HUMAN-ROBOTIC INTERACTION FOR LUNAR EXPLORATION IN THE DEVELOPMENT OF A LUNAR FAR-SIDE RADIO OBSERVATORY

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Space robotics has enabled tremendous discoveries in planetary sciences and has emerged as an incubator of technologies with major impacts on the quality of life for the Earth's growing population and with important commercial potential. The purpose of this research is to develop new paradigms for space robotics, such as quick construction, less expensive components that can be used for different types of robots, and improved user operability, and to determine how robots and humans can best interact in order to add value to human-robotics space missions. The mission-oriented approach adopted in this context consists of the investigation of several lunar exploration scenarios with the purpose of analyzing the appropriate task distribution among humans and robots. Presented in this work is a mission concept study of a lunar far-side radio observatory optimized to observe the neutral 21-cm emission from the intergalactic medium during the dark ages of cosmic structure formation and the early stages of cosmic reionization. The Self-Tending Array Node and Communication Element (STANCE) model is the concept being investigated, which combines four helices into a single interferometer element (stance) with more than 5000 stances deployed in a relatively flat area at least 10 km across on the far side of the Moon. The discussion will illustrate the scientific requirements as well as the technical requirements which they drive. Details will be provided about the elements under study, such as array configuration, deployment, site selection, power systems and thermal management, data transport and transmission to Earth. Finally, the role of astronauts and robots in the implementation of this observatory and its operations will be shown to have an impact on the design of such a complex mission, and it will be seen how this interaction poses further constraints to the different subsystems in terms of mass, power, size, and cost.

I. INTRODUCTION

Since radio interferometry techniques were first employed, new observations of astronomical objects have added a tremendous wealth of knowledge about the universe and its beginnings. Despite these accomplishments, the biggest inhibitor to further exploration, observation, and understanding has been the physical constraint of Earth-based observatories. One of the most elusive research interests in modern cosmology revolves around detailed observations of the high-redshift Universe that includes reionization, the "earlier phases of nonlinear structure formation," and the dark ages [1]. However, Earth-based interferences like Radio Recombination Lines (RCLs), terrestrial radio interference, and ionospheric distortions prohibit the collection of sound data [1] and have prohibited any useful observations to date. More specifically, an investigation into the high-redshift Universe would require looking at the redshift H I 21-cm line, a signal that is not only limited by the Earth interferences described above, but by solar radio emissions as well [2].

It is in this quest to better understand the cosmic origins of the Universe that a far-side, lunar-based radio array observatory would be ideal. A comparison with current and future lunar missions quickly shows that such a scientific endeavor has yet to be performed and has the potential to yield long-term value for further space exploration. Shielded from the harmful terrestrial and solar-based interferences, the far side of the Moon would prove ideal because of its low gravity (thus providing a stable platform as required to perform interferometry with many antennas and without expensive maintenance) [3], and due to the fact that there is no human-generated interference, solar radio emission interference, or ionosphere [2], as highlighted by previously proposed lunar-radio array missions. Furthermore, the Moon's night is two weeks long, which implies that the Sun's radiation can be avoided for such a period of time when performing measurements for cosmology and astrophysics, while on the other hand it allows studying the Sun during the two-week-long lunar day. Finally, only half the sky needs to be mapped at a time, thus simplifying instrument calibration [3]. Plans for a LRA have been proposed earlier based on scientific motivation but there was no consideration for its full integration with robotic and human operations within a single space mission or program. With an established LRA on the far side of the Moon, some of the most pressing cosmological questions about the early formation of the universe can be answered.

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II. THE LUNAR RADIO ARRAY: SCIENCE AND PRELIMINARY DESIGN

II.I Scientific Rationale

The origins and evolution of the universe have been largely investigated by a number of astrophysical missions, in which NASA has been heavily involved. Missions such as the COsmic Background Explorer (COBE), the Wilkinson Microwave Anisotropy Probe (WMAP), and recently Planck, have provided valuable data on the density fluctuations in the universe. In addition, wide-field galaxy surveys along with observations of Type-IA supernovae have produced large data sets which have shed much light on important phenomena occurred during the early stages of the universe. Although this information has led to the establishment of a standard model for cosmology, much still remains unknown about the Dark Ages and epoch of reionization. Questions that are unanswered refer to the evolution of the intergalactic medium (IGM) during this time, the formation of the first galaxies, the properties of the first stars, the birth of the first black holes and their evolution towards mature galaxies.

Hydrogen is the dominant element in the IGM, and neutral hydrogen (H I) exhibits a hyperfine spin-flip transition at a frequency of 1420 MHz. Performing a spatial and spectral mapping of the H I-line brightness temperature could enable the determination of the distribution of hydrogen throughout the universe from the present day to a redshift z ~ 100. This unparalleled data set would thus provide constraints on the properties of inflation, enable the detection of signatures of unknown heating mechanisms before the formation of the first stars, and constrain the characteristics of dark energy and fundamental gravity [1, 4].

