DIANA - Dedicated Infrastructure and Architecture for Near-Earth Astronautics

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The Dedicated Infrastructure and Architecture for Near-Earth Astronautics (DIANA) is an autonomously deployable lunar base concept for a long-duration crewed mission on the Moon's surface. It will be robotically constructed in proximity to the De Gerlache crater ridge on the lunar South pole. The base, which accommodates four astronauts with a planned 2030 arrival, enables scientific operations and local sorties for human and robotic exploration. Furthermore, its self-sustainability will increase over its lifespan. The base will be transported in a compacted form and expanded to a habitable volume by autonomous deployment after reaching the lunar surface. The multilevel base encompasses all possible habitation needs including, but not limited to, dedicated private and communal spaces, technical support systems, and a greenhouse. To establish and operate the base, the following subsystem concepts are crucial. The electrical power system consists of solar panels and a regenerative proton exchange membrane fuel cell using water electrolysis for long term power storage. Thermal insulation and adequate temperatures are provided through a closed water loop system, radiators, and the use of regolith, the latter further providing radiation shielding. The environmental control and life support system initially rely on a high technological readiness level physio-chemical approach. Over time, it will progress towards a biologically closed-loop system through the implementation of a greenhouse for food production and in-situ resource utilization (ISRU) for water and oxygen harvesting. ISRU is essential in supplying astronauts not only with life support but also with a large variety of construction materials leading to increasing self-sustainability and long-term cost-effectiveness. The communication system uses a Low Lunar Orbit communication relay satellite constellation and the Lunar Gateway. DIANA also offers a phased antenna array for radio interferometry on the far side of the Moon to perform observations of the universe.

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I. Introduction

THE mission proposal presented in this report is the result of the Space Station Design Workshop, a nine-day engineering workshop organized by the Institute of Space Systems at the University of Stuttgart. The mission statement declares that "The proposed concept of the platform shall enable scientific operations and local sorties for human and robotic exploration. The conducted scientific operations shall allow for the enhancement of our understanding of the evolution of the universe and in particular the Solar System. In-Situ Resource Utilization (ISRU) shall be integrated into the concept to the extent feasible".

The authors aimed to create a mission that pushed the known boundaries of interplanetary exploration by envisioning a constant human presence on the Moon's surface. Innovative science and technical demonstrations will help us gain a better understanding of both the Moon and the entire Solar System. The mission's name is DIANA, short for Dedicated Infrastructure and Architecture for Near-Earth Astronautics. Diana is the Roman goddess of the Moon and the crossroads leading to different worlds, so it was deemed fit to name the first permanent lunar base after her.

II. Mission Definition

A. Location

Regions around the equator and North and South poles were evaluated as DIANA's permanent location, ultimately choosing the rim of the De Gerlache crater, on the lunar South pole (88.71°S, 68.7°W) [1]. The final choice was made considering possible collaboration with other future missions in the same region, as well as the terrain characteristics, the illumination time, the polar escape trajectories to the Gateway's orbit, and the possible presence of ice in the permanently shadowed regions (PSRs) in the area [2].

The chosen location is illuminated 86% of the time throughout a year. The high exposure to sunlight is beneficial for solar power generation as well as temperature regulation. Detailed information about illumination conditions is presented in Figure 1b [3]. The temperature oscillates between 59.29 K and 244.23 K which is manageable with a suitable temperature regulation system [1].

The chosen terrain has a slope of 1.23º, providing a flat foundation for the construction of facilities. The PSRs of the crater, in the vicinity of the lunar base, provide access to water ice, which will enable further self-sustainable capabilities [1].

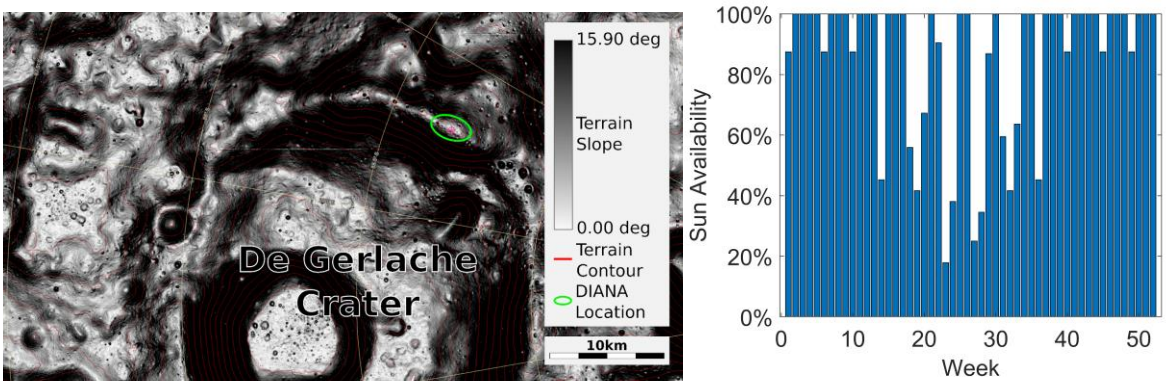

Figure 1. DIANA moon base location characteristics. *a) Moon base location terrain slope = 1.23°. b) Weekly Illumination condition*

B. Propulsion and Transport

The propulsion and transport subsystem will be responsible for transporting cargo and crew to and from the lunar base. Consequently, two different types of transportation systems will be used. The first transportation system will be capable of transporting cargo to the lunar surface. The single-use cargo vehicle will be launched into low Earth orbit (LEO) with a Falcon Heavy rocket. Utilizing a LOX/LH2 engine, similar to an RL10 [4], a bi-elliptical transfer from LEO to a lunar orbit will be performed. Electric propulsion systems were also considered, but discarded because of the electrical power system's (EPS) high mass, leading to a higher total mass. The bi-elliptical transfer will take approximately 200 days and will save 2 t of propellant mass compared to a Hohmann transfer. A total of 8 t of payload will be transported to the lunar surface with each launch.

The loads during the landing of the cargo system exceed the force that the human body can withstand. For this reason, a second transportation system will be used to transport the crew. Additionally, it is assumed that the Gateway will work as a logistical outpost in a HALO orbit around the Moon providing two docking ports. Moreover, it is expected that the Falcon Heavy rocket will be human-rated by that time. The crew transportation system will be launched into LEO by a Falcon Heavy rocket. It comprises a modified Dragon capsule and a lunar lander. The modified Dragon capsule will use an additional propulsion system consisting of LOX/LH2 engines, which are similar to a RL10 [4]. They enable a low flight time Hohmann transfer from LEO to the Gateway. Astronauts arriving at the Gateway, will have to switch to the lunar lander, which will already be docked there. The lunar lander, which has a mass of 16 t (maximum mass the cargo transporter can carry to the Gateway), is a dedicated vehicle for the transit to and from the lunar surface. The lunar lander will be equipped with a CH4/LOX propulsion system. The smaller bulk density of CH4/LOX [5] results in a smaller tank size compared to LOX/LH2. In addition, CH4 has higher boiling temperatures than LH2, which will simplify the storage on the lunar surface [6]. Another advantage of using CH4/LOX is the better cooling capacity which leads to a lower risk of cracking resulting in a longer lifetime and therefore better reusability [7].

The crew transportation system will regularly transport two crew members on a six-month rotation basis, with each astronaut undergoing year-long missions. It will, however, accommodate four astronauts, in case of an emergency requiring the entire crew to evacuate. Every crew launch requires three additional cargo launches for propellant to the Gateway to refuel the vehicle for the return flight.

An inert mass fraction of 20% has been assumed for the mission analysis and propulsion calculations [8]. Implementing the concept of flexibility on launcher selection, future launchers like Starship can reduce costs for resupply missions by lowering the overall costs per launch [9].

