medical and psychological impacts of a long-term stay on the Moon, in particular the effects of a low-gravity environment with high-level radiation. Consequently, training schedules and appropriate exercise devices have to be designed.

4.2.3 On-Site Mobility and Crew Work

The last two systems that have been considered for this preliminary design comprise crew mobility and crew operations on the Moon.

The decisions have been made in [5] to define the subjects of research that would be carried out during the mission. The primary focus is on the utilisation of in-situ resources. Indeed, one of the mission's aims is that the base should be as autonomous as possible.

The first resource that could be utilised is water which has been a major factor for the choice of the base's location. Research on water, supposing that there is water ice near the base, would be the main objective. This ensures a source of water for the base, meaning that less water has to be brought from Earth. Also, dioxygen and dihydrogen may be produced, which could be used as propellant for space vehicles that travel to the Moon.

This directly brings up the second field of interest for lunar research. Indeed, the production of propellant is a very important issue. The scientific operations could be oriented to work on the best and most efficient ways to produce propellant from water. Other chemical products could be utilised, such as Helium 3 which is quite rare on Earth [7].

The last purpose of the mission is the exploration of a certain area around the base. The study of the lunar surface could resolve questions on how the Moon was formed, for instance.

4.3 Location

Picking a spot for the lunar base will affect all the work performed there. Initial analysis focussed on polar or equatorial locations.

- **Polar**
  The lunar poles can offer almost perpetual sunlight, however it comes with a more complicated navigation and higher velocity increment requirements on the spacecraft. The craters on the poles and especially the south pole offer more abundant deposits of hydrogen and water [8].
- **Equatorial**
  The equatorial regions offer easier transport but have in some sense already been explored by the Apollo missions [9]. The equatorial region is also subjected to the lunar day, month on Earth, with 15 days of sunlight to 15 days of darkness.

4.4 Logistics

According to definition, logistics is defined as the management of material and immaterial flows. In this project, it involves the transport between the Earth and the Moon, as well as the communication and navigation.

4.4.1 Mission Modes

Three principal mission modes have been identified.

- **Cargo (One-Way Only)**
  This mode comprises heavy lifting missions to transport base segments and supplies like propellant, food and water to the lunar surface.
- **Crew**
  This mode encompasses manned missions for crew rotation and small mission payloads, such as samples, food and water.
- **Evacuation**
  In case of imminent failures of base systems, the crew must be able to perform a direct return from the lunar surface to the Earth without a docking manoeuvre in LLO.

These missions have specific and distinct requirements and will therefore require different types of space vehicles.

4.4.2 Space Vehicles

With the demands specified above a need for the following vehicles was identified.

Transit Vehicle The transport of a crew requires a spacecraft that is capable of supplying the necessary velocity increment to achieve the transit orbit from LEO to LLO and back again. It also has to protect the crew from radiation, especially galactic cosmic rays and whilst coasting through the Van Allen belts.

Lunar Landers Taking the mission profile into consideration, it seems highly desirable to have two different lunar landers.

- A disposable lander is needed for heavy lifting missions to transport base segments and supplies like fuel, food and water to the lunar surface.
- Looking at the requirements of a lunar base a reusable lander is paramount. Having access to LLO from the base simplifies the demand on the trans-lunar vehicles. The reusable lander docks to the spacecraft in LLO and thus brings down crew and supplies to the lunar surface. The goal is to fuel this lander with propellant produced on the Moon. If that is not possible it is still easier to transport the fuel rather than a new lander for every resupply mission.

Evacuation In case of imminent failure of base systems, irreparable damage or breakdown of vital systems, an evacuation is inevitable. Hence, the crew must be able to leave the lunar surface and go back to Earth. This is a safety precaution but should also alleviate some psychological strain of being off world.

4.4.3 Communication

In a space mission, communication is a crucial factor. It mainly comprises the monitoring and control of mission elements, the acquisition of telemetry data from the vehicles and equipment, and a capacity to communicate, receive, distribute, and process information. As with all critical technology in space, communication systems must be highly reliable and redundant. To ensure compatibility, every involved stakeholder needs to develop or adapt its communication system according to a predefined standard so that all systems interoperate seamlessly. Furthermore, some systems may need real-time capabilities whereas others only need store-and-forward capabilities. Anyhow, all systems should have the flexibility to be expanded and/or upgraded. [2]

Taking the proposed mission into consideration, communication can be classified into three major categories:

- lunar base $\rightleftharpoons$ Earth
- lunar base/Earth $\rightleftharpoons$ spacecraft in transit
- lunar base $\rightleftharpoons$ lunar surface

This report focusses on the first two aspects because these are the only ones that belong to the overall overview of the planned mission. The communication on the Moon itself is handled by the *on-site mobility and crew work* group [5].