Observing in this low-frequency range of the electromagnetic spectrum entails many challenges which have not yet been thoroughly overcome. First, ground observations at very low frequencies (VLF), namely below 10 MHz, are hampered by scattering and reflection by the Earth's ionosphere. Second, radio frequency interference (RFI) caused by the Earth and Sun as well as by all of the civil and military satellites making heavy use of the frequencies relevant in this context, does not make any observations feasible. Numerous low-frequency arrays exist but they all have limitations which preclude their full exploitation for such ambitious scientific goals. Ground-based arrays such as the Murchison Wide-field Array (MWA), the Precision Array to Probe the Epoch of Reionization (PAPER), and the Square Kilometer Array (SKA) all operate at higher frequencies; the LOw Frequency ARray (LOFAR) and the Long Wavelength Array (LWA) are affected by radio-frequency interference and ionospheric disturbances due to their specific collocation on our planet; the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA) will observe only at lower redshifts, after the first stars have formed and reionization has occurred; the Cosmic Microwave Background (CMB) experiments target recombination; and finally, two conceptual free-flying arrays, ALFA and SIRA, as well as the Radio Observatory for Lunar Sortie Science (ROLSS) sample too high redshifts and lack adequate sensitivity.

II.II The Lunar Radio Array

This brief survey of the current state of the art leads to the conclusion that a novel observatory is necessary and highly desirable, which overcomes all the above-mentioned shortcomings, and enables such a revolutionary type of science. A Moon-based observatory would provide such an enabling technology for the following reasons. First, the Moon can act as a direct shield against RFI thanks to its size and material properties. Second, it can provide a stable platform as required to perform interferometry with many antennas without expensive maintenance and it offers the possibility of being upgraded over time. Finally, the Moon's night is two weeks long, which implies that the Sun's radiation can be avoided for such a period of time when performing measurements for cosmology and astrophysics, while on the other hand it allows studying the Sun during the two-week-long lunar day. Furthermore, other large RFI sources such as Jupiter can be protected against by using the Moon as a shield. Finally, only half the sky needs to be mapped at a time, thus simplifying instrument calibration [3].

A number of concepts for a lunar radio array (LRA) have been discussed in recent years, in particular when NASA's Constellation Program seemed to offer the opportunity to go back to the Moon with the goal of establishing a permanent human colony [2, 5, 6]. The objective was to create the infrastructures necessary to fully exploit the lunar capabilities to carry out scientific experiments over a broad range of interests. What is proposed in this manuscript draws on such preliminary ideas and will illustrate a hypothetical scenario where cooperation between astronauts and robots becomes essential to the deployment, operations, and maintenance of a lunar-based radio observatory.

Depending on the science objectives envisioned, the degree of complexity of this type of array will vary and set constraints on cost-performance metrics. The general concept is that each of the LRA elements would comprise multiple antennas, whose signals are aligned in time and summed so that each LRA element behaves as a single very sensitive antenna. The signals emitted from each pair of elements would then be correlated with each other as an interferometer, and the different baselines that can be established between the various pairs would probe the sky across the regions of interest. In particular, the epoch of reionization could be studied by peering astronomical objects in the 50-150 MHz range, whereas a spectral coverage over a 30-200 MHz band would extend well into the Dark Ages. This has direct implications on the brightness temperature sensitivity and angular resolution necessary to perform such tasks, which in turn translates into different collecting areas, maximum baselines, and lifetime.

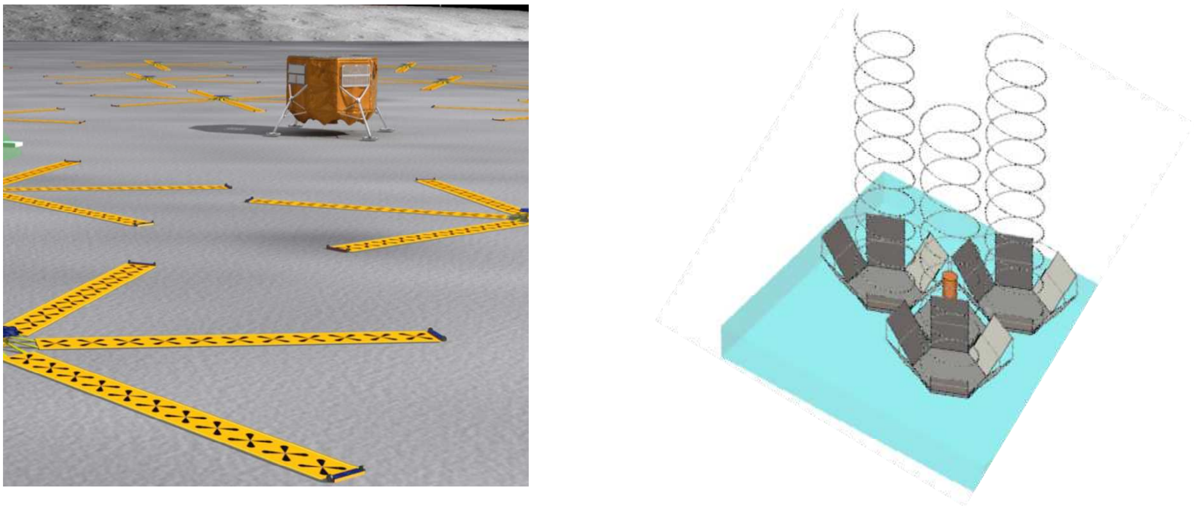

Figure 1: (Left) The DALI concept in an artist's view. (Right) A Self-Tending Array Node and Communication Element (STANCE) made of three helical antennas for the LARC configurations [2].

