# Moon exploration with the Deep Space Gateway Overall Coordination

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**Abstract**—Nobody has ever returned to the surface of the Moon since the Apollo program and the main goal of today for space projects is going to deep space and the Martian system. The Moon exploration with the Deep Space Gateway brings partial solution for both challenges. Next year will be the 50th anniversary of Apollo 11: one may say that going back there is easily doable. However, the main question is how to do it while at the same time preparing for future deep space missions.

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# 1 Introduction

MARS conquest is certainly the most fascinating and challenging area among future space missions. Who put their foot on Mars first? Will it be space agencies or private companies? Will we find any life there?

However, like any space missions conducted in the past, moving to the deep space and the Martian system has to be done step by step. Deep space is challenging because it presents distance and mission duration which is of a new order of magnitude. New technologies are already under development in order to meet the different requirements. Besides, train astronauts for that kind of mission is necessary. Deep space missions make all types of interaction between Earth and the spacecrafts more complicated (fuel consumption, time frames, communication system, etc.). Consequently, one objective is to be independent of Earth. The multi-functions deep space gateway (DSG) is developed to meet these objectives, as a lunar-orbiting station, including crew habitat and propulsion systems and capable of refueling other spacecrafts.

Besides, the Moon itself still has a lot to offer. Apollo's flights constituted a breakthrough in space history, but they *just* scratched on the Moon's surface. No return to the lunar surface has been made since those days and the far side of it has never been investigated closely. One may think that before finding existence of life further, science must be done thoroughly there.

To conclude, the cis-lunar space and the Moon constitute a training field for further deep space investigations, offering at the same time scientific interests on the Moon's surface.

This report was made while considering deep space mission requirements and by analyzing current technologies and the ones under development which may help satisfying these requirements. Outline and logistics have been planned around the final objective of the mission: produce enough water on the Moon surface for the crew living in a Lunar base. Results for medical aspects (radiation and bone loss), communication between Moon surface, DSG and the Earth (RF-Optical system), global cost based on NASA Advanced Mission Cost Model (total cost of $\$126.44$bn) and political and societal aspects are presented in this report. This mission proposal is just one of many possibilities. This report has found that it is feasible as a concept and could constitute a breakthrough in Space History.

# 2 Mission

## 2.1 Background of the project

This conceptual study on the Moon exploration with the DSG is conducted within a team, from the course *SD2905 - Human Spaceflight* at *KTH, Stockholm*, which is composed of four groups; Overall coordination, Deep Space Gateway design, Transport system between the DSG and the Lunar surface, and the Lunar exploration itself. We, the overall coordination group in Team Red, are responsible for coordinating the team, as well as researching some of the general topics related to the whole mission.

## 2.2 Why a DSG and a lunar base?

Why do we need a deep space gateway and a lunar base? There are other ways to reach deep space and a DSG could be constructed without going to the lunar surface.

The major reason to stop at a space station further, rather than closer to Earth, is the difference in $\delta V$, or potential energy required to escape Earth's gravitational field.

The escape velocity of the Moon is $2.38\ km/s$ [1] and the addition from Earth's gravity at the moon is $1.4\ km/s$ compared to the escape velocity from earth's surface which is $11.2\ km/s$ which does not including the resistance while traveling through Earth's atmosphere.

Producing fuel at a escape velocity of $3.78\ km/s$ instead of $11.2\ km/s$ is obviously beneficial as the mass to lift the first $7.5\ km/s$ from Earth greatly reduce the payload for the rest of the mission if that strategy is used. Direct environmental effects from the exhaust gases are also moved outside Earth's natural cycle.

The draw-back of establishing a lunar base and mining fuel from the Moon is that the initial cost is very large and that there is some uncertainty whether it is feasible at full scale but it is expected to repay itself and also contribute to lunar research, deep space exploration and the exploration of space by private companies. The feasibility of more detailed technical challenges are expected to be handled in a later stage if this concept is pursued. This report examines large scale feasibility.

### 2.3 Mission summation

The table 1 summarizes some basic facts about the mission by Team Red. The goal and the budget are to be discussed in this report later. The crew of four astronauts is composed of one pilot, two mission specialists, and one doctor. Here, a "doctor" is defined as an astronaut who has worked in medical fields previously and specialize in these fields during the mission. Today's astronauts living on ISS are dependent on telemedicine from Earth, and sometimes there is a doctor on board depending on the composition of the crew. It might be fine to have no doctors on board the ISS, as it takes only about 3 hours and 30 minutes to return to the earth normally [15] and one can choose an option to return to the earth in case of serious health problems. However, if any emergencies with health happens on the Moon and immediate treatments needs to be performed, there is almost no option to go back to Earth, as it takes more or less three days [14]. Therefore, it is important in missions on the Moon that a crew can be independent to a certain degree from a medical perspective. Moreover, this mission aims to send a human being back to the Moon for the first time since the Apollo missions forty years ago, which entails that no one knows exactly what is going to happen there. Having a doctor in a crew therefore is a reasonable measure to minimize concerns regarding medical issues and to maximize the capability of such research.

