Lunar base - Operation

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***Abstract*—In the year 2037, the Artemis program successfully concluded, albeit with some delays, and the first people are on their way to Mars. However, the scientific potential of the moon has become increasingly apparent, and a decision was made to build a large research station on the moon. Our team was tasked with designing the Lunar Research Station, which will be similar in size to the Amundsen-Scott Station in Antarctica and will house up to 50 people. Our focus was on planning the operations of the mission, which included excavating in-situ resources, communication, station objectives and time management, timeline for fully operational station and maintenance. In this report, we provide an in-depth analysis of each area. Our work will be instrumental in the establishment of a permanent human presence on the moon and the advancement of space exploration.**

I. Introduction

THE year 2037 marked the successful conclusion of the Artemis program, which aimed to return humans to the moon and establish a sustainable presence on its surface. With this achievement, the focus of space exploration has now shifted towards other celestial bodies, with the first people on their way to Mars. However, the scientific potential of the moon has become increasingly apparent over the years, and there is a growing interest in establishing a permanent human presence on its surface.

In response to this need, it has been recently decided to build a large research station on the moon, similar in size to the Amundsen-Scott Station in Antarctica, to house up to 50 people. Our team, the RED Team has been tasked with designing this Lunar Research Station, to be operational from the year 2040. A critical aspect of this mission is the planning of its operations, which will be the focus of our report.

When it comes to building a lunar base, the primary goal is to sustain oneself, including communication availability. This is one of the biggest challenges facing space exploration, as bringing everything needed from Earth is simply not practical or sustainable. The moon, with its unique environment and available resources, offers a promising location for establishing a self-sustaining human presence.

In addition to its potential as a base for deep-space exploration, the moon can also be utilized for excavating resources, including hydrogen, which can be converted into rocket fuel. This is a crucial component of our project, as the goal is not only to establish a research station on the moon but to also enable further exploration into the solar system.

Moreover, this station will have an important research purpose, by working into deep space radiation, fractional gravity or even long wavelength astronomy.

Our team has carefully analyzed and developed plans for the various operations of the mission, including excavating in-situ resources, communication, station objectives and time management, timeline for fully operational station and maintenance. In this report, we provide an in-depth analysis of each area.

II. In situ resources

A. *Lunar resources on the location of the base*

Even though the Moon is a harsh environment, many resources can be found on site and be used to provide energy, building facilities or necessary needs to fulfill the sustainability of the base.

The first necessary resources that can be listed is the solar power. As one lunar day lasts 27.8 terrestrial days, periods of two terrestrial weeks of sunlight are succeeded by periods of two weeks of darkness on the moon. However on the south pole, where the station will be settled, illumination is quasi constant, with an average of 84% [1] which would make solar arrays very efficient on this site as they could work quasi permanently.
However not all the south pole sees its surface illuminated because of the many craters that can be found on the Moon. The importance of these craters, and especially of the ones on the poles, lies directly in the fact that they are permanently shadowed, because of the low inclination of the moon with respect to the ecliptic plane. This is something that can be found near the station position with the Gerlache crater, and one of the reasons for this choice. It has been shown by different missions [2] that water under the form of ice can be found in these shadowed craters because of the very low temperature, preventing it from the sublimation. It would then be possible to find water in craters to excavate it.

In addition to ice, many minerals can be found in the lunar soil and the regolith. To explain denomination, lunar soil refers to grains of a size ranging from 40 µm to 800 µm and lunar regolith for particle of higher size according to [3]. Due to the position of the base, it is sure that it will be possible to excavate in areas called *maria* which are dark areas, as opposed to *highland* which are bright areas. However it might be also possible to excavate also in the *highland*. The chemical composition of the lunar surface can be described as followed according to [4] and presented in Table I :

Hence one can see that it would be profitable to excavate in the *maria* to find iron. However it would be more efficient to

TABLE I: Minerals

Compound	Composition	
	Maria	Highland
SiO_2	45.4%	45.5%
Al_2O_3	14.9%	24%
CaO	11.8%	15.9%
FeO	14.1%	5.9%
MgO	9.2%	7.5%
TiO_2	3.9%	0.6%
Na_2O	0.6%	0.61%

excavate in the *highland* if the goal is to find aluminium. In addition other metals can be found such as titanium, silicon, calcium and magnesium.

Moreover, minerals that can be either silicate, oxide and sulfide are present on the lunar surface. In addition to these, some elements that are rare on Earth can be found more abundantly on the moon, such as Helium 3, an isotope of helium, which has the potential to be used for nuclear reactions, to provide energy to the station.

B. Ice Excavation

For the excavation of ice different ideas and methods have been considered and compared.
In response to the "Break the ice challenge", a competition launched by NASA to design new Technologies and methods to mine ice on the moon, various ideas and new revolutionary methods have been developed. The ROCKET M [5] (Resource Ore Concentrator using Kinetic Energy Targeted Mining) rover sketched in Figure 1, designed by Masten Space Systems, offers a unique way to dig and collect water. It utilizes a 100 lbf rocket engine under a pressurized dome to enable, by repeated rocket fires, the excavation of a crater more than 2 meters below the lunar surface, these result in the dispersion of volatile materials, which are then funneled through a vacuum-like system that separates ice particles from the remaining dust and transports it into storage containers. According to Masten Space Systems, this rover will be able to dig up to 12 crater per day, and collect around 100 kg of water per crater, amounting to a maximum of 1.2 tons per day. The advantages of this solution are many, it would provide the station a rapid and effective way to collect water, with limited need of help by humans (only maintenance aspect) since it can work on its own, a really high life-expectancy of the rover considering that the stored water can be electrolyzed into oxygen and hydrogen, utilizing solar energy, which would continue to power the rocket engine for more than 5 years of water excavation. The characteristics of ROCKET M are listed in Table II :