Preliminary calculations [2] show the more challenging option would be the Dark Ages one, in that it would require a collecting area and a baseline about one order of magnitude bigger than the one needed for the epoch of reionization. In addition, several technological capacities would be necessary to build this observatory so as to optimize cost-performance throughout its lifecycle. Examples of these technologies are low-frequency, wide-bandwidth, low-mass science antennas; ultra-low power, radiation-tolerant digital/analog electronics; autonomous low-power generation; high-data-rate, lunar-surface data transport; and low-mass, high-capability, autonomous robots. Due to the above-mentioned problems caused by RFI, a relatively flat area several kilometers across on the far side of the Moon would be the location to choose for an LRA. Currently, there exist at least two different ways of achieving all of this; one is the Dark Ages Lunar Interferometer (DALI) and the other one is the Lunar Array for Radio Cosmology (LARC). These two concepts are described in the work of Lazio et al. [2], with substantial involvement from the MIT astronautical and space physics communities.

The DALI concept consists of a hierarchical array made of dipole antennas deposited on long strips of low-mass polyimide film. Individual antennas would be grouped into stations forming the overall array (Fig. 1, left). It is claimed that approximately 300 stations and 1500 antennas per station would be required for the full system. The main advantage of this approach is that the strips could be rolled during their journey to the Moon and unrolled directly onto the lunar surface, thus allowing highly efficient storage on the launch vehicle and possibly reducing the number of vehicles or launches necessary to transport thousands of them to the Moon. In addition, the polyimide film was proven to withstand the lunar thermal gradients through a series of test performed at the NASA Goddard Space Flight Center. Besides, using stations facilitates thermal management, power generation, and electromagnetic shielding as it would be possible to co-locate antenna electronics and other electrical parts in one central box. The challenges related to this concept are the high degree of surface flatness required by the strips when unrolled in order to function properly and the extension of the entire array once deployed. This has direct implications on the preliminary work that robots or astronauts would need to perform to clear the area and make it accessible to such a vast array, as well as on the degree and type of maintenance that could be done timely and effectively over this large area.

The LARC concept combines up to seven helical antennas into a single autonomous phased-array element also called a Self-Tending Array Node and Communication Element (STANCE) (Fig. 1, right). Several STANCEs together would form a station and the combination on the lunar surface of thousands of them would form the actual observatory. A STANCE has several advantages over the DALI concept. For instance, the antennas would be all sensitive to the same E-field polarization and be rotated so that the beam pattern resulting from the combined power has a high degree of circular symmetry. This should improve the efficiency of the antennas, thereby providing better quality in the scientific data. Each antenna would be stored in a box only a few centimeters tall and then it would self-deploy on the Moon. In addition, the stringent requirements on the flatness of the surface could be lessened by allowing each STANCE to detect the soil irregularities and be able to align itself horizontally by means of ad-hoc mechanisms.

Trade studies, at this point, are necessary to determine the specific technical requirements for such a novel observatory in terms of mass, power, volume, data rates, storage capacities, data transport and transmission to Earth, thermal management, array configuration, deployment, site selection, operations, serviceability, reliability, and cost. However, it is clear that both options entail a large number of elements that are to be launched from Earth and deployed on the Moon. This sets constraints on the number of elements that can be carried on board of a single launch vehicle as well as on the number of launches required.

Preliminary calculations were performed in order to estimate the mass of the antennas, which represents the main driver of the system, as well as their volume. The working frequency was selected to be 90 MHz, so each helix has a diameter of 1.27 m and a height of 8.66 m with 10 turns. In order to meet the requirements for effective aperture and field of view, the ten-turn helices will be separated by 1.8 m on the lunar surface. In this case study, each station is made of 7 antennas. Figure 2 shows the MATLAB-simulated three-dimensional beam pattern at 90 MHz for such a configuration. Assuming the antenna to be made out of aluminum, an estimated mass of 8.67 kg per antenna was derived. In addition to this, the antenna support structure and the hexagonal base were included in the mass calculation for a total of ~100 kg per antenna.

The hexagonal shape of the base plate was chosen because it maximizes the number of antennas that can be stowed in the cylindrical cargo bay of NASA's Space Launch System (SLS), which will be one of the launch vehicles adopted for this mission, as explained later in Section III.I.I. In the stowed configuration, the antenna was assumed to be no taller than 0.5 m, which yields a volume of 0.065 m^3 per box. It is important to note that the stations are to be placed on the lunar surface so that the required angular resolution can be achieved. This varies between 3' for a nominal ~800-antenna LRA to probe the epoch of reionization to 1.4' for a ~10000-antenna Dark-Ages LRA [2]. While it is possible to estimate the maximum baselines for both options, respectively 5 km and 10 km, further studies will be necessary to derive the exact position of each station on the lunar surface in order to meet the aforesaid angular-resolution requirement. Figure 3 shows the beam pattern and its high degree of circular symmetry.