Since the proposed mission is a manned one, there should, for safety reasons, be a continuous data connection to the Earth. So, in case of an emergency situation on the lunar base the ground control centres are immediately informed and can assist in taking proper action. The spectrum of potential hazards is quite manifold and not only limited to the base itself. For instance, if the health condition of the astronauts is permanently monitored and transmitted in real-time, a team of medical experts on the Earth may identify possible issues at an early stage.

4.4.4 Navigation

For a space mission, navigation is also an essential aspect. In the planned mission, not only navigation of the space vehicles is important but also the guidance of rovers and astronauts on the lunar surface. In principle, the same requirements as of the communication systems apply in this context. Hence, navigation systems are also a critical technology and must likewise be highly reliable, redundant and fully compliant with predefined standards. [2]

This report mainly focusses on the navigation of the space vehicles and just briefly deals with the guidance on the Moon itself because only the former case is part of the overall overview of the planned mission. The latter case is particularly addressed by the *on-site mobility and crew work* group [5].

4.5 Off-Nominal Cases

Since nothing is 100% safe, off-nominal cases have to be considered. In the following, two main failures are addressed.

Launch Failure One of the most critical parts of a space mission is the launch of the rocket, thus a respective failure should be taken into account. In case of a cargo mission for resupply in water and food, it is planned to have stockpiles for at least 6 months on the base as presented in [4]. Moreover, additional rockets to replace a failed one could be planned. Consequently, these two solutions must be then considered in the cost budget. For the crew rotation, the manned launches are scheduled before the end of a maximum stay one year period in order to have at least several available launch windows [4].

Life Support Systems Failure Another critical part of the mission is the astronauts' safety in the lunar base. Many astronomical phenomena such as meteoroids may irreversibly damage the base endangering the astronauts' lives as well as the breakdown of the base systems. The first resort is the maintenance operations. These must be designed in order to detect any system failure which can be perilous as early as possible, and allow the supply of corresponding spares. If a repair is not possible, an evacuation device must be designed.

4.6 Constraints by the other Subsystems

The main constraints from the other subsystems of the team are about the duration of the stay on the Moon. Indeed, the considerations on radiation and the design of both the base [3] and the life support systems [4] determine the maximum stay of one year. Finally, because of psychological and obvious safety reasons, astronauts must not stay or travel alone. The second sort of constraints is about the launching order of the scientific packages. In [5], it is planned to launch a preliminary robot to test the water process before launching the final robot.

4.7 Costs and Funding

4.7.1 Costs

For the launches to the lunar surface, rockets are needed that can take large payloads, while not being too expensive. A possible solution would be to use different versions for different needs: a more expensive one when a large payload is needed at once, and a cheaper one when there are smaller payloads.

For the ground operations connected to the lunar base, it is assumed that the control centres for ISS can be used. It is also assumed that the costs for the ground operations will be comparable with those current costs for running ISS.

To run the lunar base, a large support organisation at Earth with one or more control centres is needed. Since the lunar base is supposed to replace ISS, it is assumed that the same control centres can be used. For the cost of operating these, it is assumed that they will be around the same level as the costs of ground operations for ISS.

Added to the launch costs and the ground operations, there are also costs related to the construction of the base, the human presence at the base and the activities carried out on the lunar surface. These costs are provided by the other groups in the team: the base group, the life support group and the crew work group.

4.7.2 Funding

Since the lunar base is going to replace ISS as the manned human outpost in space, it is assumed that the funding currently available from the governmental space agencies for ISS will be used for the lunar base.

A possible source of additional funding could be commercial companies interested in using the base for various purposes. On the other hand, that would also increase the costs, and it cannot be expected to receive more funding to the main base concept from this source.

5 Results

Thoroughly reviewing the aforementioned analyses, results were deduced for the different aspects of the project.

5.1 Location

Due to the abundance of sunlight, deposits of hydrogen and possibly water, the location was set to the south pole. After a study by the base group, the rim of the Shackleton crater was chosen [3].