C. Landing Site

The landing site provides capabilities to refuel the arriving landers with LOX2 and LCH4. Therefore, an oxygen tank connecting to the ISRU systems through pipelines will be installed nearby. The oxygen will be obtained through the electrolysis process of water and a subsequent liquefaction process. The LCH4 tank will mainly be supplied by resupply missions. A layer of 3D printed regolith around the tanks will reduce hazards caused by a potential lander failure and micrometeoroids impact.

The close proximity of the lander to the tanks will enable astronauts to perform the refueling process with robotic system support.

D. Mission Analysis

The DIANA mission bat chart shows the development of the mission, giving an orientation of its expansion and required resources (Figure 2). This chart covers the complete cycle of development of the station from the first launches in 2027, until the expected point of self-sustainability around 2045. The use of the Gateway as an outpost for the deployment of resources on the lunar surface is noteworthy.

As shown in the bat chart, the mission development will be divided into four phases:

1) Phase 1: Equipment arrival: The communications relay will be deployed in low lunar orbit (LLO). The first rovers and power generators will land on the lunar surface. The robotics will prepare the location for the inflatable modules. Finally, mission rovers and environmental control and life support system (ECLSS) resources will be delivered. By the end of 2030, the first crew will arrive, initializing a permanent human presence on the Moon.
2) Phase 2: Base Stabilization: The stabilization of the lunar base will ensure its future expansion. Therefore, an ISRU refinery will be deployed to ensure the self-sustainability of the mission. The radio telescope array modules will also arrive and be deployed by autonomous landers. Scientific research with rovers will begin.
3) Phase 3: Nominal Operations: More radio telescope array modules will be deployed, and observations of the universe will begin. More scientific research with rovers and extra-vehicular activities (EVAs) will be conducted. At the end of this phase, the expansion of the base will begin with four additional modules.
4) Phase 4: Expansion: Once the base approaches self-sustainability, expansion will continue using ISRU resources. Consequently, resupplies will be gradually diminished. More mission rovers and radio telescope array modules will be deployed. Scientific research will be continually conducted.

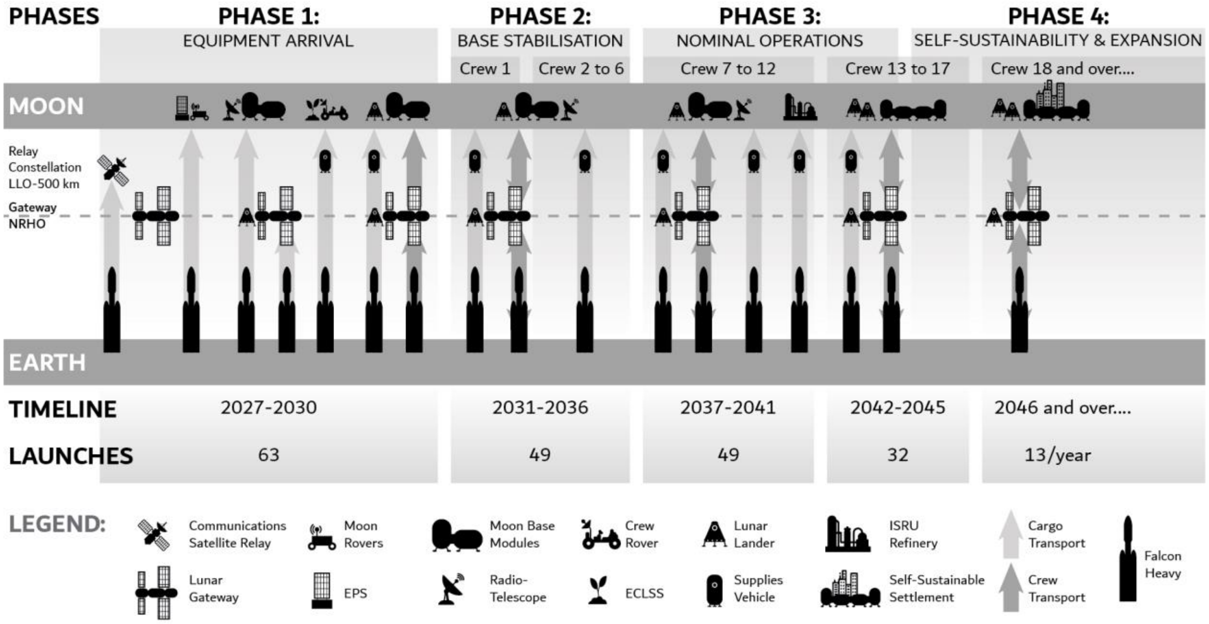

Figure 2. Bat chart of the mission DIANA.

E. DIANA Setup

The DIANA Base (Figure 3) is divided into five segments. The Solar Park will provide electrical power for the DIANA Settlement which consists of the habitats and the ISRU equipment. The Radiators dissipate excess heat. The Landing Site will enable refueling as well as safe landings on a plateau. The Astrophysics Valley will provide scientific data on the observation of the universe. It will send this data to the receiver station, located at the DIANA Settlement.