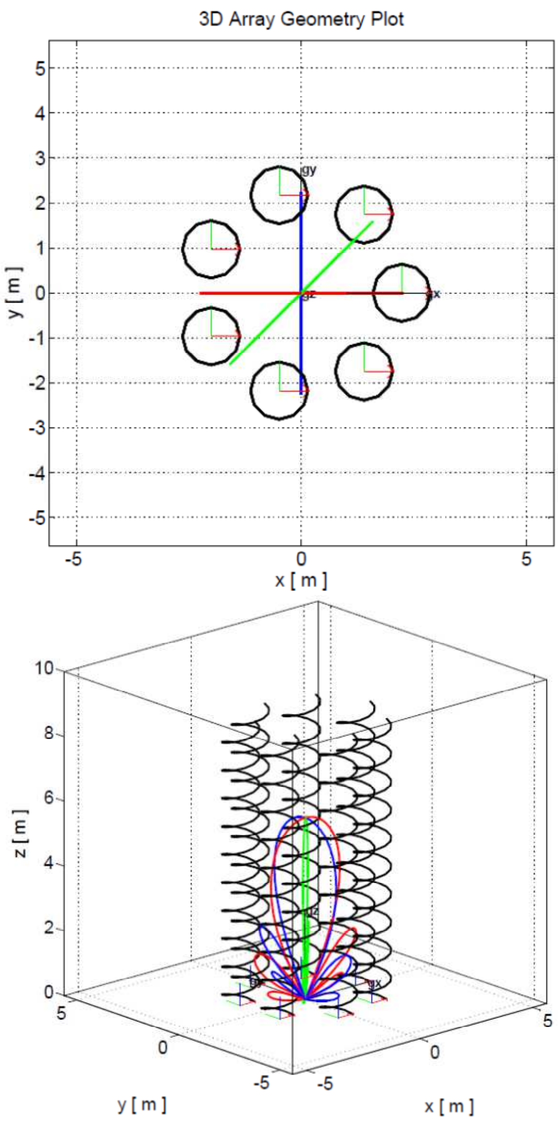

Figure 2: (Top) Top view of a station made of 7 antennas placed in a circular fashion. The station is about 5 meters across. (Bottom) 3-D view of the station and E-field directivity pattern along the three axes.

Each STANCE's digital signal processing unit includes a polyphase filter bank that selects a 16-MHz band, trims the data to 4-bit complex samples, and packetizes the header information. The packets are passed to a laser transmitter which transmits the data to a central correlator, possibly via local communications nodes. Each laser will be pointed mechanically in azimuth and elevation, and at the receiving station the optical signal will be focused onto arrays of avalanche photodiode detectors. The data rate transmitted to the correlator for each STANCE is assumed to be 128 Mbs. It is also estimated that each STANCE will consume about 250 mW. The LARC concept has a nominal lifetime of 3 years.

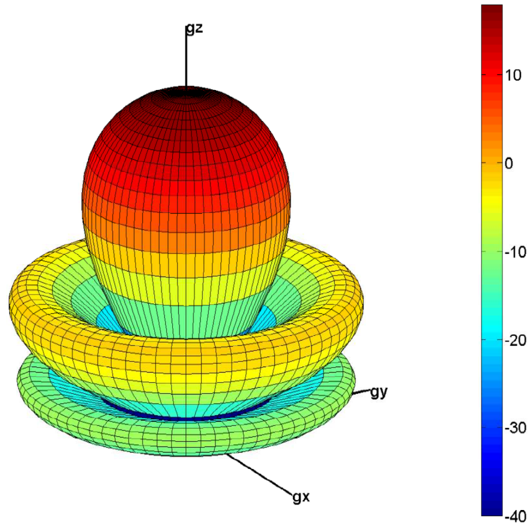

Figure 3: 3-D beam pattern plot. The peak directivity is equal to 17.75 dBi at a frequency of 90 MHz for a station made of 7 helical antennas. It is clear from this plot that helical antennas generate circularly symmetric beam patterns as required to perform this type of science.

It is necessary at this point to estimate the number of antennas that can be transported by the SLS and landed on the Moon through the lunar surface access module, Centaur (see Section III.I.III). It was assumed an initial mass of propellant equal to 65000 kg. In order to land on the lunar surface, a ΔV = 1.87 km/s is needed. If the propellant used is liquid oxygen (density = 1141 kg/m^3, specific impulse I_{sp} = 455 s), then approximately 23000 kg of propellant will be used to land on the Moon and 14000 kg will be expended during ascent to Low Lunar Orbit (LLO), for a total of about 37 metric tons (mT). This propellant mass needs to be carried in the SLS. It was assumed that it will be stored in tanks whose total height will be about 2 meters. At this point, 20 mT remain worth of cargo. The size of the antennas and the diameter of the cargo vehicle (8 m) allow for a maximum of 18 antenna units on the same layer, whose total mass will be 1.8 mT. 11 layers are thus equivalent to 19.8 mT, 198 antennas, and a total length for the cargo vehicle of at least 5.5 m. In order to account for the different interfaces between propellant tanks and the lunar lander, as well as allowances between the different aforementioned parts, a total length of 7 m was deemed appropriate.

II.III Mission concept of operations

The observatory would be built and assembled in several steps, with initial prototypes having a smaller number of antennas but all scientifically productive. The deployment of the first 198 antennas would allow initial testing and verification, but a target number of 800 antenna units could enable verification of ground-based observations of the epoch of reionization. In a second phase, the initial infrastructure would be upgraded and completed with a bigger number of antennas up to about 10000.

On launch from the Earth's surface, the astronauts will occupy the Crew Exploration Vehicle (CEV) while the Lunar Surface Access Module (LSAM) will harbor living space, life support equipment and work tools for the astronauts during their deployment on the lunar surface, as well as the cargo and Lunar Roving Vehicle (LRV) required for executing the science mission. After escaping from the Earth's gravitational potential, the CEV and LSAM will perform either Earth Orbit Rendezvous (EOR) or Lunar Orbit Rendezvous (LOR). It is at this juncture where the astronauts will transfer themselves from the CEV to the LSAM. One or two Earth Departure Stages are also required in these respective cases to perform the Trans-Lunar Injection (TLI) to reach lunar orbit. Once stable in lunar orbit, the LSAM will then separate from the CEV to perform a Powered Descent Insertion (PDI) and land at a specified location on the far side of the Moon. Upon safe landing, the astronauts will execute the science mission. With the aid of the onboard LRV, the astronauts will deploy individual or groups of antenna units at their assigned locations. The entire mission will last 7 days and should be executed during a period within a month when the designated landing site for the LSAM remains on the Far Side for at least 7 days. Since it takes approximately 6 days to travel from Earth to lunar orbit and back, the entire mission duration in space will be approximately 2 weeks. After completing deployment and testing of all antenna units, the astronauts will return to the LSAM, which will perform a powered ascent and a rendezvous with the CEV that remained in lunar orbit throughout the mission duration. The crew will then return safely to Earth in the CEV.