5.2 Logistics

5.2.1 Space Vehicles

When it comes to finding suitable space vehicles for a manned mission to the Moon, the choice is rather limited. This is basically due to two reasons. Firstly, there are just a handful of rockets that are technically capable of bringing a certain payload, i. e. a manned or cargo-equipped lander, to a low lunar orbit. Secondly, not all of the already available or proposed space vehicles can assumed to be used if the current geopolitical situation is taken into consideration. However, the most promising space vehicles are built by nations that ESA already cooperates with. In addition to that, only existing or at least roughly specified future space vehicles were considered in the research.

NASA Space Launch System is an upcoming launch vehicle that is mainly derived from NASA's discontinued Space Shuttle. It is the prospective U. S. American launch vehicle for deep space exploration outperforming NASA's Saturn V. By the year 2021, both versions of the new launch vehicle will be fully operational, a manned and cargo one. The crewed version uses NASA's Orion capsule as human habitat which is elaborated on later in this section. According to the latest available information, the manned version can carry about 25 t and the cargo version about 45 t of payload to a lunar orbit [10, 11]. Still, the launch vehicle is to be upgraded over time with more powerful versions. [12]

SpaceX Falcon Heavy is a launch vehicle that is developed and manufactured by a privately held company. SpaceX is one of the world's most successful commercial players in the space business and aims at effectively bringing down the costs per launch. In comparison, a SpaceX Falcon Heavy launch is significantly cheaper than a NASA Space Launch System launch [13, 14]. SpaceX's launch vehicle can carry up to 16 t to a trans-lunar trajectory and is expected to be fully operational very soon. [15]

NASA Orion is a reusable crewed spacecraft that is transported with the manned version of NASA's Space Launch System. The first mission for this constellation is scheduled for the year 2021. The capsule can carry up to four astronauts and is designed for deep space exploration. The total mass of the spacecraft (approximately 30 t) exceeds the lunar payload capacity of the SpaceX Falcon Heavy for which this combination cannot be used for a mission to the Moon. The capsule provides a habitable environment for a crew of four astronauts for at least 21 days. [16, 17]

NASA Altair is a lunar lander that was a key component of NASA's Constellation program. Two versions of the spacecraft were planned, a manned and a cargo one. However, in the year 2010 the aforementioned spaceflight program was cancelled due to insufficient funding and thus the lander dismissed [18]. Anyhow, the NASA Altair will serve as an indication of what is technically feasible. Therefore, it is assumed that the development of derivations of this spacecraft is resumed and it is built for the proposed mission to the Moon.

Lunar Landers Since the NASA Altair is cancelled and no other concepts have been planned or found, some liberties have been taken with the lander concept. The three modes described in paragraph 4.4.2 will be kept. It is assumed they operate autonomously and perform lunar surface landing unmanned.

- **Disposable**
  A heavy lander version transports the heavy initial payloads, mainly the base segments, 3D-printing robots and potentially stockpiles. This is based on the NASA Altair cargo version, capable of landing 15 t of payload (see table 1).

  A light lander is manufactured for the SpaceX Falcon Heavy. This smaller spacecraft will serve as a more cost-efficient resupply vehicle because a launch of SpaceX's rocket is substantially cheaper than one of NASA's counterpart. The technical specifications of the different lander versions can be found in table 1. The figures for the additional light lander version of the NASA Altair have been derived by the method of similitude [19]. [20]
- **Lunar Hopper**, to hop up and down between the lunar surface and LLO to rendezvous with the NASA Orion crew capsule or resupply vessels. This one is based on the crewed version of the NASA Altair lander but built in one stage and refuelable to get the effiecency of reusability. It will have the NASA Altair crew compartment for 4 astronauts and 1 t mission payload.
- **Escape**, the evacuation craft is solved by landing the first NASA Orion capsule together with an ascent stage. This could also serve as a shelter from radiation since the NASA Orion is built for deep space exploration.

version	manned	cargo	cargo†
diameter [m]	7.5	7.5	5.0
height [m]	9.9	9.9	7.5
payload [t]	1.0	15.0	5.0
tot. weight [t]	45.0	45.0	15.0

Table 1: *Technical Specifications of the Lunar Landers [21]*

5.2.2 Launching Strategy

In the previous sections, the different candidates for the transport between the Earth and the Moon, and respective constraints have been presented. For the launching strategy, there is a trade-off between the launching costs and the efficiency of the schedule. The costs are related to the launching frequency and the chosen vehicles. The more frequent the launches are, the more expensive the project is.

Three different modes can be defined: the base settlement, the crewed missions and the resupply missions. These modes are shown in appendix A.3.