TABLE II: Rocket M Properties

Rover	Mass	estimated ice excavated per day
ROCKET M	1118 Kg	1.2 tons

1) Uses: The excavation of water is an essential task that needs to be fulfilled in order to have a constantly manned lunar base. It is in fact a necessity to not be dependent of launches from Earth for the supply of drinkable water and oxygen, since

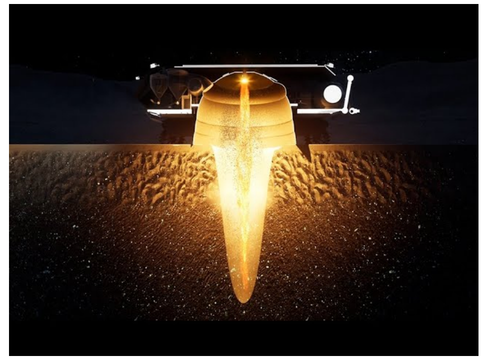


Fig. 1: Rocket M

it would greatly decrease the number of launches per year needed to operate the station and it would also facilitate the storage of water and oxygen (no need of big tanks in the station for water storage or oxygen storage) , since the case of having no water shipped to the station is not a problem/emergency.
Furthermore if a substantial quantity of water is excavated, part of it can be employed in the production of propellant, in the form of liquid oxygen and liquid hydrogen.

2) Numbers: In order to have some redundancy with the rovers, the availability of 2 ROCKET M rovers was considered, according to table II an amount of 1.2 tons of water per rover per day can be excavated and turned into water, but to be more conservative and realistic, considering that this rover hasn't been built or tested yet, an efficiency of: 0.8 will be assumed, resulting in the following quantity of ice excavated in tons of water per year:

$$\begin{aligned} m_{water} &= n_{rovers} \cdot \eta \cdot \dot{m} \cdot 365 \\ &= 2 \cdot 0.8 \cdot 1.2 \cdot 365 \\ &= 508.8 \quad tons \end{aligned} \tag{1}$$

Considering the requirements of water / oxygen for the station and what is needed in terms of propellant (roughly 180 tons per year were requested from the Logistics Team), the maximum mass of water is considerably higher than what's required, which is great for the following reasons:

- good for the lifespan of the rovers, since they don't have to be pushed to the limit
- takes into account a possible malfunction of the rovers
- gives a more realistic operational time schedule, for example 4/5 days a week of excavating

C. Regolith Excavation

As for the ice excavation, the mining of regolith is an essential task for a future lunar settlement, for this reason different ways and methods have been analysed and compared. NASA is currently developing a rover called RASSOR [6] (Regolith Advanced Surface Systems Operations Robot) sketched in Figure 2, it will be a teleoperated mobile robotic platform with a revolutionary concept for regolith excavation.

RASSOR will use counter rotating bucket drums on opposing arms such that almost no reaction force is used, allowing

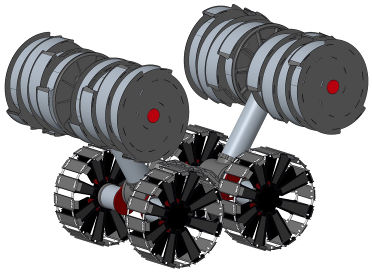


Fig. 2: RASSOR CAD model by NASA

the excavation not to be reliant on the traction or weight of the mobility system to provide a reaction force to counteract the excavation force, which is one of the most challenging obstacles of excavating in a low gravity condition. Moreover it will be able to traverse steep slopes and rough terrain, essential for the operation of the rover. The minimalist design design of RASSOR reduces complexity and makes it really weight efficient. The characteristics of the rover are presented in Table III:

TABLE III: RASSOR Properties

Rover	Mass	estimated regolith excavated per day
RASSOR	66 Kg	3 tons

1) Uses: The excavation of Regolith is a central feature for the realization of the lunar base, infact since the first weeks a considerable number of regolith excavating rovers needs to be operating on the moon soil in order to construct the base. In particular, first they are going to excavate the spherical shapes in which the station will be built in, and then provide the additional regolith to cover the base from radiation (roughly 3 meters of coverage). At the moment these are the only uses planned for the regolith excavating rovers, but in the future regolith could be used in other ways, for example the minerals described in Table I could be extracted and used.

2) Numbers: For the realization of the base, the Station Design Team estimate that a total volume of roughly 5768 m^3 is needed (this value includes both the volume needed for excavating the holes for the different modules of the base and the volume for covering them), considering an average density of 1500 kg/m^3 for the regolith [7], the total mass that needs to be excavated is: $m = 5768 \cdot 1500 = 8652$ tons. To fulfill the duration requirements concluded with the Station Design Team a total number of 10 RASSOR rovers was chosen to be sent for excavation purposes. Hence the following number of days of excavation will be needed in total:

$$t = \frac{m}{n_{rovers}\dot{m}} = \frac{8652}{10 \cdot 3} = 288.4 \quad days \tag{2}$$

where $\dot{m}$ is the amount of regolith excavated per day from 1 rover equal to ca. 3 tons/day. The number of days required for the total excavation is useful in giving a rough estimate for the realization of the base, but it is an ideal value, which doesn't consider the accidents and problems that can happen in a real world.