The table 1 also mentions several basic facts about the DSG, the lunar base and the transport vehicle traveling between DSG and the lunar base, which are to be explained in the reports from each respective group.

TABLE 1: Basic facts about the mission.

| | | |
|---|---|---|
| Mission | Goal | Water production on the Moon |
| | Crew | 4 (1 pilot, 2 mission specialists, 1 doctor) |
| | Estimated cost | 126.44 billion USD |
| DSG | Orbit | Near Rectilinear Halo Orbit, L2 southern orbit |
| | Configuration | 6 modules (at full capacity) |
| | Pressurized volume | 480 $m^3$ |
| | Mass | 62100 kg |
| | Capacity | 4 people |
| | Power | Solar power |
| Lunar base | Placement | Shackleton Crater (near South Pole) |
| | Dimension | $\phi$ 6 m dome |
| | Power | Solar, nuclear power |
| | Total mass | $\sim$ 10000 kg |
| Transport vehicle | Total time | 2h 38min (from DSG to the Moon) |
| | Payload to surface | 4300 kg |
| | Fuel | Liquid $O_2$ (LOX), liquid $H_2$ (LH2) |
| | Dry mass | $2 \times 13500$ kg |

## 3 Conceptual sketch

The final goal of our mission is to produce enough water for a crew, and it is composed of three phases. As stated earlier, it is assumed that a pre-study on the Moon has already been done by satellites and/or rovers on the lunar surface, and that a sufficient amount of water has been found around the poles of the Moon and more particularly close to the *Shakleton crater*. Therefore, the method to search for water on the Moon will not be considered in our mission.

The target of phase 1 is to set up a lunar base which can accommodate the crew of four. Setting it up is done automatically by rovers/robots and by using 3D printers, which will be described in detail in the report written by Lunar Exploration group.

Phase 2 starts after constructing the lunar base, aiming to install a pilot plant for water extraction. This phase aims to confirm if the method to extract water which has been validated on Earth also functions well on the moon. Since installing a plant may require some help of man, a crew of four astronauts will be sent to the DSG to configure it and then ascend to the Moon at the beginning of phase 2 and start living in the lunar base which has been set up in phase 1.

After confirming the method of extracting water in phase 2, final water production will be addressed in phase 3. Specifically, it is aimed to produce enough water for life support for a crew of four.

As it can be seen from these three phases, our mission is basically specialized in water production on the moon by utilizing some new technologies such as 3D printer. After finishing the mission, it is anticipated that other missions on the Moon such as exploration and production of fuel and more energy will be conducted.

## 4 Logistics

Missions with human spaceflight require some kind of support from Earth unless there is total recycling or enough resources to not require additional input into the system within a relatively long time frame.

A trip to Mars would not be able to be resupplied as easily as the ISS and the same goes for a base around the Moon. The payload capacity is roughly one third to the DSG in lunar orbit compared to ISS in lower Earth orbit.

The initial and continuous logistical plan can be seen in Figure 1. The only logistic part not shown is the continuous refueling of the DSG and the lunar lander from Earth.

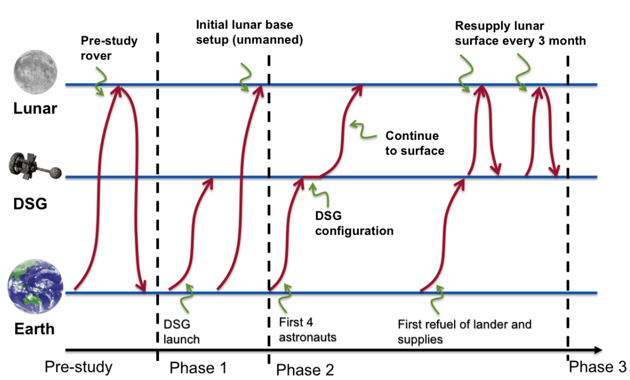


Fig. 1: Logistic plan for the mission

This mission starts at Phase 1 where a pre-study has been conducted which has found a good sight to build the lunar base and also where it is possible to extract water and put up a solar power plant in the close vicinity of the base at the Shackleton crater.

If it is necessary to bring back samples from the surface then the pre-study lander has to return to ISS or to Earth depending on where the analysis can be conducted. This mission is unmanned.

### 4.1 Initial launches

In order to launch the initial system which weighs roughly 100 tons, 5 Falcon Heavy Rockets from SpaceX [10] are required. The payload that is possible to bring to lunar orbit has been estimated by the DSG group.

The DSG is launched first in what has been become Phase 1 of the mission. Shortly after that the lunar base can be launched directly to the moon in order to save fuel and be able to do the most effective transfer.