In the first phase of the mission, rockets that can carry a large amount of mass are necessary. Thus, a combination of the NASA Space Launch System

†figures for SpaceX Falcon Heavy (indicative only)

cargo version and the heavy disposable lander was chosen, so that 15 t can be brought to the Moon per launch. Two of such constellations are necessary to launch the base modules and the systems needed before the first crew can be sent. The composition details of these two launches are presented in table 2.

payload	**1st launch**	**2nd launch**
base module 1	13.00	
rover 1	1.00	
robot 1	0.25	
base module 2		7.00
life support sys.		3.70
robot 2		2.30
water sys.		1.20
total	**14.25**	**14.20**

Table 2: *Composition of the Launches (masses in tons)*

The combination of the NASA Orion capsule and a reusable lander will be used for the crewed missions. The manned version of NASA Space Launch System will launch the NASA Orion capsule and the lunar lander. The following explanation is summarised in appendix A.3. In LLO, the crew members reach the crew compartment of the lander. Two cases are possible. For the first crewed mission, both the capsule and the lander reach the lunar surface. This vehicle will be used as an evacuation vehicle. For the following crewed missions, in LLO, the lander separates from the NASA Orion capsule and lands on the lunar surface, where the two crews switch. Since 8 people are present on the Moon at the same time and the base is designed for less people, two people alternatively stay in the lander capsule. This critical phase is supposed to last only a few days. Since the life support systems are designed to ensure that each crew member can stay one year in the base, such a mission is planned every year.

The third mission mode is the resupply of the base with food. Water and propellant could be provided at least for the first part of the mission, while the processes for water and propellant produced from lunar resources are not fully operational. The cargo version of the SpaceX Falcon Heavy is then used, which is able to launch 5 t to the lunar surface. Due to the psychological benefit of having resupplies frequently, these missions are planned for every six months.

5.2.3 Communication Systems

For the given south pole location on the Moon, a continuous connection to the Earth can be established. At any time, there will be a line of sight to at least one ground tracking station of ESA (see proof in appendix A.2) [22].

Concerning the data connection between the lunar base and Earth, there is only one technology that fulfils the earlier mentioned requirements of real-time transmission and reliability. It is the conventional approach of a radio connection within the K_u band. This is a well-established technology used for many satellites and spacecraft. Another promising approach is an optical link between the Moon and the Earth, namely a laser. This technology has already been successfully tested providing unprecedented data transmission rates but is not yet reliable enough for productive use [23]. [2]

The intercom between the lunar base or the Earth and the spacecraft in transit works with the on-board capabilities of the space vehicles.

5.2.4 Navigation Systems

The navigation of the space vehicles in orbit is a challenge because there is no such accurate system as *GPS* for space missions. However, the Apollo missions already illustrated how to navigate in space, particularly in lunar vicinity. The space vehicles in those days were dependent on navigation data from various terrestrial ground stations of the *Deep Space Network*. The drawback was that only landing sites on the near side of the Moon could be considered because a line of sight to the destination was required. Since there is no alternative to this well-tried navigation method so far, the space vehicles for the proposed mission are to make use of it as well. In the present case, this does not affect the mission as the polar landing site on the Moon is constantly in line of sight to the *Deep Space Network*. An advantage of using the aforementioned approach is the cost-efficiency because there is hardly or no extra costs using an already existing network. What one should be aware of is the relatively low accuracy for this kind of navigation. At least in LEO, the utilisation of the *GPS* system can aid the navigation accuracy. [2]

Since there is no in-situ navigation system available on the Moon, guidance for rovers and astronauts is problematic. Taking basic navigation principles into consideration, there are at least some preliminary ideas for this problem. For instance, celestial navigation, i. e. determining one's position with respect to the stars, or a network of lunar radio beacon stations could be used. Still, these are only initial considerations wherefore it is strongly recommended to review [5].

5.3 Costs and Funding

5.3.1 Costs – Subsystem by Subsystem

For the launching vehicles, there are two different cost levels. For the NASA Space Launch System, the cost is estimated to $500 million per launch [14] while the SpaceX Falcon Heavy is estimated to cost $85 million per launch [13].

There are two initial NASA Space Launch System launches, followed by one NASA Space Launch System launch and one SpaceX Falcon Heavy launch each year. This gives the launching costs as $1 billion for the start and $585 million each year.

For the ground operations needed to support the lunar base, the figures from NASA's support for ISS were assumed, which are $1.2 billion annually [24].

From the base group, an estimate of the lunar base construction costs was provided [3]. For the capsule used as a first node, $300 million are estimated. For the inflatable structure that will be used as structural support, $200 million are estimated. For the solar arrays used to power the base and an antenna for communication, a total of $11 million is estimated. The robots taking care of the 3D-printing of the base structure are estimated to a total of $4 million.