III. Station Objectives

A base on the moon will offer new opportunities for science in many different disciplines. It's key to learn more about the space environment and its effects on humans for exploration further into the solar system. It's crucial to make staying on the moon feasible with regards to resources and infrastructure. A short summary of possible lunar missions will be presented and a priority will be made for scheduling missions.

A. Deep Space Radiation

Heavy Nuclei presents a risk but also possibilities on the moon. The chronic exposure to galactic cosmic rays and sporadic solar particle events presents radiation exposure. When the radiation interacts with the lunar dust grains that's electrostatic charged by the moon's interaction with the local plasma environment it leads to a composition of neutral particles, i.e. neutrons and gamma radiation [8], [9]. China's Chang'e 4 lander has made some precise observations that have improved the understanding of radiation exposure in the lunar environment. There is still research that can be done to understand the lunar environment specifically and more thoroughly. The moon can act as a physics test bed for the interaction between surface and the airless body with the radiation, plasma and magnetic fields from the sun and earth's magnetosphere [10].

B. Heavy nuclei fission reactor

Heavy nuclei also present the possibility to extract energy from it in a fission reactor, where you split a heavy atomic nuclei into lighter nuclei, thereby releasing energy. The reactor needs to be sent from earth and maintained on the lunar surface. NASA hopes to make 40-kilowatt class fission power systems that last for at least 10 years in the lunar environment, which can be used as a good reference point for the feasibility and utility of a fission reactor.

C. Fractional Gravity

The human body is evolved to function on earth. Decreasing the gravity makes blood gather in the upper body and head, the body temperature is increased and the immune system is reduced [11]. For further space exploration better understanding about these effects is required and therefore the lunar base could be a suitable place for research.

Similar to humans, plantation has evolved to survive on earth. To decrease cost and increase feasibility of future missions food production can take place in space. There is already progress being made on this area on ISS [12]. However, the lunar base can offer a more feasible place for further and scaled up research to eventually reduce the need of supplies sent from earth. To grow plant Artificial sunlight will be needed. This will require about 100 watts per square meter.

D. Transportation and other lunar engineering

The desire to move around on the lunar surface will be an increased need by time. The equipment for astronomy will need to be carried to the far side of the moon, as well as the people executing it, minerals can be excavated on other parts of the moon and so on.

E. Earth Climate Monitoring

The far side of the moon presents an unique opportunity for scientific observations without interaction with human disturbances from powerful transmitters on earth. Earth's climate can be monitored by observing the "earthshine" [13]. "Earthshine" shows earth's reflectance of sunlight.

The near side of the moon presents a new opportunity to observe the whole disc of earth at the same time. There are currently no satellites covering the whole surface of the earth at such a scale. At geosynchronous orbit a third of the area is observable but it always faces the same side of the planet. From the moon all of earth's surface is observable both at night and day [14].

There has already been one telescope at the near side of the moon, a Chinese telescope landing with Chang'e 3. The telescope was used to monitor bright variable stars in the near UV for periods of up to 12 days and to carry out a near UV sky survey at low galactic latitude [15]. However, Due to the vicious lunar surface climate the telescope needs regular checks and maintenance to be able to operate for longer duration's of time.

F. Long Wavelength Radio Astronomy

Apart from "earthshine", long wavelength radio astronomy, otherwise heavily polluted by human made radio transmissions, can be observed from the far side of the moon. A radio receiver (2-60 MHz) would explore the suitability of the far side of the moon for "dark age" astronomy.

G. Other science areas

With the lower gravity and lack of atmosphere, It's cheaper to send up things into orbit from the moon compared to earth, opening a possibility for no gravity science similar to the science carried out on the ISS. Science that benefits by lower gravity will also be executed in the lunar base. To go into detail of these subjects and to give a detailed plan is assessed to be outside of the scope of this report. However, some other areas of science that can take place on the moon is: Fluid physics, Material physics, Fundamental physics, Combustion, Biology, Human physiology & performance, Optical and Electrical engineering.

H. Required Payload of Missions

To understand the feasibility of the missions with respect to possible launches an estimation of required payload was done and can be found in Table V and IV. Table VI give an estimated overview of what's specifically needed for the different missions.

TABLE IV: Importance and required payload of the lunar surface missions

Mission	Importance	Required payload
Lunar Surface Science (excavation)	4	E
Deep Space Radiation	5	C
Fission Reactor	2	E
Fractional Gravity - Humans	4	B
Fractional Gravity - Plantation	4	D
Transportation on the lunar surface	4	A
Earth Climate Monitoring	3	A
Long Wavelength Astronomy	1	E
Other Research areas	3	(mostly) C

TABLE V: Categories of payload

Category	Payload
A	0 - 50 kg
B	50 - 400 kg
C	400 - 1000 kg
D	1000 - 2000 kg
E	$>$ 2000 kg

TABLE VI: Estimation of Needed equipment

Scientific Area	Equipment Needed
Deep Space Radiation (C)	Payload rack, additional equipment, rovers, and telescopes
Fission Reactor (E)	Reactor (40 kW, up to 6.6 tons)
Fractional Gravity Experiments, Humans (B)	Testing equipment
Fractional Gravity Experiments, Plantation (D)	Centrifugal motor, plantation that takes up space
Transportation on Lunar Surface (A)	Additional payload for building roads
Earth Climate and Long Wavelength Astronomy (E)	Telescope and means of transportation to the far side of the moon
Lunar Surface Science (E)	Two rovers
No Atmosphere (C)	Payload rack
Other Areas (C)	Payload racks

I. Expected timeline of Missions

The operational use of the lunar base is highly conceptual and the same goes for the timeline. A suggested timeline in Figure 3 based on when the payload can arrive has been done but will be left without more detail. Green indicates that material will be delivered but science will not be executed and red that the science is conducted.