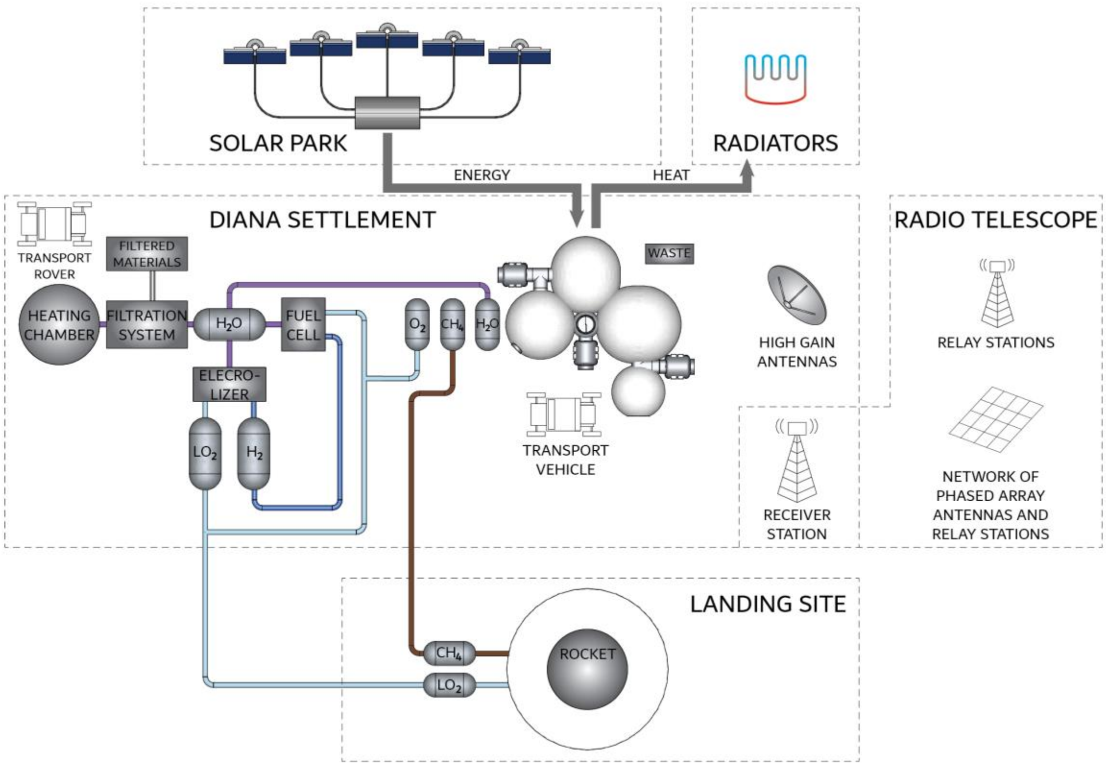

Figure 3. Setup of the DIANA Lunar Base

III. Robotics

A. Lunar Base Construction

The successful deployment of the initial phases of DIANA requires highly autonomous and heavy robotic systems that shall enable the construction of the base by providing long-term excavation, transportation, and crafting capabilities. The chosen robotic systems are derived from a detailed analysis of their operational capability and mission requirements, while keeping the mission timeline in focus. These robotic systems shall also have teleoperation capabilities so that they can be controlled with respect to mission demands and requirements. The principal constituent of the self-sustainable lunar base is the lunar regolith. Hence, the excavation of regolith is, initially, the most important task. If not executed correctly, this excavation comes at the cost of efficiency losses and system failures. A conventional approach to regolith mining, e.g. drilling and excavating, is subject to component wear and dust-related mechanical issues [10]. The majority of said issues can be addressed with a pneumatic excavation system. DIANA employs a pneumatic excavation robotic system called REG-X, a system concept adapted from Zacny et al., 2008 [11]. The REG-X rover uses the Venturi effect to excavate soft regolith off the lunar surface. This mechanism will prevent post-excavation issues such as dust elevation and expulsion. Excavated regolith can be collected in the REG-X rover and then moved into a larger hauling module, which can also be used to transport the regolith from the excavation site to the construction site. The transportation of the regolith-filled hauling module to the regolith deposition site can be performed using NASA's Chariot rover [12]. To construct building structures, the regolith will be filtered and processed for 3D printing. The Deployable Contour Crafting Machine with an integrated robotic arm shall extrude the processed regolith cement into the desired form and size. NASA's Athlete rover (2. gen.) will provide a platform for the locomotion of the 3D printer and will be powered by a radioisotope thermoelectric generator and secondary batteries. The Athlete shall make the 3D printing of the regolith layer over tall structures feasible. For a smooth and redundant operation, three 3D printing rovers will be employed alongside three additional Athlete rovers [13]. The latter shall also be equipped with various construction capabilities, such as drilling, clamshell, excavating, and gripping-hand abilities, which shall be employed to address specific construction needs. The 3D printing robotic ecosystem shall operate autonomously and could be programmed according to the mission timeline to shield the habitat before the crew's arrival [14].

B. Robotic Water Supply of the Base

To ensure that the water ice [15] found underneath the De Gerlache crater can supply the base, a robotic infrastructure will be developed. It shall locate potential extraction sites, extract the water ice from the crater, and transport it to the base. To recover the water ice from the crater, the mining and transportation tasks will be performed autonomously due to the considerable distances that must be traveled (approx. 20 km) [1].

The first robotic systems shall land inside the crater and excavate beneath the surface for water ice. This will be done by a robotic system based on the INSPIRE rover developed in 2021 as part of a project work at the University of Stuttgart [16]. It will be equipped with ground-penetrating radar to scan the subsurface for potential water ice locations to be sampled. For this purpose, an integrated meter-long ice core drill will be used. The samples will then be analyzed with an Alpha particle X-Ray spectrometer. If the water content of the sample exceeds 60%, a signal will initiate the digging for water ice at the sampling site and will transport it to the first checkpoint, where the water ice is loaded into a transportation rover. This transportation system shall then drive it to a second checkpoint, which is about 8.5 km away from the inside of the crater. At this checkpoint, the water ice will be transferred to a secondary transportation rover, which can operate at higher speeds in familiar territory. Additionally, the initial rover, which is specialized in operating in high gradient areas, can immediately return to the crater. The excavated water ice will be driven to the DIANA Settlement by the secondary rover where it will be processed for further use.

Once the extracted water ice arrives at the water preparation station, it will be loaded into a heating chamber with a diameter of four meters. For safety reasons, 13400 l of the 16750 l chamber is filled with water ice. This corresponds to a mass of 15400 kg of extracted water ice which, taking into account various loss factors, will result in a quantity of approx. 6000 l of water which should account for a yearly supply including margins.

Since the extracted water ice will not be pure, the remaining material will be filtered out and stored separately. The resulting water can then be piped into a tank from where it will await transfer to the life support system (LSS) or electrolysis equipment. During the electrolysis process, the water will be split into its main components, hydrogen and oxygen, to supply the base and landing site with the necessary oxygen. The required infrastructure for this purpose is shown in Figure 4. Since the components for this water treatment system will not be fully functional upon arrival on the lunar surface, the first crew will need to ensure, in cooperation with robotic systems, that the system will be operational for phase II and will cover the water budget of the DIANA Settlement over a longer period of time.

In the future, this system will be expanded with more tanks, a second heating chamber and more rovers to speed up and optimize the process. After further investigation of the crater material, the extraction of carbon from the PSRs [17] will also be considered for future phases. Together with the generated hydrogen, they can provide the methane necessary for refueling the lander.

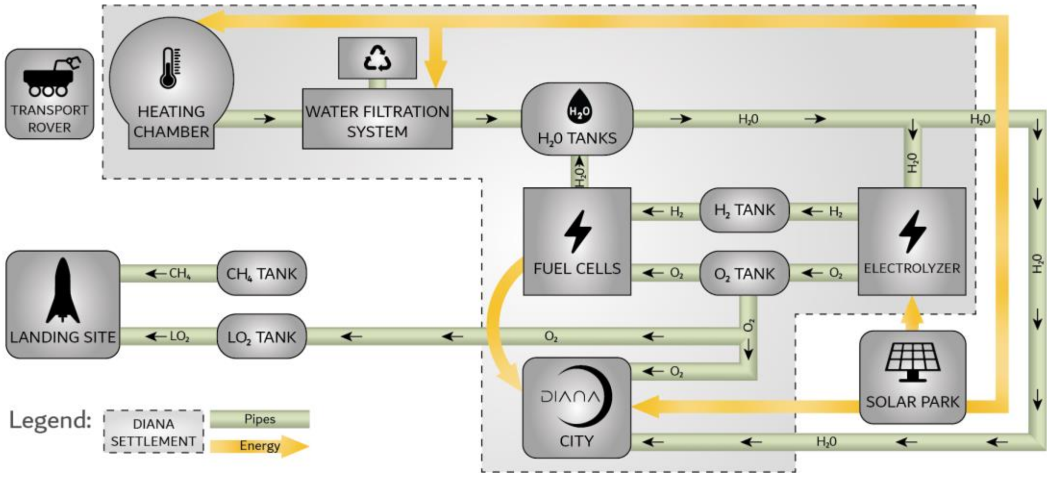

Figure 4. Water Management System

IV. Architecture and Structural Shielding

The DIANA architecture approach is based on the development of an integrated deployment mechanism that fulfills transportation constraints as well as the mission and habitability requirements imposed by the lunar environment. To build a sustainable lunar base that focuses on scientific research and long-duration human habitation, four different modules were developed: a multipurpose lab, a social module, a greenhouse, and a window module.

All four modules offer different functions, and therefore have different shapes. They are laid out in a rectilinear grid form (cruciform scheme) with three nodes connecting the modules. The primary node includes the main airlock and is located between the social, greenhouse, and multipurpose lab modules. There are two emergency airlocks for safety purposes. The initial phase will also provide the connectors to future modules for the upcoming expansions (Figure 5).