From the life support group, estimates of the costs for some of the life supporting systems were provided as well. For the food, $300 per day and crew member are estimated. With four crew members continuously occupying the base and another four crew members in space for about two weeks during crew rotation, the cost for the food will be about $500k per year. For production of some of the food for the base, four greenhouses are needed at an estimated cost of $400k. [4]

From the on-site mobility and crew work group, cost estimates for the planned operations at the lunar surface are available. For an initial rover to test the water extraction process, $1 billion is needed. For the next two rovers, $1.7 billion for a mining rover and $2 billion for an exploration and transportation rover are estimated. The water processing plant is estimated to cost $3.2 billion. A final rover, larger and equipped for long range exploration, has a cost estimate of $4 billion. For the space suits, the costs for the lunar surface rated ones will be $10 million each. With four astronauts continuously occupying the base, and one spare suit, this will add $50 million to the total costs. [5]

5.3.2 Total Costs

Finally, all cost estimates together lead to the following figures:

- $13.5 billion of initial costs
- $1.8 billion of annual costs

5.3.3 Funding

The annual NASA budget includes $3.2 billion for ISS [24], which is assumed to be available for the lunar base.

ESA's costs during its engagement in ISS is averaging about $700 million annually [25], hence it is assumed that the same level of funding is provided for the lunar base.

For the Russian contribution to ISS, there are no useful figures available for which any potential funding from this side was excluded.

This means that the total available funding for the lunar base is $3.9 billion annually.

5.3.4 Financial Situation

With the estimated annual costs and funding, and with the initial costs spread over the estimated timespan for the base, this project will be possible from a financial point of view.

6 Discussion

In the project certain assumptions and simplifications were made that will be discussed or justified subsequently.

Firstly, the major assumption made for the project is the presence of water near the base location. The choice of the location and lunar water utilisation have been done according to NASA's statement regarding the potential presence of an ice cap near the Shackleton crater [8]. Still, space probes will be sent in the next years to verify that. Nevertheless, the launch of a prospecting space probe is scheduled in this project before the launch of the first astronauts. Thus, if there is no or not enough water available to satisfy the needs, the launching strategy can consequently be modified.

Secondly, assumptions have been made about the launching vehicles and a lunar lander. The available figures from the space agencies and companies were used as a starting point and a reference, from what possible payload masses were extrapolated. Similarly, the NASA Altair lander serves as a reference in terms of technological feasibility and to indicate that the given requirements can be met by the year 2024. For example, it has been mentioned that the lander needs to be reusable and refuelable. Such a lander has not been designed or planned for development yet.

Another assumption is related to the landing of the capsule-lander constellation on the lunar surface. The current NASA Orion project does not involve this scenario. The capsule is supposed to separate in LLO. However, considering that a 15 t package for the base construction can be landed and the capsule's mass is about 11 tons, this scenario is not completely unrealistic. It can be assumed that by the year 2024 this can be done with human-rated systems.

Finally, the effects of radiation on the lunar lander staying in LLO have been neglected. It might be necessary to regularly replace the lander.

7 Conclusion

After sobering comments from Sven Grahn on the presentation workshop, the proposed mission seems challenging. To a certain extent, simplifications and assumptions have been made. Still, if the mission is postponed by approximately a decade and more effort put in the development of necessary space vehicles, the planned undertaking seems technically and financially feasible. In this context, one should keep in mind that all of the Apollo spacecraft for the Moon missions were largely developed, designed and tested after Kennedy's famous speech in the year 1961. So, once a determined decision for a manned lunar base has been reached, quick progress could be made.

8 Future Work

In addition to the work that has been carried out so far, there are some aspects that could be pursued by future works.

After extensive research and experiments on the Moon have paved the way, resources could be utilised commercially. This, however, requires further planning and design for a large-scale utilisation.

Also, effort could be put into making the lunar base as self-sufficient and self-supporting as possible so that the resupply frequency is reduced to a minimum. As a side effect, costs might decrease as well. Still, off-nominal cases must be considered to avoid potential dangers in case of whatsoever failure.

An alternative technology for resupply vehicles could be electric propulsion, which is significantly more efficient than its chemical counterpart. Yet, the low thrust level of electric propulsion limits this technology to usage in space, meaning that the vehicle itself has to be launched by an ordinary rocket at least. The longer travel times of electrically propelled vehicles are not critical in the case at hand because a resupply mission is unmanned. The only constraint is that the resupply frequency of the lunar base can be achieved and this seems very probable for the planned launching strategy. The main advantage of this resupply method is the reduction in costs.