J. Organisation in the lunar base

50 people will be at the lunar base at a time, and everyone will stay for at least one year. People will have various tasks and the main idea is to have personnel running the base and making it possible for researches to use the base. To learn more about this the reader is referred to the human aspect report. Scientist, engineers, doctors and so on will do research on the moon without working to maintaining the base. The researches are not employed by the base and therefore not obligated to work certain hours. However, for the purpose of planing the research on the moon every researcher is expected to work 40 hours per week. There will be room for 25 researches, resulting in 1000 hours of work per week.

	Year	1st	2nd	3rd	4th	5th	>5th
Mission	Deep space Radiation						
Mission yearly payload (kg)		2000	500	0	0	0	0
	Lunar Surface Science (excavation)						
		2000	100				
	Fractional gravity - Humans						
		300	300	0			
	Fractional gravity - plantation						
		1650	1000		0		
	Transportation on the lunar surface - Reserch						
		50	0	0			
	No atmosphere Science						
		1000		1000	0		
	Transportation on the lunar surface - Construction						
			100	1000			
	Earth Climate						
		3000		0	0	0	0
	Long wavelength Astronomy						
					1000	1000	1000
	Other Research Areas						
					1000	1000	1000
	Total Payload (kg)	10000	2000	2000	2000	2000	2000

Fig. 3: Mission timeline

IV. Communication

Communication is a key issue concerning the development of a lunar base. Human life is the most important factor at stake. One cannot afford to send astronaut to the moon if one can not be aware of what is happening when they are there. Moreover, before sending humans to live on the moon, it is needed to have built at least some parts of the station and to have collected resources that will be needed for human life on the moon. To do this a strong communication to the moon that includes a big data rates, video sharing should be set up.

A. NRHO : an orbit for the gateway and a new satellite

The aim is to be able to communicate 24/24 with the Earth. The lunar base will be located in the south pole of the moon. But it is known that the axe of the moon is tilted with an angle of 1.5°. Because of this phenomenon there is not always a well direct line-of-sight with the Earth from the lunar base. There will be an amount of time when the Earth will not be seen correctly from the camp, thus limiting direct communication between the Earth and the lunar station. Something else is needed then. One of the assumption made in this paper is that the gateway will be implemented. Thus, it can be used to relay information from the lunar base. However like every other satellite or space station the gateway while orbit the moon so that there will be a lack of communication during a few hours or days when the Gateway is near the north pole of the Moon. In fact the Gateway follows an NRHO orbit and let's assume that it is chosen so that the gateway is facing the south pole most of the time.

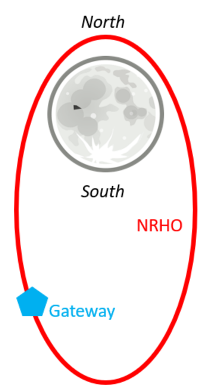


Fig. 4: orbit NRHO

In the Figure 4 one can see that the big eccentricity of the orbit makes possible to spend lot of time for the gateway facing the south pole of the Moon. However there will be some time when the Gateway is at the north pole and cannot be seen from the station, making the relay to the earth impossible with this configuration.

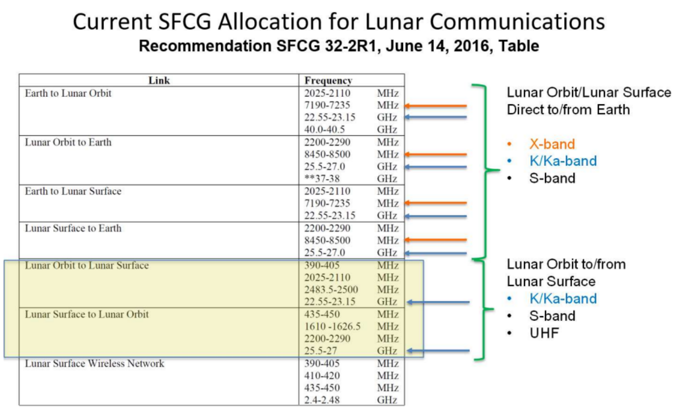
The idea in order to overcome this lack of communication during the time when the gateway will be near the north pole of the moon is to add a satellite that will take exactly the same NRHO orbit than the one of the Gateway but with an offset so that while the gateway is near the north pole, the satellite will have a line-of-sight to the south pole. Thus there will be no communication interruption. This idea was picked from [16], [17] and [18].

B. Link from the Earth to the station

1) Communication radio band designations: The communication radio bands that are most used for space missions are S, X, K and Ka bands. Their use depends on the information that are needed to be shared.

If a lot of information such as videos and speaking communication are needed to be shared then it is imperative that these information are shared the fastest way as possible and the more accurate as possible. Then a big data rates and bandwidth are needed. In this case the Ka band is more accurate or the X-band.Nevertheless, the choice of the band depends also of the free space. In fact Ka-band is more and more attractive for satellites because they do not need big antenna. However most of satellites have only S-band because there is not a lot of information when it is just about coding the satellites. S-band even if they do not have a big data rate have other benefits such as that they have a better ground penetration. That is to say it will be easier to pick up signal from the Earth. Another mean of communication is the laser communication. This could be used to transport lots of information at a high data rate.