To carefully plan the development of the DIANA architecture and construction, we have looked deeper into Bigelow Expandable Activity Module and TransHab inflatable habitation, which were originally designed as

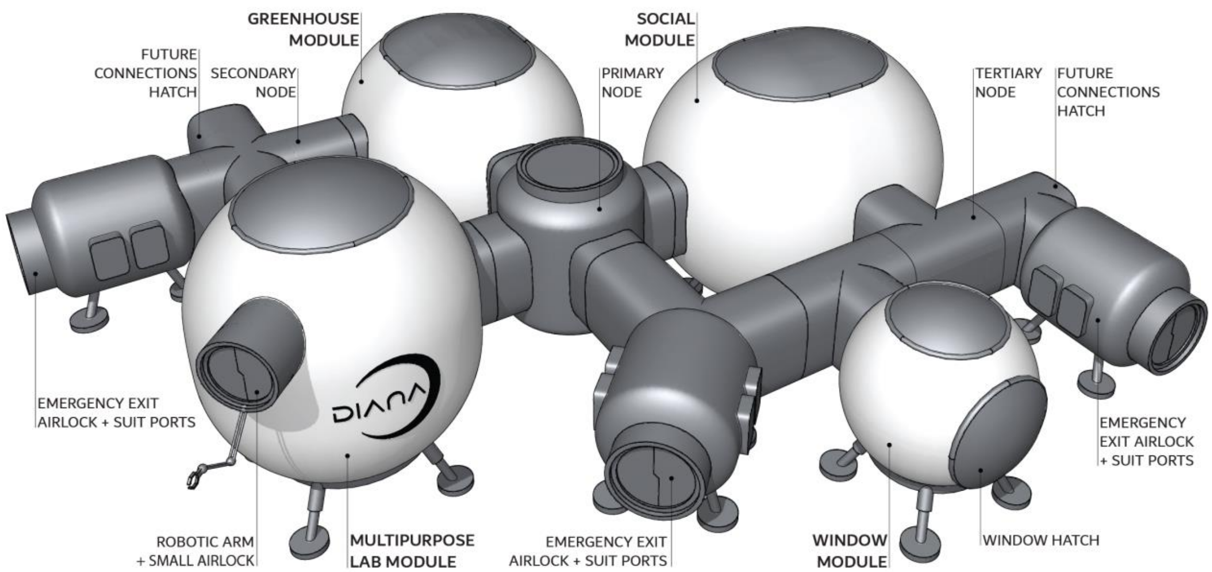

Figure 5. DIANA Modules Overview

expandable space station modules. TransHab was intended as a replacement for the already existing rigid ISS crew habitation module and Bigelow as a temporary ISS module [18]. DIANA proposes a similar design, but as a lunar habitation base that supports partial gravity crew operations in the form of a hybrid space structure that synthesizes a rigid central core with an inflatable exterior shell. Its dimensions and layout are optimized for flexible, long-term use by the diverse crew. It can be packaged into a smaller volume for launch and deployed on the lunar surface to provide a much larger, more usable volume and offers both a variety of architectural opportunities and tremendous technical and design challenges. The largest packed volume is 6.2 m x 4.6 m x 4.6 m. Hybrid inflatables can support the habitable volume necessary for long-duration human exploration with several advantages: 1) a greatly reduced mass penalty over hard-shelled spacecraft at comparable volume, 2) the amount of metal, which can be activated through radiation, can be minimized which leads to a reduced radiation risks for crew, and 3) lower risk of depressurization at launch due to in-situ deployment [19].

The inflatable shell is a separate system from DIANA's skeletal structure and thus can be optimized in its function as a pressure shell. Folded and compressed around the core at launch, it will be inflated and deployed on the lunar surface. It is composed of the following elements starting from the interior: an inner scuff barrier and structural restraint layer (Kevlar layer 10 mm), a pressure bladder (two Vinyl Polymer Foam layers 230 mm each), and a thermal protection blanket (two Carbon layers 10/20 mm). The shell provides orbital debris protection and thermal insulation, contains the crew's living and working space, and offers extra space for crew multi-functional activities providing relief from closed and cramped hard module confinement [20].

The rigid core is made of aluminum 7075-T6 alloy and comprises four primary components: the crown, the bottom base with legs, the telescopic pillars, and the foldable beams. Secondary components are movable modular panels and acoustic wall panels as shown in Figure 6. The crown and bottom base are manufactured as single pieces of lay-up composites and serve as connection points between the inflatable shell and the frame. Either four or six (based on module size) telescopic pillars are built-in between the crown and bottom base and will be extended in the deployment process at the time of shell inflation. They provide vertical reinforcement between the ceiling and the floor (crown and base) and are connected with foldable beams that stretch out horizontally during the deployment process. After the inflation of the shell, the secondary components can be detached and reconfigured. Movable modular panels will be placed on the top of the stretched beams to form floors and ceilings for the occupants. Together, they provide multistory space which can be divided by wall panels to separate private and shared areas [19]. For protection from radiation over extended periods, the construction of a regolith shield is an effective alternative to transporting heavy shielding from Earth (Figure 6). The 3D printed regolith shell, built from surface regolith, has many advantages. It protects from cosmic radiation, solar flares, micrometeoroids, and temperature variations, as well as increases the durability of the habitat modules and other components [21].

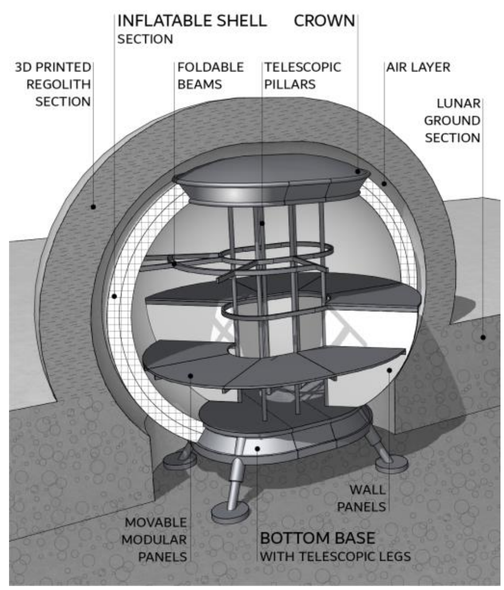

Figure 6. DIANA interior structure with 3D printed regolith protective shield

Since the doors and the window cannot be covered with regolith, other possibilities had to be found to protect them from micrometeoroid impacts and to mitigate the effects of radiation. The Mesh Double-Bumper (MDB) shield is made of four adjacent materials: a mesh bumper using aluminum 5056 wires, a second aluminum bumper, Kevlar as an intermediate bumper, and aluminum 7075-T6 as the rear wall. The MDB shield provides higher effectiveness in terms of micrometeoroid protection as well as a lower mass for the doors. The mass of a door using the MDB shielding would be 89.9 kg, enabling the astronauts to open them with electric actuator support. Following industry standards [22], transparent polycarbonate, which is used on the ISS, will be used as the window material. The conditions for the window are the same as for the door, i.e., it shall withstand an impact of a micrometeorite with a diameter of 0.5 cm at a maximum speed of 70 km/s. In this case, these conditions must be fulfilled for the attached spall threshold as the worst acceptable case of window damage. The calculated mass of the window is 868 kg. Despite the large mass penalty of the window, it has been deemed an essential component for positive astronaut psychology due to the long-duration missions within the confined space of the habitat. The large thickness of the window not only adequately protects against micrometeorites, but also provides good radiation protection.

V. Radiation Protection

From a radiation point of view, the mission can be divided into three parts: 1) launch, transit, and landing on the lunar surface, 2) accommodation at the habitat, and 3) EVAs. During launch, transit and landing the crew will be largely protected by the launcher and through mission planning. Radiation-intensive windows have been minimized and space weather will be considered in scheduling. The launcher also has a safe haven in case of sudden high radiation events. For the accommodation at the habitat and the EVAs on the lunar surface a special radiation protection concept has been designed.