III. OVERALL SYSTEMS ARCHITECTURE

After establishing the science mission and the concept of operation, the next step in mission planning is to develop the space systems architecture that will make it realizable. The essential components of the systems architecture are: Mission Architecture, Launch Vehicles, Crew Exploration Vehicle (CEV) and Lunar Surface Access Module (LSAM).

III.I Mission Architecture

Following the recommendations provided in NASA's Exploration Systems Architecture Study (ESAS) report [7], the 1.5-launch EOR–LOR option was selected as the mission architecture for this study, as it had the best tradeoffs, most robust technical performance, low probability of loss of crew, low probability of loss of mission, and low lifecycle cost.

By way of comparison, in a 2-launch EOR-LOR mission architecture, 2 launches are required, with the first launch for delivering the CEV and crew and the second for the EDS, LSAM and relevant cargo. After successful launch from the Earth's Surface, the CEV and LSAM will perform an EOR at LEO. Only one large EDS will be required to deliver the combined CEV-LSAM to lunar orbit via TLI. The CEV-LSAM will dock with the EDS in Earth orbit before the EDS performs TLI. After the crew transfers themselves over to the LSAM, the CEV Command and Service modules (CM and SM) are left unoccupied in Low Lunar Orbit (LLO). After a lunar stay of up to 7 days, the LSAM returns the crew to lunar orbit and performs a LOR to dock with the CEV, and the crew transfers back to the CEV. The CEV then returns the crew to Earth with a direct-entry-and-land touchdown, while the LSAM is disposed of on the lunar surface [7].

The 1.5-Launch EOR–LOR has a large difference in size and capability of the launch vehicles as compared to 2-Launch EOR-LOR. It is essentially a lower-mass launch option made possible by the use of LOX/LH_2 propulsion on the LSAM, which sufficiently reduces the architecture masses. While 2-Launch EOR-LOR uses one heavy-lift Cargo Launch Vehicle (CaLV) to launch cargo elements and another heavy-lift Crew Launch Vehicle (CLV) to launch the CEV and crew, the 1.5-Launch EOR-LOR architecture divides its launches between one large and one relatively small LV. The heavy-lift CaLV will first launch the LSAM and EDS to LEO while a second launch of a smaller CLV will deliver the CEV and crew to orbit. The vehicles will then perform EOR and docking. The EDS then performs the TLI burn for the combined LSAM and CEV before being discarded in space. Upon reaching the Moon, the LSAM performs LOI for the combined LSAM-CEV unit, and the entire crew transfers to the LSAM, undocks from the CEV, and performs PDI to the lunar surface. Like the previous mission architecture, the CEV is left unoccupied in LLO. After a lunar stay of up to 7 days, the LSAM returns the crew to lunar orbit, where the LSAM and CEV dock and the crew transfers back to the CEV. The CEV then returns the crew to Earth with a direct- or skip-entry-and-land touchdown, while the LSAM is disposed of via impact on the lunar surface.

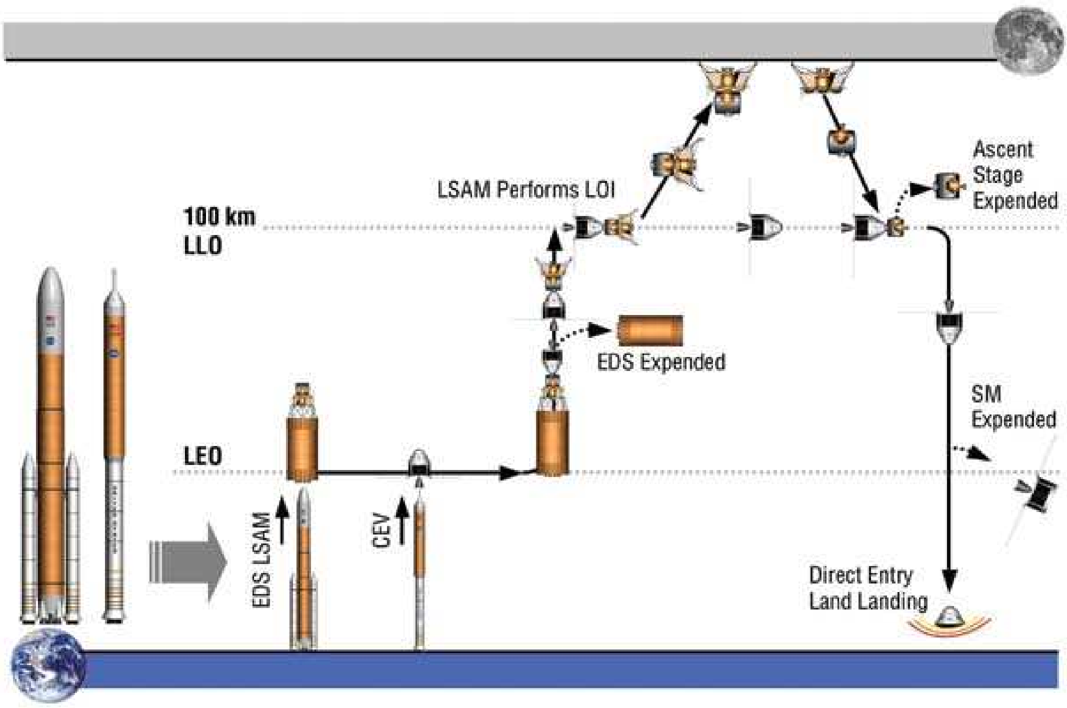

Figure 4: 1.5-launch EOR-LOR mission architecture with LOX/LH_2 lander descent stage propulsion. The heavy-lift CaLV will carry the cargo, LSAM and EDS, while the lighter CLV will deliver astronauts and CEV into LEO [7].