In this mission the frequencies of the communication will be those suggested by the NASA in 2016 that can be seen in Figure 5.


Current SFCG Allocation for Lunar Communications
Recommendation SFCG 32-2R1, June 14, 2016, Table

Link	Frequency	
Earth to Lunar Orbit	2025-2110	MHz
	7190-7235	MHz
	22.55-23.15	GHz
	40.0-40.5	GHz
Lunar Orbit to Earth	2200-2290	MHz
	8450-8500	MHz
	25.5-27.0	GHz
	**37-38	GHz
Earth to Lunar Surface	2025-2110	MHz
	7190-7235	MHz
	22.55-23.15	GHz
Lunar Surface to Earth	2200-2290	MHz
	8450-8500	MHz
	25.5-27.0	GHz
Lunar Orbit to Lunar Surface	390-405	MHz
	2025-2110	MHz
	2483.5-2500	MHz
	22.55-23.15	GHz
Lunar Surface to Lunar Orbit	435-450	MHz
	1610 -1626.5	MHz
	2200-2290	MHz
	25.5-27	GHz
Lunar Surface Wireless Network	390-405	MHz
	410-420	MHz
	435-450	MHz
	2.4-2.48	GHz

Fig. 5: Band used [19]

2) Directly from Earth to the Lunar base: To communicate from the Moon to the Earth, the gateway and the satellite will be used. However it is needed to have also a direct connection in case of emergencies. Since emergencies are the worst cases when you just have to broadcast information and not video or big data SBand will be used. In fact on Earth there is a large Network of stations, the Near Earth Network (NEN). It is supposed to provide constant communication and tracking services to missions near Earth (including lunar). However the majority of NEN have S-band and X-band but only one ground station supports Ka-band communications. That is why for emergencies S-band will be used to contact directly the Earth from the Moon.

3) Communication using NRHO: Since it is needed to broadcast the mission advancement a lot of data are needed to be send to Earth. Then the Ka band or optical communication is needed. It is known from the NASA that the configuration of the gate way will be as followed in Figure 6 :

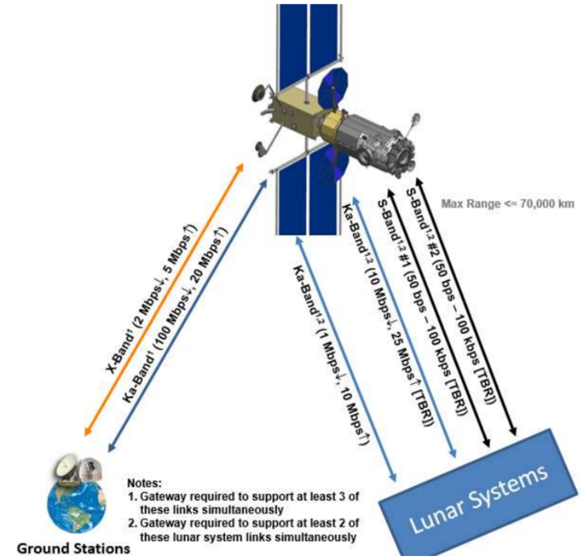


Fig. 6: 2024 Nominal Gateway Comm Architecture from NASA [19]

Then, there will be no optical communication but only radio frequencies. Because of this configuration the station on the moon will also use Ka band and S band. Ka band will be used for big data rates and the mission advancement such as videos, audios ... The S-band will be used for navigating, tracking and also emergency. That is to say with the Ka-band one is able to broadcast a lot of data with big data rates while the S-band enables only low data rates. The communication between the satellite on the NRHO orbit will be the same as in the gateway except for X band which will be changed into Ka band. That is to say, receiving Sband and Ka band but also send S-band and Ka BAND.Ka band will not be a problem given the fact that the antenna are very small compared to other. The communication toward the Earth is resumed in the Figure 7.

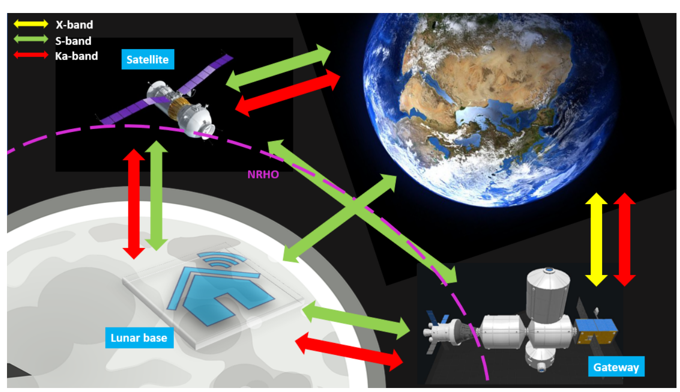


Fig. 7: Overall communication

C. Communication on the lunar ground

1) During EVA: On the lunar ground a communication inspired by the HLS communication NASA will be used [19]. Between the base and the crew that is performing an EVA, or the rover there will be communication needed. During the missions on the moon different data will be needed to be broadcast such as videos (which need a big data rates) and voices etc...

In order to broadcast that (like videos ...) a Wifi connection will be used that has a data rate from 100 Mbit/sec to 1Mbit/sec depending on the distance. For this mission an assumption will be made : there will be technologies for wifi that have a scope of 1.5km. This assumption seems right because in 2019 there was already technologies that had a scope of 0.5km and research were already beginning for finding a solution to improve this until 1.5km.