Regolith provides basic protection against radiation and is more cost-efficient than transporting shielding material to the lunar surface. The shielding design was based on NASA's On-Line Tool for Assessment of Radiation in Space for measuring radiation intensities coupled with historical high-radiation-event data [23]. The habitat will be covered with a 240 g/cm^2-thick regolith layer. With a mean regolith density of 1.5 g/cm^3 [24], this amounts to a 1.6 m-thick shield including a 20% margin. The safe haven will provide a longer term shelter for crews during radiation-intensive periods. It is located in the lower level of the social module, including the crew quarters, a hygiene facility, and access to food. The social module consists of a bilayer protection of 180 g/cm^2 regolith and 60 g/cm^2 polyethylene, resulting in a thickness of 1.2 m of regolith and 0.6 m of polyethylene. Bilayer protection is more effective than solely regolith shielding because it can repel both high- and low-energy particles. In addition, it will reduce the thickness and increase efficiency [25].

The as low as reasonably achievable principle has been applied to define the secondary protective measures. The base will be equipped with passive dosimeters at multiple locations and crew members will be equipped with body-worn active dosimeters. Although the spacesuit will give about 0.3 g/cm^2 protection due to shielding by mass [26], EVAs will be limited in time and number based on NASA radiation exposure guidelines. Furthermore, space weather will be continuously monitored by NASA's Solar Particle Alert Network in case of sudden Solar Particle Events, allowing at least 20 minutes of warning.

VI. Thermal Control System

The objective of the Thermal Control System (TCS) is to guarantee that all units, equipment, parts, and components remain within their design temperature ranges throughout the mission lifetime. The lunar surface is susceptible to dramatic temperature changes between day and night. Regions in the lunar South pole are either permanently shadowed or semi-permanently sunlit. Lunar regolith is an excellent insulation material due to its extremely low thermal conductivity of 0.004 W/mK [27]. Therefore, the 1.6 m thick layer of sintered regolith shielding used for radiation protection will double as thermal heat insulation. The underground regolith can also provide a stable thermal gradient that is relatively insensitive to the surface temperature variations. The conceptual lunar base model made for TCS design estimations is composed of a spherical and cylindrical base structure with half of its surface area being buried below the lunar surface. The overall external area of the modules is approximately 490 m^2.

The astronauts can control the air temperature within each module ranging from 19 °C - 25 °C. The air will be drawn out through the ceiling of the module and transported to the ECLSS where it will go through a water-driven heat exchanger and be, subsequently, released at various locations within the habitat.

Since the insulation will ensure a heat loss through the wall of less than 1kW, the internal heat dissipation will be sufficient to keep the station warm. In fact, the heat exchanger will only need to provide cooling capabilities, which will be achieved through a 3 °C and a 21 °C water loop. An additional 1 kW electrical heater will be built into the air ventilation to provide heating in case of low heat dissipation by other equipment. All high heat-dissipating equipment will have additional connectors for water cooling to transfer thermal energy directly to the cold-water bus instead of releasing it to the habitat's air.

Within the lunar habitat, the systems and crew combined will dissipate between 10 kW and 70 kW of heat. The key driver for the design is the release of heat which will be dissipated within the station during daytime temperature conditions (244.23 K) [1]. The module's water loops will usually be arranged in a parallel manner to achieve a constant intake temperature at the heat exchanger. Two central heat exchangers outside the station will connect the water loops with a two-phase pumped ammonia loop on the other side. The ammonia loop will be connected to radiators. The expected wall temperatures of the radiators are -6 °C and 13 °C. Radiators will be placed flat and horizontally on the lunar surface. A heat rejection of more than 200 W/m^2 for the -6 °C and around 300 W/m^2 for the 13 °C can be realized in this configuration and location throughout the entire year [28]. This will lead to an overall radiator area of 520 m^2. The overall heat rejection capability of 130 kW is mainly determined by the efficiency of the electrolysis process and the liquefaction process.

VII. Environmental Control and Life Support System (ECLSS)

Due to the constraints of a lunar habitat, neither an open life support system (LSS) nor a fully closed loop LSS will be feasible during mission phase one. Hence, a proven LSS will be used initially, and further improved upon as the base develops.

The initial ECLSS concept will consist of a physico-chemical LSS with the addition of a modular photobioreactor (Figure 7). The high technology-readiness-level (TRL) technology of the physico-chemical LSS will provide reliability. It will consist of the waste processing system (WPS), water recovery system (WRS), trace contaminant control (TCC), temperature and humidity control (THC) and ESA's advanced closed-loop system (ACLS) already in use on the ISS. The WPS will consist of the heat melt compactor (HMC), for the WRS it will be use the Vapor phase catalytic ammonia removal (VPCAR), adsorption and catalytic oxidation will be applied for TCC and the first-generation condensation (FGC) module will be used for THC. The ACLS [29] consists of the Oxygen Generation Assembly (OGA), the Carbon-dioxide Reprocessing Assembly (CRA) and the Carbon-dioxide Concentration Assembly (CCA), which is a two-bed cycling system (2BCS). The modular photobioreactor [30], which uses *Chlorella vulgaris* algae, will increase the efficiency and self-sustainability of the base. Using these edible algae, which have already been selected for an experiment on the ISS, CO2 can be transformed to oxygen and food. Its modular design will provide redundancy and multiple points of failure to ensure minimal outages of the system. Since ECLSS systems are crucial for the survival of the astronauts, systems like the ACLS will be redundantly spatially distributed over the base, in case of a critical event in one of the modules. Finally, chemical CO2 absorbers will be available in case of an emergency. For the crew safety a fire detection and suppression (FDS) system will be installed. The fire detection components consists of ionization smoke detectors and flame detectors, which will be placed in open areas of the habitat and strategic locations to assure detection redundancy and localizing the fire. The crew will be notified of a hazard condition through the alarm system. For the fire suppression it will be installed a distributed suppressant system, which consists of a bottle of suppressant (CO2) that will be placed in each enclosed volume and linked to an activation system. Secondary suppression will be also considered with portable extinguishers that will be placed in open areas in each module.

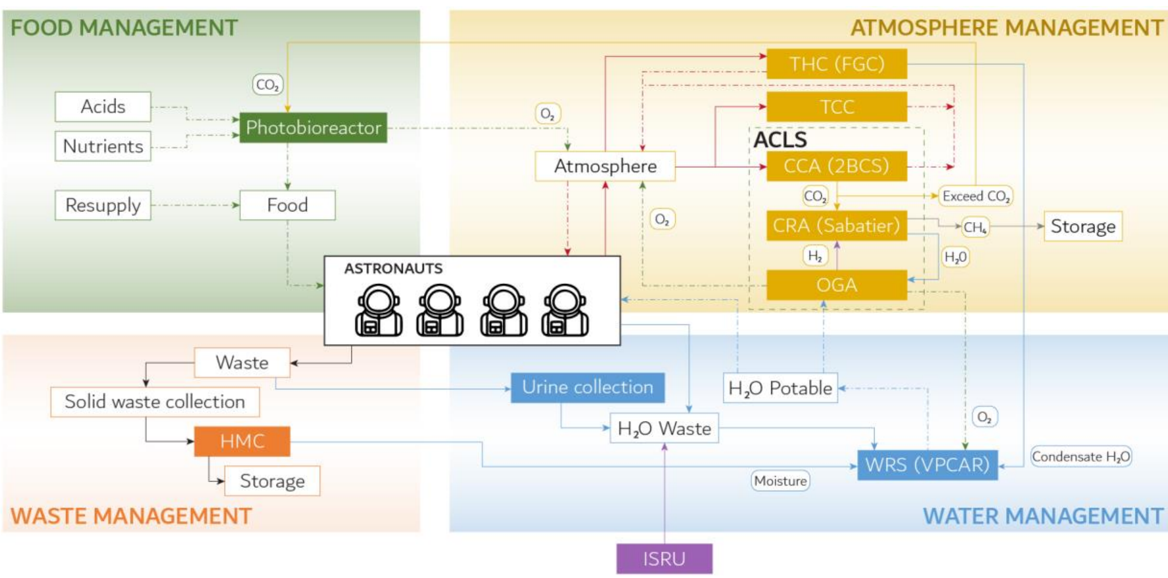

Figure 7. ECLSS Architecture Overview

The CH4 produced by the ACLS (approx. 530.91 kg/year) will be stored and used for the lander. Since the lander will use around 1600 kg/year, the reduction of this resource will be approximately of 33.2 % per year minimizing resupplies from Earth.