While launching the configuration crew to the DSG then no fuel has been launched for the two lunar landers which means that additional launches are required before the crew can go down to the lunar surface after configuring the space station.

### 4.2 Operational launches

Each crew cycle is going to be six months long in Phase 2 unless any problem is found which needs to be resolved before extending the mission time cycles. During these six months two landings has to be done by the lunar lander to resupply the crew with food and water (which can be convert to oxygen as well). The lander has capacity to bring back samples and/or trash to the DSG.

The operational payload required is about 45 tons every 3 month which means 9 launches a year. During operational condition the DSG will be resupplied with evenly distributed launches.

### 4.3 Future launches

When the mission is able to produce different levels of water (sufficient for oxygen production, hygiene water and drinkable water) then the mission doesn't need as much supplies from the DSG but the fuel for landing the lander is still fairly high so stocking up more supplies in the lunar station is possible as the diet requires less supplies from outside the lunar system.

Eventually when the lunar surface becomes self supported in terms of water and fuel, resources can be brought up to the DSG to later refuel space missions past the moon.

## 5 Communication

Communication is one of the main requirements of human space vehicles. The chosen system is used for video, data and audio communication together with command up-link and telemetry down-link to the ground or to relay satellites. According to NASA, high-rate and reliable communications should be provided by the vehicle. [2]

### 5.1 Reliable communication system

Since day one in space history, radio frequencies (RF) have been used in order to communicate. It started with Sputnik-1 with frequencies between 20 and 40 MHz. Then, it continuously increased due to a growing demand and restricted bandwidth. A recent example is the ISS communication system: a RF-system, using S-Band (2 - 2.7 GHz) and Ku-Band (10.7 - 18.1 GHz) duality and relay satellites to communicate [3]. It is a proven reliable technology and is therefore the main system of communication. These radiowaves are efficient for distances in the order of magnitude to ISS (400 km), but when it comes to deep space, shorter wavelengths have to be considered in order to increase the provided bandwidth. The current state-of-art deep space-communication is the dual RF-system using X-Band (8-9 GHz)/Ka-Band(23-27 GHz) [3]. X-band is very similar to S-band in utilization (many spacecraft carry complementary S-Band and X-band transmitters) and is mainly used for communication, both up-link and down-link, whereas Ka-Band will be used to send data, mainly for down-link.

### 5.2 High-rate communication system

One may think that RF data rate is not sufficient enough for that kind of distance, particularly considering the final objective of going to the Martian system. The need of a new solution may be covered by optical communication systems. Thanks to a much smaller wavelength, thousands of times smaller [5], optical communications presents several advantages, in relation to the RF solutions. Firstly, they have a much larger bandwidth, as a result of the correlation between bandwidth and signal frequency. Besides, it is an unlicensed bandwidth which offers a solution to allocation restrictions. Then, lasers have a smaller beam divergence. Since the signal gain is a function of beam divergence (see Equation 1), one obtain the same gain with both RF- and optical system but with less mass, volume and power requirements for the latter. NASA mentioned in 2014 that optical communications could achieve 50% savings in mass and 65% savings in power which either decrease costs and increase mission life time or simply mean more mass and power for others scientific instruments [6].

$$\frac{Gain_{Optical}}{Gain_{RF}} = \frac{4\pi/\theta^2_{div(Optical)}}{4\pi/\theta^2_{div(RF)}} \tag{1}$$

with $\theta$ the beam divergence angle. For same mass, volume and power requirements, $\theta_{div(RF)}$ is much larger than $\theta_{div(Optical)}$ which means that $Gain_{Optical}$ is much larger than $Gain_{RF}$.

Finally, the main result of interest here is the data rate. The best data rate (down-link) obtained for RF-system was $100$ Mb/s, in 2009 with the Lunar Reconnaissance Orbiter. In 2013, the Lunar Laser Communications Demonstration obtained a data rate of $622$ Mb/s [4]. This order of magnitude difference between RF- and Optical system means that for deep space mission, something sent in minutes with lasers would take hour(s) with RF.

As one can notice, optical systems are not widely used today, mainly because it is a new technology that needs to be proven reliable but also because it has drawbacks, or at least challenges, listed below [5] :

- Absorption and scattering loss through Earth's atmosphere (mainly due to fog, snow, rain)
- Atmospheric turbulence causing beam wander, spreading or scintillation
- Cloud blockage
- Pointing loss: narrow beam is an advantage, but high directional link can be risky in case of a slight misalignment

These challenges are the reasons why Lasers are still under development, in order to obtain reliable technology at reasonable costs.
To conclude, DSG and Lunar base will then present combined RF-Optical systems satisfying both reliable aspect and high-data rate and will then be used for new communication technology demonstrations.