III.I.I Choice of Launch Vehicles

After deciding upon the mission architecture, the next step is to decide which Commercially-Off-The-Shelf (COTS) products would be most suitable for the CaLV and CLV. COTS LVs are most preferred as development costs can be saved for the mission LCC.

For the heavy-lift CaLV, NASA's Space Launch System (SLS) is the most ideal candidate. While the manufacture of the SLS has yet to be completed currently, it is potentially available midway through the developmental phase of this project. The 130-mT variant is preferred due to the higher cargo capacity available for executing the science mission [8]. The SLS has been designed as the most powerful rocket in history, designed to be flexible and evolvable, to meet a variety of crew and cargo mission needs. It is also designed to be equipped with the EDS on its second stage (Block II) that will be necessary for performing TLI. Hence, the SLS is capable of providing an entirely new capability for science and human exploration beyond Earth's orbit. The SLS is thus the LV of choice for carrying the cargo and LSAM into space.

For the lighter CLV, the LV of choice is Falcon 9 Heavy manufactured by SpaceX [9]. Although SpaceX is relatively new to the aerospace industry, SpaceX has been developing a new family of LVs, and they have credible experience in designing LVs and engines, SpaceX can potentially be designing the world's first fully reusable LVs. Usage of its products may help reduce lifecycle costs for this project if multiple missions are being appended in the future. The Falcon 9 Heavy configuration consists of a standard Falcon 9 with two additional Falcon 9 first stages acting as liquid strap-on boosters. Falcon 9 Heavy will be capable of launching a 53-mT payload to LEO. The Falcon 9 Heavy is also human-rated and studies have shown that structural safety margins are 40% above flight loads, which is higher than the 25% margins of other rockets. As such, the Falcon 9 Heavy will be the CLV for carrying the crew and CEV.

III.I.II Crew Exploration Vehicle - Orion

To ensure that the proposed lunar mission can be executed safely by the astronauts, there is a need to design and develop a CEV capable of transporting and housing crew on LEO and lunar missions. The envisioned CEV will contain a pressurized Command Module (CM) to support the Earth launch and return of a crew of 4 astronauts, an unpressurized Service Module (SM) to provide propulsion, power and other supporting infrastructural capabilities, and a Launch Abort System (LAS). The ESAS study also recommended using an improved blunt-body capsule for the CM, as it was found to be the least costly, fastest, and the safest approach for conducting lunar missions [7]. A blunt-body configuration is also lower in weight, and its similarities with more familiar aerodynamic designs from past human and robotic missions imply that development cost and time will be lower. Other factors recommended for consideration in the design of the CEV are acceptable ascent and entry abort load levels, crew seating orientation ideal for all loading events, easier LV integration, and improved entry controllability during off-nominal conditions. Over the course of the mission, the CM of the CEV will provide habitable volume for the crew, life support, docking and pressurized crew transfer to the LSAM, and atmospheric entry and landing capabilities.

Since the general mission concept includes a safe landing in the water, a combination of parachutes and airbags should be included on the CEV for a nominal land touchdown with water flotation systems required for water landings. After recovery, the CEV can be refurbished and reused for extended future missions. In choosing a suitable CEV that will be capable of performing the proposed science mission, existing technology and COTS products are greatly preferred since they will save significant development cost and time. With that motivation, the project intends to leverage the existing *Orion* Multi-Purpose Crew Vehicle (MPCV) [10]. The Orion will be delivered to LEO by the Falcon 9 Heavy LV as detailed by the 1.5-Launch EOR-LOR mission architecture.

As the payload capacity of the Falcon 9 Heavy is 53 mT, there is a need to ensure that the total weight of the Orion, 4 astronauts, infrastructure and other scientific instruments do not exceed this limit. To be conservative, a 20% buffer will be applied to the weight of the delivered payload on this mission. As such, the total payload mass to be delivered should not exceed 42 mT. This is a precautionary measure taken to avoid operating at technically risky boundaries and also in the event that more equipment may be loaded onboard the Orion. The gross liftoff weight of the unmanned Orion is 31380 kg [10]. Assuming an average weight of 80 kg for each astronaut and the sum of all life support equipment, infrastructure and scientific instruments to be 3300 kg, the total liftoff weight will be approximately 35000 kg (35 mT). This operation is viable as it is still below the limits of 42 mT.