In later expansion phases, the ECLSS will be improved by updating the exiting greenhouse. This will be implemented on a small scale at the beginning of the mission and then further expanded upon. The greenhouse will be an open design, meaning that it will have the same atmospheric conditions as other human habitats. Therefore, the greenhouse will produce oxygen, clean water via evaporation, and food. Since the greenhouse will be completely covered by regolith to protect the plants from radiation, artificial lighting will be used. Hence, the environment in which the plants grow can be well controlled, subsequently allowing the plants to grow at a faster rate. Overall, the greenhouse processes CO2, feces, wastewater, and urine. In the first phase, the greenhouse will serve as an organic laboratory in which various plants will be investigated to determine which ones provide sufficient nutrition and a high growth rate. Those are critical parameters, since food supply should primarily be provided through the greenhouse in later phases. Importantly, it will further close the LSS loop and provide important psychological benefits for the crew. Overall, the ECLSS is expected to have a power demand of 30 kW once the biological systems contribute to the design. The provided area in the greenhouse is 21.71 m^2.

Due to the inclusion and expansion of biological LSS concepts, the self-sustainability of the ECLSS will increase over time. As a result, decreasing reliance on resupply missions from Earth can be expected as the system becomes more efficient. The water generation from ISRU will also be an important resource to feed the ECLSS water recovery system, which will be around 53 % (6000 l) within two years, and from the fourth year, with the implementation of a second chamber, it will cover the water supply of the system, allowing the total reduction of resupplies that come from Earth and its self-sustainability.

VIII. Mission Operations

To ensure the operational efficiency of the lunar base, certain parameters were considered, such as crew size and schedule. Astronaut safety is paramount to mission success. Hence, medical support and emergency scenarios were analyzed. Long duration missions on the lunar surface require adaptations to both the environment (which are addressed with architecture, design and technology) and the individuals. Astronauts will face a variety of stressors, physical and mental [31]. Therefore, necessary countermeasures have been incorporated into the operations.

Initial crews will comprise four astronauts. As the habitat expands in expansion phase I, up to eight astronauts will be accommodated. In the final phase, the habitat will expand even further and will comprise traditional astronauts and space tourists. As on the ISS, exercise will be mandatory at DIANA. The current ISS regimen will be used initially. As our understanding of the long-term impacts of lunar gravity improves, this regimen will be adapted as needed. Ergonomics and the placement of the exercise equipment within the greenhouse will make it a more pleasing experience, emulating exercising outdoors. Furthermore, the use of VR/AR will expand this by providing variety and simulating specific locations on Earth [32].

IX. Communication System

The communication system is divided into the communication between DIANA and Earth and the communication on the Moon which includes subsystem data exchanges and astronaut communication. A constellation of six satellites flying in a stable elliptical orbit will be used to ensure a stable connection with Earth. The stable orbit will have an 86° inclination with its closest approach to the lunar surface at 720 km. The constellation will be one of the first elements of DIANA to be launched from Earth. Each satellite will be equipped with two 0.5 m high-gain antennas with a pointing mechanism to increase accuracy and provide the necessary redundancy. In addition, they will be equipped with an optical communication system to exchange information and housekeeping data between satellites in the constellation. With this setup, it will be possible to provide redundancy with at least two satellites in the field of view of the base at all times. The European Space Agency's (ESA) ESTRACK network [33] will be used for receiving and sending data to and from Earth. Communication between the base, the satellites, and the ground station will operate at Ka-band frequencies between 29.1 GHz (uplink) and 30 GHz (downlink). For this purpose, two 1.5 m diameter parabolic high-gain antennas will be placed next to the base to enable communication between the satellite constellation and DIANA. Table 1 shows the Link Budget of the system. For lunar surface communications, an X-band network corresponding to frequencies

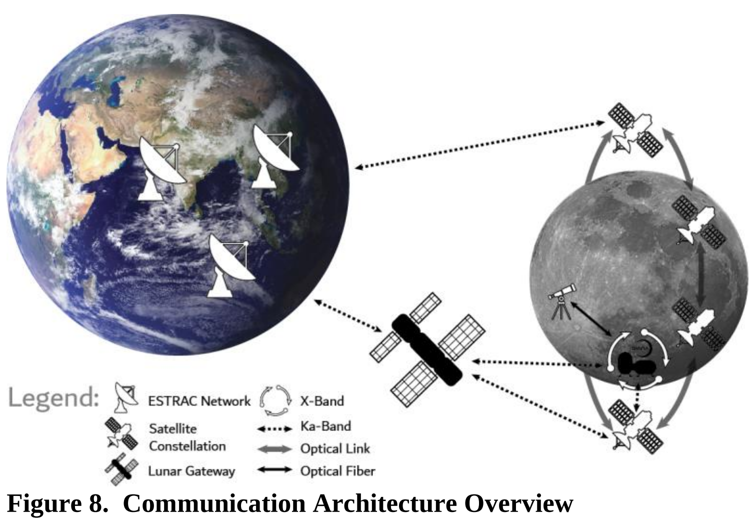

Figure 8. Communication Architecture Overview

from 9.3 GHz (uplink) to 9.8 GHz (downlink) will be used. The overall communication architecture for DIANA is roughly summarized in Figure 8. If the constellation arrives at its intended orbit too late or is non-functional, it will be possible to establish a secondary connection to Earth via the Gateway which would act as a backup relay station.

Table 1. Link Budget

Parameter	Symbol	Unit	Best Case	Worst Case
Transmitter Power	P	dBW	17.78	17.78
Transmit Antenna Gain	Gt	dB	51.00	47.90
Propagation Path Length	S	m	3.63E+08	4.06E+08
Free Space Loss	Ls	dB	-232.93	-233.89
Receiver Antenna Gain	Gr	dBi	64.00	64.00
Data rate	R	bps	6.21E+08	6.21E+08
Energy per bit to Noise-density	Eb/No	dB	15.73	10.77
Bit Error Rate	BER	-	1.00E-07	1.00E-06
Margin	**-**	**dB**	**10.48**	**3.02**

X. Electrical Power System

The power generator, the power control and distribution unit (PCDU), and the buffer batteries comprise the Solar Park, whereas the long-term power storage is located at DIANA Settlement. The final EPS component is the energy user, referring to each energy-consuming subsystem or piece of equipment.