### 5.3 Other satellite needed

With the DSG orbiting in the L2 near rectilinear halo orbit (NRHO), there will be a down-time of no communication direct line between DSG and the Lunar base. For this orbit, the south pole coverage by the DSG can reach up to 86% [7]. With a period of 6.7 days, the down-time (less than a day but countable in hours) can not be neglected which means that at least one secondary satellite is required to obtain a full-time communication. The next issue is then to decide where, in which orbit, to put this relay satellite. There are plenty of opportunities, but one simple solution would be to choose DSG's orbit. In that way, one may think that DSG and this communication satellite could be brought in the same payload before being separated once in orbit. This solution may be the most cost-effective.

## 6 Medical Aspects

Medical aspects are one of the important issues to be addressed in every manned space mission, especially when it is a long-term mission. The distinct environment in space and on the moon often cause several problems on astronauts physically. In this chapter medical aspects in space environment are discussed in two parts; radiation and loss of bone.

### 6.1 Radiation

What makes space environment so distinctive and harsh is the existence of radiation. The radiation dose can be quite high on the Moon since there is nearly nothing which can protect astronauts from severe radiation, while humans are partly protected from them thanks to the magnetic field and atmosphere on Earth.

There are mainly two types of radiation which have influence on an astronauts' body; *Solar Particle Events* (SPE) and *Galactic Cosmic Rays* (GCR). SPE is produced irregularly when there are Solar Flares and/or Coronal Mass Ejections from the Sun, whereas astronauts are constantly exposed to GCR, which is produced outside the solar system [20]. Therefore, the first remark is that protection against GCR should be addressed with deep consideration, since GCR is the main source of accumulating radiation dose during the mission.

The radiation dose during EVAs should also be investigated, since astronauts are exposed to radiation with only a relatively thin spacesuit. An investigation was done by Adamczyk et al. (2011) to calculate how much radiation an astronaut will get during EVAs and throughout missions [17]. What they found out was that the effective radiation dose during EVAs per hour is estimated to be $4.035 \times 10^{-2}$ mSv/h. If EVAs are conducted 24 hours a week, assuming that 8 hours of EVAs are done almost every other day, the total GCR exposure during six-month mission is estimated to be about 26 mSv. This radiation dose is sufficiently low compared to the limits defined by NASA (see the Table 2). The research also estimated the SPE radiation dose to be $1.033 \times 10^{3}$ mSv for one SPE, assuming that it is the same scale as the one in August 1972. If astronauts receive 20% of total amount, it exceeds 200 mSv, which is quite close to the limit for 30 days. Therefore, feasible countermeasures are necessary to prevent acute short-term radiation doses. More plausible forecast of solar weather and feasible evacuation strategies should be considered.

### 6.2 Bone Loss

One of the biggest differences between Earth and space is gravity. The gravity on the lu-

TABLE 2: NASA's limits on radiation exposure. [1]

| Exposure Period | Limits [mSv] |
|---|---|
| 30 days | 250 |
| 1 year | 500 |
| Career, from age 25 | 1000 (female) |

nar surface is 1/6 of the gravity on Earth, which can cause several physical problems on astronauts such as loss of bone. A measurement found out that the BMD (Bone Mineral Density) of more than half of the astronauts who stayed in space for six months decreased by 1.5%/month, even though they worked out during their stay [18]. Although there is gravity on the Moon, it is not assumed to be enough to sustain the astronauts' BMD. Effective countermeasures would be to use ARED (Advanced Resistive Exercise Device) as a device to exercise, and to dose astronauts with Bisphosphonates, a medicine used to prevent the loss of BMD and to treat osteoporosis. There was an experiment conducted on the International Space Station to study the effectiveness of ARED and Bisphosphonate in space, which made it clear that the loss of BMD could be diminished by using both ARED and Bisphosphonate [19]. However, the effectiveness of Bisphosphonate itself is still obscure, since there was no experiment conducted without exercise. Further studies on medical aspect in space are anticipated both before and during the mission.

## 7 Cost Analysis

In order to estimate the feasibility of an early stage proposal the cost of it is most definitely crucial.

There are different ways to estimate the cost of a space mission, or any project in general. The first and most intuitive way is to look at all pieces of a project and then just add them up to the whole price tag. These methods are called bottom-up as they start at the bottom and sum it up. The problem with these methods is that they require a lot of knowledge about the project and its details and the cost of those details. In order to address the cost at a stage as early as the one in this report another method is required.

The other method is to start at the big picture and estimate the cost of the big parts which will be the base to include extra costs that are not directly visible on the end result. These methods are called top to bottom as they start at the top with the big picture. These methods are not always the most accurate but they can be used at a conceptual stage to estimate the cost of the entire mission before proceeding with, or scraping the idea.

This cost analysis is based on the Deep Space Gateway (DSG), lunar lander and the lunar base for its cost analysis. All these systems have individual development and production costs along with operational costs that can be separated between the missions.