Concerning communication between the Earth and the Moon, promising laser link connections could be reviewed that might reach a sufficient level of reliability in the near future. Thus far, this technology is not yet suited for productive use because atmospheric disturbances on the Earth can cause the connection to interrupt. [23]

In the field of navigation, an accurate in-situ navigation system seems very vital. With such a technology, the far side of the Moon could be explored and navigation in general could be improved in terms of accuracy, reliability and redundancy. The accuracy requirement for precision landing is probably the top performance driver for such an architecture. However, the undertaking of setting-up a sophisticated navigation architecture for the Moon is quite complex and costly because it requires to place satellites into a lunar orbit. [2]

Acknowledgements

We thank *Christer Fuglesang*, *Emil Vinterhav* and all other groups of our team for their assistance and support in the project.

References

[1] D. N. Adams. *The Hitchhiker's Guide to the Galaxy*. 1979.

[2] P. Eckart. *The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations*. McGraw-Hill, 2006.

[3] J. Altmeppen, N. Borko, T. Bour, F. Coutand, and G. A. Vieira. Manned Lunar Base: Base Construction and Lay-Out. Technical report, KTH Royal Institute of Technology, Stockholm, Sweden, 2015.

[4] M. Boje, S. Caleb, F. A. B. Nassar, and F. Thuillet. A Conceptual Study of the Life Support Systems and the Human Aspects on a Lunar Base. Technical report, KTH Royal Institute of Technology, Stockholm, Sweden, 2015.

[5] S. Chandrashekar, G. Daggenfelt, C. Krantz, P. Monmousseau, and T. Tsikis. Analysis of On-Site Mobility and Crew Work on a Lunar Base. Technical report, KTH Royal Institute of Technology, Stockholm, Sweden, 2015.

[6] European Space Agency. Lunar 3D-printing [online]. 2013. URL: http://www.esa.int/Highlights/Lunar_3D_printing.

[7] University of Wisconsin-Madison. Lunar Mining of Helium-3 [online]. August 2014. URL: http://fti.neep.wisc.edu/research/he3.

[8] D. R. Williams. Apollo Landing Site Coordinates [online]. 2000. URL: http://www.nasa.gov/content/goddard/lro-lunar-hydrogen/#.VPhRhcs54yo.

[9] B. Steigerwald. NASA's LRO Discovers Lunar Hydrogen More Abundant on Moon's Pole-Facing Slopes [online]. 2015. URL: http://nssdc.gsfc.nasa.gov/planetary/lunar/lunar_sites.html.

[10] Augustine, Austin, Chyba, Kennel, Bejmuk, Crawley, Lyles, Chiao, Greason, and Ride. Review of U. S. Human Spaceflight Plans Committee: Seeking A Human Spaceflight Program Worthy of A Great Nation, 2009. URL: http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf.

[11] E. Kyle. NASA Space Launch System - Data Sheet [online]. 2014. URL: http://www.spacelaunchreport.com/sls0.html.

[12] National Aeronautics and Space Administration. NASA Space Launch System, 2014. URL: http://www.nasa.gov/sites/default/files/files/SLS-Fact-Sheet_aug2014-finalv3.pdf.

[13] SpaceX. SpaceX - Capabilities & Services [online]. 2015. URL: http://www.spacex.com/about/capabilities.

[14] NBC News. NASA's huge new rocket may cost $500 million a launch [online]. 2012. URL: http://www.msnbc.msn.com/id/49019843/ns/technology_and_science-space/#.UFIyOxii5i4.

[15] SpaceX. SpaceX Falcon Heavy [online]. 2015. URL: http://www.spacex.com/falcon-heavy.

[16] National Aeronautics and Space Administration. NASA Orion, 2014. URL: http://www.nasa.gov/sites/default/files/fs-2014-08-004-jsc-orion_quickfacts-web.pdf.

[17] NASASpaceFlight.com. NASA ESD set key Orion requirement based on lunar missions [online]. 2012. URL: http://www.nasaspaceflight.com/2012/07/nasa-esd-key-orion-requirement-lunar-missions/.

[18] Washington Post. NASA budget for 2011 eliminates funds for manned lunar missions [online]. February 2010. URL: http://www.washingtonpost.com/wp-dyn/content/article/2010/01/31/AR2010013101058.html.