On the other hand, in order to share data and voices between the astronauts and the lunar base, UHF will be used with a maximum distance of 1.5km and a data rate of approximately 500kbits/sec.

There will be no direct connection between the astronauts and the Earth in order to suppress the need of directional antennas. But in case there is a problem of communication there will always be two types of communication (wifi and UHF).

2) Big antenna on a mountain: With all the different means of communication presented above, the communication between Earth and the lunar base can be easily done. However sometimes failures can happen and something can go wrong. Let's say there is a problem with the satellite in the NRHO orbit and that the lunar base has no line of sight with the Earth or with the gateway, then how is the communication supposed to go on? There may be a solution.

The solution would be to add an antenna in a very specific place on a mountain where there will be both a line of sight with the earth and with the lunar base. However in order to get there and build the antenna there will be an extra cost. Note that the landscape where the antenna should be put is hilly so that is an issue for the rover to get and easy access to the site. But this idea could be implemented afterward.

Finally, the final configurations of the communication system is illustrated in Figure 7, it consist in one satellite orbiting the Moon in the NRHO which will communicate with the basement and the Earth with S-band and Ka-Band, and with the Gateway with S-Band, whereas on the lunar ground, Wifi and UHF will be used. The frequencies of the different bands for the different types of communication will be the same as in Figure 5. That is to say the frequencies from Earth to the lunar ground will be from 2025 to 2110 MHz while from the lunar ground to the earth they will be around 2200-2290MHz. The frequencies from the satellite to the lunar ground will be 22.55 to 23.15 GHz for the Ka-band while the frequencies form the lunar ground to the satellite will be 25.5 to 27 GHz for the Ka-Band.

V. Maintenance plan

Knowing the importance of a Lunar research station for research and the financial resources put into such a project, it is crucial to execute maintenance regularly on critical and research equipment in order to keep the base running.

A. Categorization

1) Regular inspections: Maintenance is not only corrective, it is also preventive in order to identify any problem or issue and be able to fix these before the breakdown of the systems. These inspections need to be done regularly and ideally to be controlled constantly. For critical equipment and systems (life support, power and energy) such inspections being done on a weekly basis would be a good time interval. Concerning research equipment, these regular inspections can be carried out by the researchers that use them on a daily basis. Moreover, a monthly inspection of the whole base, done under the direction of the commanders of the base, is a great way to assess its overall condition and identify any necessary maintenance.

2) Scheduled maintenance: Even if there is no breakdown of the systems, it is important to keep them in good condition to avoid any future issue for as long as possible. This includes regular cleaning, lubrication and calibration of equipment according to the manufacturers' specifications. Some systems need more maintenance than others such as water treatment and air filters systems that would need maintenance to be conducted on a quarterly basis. Maintenance on the station solar panels and power storage systems would need to be conducted at least twice a year to ensure optimal performance.

3) Emergency response plan: The consequences of a critical system breakdown can be disastrous whether it be in terms of human life or financial resources, hence a carefully prepared response plan is needed to be prepared for any situation. It is needed to develop a comprehensive emergency response plan that outlines the roles and responsibilities of all personnel in the event of an emergency, including critical system failures or medical emergencies. Moreover, emergency response drills have to be conducted regularly to ensure that all personnel are familiar with the emergency response plan and their respective roles. These emergency protocols have to be carefully prepared before even settling on the research station.

4) Spare parts and inventory management: Maintenance on such a large research station and with so many people would need a large amount of specific resources, it is hence really important to maintain a detailed inventory of all spare parts and supplies necessary for the operation and maintenance of the station. Moreover, it is needed to conduct regular inspections of spare parts and supplies to ensure that they are in good condition and ready for use in the event of an emergency. Finally, the last step would be replenish spare parts and supplies as needed to maintain adequate inventory levels.

5) Training and education: Every person on the research station have really specific roles and need to know exactly what they have to do to ensure that the base functions well. Hence, it is crucial to provide regular training to all personnel on the operation and maintenance of critical equipment and systems, as well as emergency response procedures. As these procedures can be pretty complex and time-consuming, it would be good to conduct annual refresher training to ensure that all personnel are up to date on the latest equipment and procedures.

6) Documentation and record keeping: Organization on such a research station is vital to ensure optimal progress, thus maintaining detailed records of all maintenance activities, including inspections, repairs, and replacements is crucial. Additionally, these records can be used to identify trends, track the lifespan of equipment and inform future maintenance plans. Maintaining a detailed log of all emergency response will help improve the emergency response plan and identify areas for improvement.

VI. Timeline for fully Operational Station

A. Timeline for the construction of one module

In order to make possible some research on the Moon and also life on the Moon the first need is to construct the lunar base. The lunar base designed by the Station Design Team will consist in 7 modules which look like spheres. Each module will consist of layers of aluminium and regolith. So there is a need to excavate regolith and move it to the very location where one wants to build. Each module will be constructed by the following way :

- Digging a hole that will be the size of the module (spherical) thanks to 10 rovers
- Construction by special robots of the aluminum layer and at the same time construction of corridors
- Covering the module with regolith layers
- Construction of the inside of the module made by humans

In order to do the first step for one module there is a need to excavate regolith during approximately 28 days. The recovered regolith from the digging can be used to cover the module afterwards. It is known that 100 days more of excavating are needed to collect all the regolith needed to cover all the 7 modules. That is why in the timeline the duration of digging will be set up at 40 days so that there will be enough regolith to cover all the 7 modules. For the second step two special robots chosen by the Station Design Team will be used to create the aluminium layer of the module. They expect that it will take approximately 18 days per module. The third step consist of 30 days to cover the aluminium layer with an certain amount of regolith. The last step will be performed by humans who will construct all the inside of the module. It will take approximately 39 days.