Orion is initially designed to support long-duration deep-space missions of up to 6 months, fully equipped with unique life support, propulsion, thermal protection, and avionics systems. As such, the Orion is more than capable of supporting 4 astronauts on a 14-day space mission. Incorporating design concepts from the Apollo and Space Shuttle programs, the Orion spacecraft is built which includes both crew and service modules and the LAS that will enhance safety of the astronauts. As Orion is built to harbor more astronauts, for longer durations, Orion's CM is designed to be much larger than Apollo's [11]. The widest diameter of Orion is 5.37 m, which is much larger than the 3.66 m diameter of the Falcon 9 Heavy LV. As such, a spacecraft adapter will be needed to mount the Orion onto the Falcon 9 Heavy. The SM will provide the fuels and propulsion for the spacecraft as well as storage for necessities such as breathing air, water and food for the astronauts. The SM can be flexibly designed to either mount scientific experiment modules or carry cargo. More importantly, the Orion is also equipped with physical infrastructure and GNC systems necessary for EOR with the LSAM.

III.I.III Lunar Surface Access Module – Centaur-Based Vehicle

The *Centaur*, which is the upper stage on the current Lockheed Martin Atlas V rocket, was deemed the more ideal candidate for the future development of a reusable lunar lander [12]. With over a hundred consecutive successful flights, Centaur has proven to be an extremely robust and reliable platform, and it can potentially be modified as a robotic and possible human transport vehicle to the Moon. As such, modifications to the current Centaur design would allow it to function as an in-space propulsion system capable of supporting human operations and robotic probe landings. Centaur is also directly extensible to larger landing tasks including high-mass crewed missions, which is exactly what is entailed in this proposed mission.

The crewed lunar mission to Moon onboard the modified Centaur-based spacecraft will also be distinctively different from other known lunar missions, as it will be designed based on the *horizontal landing* philosophy instead of the traditional vertical landing [12]. As such, the proposed mission will require the use of the modified Centaur stage that will able to carry crew and perform missions to the Moon with a horizontal landing. The basic propulsion capability of the modified Centaur-based spacecraft will also be extended to longer durations and heavier payloads to suit the purposes of the proposed mission.

The modified Centaur stage for crew exploration in its horizontal landing position is shown in Figure 5 [12], and as previous lunar landers, it contains an ascent module (AM) and a descent module (DM). The vehicle will be designed to deliver 4 astronauts to the Moon. As a contingency measure, it should provide all life support equipment and necessities for a period of at least 14 days. The main components of the Centaur-based spacecraft are also shown, and the AM is a hemispherical unit that provides the astronauts of panoramic view of the surroundings. The airlock is located in the lower half of the AM closest to the lunar surface and it provides the staging platform for the astronauts prior to conducting surface Extra-Vehicular Activity (EVA). The Centaur-based spacecraft will run on liquid bipropellant of a LOX/LH_2 mixture and sufficient amounts have to be stored onboard the AM and DM to perform both powered descent and ascent to and from the lunar surface respectively. The vehicle will also separate and insulate the cryogenic structures from other components. A Heat Rejection System is also necessary to regulate the thermal conditions for normal operating conditions. A sun shield may also be required while in LEO or LLO. The vehicle will also be installed with layers of internal insulation, vapor cooled structures and efficient heat pump/rejection systems to maintain required temperatures while on the lunar surface. Photovoltaic cells will be installed on the top to harness solar power required for communications and avionics subsystems on the Centaur-based spacecraft. However, docking infrastructure is currently not shown and it has to be modified in future if it is designed to perform an EOR with the Orion spacecraft recommended for the CEV.

Mass and dimension compatibility issues were then assessed for the modified Centaur-based spacecraft with respect to its LV. As mentioned previously, the 130-mT SLS will be the CaLV. Since the unmanned Centaur spacecraft and cargo required for the science mission would be carried onboard on this launch, the 130 mT Block II Cargo variant of the SLS would serve as the CaLV of choice for this mission. This variant of the SLS contains 2 core first stages stacked on top of one another, and each stage has a diameter of 8.4 m. The diameter of the AM will be designed to have a diameter of 8.4 m to match the diameter of the SLS core first stage. As mentioned in the earlier description, a circular base area with a diameter of 8.0 m will be used for storing a layer of 18 antenna units. The antenna units will be stored in the cargo section, which will predominantly be in the DM. As calculated earlier, 11 stacks of antenna will measure 5.5 m in length across the cargo section of the DM.