[19] S. J. Kline. *Similitude and Approximation Theory*. Springer, 1986.

[20] National Aeronautics and Space Administration. NASA Altair Lunar Lander, 2008. URL: http://www.nasa.gov/pdf/289914main_fs_altair_lunar_lander.pdf.

[21] National Aeronautics and Space Administration. Lunar Capability Concept Review, June 2008. URL: http://www.lpi.usra.edu/pss/presentations/200806/12neal.pdf.

[22] European Space Agency. ESTRACK tracking stations [online]. 2013. URL:

http://www.esa.int/Our_Activities/Operations/Estrack_tracking_stations.

[23] National Aeronautics and Space Administration. NASA Laser Communication System Sets Record with Data Transmissions to and from Moon [online]. October 2013. URL: http://www.nasa.gov/press/2013/october/nasa-laser-communication-system-sets-record-with-data-transmissions-to-and-from/.

[24] National Aeronautics and Space Administration. NASA Budget for Space Operations [online]. 2013. URL: http://www.nasa.gov/pdf/632684main_NASA_FY13_Budget_Space-Ops-508.pdf.

[25] European Space Agency. How much does it cost? On ESA's costs for ISS [online]. 2015. URL: http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/How_much_does_it_cost.

[26] J. Cappellari. Where on the Moon? - An Apollo System Engineering Problem. *The Bell System Technical Journal*, 51(5):955–1127, 1972.

[27] M. et al. Duke. Strategies for a Permanent Lunar Base. In W. Mendell, editor, *Lunar Bases and Space Activities of the 21st Century*, pages 57–68. Lunar & Planetary Institute, Houston, TX, 1985.

A Appendix

A.1 Lunar Base Development Phases

In table 3 the lunar base development phases are summarised comprising the essential properties.

Phase	Elements	Tasks/Capabilities/Characteristics
Precursor	• orbiters • robotic surface rovers	• lunar topographic mapping • site selection • resource assessment • subsurface data collection • gravity map production • seismic data collection • robotic surface surveys • robotic site preparation • sample return • experiment definition • instrument definition • space transportation system development
Pioneering	• lander(s) with habitats • temporarily occupied minimum base	• lunar base site preparations • limited science facilities • surface mining pilot plant • lunar oxygen pilot plant • instrument package emplacements • short range surface transportation
Consolidation	• extended surface facilities • permanently occupied facility	• extended science capabilities • extended mining facilities • lunar oxygen production plant • longer-range surface transportation
Settlement	• fully operational lunar base	• advanced laboratories / industrial research facilities • large-scale mining facilities • large-scale oxygen production / oxygen export capabilities • lunar manufacturing facilities • satellite outposts • long-range surface exploration • resupply from Earth minimized • support of Mars missions and other exploration missions • expanding population base

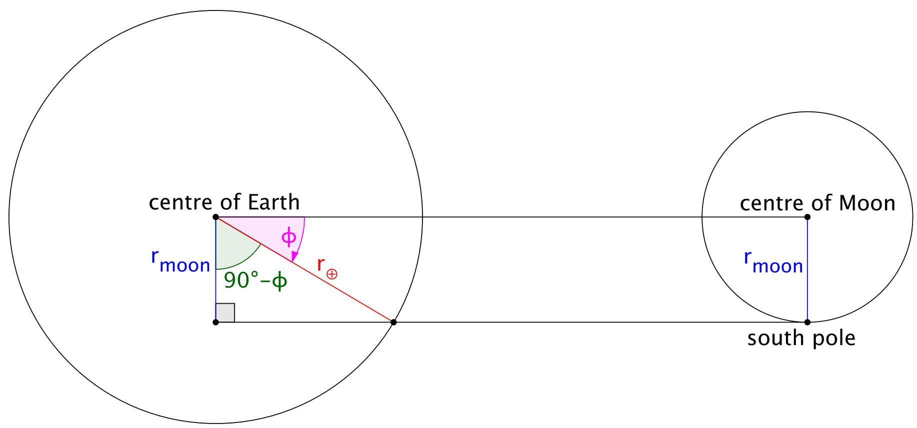
Table 3: *Lunar Base Development Phases [26, 27]*

A.2 Communication

In order to establish a connection from the Moon's south pole to the Earth, there must be a line of sight between those two.