Models developed before the *NASA - Johnson Space Center*-model below were only considering mass and the mission characteristic. In order to incorporate a more detailed analysis several other parameters were introduced in a model based on regression analysis.

### 7.1 Advanced Mission Cost Model

The Advanced Mission Cost Model (AMCM) has been developed by NASA [1] and it is founded in statistical costs of previous space missions. The cost is depending on type of mission, its innovativeness and technical difficulty along some other factors which are explained below.

The model calculates the development and production costs but not the operational costs as they heavily depend on the type of mission and these costs can usually be estimated by making assumptions and using some mission insight.

The model first takes care of direct development and production costs which are the costs of the piece of equipment that will be launched into space. With these costs the associated costs around other functions can be calculated. The additional development costs consist of feasibility studies, working sites, astronaut training, launch & landing development costs and fees.

### Development & Production

The Development and Production costs are calculated by the following formula:

$$C = \alpha Q^{\beta} M^{\Xi} \delta^{S} \epsilon^{(1/(IOC-1900)} B^{\phi} \gamma^{D} \tag{2}$$

The constants in Equation 2 are explained in the Table 3 while the parameters are explained in the text below.

TABLE 3: Cost analysis input constants

| Parameter | Value |
|---|---|
| $\alpha$ | $5.65 \times 10^{-4}$ |
| $beta$ | 0.5941 |
| $\Xi$ | 0.6604 |
| $\delta$ | 80.599 |
| $\epsilon$ | $3.8085 \times 10^{-55}$ |
| $\phi$ | $-0.3553$ |
| $\gamma$ | 1.5691 |

The parameters in the formula are $Q$ which is *Quantity*, $M$ is *Mass*, $S$ is *Specification*, *IOC* which stands for *Initial Operational Capability*, $B$ is the *Block number* and $D$ states the *Difficulty* or complexity. All these parameters are further explained below.

*Quantity* is the number of products or systems that is produced. If there are mock-ups, simulators or systems that are destroyed in testing then they should be included as additions in the *Quantity*. In Equation 2 $Q$ is raised to the power of $\beta$ where $\beta < 1$ which means that the cost doesn't increase linearly (it gets cheaper with increasing Quantity).

$C(Q = 2)/C(Q = 1) = 1.509$ so the cost of a second equal system is $50\%$ of the first.

The *mass* is the dry mass of the system in pounds. The exponent of the mass in Equation 2 is similar to the one for the quantity thus a similar behavior between increasing mass and quantity.

The *specification* number is dependent on what kind of system it is. $S$ is given in the range $[2.0; 2.5]$ for human spaceflight missions and is the power to $\delta$ which is $= 80.599$. Therefore does the mission type affect the cost greatly. $C(S = 2.4)/C(S = 2.1) = 3.71$.

A planetary lander has the value $2.46$, a planetary mission $2.39$, human reentry $2.27$, rovers $2.14$ and human habitats $2.13$.

*IOC, Initial Operational Capability*, is the first year the system is operating and has 1900 as a reference year which can be seen in Equation 2. Increasing year increases the cost of the mission by this model.

The *block number* is which number in line the system is compared to its precessors. A completely new system has Block number 1 and a second mayor change to a system will get block number 2. An increasing number decrease the total development and production cost.

The last variable is the *difficulty* factor. It ranges from $2.5$ which is "*extremely difficult*" to $-2.5$ which is "*extremely easy*" with $0.5$ increments and $0.0$ being "Average". The difference between the *hardest* and *easiest difficulty* is a factor of $9$ and the difference between *easiest/hardest* and *average* is a factor of $3$.

### Mission parameters

The different variables chosen are presented in Table 4. Not that ***M*** needs to be converted to $[lb]$ for Equation 2 to generate a cost in million of US dollars (1999).

TABLE 4: Parameters production & development

| | DSG | Lunar base | Lunar Lander |
|---|---|---|---|
| ***Q*** $[-]$ | 1 | 1 | 2 |
| ***M*** $[kg]$ | 61000 | 10000 | 13500 |
| ***S*** $[-]$ | 2.13 | 2.39 | 2.46 |
| ***IOC*** $[yr]$ | 2025 | 2025 | 2025 |
| ***B*** $[-]$ | 2 | 1 | 1 |
| ***D*** $[-]$ | 1 | 1 | -0.5 |

The *Specification* parameters are *human habitats*, *planetary mission* and *planetary lander* in the same order as stated in the table.

The *block number* and *difficulty* goes hand in hand. The block number can be set to $1$ for the DSG for example or above $1$ for the lander but that would make a change in difficulty.

For this mission the *DSG* is seen as a successor to ISS but not to its precessors Freedom (planning) and MIR as much time has passed and the resemblance is questionable. It is estimated to be rather difficult to put a space station around the moon as there are radiation exposure which would be much lower in *lower Earth orbit* due to the magnetic field around Earth. There are also distant related difficulties with a base around the Moon (e.g. logistics and communication).