One can find in Figure 8 the timeline of the construction of one module. Note that the first human spaceflight of the mission will be done at the moment when the construction of the inside of the module begins.

B. Timeline of the construction of the base

In order to get the timeline of the whole lunar base construction it is only necessary to superimpose the construction of a module one after the other. That is to say when the rovers are finished with digging the first hole, they can begin to do the hole of the second module. It is the same for the construction of the outside of the module. Given the fact that there are 2 specialized robots it is possible to follow the timeline in Figure 9.

Note that humans will be sent on day 95 in order to begin to construct the inside of the first module.

Finally the lunar base could be finished after 374 days but since there are always delay, it will be said that the station could be finished in on year and a half.

VII. Station Operational Budget

A. Station maintenance

The United States have a total $67.52 million for operating research bases on Antarctica that can hold up to 1407 people. Scaling it for a research station of 50 people and based on the moon, we estimated that a budget of $100 million annually is a reasonable amount given the fact that technologies will be more complicated and more expensive.

B. In situ resources

For excavating ice, there is a need of two rovers, each costs $250 000 000, while for excavating regolith there is a need of 10 rovers, each costs $100 000 000. Concerning electrolysis, 8 of them will be needed knowing that one costs $30 000. When it comes to water storage, it will cost approximately $30 000. Finally the total cost of everything related with in situ resources is about $1 500 270 000. It is good to note that the two thirds of this cost is the need of the 10 RASSOR to excavate the regolith for the constuction of the base in time. By reducing the number of rovers, one can reduce the cost of the mission (by reducing the cost of rovers and reducing the weight to launch) while increasing the construction time. Therefore a trade-off had been made here with the Station Design Team, but which can be re-discussed.

C. Communication

Concerning communication the budget has been chosen thanks to budgets found for different projects [16], [17], [18], which take into account approximately the same amount of devices, such as satellites and antennas ... The budget of everything regarding communication is about $800 000 000.

VIII. Off-nominal case

To make this mission more reliable and sure by handling possible issues, some off-nominal case have been considered.

First one can address the case: ”What if the Gateway or the satellite orbiting the Moon stop working properly ?”. To handle this possibility, the use of a big antenna settled up on a hill have been presented. This solution would enable to continue communication when there is no satellite in view to ensure the link with Earth. However this would only be a temporary solution as the data link would be lower than the one enabled by the satellites.

Secondly, one can consider the case: ”What if communication is lost with an astronaut or a problem happen during EVA ?”. First one should consider the basic rule that no EVA have to be conducted alone, the minimum crew will be made of two persons. This is done such that if one of the two person lose communication, the other one still have it and can communicate directly with the other member. If both of them lose communication, there might be a real issue and both of them have to come back to the base. However this can be complicated without communication. To facilitate this, each suits have to be equipped with a non-electronic map of the surrounding of the base. However, a compass would not be directly useful to find direction on the Moon because it