Power generation will be achieved using solar arrays. Due to political constraints, nuclear power generation has not been considered. To minimize the amount of supply missions, chemical-based power generation has not been considered. To save power for the lunar night, electrical power will be stored in long-term power storage, which consists of a closed-loop system of a Regenerative Fuel Cell (RFC), a water tank, a hydrogen tank, and an oxygen tank. Due to the RFC's high response time, a buffer battery has been implemented within the design to eliminate constraints for the energy user. The PCDU will be responsible for controlling, distributing, and regulating the power between the four remaining components. Within each module, other distribution units will be installed. To have full flexibility, the highest priority for the PCDU is to provide the required power to the modules. The second highest priority is to charge the buffer battery before power is stored within the long-term power storage. The energy consuming systems can be turned on or off automatically or manually.

The main power generation will be achieved by using TJ Solar Cell 3G30C - Advanced triple-junction solar cells (GaInP/GaAs/Ge) from AZUR Space, which provide a cell efficiency of 30% at beginning of life (BOL) [34]. A degradation of the solar cells has been modeled with an exponential function with a degradation factor of 2.75% per year. Under BOL and best illumination conditions, the solar panels will have an output of 175 kW including a margin of 20%. After 15 years the solar power yield will be 115 kW. For easy transportation, the solar cells, with a total area of 483 m^2, will be mounted on a foldable structure.

Due to the low solar elevation angle during the lunar day, the solar panels will unfold vertically so that the solar cells face the horizon. Each solar panel is a self-sustaining unit equipped with a drive mechanism to ensure it always points towards the sun and with a TCS to maintain an adequate temperature. Additionally, the panels need to be sufficiently separated to avoid shading.

A redundant pair of Proton Exchange Membrane Regenerative Fuel Cells (PEM-RFC) is implemented in the DIANA Settlement to store surplus energy from the lunar day. The stored energy will be used during the lunar night to power the station. Due to high demand and the RFC's short lifetime, a two-year replacement cycle has been proposed. The PEM-RFCs are cold redundant, so that one can serve as a backup in case of a fault of the main PEM-RFC. Additionally, the replacement process will not affect the station's operation in this configuration. For safety reasons, tanks as well as pipes will be redundant. Note that liquids will be distributed equally on the tanks to avoid system failure in case of a broken tank. The complex illumination conditions (Figure 1b) will require a power capacity of 22 MWh during the first winter. Because of solar cell degeneration, the required time for "recharging" the fuel cell will increase over time. Therefore 42 MWh will be stored for the winter after 15 years. Detailed information about the storage is provided in Figure 9a.

When surplus power from the solar panels is available, an electrolysis process will be initiated to split water molecules into oxygen and hydrogen. When electrical power is required, the RFC can reverse the chemical process.

The electrolyzer of the NASA Glenn Regenerative fuel cell system operates with an efficiency of between 88% and 92%, and the fuel cell works at around 60% efficiency, yielding an overall storage efficiency of 50% [35].

Initially, 8000 kg of water will need to be transported from Earth to the Moon to provide enough storage capacity. Within the next eight years, an additional 5000 kg will be needed to increase storage capacity due to a lower electrolysis rate, resulting from less surplus power as the solar panels degrade. This water can be transported from Earth or produced through ISRU. An overall power storage charge status is presented in Figure 9a.

To store oxygen and hydrogen, the gasses need to be liquified. The water tank has a mass of 828 kg and tanks for the liquified oxygen and hydrogen have a mass of 623 kg and 1266 kg, respectively.

To eliminate user constraints, a Li-Ion buffer battery is built into the design. The battery has an overall gross capacity of 300 kWh. Due to the high capacity of the battery, low discharging rates (c-factor) can be achieved, extending the battery's lifetime. Better cycle stability of the battery will also be achieved through an allowed Depth of Discharge of just 30%. The PCDU will provide a Maximum Power Point Tracker to enable optimal solar panel performance. Electrical power will be distributed to the modules by a 160 VDC regulated bus. Within the modules, other PCDUs will distribute the power to every single load. These PCDUs will also provide a 160 VDC bus for high power-demanding loads and a 28 VDC bus for low power-demanding loads. Based on a detailed power consumption model, the daily power consumption of the astronauts and subsystems is presented in Figure 9b. Fuel production will rely solely on surplus power and is therefore not included in this figure. The surplus power will enable a yearly fuel production of at least 30 t, which will cover the oxygen demand.

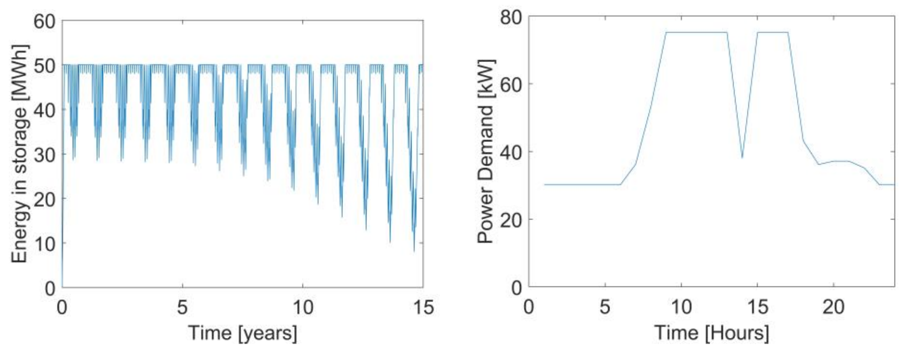

Figure 9. EPS. *a) Energy in Long Term Storage, b) Daily Power Demand*

XI. Radio Telescope

Several approaches have been considered for a lunar radio telescope: a single crater or phased-array antenna (PAA) or very long baseline interferometry (VLBI) approaches of both. The PAA VLBI approach emerged most successfully from the trade-off study, as the antenna deployment can use already existing strategies for unfolding solar panels, it is very modular and therefore easily extensible, and has less location restrictions than crater antennas. In addition, the VLBI approach promises a much higher spatial resolution, which is no longer determined by the diameter of a single antenna alone, but by the largest baseline between the antenna stations.

The proposed telescope architecture - a phased antenna array radio interferometer (PAARI) - consists of three basic modules: the PAA and relay stations that are distributed over the lunar surface, and a receiver station right next to the lunar base, as shown in the concept drawing in Figure 10. The Radio Telescopes will be located on the far side of the moon (approximately 100 km from the base). For data transfer, the stations will be connected by free-space optical communication using modulated infrared lasers, visualized by red lines in Figure 10. The receiver station, however, will be connected to the base by fiber optical cable, to ensure good transmission of the combined data load from

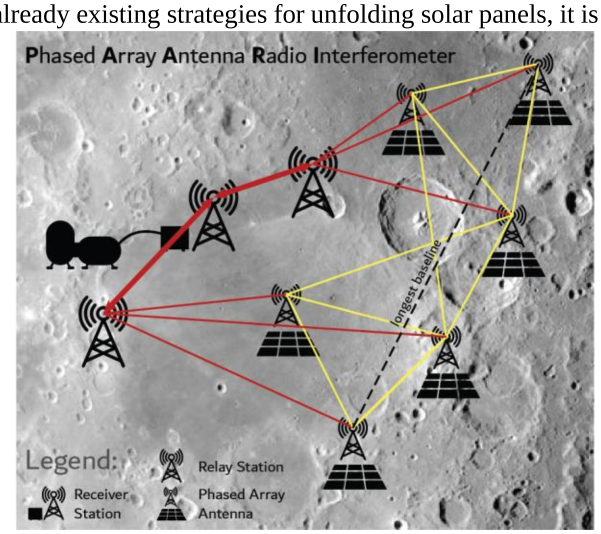

Figure 10. Radio Telescope Overview

all field stations. For the VLBI, the distance between the PAA stations must be known at all times, which will be realized by laser time-of-flight measurements, represented by yellow lines in the drawing.