The *Lunar base* is a first of its kind and the block number is 1 while the difficulty is rather high with, for now, some conceptual technology that has not been proven to work yet (3D-printing). There is gravity, however, which makes it easier in comparison to a space station. One difficulty, though, which doesn't occur in space but is present on the Moon is the dust, which will wear down the equipment. The radiation is still a problem as there is no atmosphere on the moon nor magnetic field.

At last the *Lunar lander* is estimated to be a first of its kind with a lower difficulty compared to the DSG and the Lunar base. Human lunar landers have been made before but not with the same capacity and requirement for robustness as is needed for this mission. Therefore is the block number set to 1 as the concept is new even though landers already exist. The difficulty however is not very high as there have been landers previously which are both human carrying and not.

### *Additional development costs*

Additional costs outside the design, development, test, evaluation and production in the later phases are usually based upon these and NASA has some generic values for human spaceflight [1].

TABLE 5: Additional cost

| **Parameter** | **Value** | **Applies to** |
|---|---|---|
| Advanced development | 3.5% | D&P |
| Phase A conceptual studies | 0.3% | D&P |
| Phase B definition studies | 3.5% | D&P |
| Program support | 15.0% | D&P |
| Operations cap. dev. | 15.0% | D&P |
| Launch & Landing | 8.0% | D&P |
| Program management | 10.0% | All |
| Fees | 10.0% | D&P |

D&P in Table 5 stands for *Development and Production*.

*Advanced development* costs are the cost associated to the feasibility study which conclude whether the technological solutions are possible.

*Phase A conceptual study* is the first study phase in the development which NASA calls *Phase A*. The program has Phase A to D during development and Phase E is when the program has started operating. Phase C and D are dedicated to development (mainly C) and testing (mainly D).

The *definition studies* in Phase B is further work on the conceptual study from Phase A which has passed certain tollgates and been accepted into further investment. The percentage of the wrap factor indicates the magnitude of Phase A and B.

*Program support* is support budget that finance areas outside the main contractor's agreed financial support. It contains engineering analysis, management and overseeing of projects, testing and verification, support software and simulation.

*Operational capability* is the cost related to preparing for missions. It is preparatory work before the mission, planning of crew training, preparing operational support etc.

*Launch & landing* are costs related to preparing for launch and landing at already existing sites. It includes changes and adaptation to the launch and landing control center.

*Program management and integration* are the management and integration costs across all projects covered by the mission. It adds on 10 % to all development and production costs (including other extra costs stated here).

The fees are human spaceflight specific and apply to the development and production costs.

## 7.2 Operational costs

The operational costs are expenses that are needed over time to run the mission. These costs are not included in the *AMCM* but one of the extra costs affect all costs (including operational ones).

For this mission the operational cost for the stations themselves and ground control are neglected as the launch costs for new supply is so high. The launch costs are rather easy to estimate in comparison to the others which makes the analysis doable with sufficient accuracy. In order to resupply the DSG Falcon Heavy rockets [10] are used. These can carry $63.8$ $tons$ of payload to LEO which, by comparing other lunar shuttles, translates into $20$ $tons$ to *L2 southern halo orbit* where the DSG is positioned. The launch cost provided by *SpaceX* is $\$150$M for a non-reusable rocket. Since the required payload is known along with the mass of the initial system the initial launch costs and operational launch costs can be calculated.

On average every 3 month $2150$ $kg$ payload needs to be brought down from the DSG by the lunar lander to supply the astronauts on the lunar surface. The lunar lander also needs fuel to go to the lunar surface and a trip with a $2150$ $kg$ payload requires $43000$ $kg$ of fuel. Which means that every 3 month almost $45$ $tons$ of payload needs to be transported to the DSG. This means 9 Falcon Heavy Rockets every year and an annual cost of $\$2.03$bn. This assumes that the Falcon Heavy rockets are utilized to their full potential and spare resources can be stored in the DSG until the next Lunar landing.

### 7.3 Total costs, comparison and analogy

The total cost of the mission are presented in Table 6.

TABLE 6: All costs

| **Area** | **Cost** [$bn$ USD] |
|---|---|
| ***DSG*** D&P | 18.78 |
| ***Lunar Base*** D&P | 22.79 |
| ***Transport*** D&P | 29.01 |
| **Total D&P** | **70.58** |
| Advanced development costs | 1.59 |
| Concept phase A | 0.14 |
| Development phase B | 1.59 |
| Program support | 6.82 |
| Operational capacity | 6.82 |
| Fees | 4.54 |
| Launch & landing | 3.64 |
| **Total additional costs** | **25.13** |
| Initial launch cost | **1.10** |
| Annual operational cost | 2.03 |
| Reserve (35%) | **27.60** |
| **Total mission cost** | **126.44** |

The **bold** numbers are the ones added up to the total initial cost. The reserve budget is depending on risk and difficulty of the mission but is recommended to be between $30$ and $40\%$ for human spaceflight missions and is therefore put as the average.