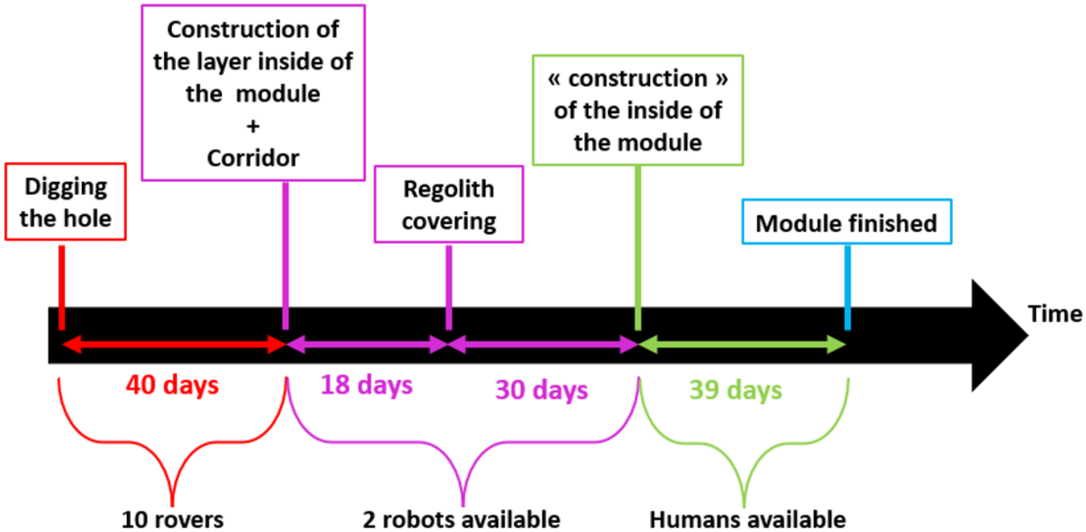


Fig. 8: Timeline of the construction of one module

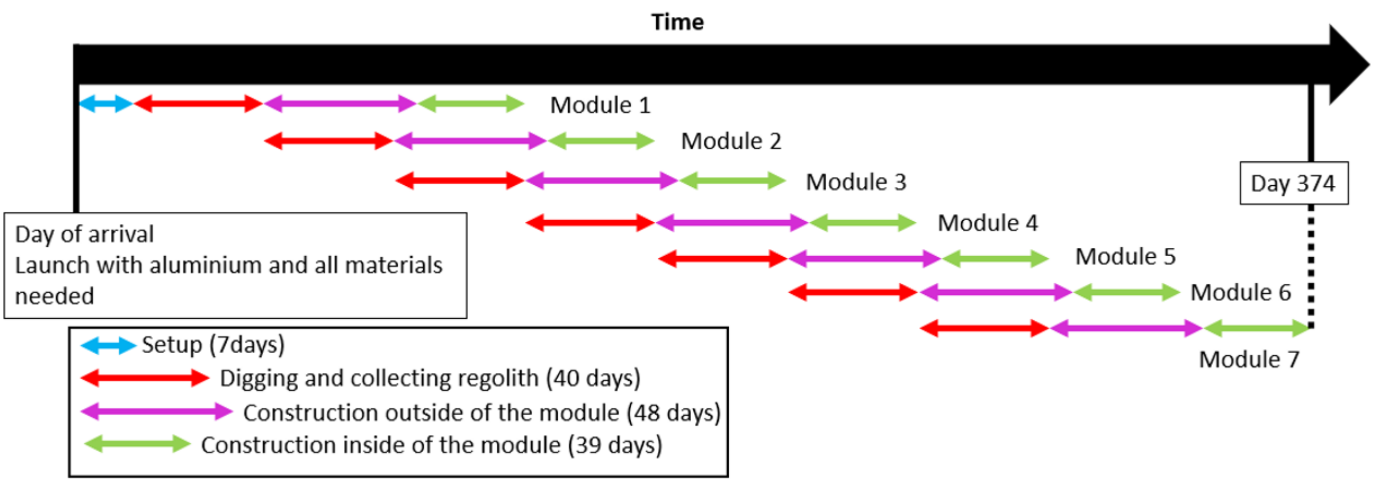


Fig. 9: Timeline of the construction of the base

does not have a global magnetic field like the Earth does but small, localized areas of magnetism. Therefore, to know what your compass is pointing to, you almost have to know where you are. To enable this, the provided map have to include the principal landmarks of the environment that can be natural or sat up at arrival such that the astronaut can determine their position based on the direction to this landmark and the closest area of magnetism. It is also to note that the position of those area of magnetism have to be found and marked on the map to ensure good navigation around the base. Moreover, each suits should emit a signal such that even if the communication is down, the station can determine the position of the astronaut and if required, send an other crew to determine what is the problem and if the previous crew need help. Therefore, the suit of each suits should include a map of the zone up to date, a compass and a separate emitter to ensure the astronaut can come back safely and receive help if this is needed.

For an off-nominal case, this is when the emergency response part of the maintenance plan comes into play. Every member of the team has to know exactly its role within the bigger picture and this is precisely the goal of preparing a carefully studied emergency response plan.

IX. Division of Work

Regarding division of work, the team feels like the work has been equally divided among the members. **Elise Walch** was the group leader in this team. She was in charge of communication section and the mission timeline, with **Paolo Ranno**. **Paolo Ranno** and **Hippolyte Gobet** worked on the in-situ ressources and the excavation of these ressources. **Jacques Bénand** dealt with the maintenance plan. **Willion Olsson** focused on the astronaut mission roles and time management.

References

[1] *Science Definition Team*, "Artemis iii eva opportunities on the rim of de gerlache crater," 2020.

[2] 2023-04-12. [Online]. Available: https://www.nasa.gov/press-release/nasa-s-sofia-discovers-water-on-sunlit-surface-of-moon
[3] *GRANT H. HEIKEN, DAVID T. VANIMAN, BEVAN M. FRENCH*, *Lunar Sourcebook*, 1991.
[4] 2023-04-12. [Online]. Available: https://en.wikipedia.org/wiki/Lunar_resources
[5] 2023-04-12. [Online]. Available: https://masten.aero/blog/masten-designs-rocket-mining-system/
[6] 2023-04-12. [Online]. Available: https://ntrs.nasa.gov/citations/20210011366
[7] 2023-04-12. [Online]. Available: https://curator.jsc.nasa.gov/lunar/letss/regolith.pdf
[8] [Online]. Available: https://www.space.com/moon-radiation-dose-for-astronauts-measured
[9] R. R. V. Timothy J. Stubbs and W. M. Farrell, "A dynamic fountain model for lunar dust," 2005.
[10] "Esa strategy for science at the moon, esa unclassified," 2023.
[11] V. G. Ph.D, "The lunar environment as a fractional-gravity biological laboratory," 1994.
[12] J. Z. Kiss, "Plant biology in reduced gravity on the moon and mars," 2013.
[13] 2023-04-12. [Online]. Available: https://hr.caltech.edu/news/scientists-watch-dark-side-moon-monitor-earths-climate-472
[14] P. Hamill, "Atmospheric observations from the moon: A lunar earth-observatory," 2016.
[15] J. W. et al., "Astrophys. space sci 360:10 doi 10.1007/s10509-015-2521-2," 2015.
[16] *Lunar BOWIE*, "Aiaa proposal, california state polytechnic university, lunar base outfitted with interchangeability and expandability," May 2020.
[17] O. H. L. B. C. University of Texas at Austin design report, "Aiaa proposal," 2020.
[18] P. S. Virginia Tech Aerospace Engineering, "Aiaa proposal," 2020.
[19] A. NASA, "Hls 2024 communication architecture overview."