From figure 4 it becomes apparent that only lines of sight to positions on Earth with latitudes $\phi > 90° - \arccos\left(\frac{r_{Moon}}{r_{\oplus}}\right) = 15.83°$ S are possible. This, however, is not completely true because the Moon's orbital plane is at worst about $\Delta i = 5.35°$ inclined with respect to the Earth's orbital plane. So, in the worst case the latitude ϕ of the ground stations must at least be 21.18° S. Furthermore, at minimum one of the ground stations fulfilling the aforementioned criterion must be in the line of sight at all times. This holds true if the longitudinal spacing $\Delta\lambda$ between the them is less than 180° (half of the Earth is seen from the Moon).

ESA's tracking station network fulfils all these requirements [22].



(not drawn to scale)

Figure 4: *Geometrical Requirement for Line of Sight between the Moon's South Pole and the Earth*

A.3 Launching Strategy

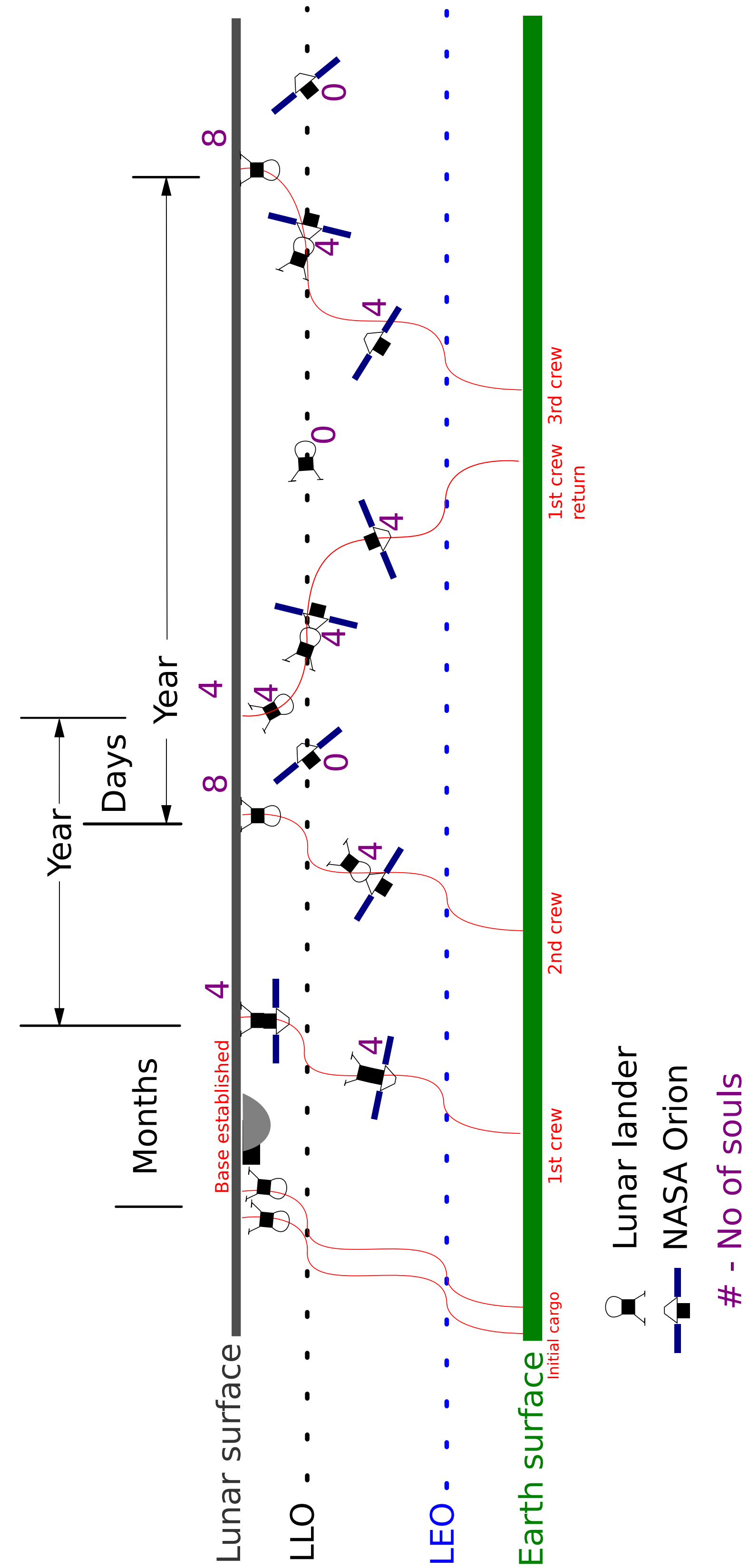


Figure 5: *Startup Launching Strategy*