The cost of \$126.44bn is converted to 2018s dollar worth instead of the value of 1999 that the model gives as an output.

The International Space Station (ISS) has accumulated a total cost of $100$bn USD since it was built (2013) [11]. A quick Google search however gives the number $150$bn USD. However the magnitude is comparable to this Deep Space Gateway mission and it can be seen that a mayor human space flight project is expensive. The Apollo mission had a total cost of $25.4$bn USD in 1973 [12] which is $174$bn USD adjusted to today's value with NASA's inflation index [13].

## 8 Political and societal aspects

If we could simplify the discussion about political and societal aspects of space exploration, it could be summarized to the following questions: who pays the bill for space exploration? Who owns the rights of what is discovered? How can the results be beneficial to the society or mankind as a whole?

It is important to address the question of why people want to expand their frontiers and explore new worlds in the first place. Exploration means risk and uncertainty, as we are traveling into the unknown. People may get hurt or even killed and the involved costs are difficult to predict in advance. Moreover, there is most probably no financial return in the first exploration expeditions to a new destination.

According to Dr. Neil Degrasse Tyson, Astrophysicist and Director of the Hayden Planetarium in New York, there are two main drives in peoples mind to explain the urge for exploration [16]. The first one is *I dont want to die*, meaning that a major threat may be the cause of whole nations concentrating in a common goal. As seen during cold war and the race for the Moon, enormous amounts of resources were made available from both USA and the

Soviet Union to develop the required new technology to first put a man on the Moon. It was a matter of showing technological supremacy and thus, power.

A second driver can be summarized in *I dont want to die poor*, where Dr. Tyson means that economic pressure to find new sources of resources or new routes to them. That was the reason of the journeys that end up discovering the American continent a few hundred years ago. Spain wanted to find a new way to get to India different from that used by their enemies, and in such way to control the valuable spicery commerce to Europe.

George Mallory gave a third reason for human endeavours into risky adventures to the unknown as he answered the question why he wanted to be the first to climb Mount Everest: *Because it is there*. That simple answer may translates the curiosity, need to find answers and thirst for knowledge and understanding which are so typical for human spirit.

Historically, all big exploration movements have always been led and funded by State governments. So was the case of the voyages of Christopher Columbus, sailing in the name of the Crown of Castille, so was the case of the race to the Moon driven by one side, the United States of America, and by the other side, the Soviet Union. Those were huge human endeavours that required enormous allocation of resources in proportions that only nations would have the power and financial condition to achieve, as well as to accept the kind of risks involved in those big explorations.

Once the route to the explored object had been secured and the risks and possibilities duly assessed, then it was time to open the door for exploitation to private initiative. While the first exploration phase goal is to learn and discover if there is anything interesting there, the second phase goal is to exploit what was previously discovered and to make money out of that. Private companies are generally more efficient than government structures in organizing themselves to produce profit, but they only get interested in participating if there is a favourable proportionality between risk and profit.

According to that model of governments financing the exploration of new frontiers and private companies carrying out its exploitation, it should be to expect that the next steps in space exploration, namely return to the Moon and human flight to Mars, would be accomplished by one of the major space agencies or a cooperation among them. Even though man have already been on the Moon before, nothing has been found there that would justify an economic exploitation of a certain resource by a private organization. Moon exploration is still, as well as a Mars mission, an activity with no promise of future profit.

However, there are nowadays private corporations, with budgets comparable to those of entire nations, that show interest in space exploration. If one or some of those corporations could build a business case envisaging interesting enough financial returns in the future, they would possibly be able to assume those risks involved in the first phases of space exploration where no return is expected.

Thus, a new model may be being designed, where private initiative could take over the role previously played only by public entities. One big advantage of that is that the decision-making structure is much sleeker and faster than that of a government, where budgets must be politically approved by a senate or parliament. Another possible alternative could be that of public and private initiatives joining forces and spreading the costs and risks.

One important issue that should be addressed at some point to avoid and/or regulate future disputes is the question of property and exploitation rights. Imagine, for instance, that one asteroid made of gold or any other valuable material is found, and someone decides to mine it, bring the production back to Earth and commercialize it. Who owns the asteroid in first place? Who would be allowed to exploit its content? Should the introduction of the alien material to Earth be limited in some way or not? Who should participate in establishing the regulation of Space?

All those questions are not simple to assess and probably there are no straight forward answers to them. A lot of discussions and negotiations should be carried out before reaching a global consensus and agreement on a regulation for space exploration.

## 9 Off-Nominal Case

For missions off-nominal case, we decided to study the situation where the DSG is lost for some reason (major malfunction, total power loss, pressure loss due to meteorite collision, etc) and the crew is on the Moon preparing to depart back to Earth at the end of their mission.