Comparable telescope arrays on Earth, like LOFAR [36], can collect several hundreds of gigabytes of data per hour, which makes it indispensable to reduce the data before transmitting it to Earth. Therefore, the astrophysics section of the DIANA multipurpose lab module will have a supercomputer for VLBI signal processing and data analysis. Until the lunar base has the capacity to employ its own astrophysicist-astronauts that can work with the full data on the Moon directly, astronauts will receive standard procedures to supervise which data are most important to send to Earth for further research.

The field stations will be deployed by autonomous landers that set up the communication to the other stations, and also unfold the PAA station's radio antenna. This modular approach will allow the telescope to be gradually expanded with the growing lunar base. At the same time, it adds to another one of DIANA's aspirations as it encourages international as well as public-private collaboration; anyone can contribute to increasing the telescope's observation capabilities by financing an additional station, and therefore be a part of PAARI's mission to explore the radio universe.

XII. Cost and Risk Management

A. Cost Estimation

A detailed cost estimation for the DIANA lunar base concept was performed. Based on the scope of this project, the TRANSCOST system was used to evaluate transportation costs and NASA's Advanced Missions Cost Model was used to estimate the full system cost for human-rated systems [37]. It improves upon solely mass-based estimations by taking further parameters into account. In DIANA's case, these parameters were chosen based on available data and validated by cost experts.

The total cost for the concept for the first 15 years of operation until 2045 will amount to €120bn. In comparison to an estimation for the ESA Moon Village, this is comparable to the cost in the transition phase from experimental to an industrial setup [38]. A detailed distribution of these costs over the setup and operation time is given in Figure 11.

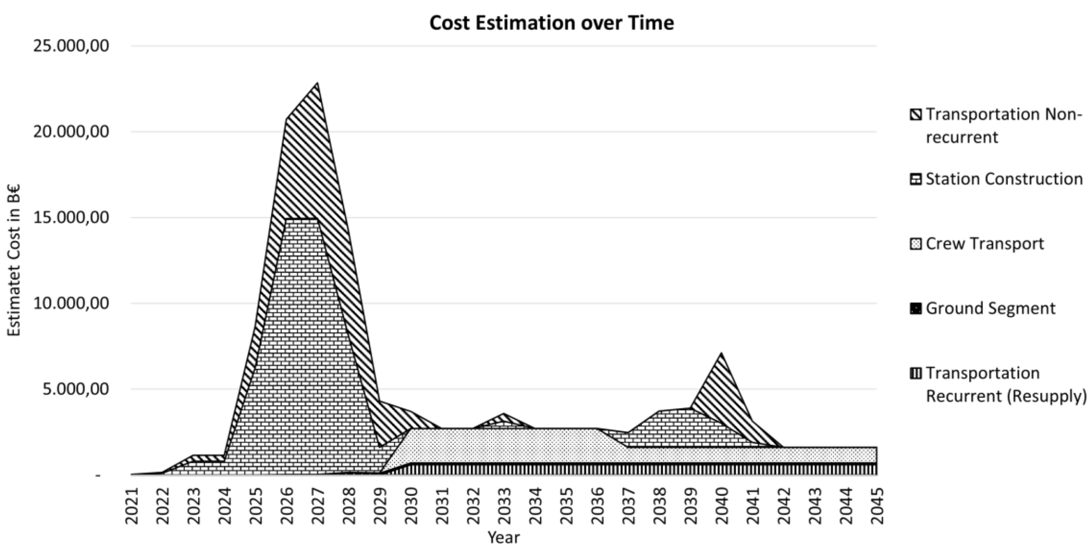

Figure 11. Cost Estimation over Time with usage of the Falcon Heavy as launch vehicle

These costs can be further differentiated. Due to the considerable size and complexity of the first habitat, as well as the development and modification of cargo and crew transport systems, 72% of the costs are non-recurrent. These include €54.6bn for the station itself and €32.4bn for the transportation systems. The recurrent cost consists of roughly €22.2bn for regular crew transports, €9.6bn for resupply missions, and about €2bn for the ground segment. The current technology levels were taken into account and development costs for adaptations of existing systems or new system developments, including prototypes and testing phases were taken into account and distributed over several years based on the Beta Curve cost-scheduling relationship [37].

Options to reach long-term self-sustainability were considered. The crew transport cost can be reduced from 2036 forward due to the usage of propellants supplied by the ISRU facilities. Space tourism and end-of-mission residual value of the station were also considered. With one tourism mission per year, about €0.9bn could be made with three tourists that would pay roughly €0.5bn accounting for their training amongst other mission-specific costs. With a residual value of the station of €4.3bn, the total costs could be lowered by almost €15bn. Selling consumables based on ISRU facilities is a long-term option to further increase financial self-sustainability. For this calculation, Falcon Heavy was considered as the main launch vehicle for a more conservative view on cost development. Should Starship be operational, the expected cost for transportation will be considerably lower.

B. Risk Assessment

Human space endeavors are burdened with a significant amount of risk, impacting technical, schedule, and cost performance. Thus, during the DIANA lunar mission, risk management cannot be neglected.

The analysis for DIANA is based on the ECSS-M-ST-80C [39] standard. Potential failure situations in the technical domain were identified in the areas of mission, robotics, architecture and structural shielding, radiation protection, thermal protection, ECLSS, mission operations and human factors engineering, electrical power subsystem, and scientific infrastructure. Programmatic risk is covered in the project management area. Together, this formed a list of more than 60 potential failure scenarios. Those situations were evaluated using probability and severity factors. Both factors are based on a five-degree scale, moving from lowest to highest severity and probability with increments based on logarithmic growth. Then, using the matrix proposed by the ECSS standard, risk level was assessed either as very low, low, medium, high, or very high.

Table 2 depicts the highest risk situations for each area. The failure of technical components is not expected to present a significant risk. The highest risk is present in the area of project management. Mitigation, such as using time costing methods and comparable time management, should be implemented.

Table 2. Failure Situations of DIANA for each Risk Area

Risk Area	Failure Situation	Probability	Severity	Risk Level
Mission	Launcher failure	1	4	Very Low
Robotics	Rover Breakdown	3	3	Low
Architecture and Structural Shielding	Structural Damage due to debris impact	2	4	Low
Radiation protection	Degradation of electronics due to radiation	2	5	Medium
Thermal protection	Failure of heat exchanger	3	3	Low
ECLSS	Habitat depressurization	2	5	Medium
Mission Operations and HFE	Conflict within the crew	1	4	Very Low
Communication	Destruction of the antenna due to micrometeorites	2	3	Low
EPS	Solar panels partially damaged by meteorites	2	3	Low
Radio Telescope	Losing a telescope due to electric power failure	4	3	Medium
Project management	Reliance on advances in low TLR technology	4	4	High
Project management	Cost and schedule overrun	4	4	High

XIII. Conclusion

The proposed lunar base, DIANA, will enable the permanent habitation of four astronauts at the lunar South pole, at the rim of the De Gerlache crater. The suggested location provides not just a high illumination rate but also proximity to PSRs within the crater, where water ice is suspected. Both aspects in combination with a solar-power-based energy supply predestined the base for the use of ISRU. Through increasing ISRU, resupply missions can be gradually reduced. The ISRU will focus primarily on the use of water ice for energy storage, refueling the lunar lander, as well as providing potable water for astronauts. Further independence from resupply missions will be achieved through a greenhouse providing vegetables. In later phases, the food supply shall be provided entirely by the greenhouse. A habitation module, a multipurpose lab and a windows module are also part of the DIANA Lunar Base. The modules will be covered with a 1.6 m-thick layer of regolith which serves as heat insulation as well as a radiation shield. DIANA is also the base of a radio telescope on the far side of the Moon.

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