The DSG has three main functions that in this case wont be available anymore:

- it serves as an intermediate platform to allow docking of the lunar transporter coming from the Moon surface, and to allow boarding the re-entry vehicle for the return flight to Earth;
- it is an extra storage place for all needed resources as fuel, oxygen, water and food;
- it works as a communication satellite linking the Lunar Station to Earth.

With the loss of DSG, the major problem is that the crew has no means of returning to Earth, as they presumably wont have access to the re-entry vehicle. They will have to stay in the Lunar Station waiting for a rescue mission to be prepared, launched and to arrive in lunar orbit.

The first requirement risen from this off-nominal case study is that a rescue crew and vehicle shall be trained and prepared for that eventuality. The elapsed time between the SOS signal from the Lunar Station and the launch of the rescue mission from Earth shall be well known and as short as possible. The rescue vehicle shall be able to rendezvous and dock with the lunar transporter in a pre-established orbit. And, of course, there shall be enough capacity in the rescue vehicle for both crews to make a safe return journey and re-entry to Earth.

The second requirement is concerning the availability of resources in the Lunar Base. As the crew will have to wait on the Moon for the rescue mission arrival, there should be enough resources for that extra period. Therefore, an emergency supply storage shall be established since the beginning of the mission to provide resources for the crew during the waiting period for the rescue. Besides, in case the normal supplies run low, for some reason, the mission shall be resupplied or aborted rather than for emergency supplies to be used. The amount of emergency supplies is depending on the time it takes to send an SOS-signal to docking with the rescue vehicle and thereby getting resupplied from Earth before returning home.

The third and last requirement is concerning communication. As there is a certain period in the DSG orbit where it cannot communicate with the Lunar Station and thus the connection to Earth is temporarily lost, a communication satellite has been considered to cover up during those eclipse periods of DSG. Considering the off-nominal possibility, an extra communication satellite is required as back-up, so that communication with Earth is guaranteed even is DSG in non-operational. Full-time coverage is not necessary if the DSG is lost but the worst possible down-time of communication needs to be considered while deciding how long the emergency supplies should last.

## 10 Conclusion

This study together with those carried out by Red Teams DSG, Lunar Station and Transport groups shows that the lunar exploration using the Deep Space Gateway Station as start point and support is conceptually feasible.

It was important to very well define right from the start the point where the study would depart and what we wished to achieve at the end. It was agreed that our mission starts with the knowledge of where and how much water is to be found on the Moon. Therefore, at least one previous unmanned mission will be required to confirm the existence of water and map the region to be explored. The conclusion of the mission was agreed to be the installed capability of producing enough water to supply the crew, so the station could become autonomous and the astronauts could continue their exploration activities independent from external supplies, other than food.

The technologies considered in this study are in general evolution of known and field proven ones. The DSG was dimensioned based on the ISS and its operating systems; the Transport

Vehicle, though with much larger payload capability, has the same basic concept as former lunar landers; the Lunar Station main systems are based on those used in ISS and in previous unmanned missions. What will be completely knew is the 3-D printing of the Lunar Station structure using lunar regolith, described by the Lunar Group, that will occur in Phase 1. To mitigate that uncertainty the 3-D printing process, a test shall be included in the unmanned previous mission in preparation for this one.

Another new technology is the process of mining and recovering potable water from the lunar soil. Due to the uncertainties, we found important to install during Phase 2 a pilot plant to test the process *in situ*. Only when the process is completely understood and operational, the final water production plant shall be installed in Phase 3.

Other new technologies will be used in parallel to conventional solutions, as the laser technology for communication, mentioned earlier in section 5.2 and the Flywheel Energy Storage System suggested by the Transport Group to be used in the Transport Vehicle.

Although the estimated costs of the mission seem high at first view, they are in the same order of magnitude of other recent space projects. Other interesting aspect to be taken into account is the fact that there are nowadays private organizations with annual budgets much higher than the costs involved in space exploration and some of them are even interested in it, as Amazon and Google, to mention a few. Space exploration is taking another profile with those new players other than only national space agencies.

The time required for the mission to be launched depends on the funding and how strong is the flow of capital into the project. However, based on ISS project and considering the development of engineering activities to demand around three years and manufacturing, testing and assembly in space to take other three to four years, with some overlapping among them the total time required before launching the mission would be around five to six years after receiving the go-ahead signal. That is also considering that the project is run in a normal pace and the three groups DSG, Transport and Lunar Station run in parallel. That period would also fit the period of selection and training of new astronauts, if required.

Once the mission is completed and the Lunar Base can provide conditions for the astronauts to explore the Moon, the next goal for future missions could be either to find raw material to produce fuel or to enhance water production to a level where oxygen and hydrogen could be generated in volumes sufficient to propel spacecrafts. That propellant would then be stored in the DSG, which could serve as a space fuel station for spaceships, for instance, on a Mars mission.

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