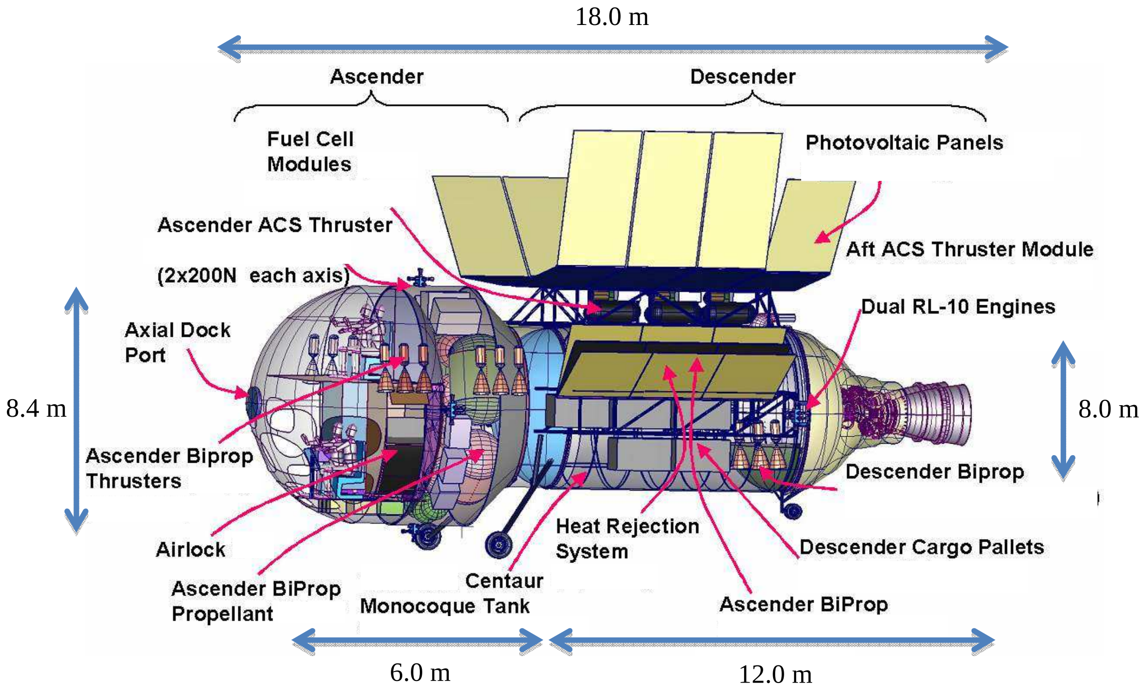

Figure 5: Conceptual Centaur-Based Lunar Lander in the horizontal landing position. Adapted from [12].

A Lunar Roving Vehicle (LRV) is also required for the astronauts to transport antenna units from the spacecraft to their designated deployment locations. As 7 antenna units are required to be deployed at each station, the LRV used in this mission must have at least a payload capacity of 700 kg. As such, a conservative estimate would be a capacity of 750 kg. Further conservative estimates were also made for the LRV, and it would measure 3.5 m across its frame, 2.5 m across the wheelbase, and 1.5 m in height. The estimated weight of the modified LRV was 300 kg. The LRV would be stored width-wise within the cargo section. Storing the LRV would thus require at least another 4 m in length across the cargo. The LRV would also have a detachable trailer that would allow loading of the antenna units.

As such, a cargo storage space with base area measuring 8.0 m in diameter and horizontal length of a total of 10.0 m will be designed into the Centaur-based lunar lander. The Tsiolkovsky rocket equation was also used to calculate the amount of propellant required to be stored onboard. The lunar lander was conceptualized to perform both powered descent and ascent to and from the lunar surface respectively. The Delta-V requirements for travelling from LLO to the lunar surface, as well as from the lunar surface back to LLO, was 1870 m/s. Using a LOX/LH_2 liquid bipropellant would provide a specific impulse of 455 s. The effective exhaust velocity V_e was thus 455*9.8 m/s = 4460 m/s. Assuming an initial mass of 65000 kg (65 mT), the remaining total mass of the spacecraft after performing powered descent from LLO to the lunar surface was 42735 kg.

After performing an ascent back to LLO, the total mass was reduced to 28096 kg. Using buffered estimates, the amount of propellant consumed would be approximately 40000 kg (40 mT). Given that the density of LOX is 1141 kg/m^3 and much higher that of LH_2 such that the latter was negligible, the volume occupied by the propellant would be approximately 35 m^3. Supposing this volume was spread across the circular base area assigned to the DM, the liquid propellant would occupy up to a length of 0.7 m across. This value was then rounded upwards and the liquid propellant tanks containing LOX/LH_2 would thus measure 1.0 m in length across the DM. However, additional space is required to insulate the cryogenic structures from the cargo, or store any other scientific equipment or infrastructure. As such, a further extension of 1.0 m in length across the DM was estimated.

Therefore, the DM would measure 10.0 +1.0 + +1.0 =12.0 m across in length as shown in Figure 5. Assuming that the AM would measure 6.0 m in length, the entire Centaur-based lunar lander would thus measure 18.0 m across in length with a height of approximately 8.4 m. Further calculations were then performed to demonstrate why such a deployment is possible. The volume of the payload section on the Block II Cargo 130 mT variant of the SLS is 1104 m^3. Assuming the entire Centaur-based lunar lander to be a cylinder measuring 8.4 m in diameter and

18.0 m in height, the volume would be 997 m^3, thus fitting into the payload section.

The original mass quoted for the vehicle frame and onboard equipment was 4.3 mT. Given that the LRV was estimated to weigh 300 kg, the total mass of the 4 astronauts was to be 320 kg, the propellant mass was safely overestimated to be 40000 kg (40 mT), and the cargo to be 20000 kg (20 mT), the total mass of this vehicle would approximately be 65000 kg. As such, the entire Centaur-based lunar lander would weigh 65 mT, thus validating the above assumption made in the calculations earlier. Therefore, adapting and scaling the Centaur in order to support an efficient and reliable crewed landing would be technically feasible.

Surface operations will require significant effort from the four-member crew, so having a safe, habitable environment to return to in Centaur is essential. The Centaur lander itself will have a pressurized volume of 29 m^3 after deployment of inflatable habitat structures, translating to a habitable volume per crewmember of 7.25 m^3/crewmember, more than double that of the Apollo 17 LM at 3.325 m^3/crewmember [13]. Approximately 10 m^3 of this volume will be relegated to crew storage of gear, consumables, and other cargo. The inflatable habitats will be connected to and share the Ascent Environmental Control and Life Support Systems (ECLSS) within the Ascender module. Two airlocks are also installed in Centaur, allowing for ready and efficient access to the surface [12]. Between the Ascent and Descent modules of Centaur, the Ascent module will receive all of its power on the surface from the Descent module, in addition to airlock cycle regulation, pressure, breathable air, and thermal regulation [12].

III.II Moon Landing Sites

Performing a mission on the far side of the Moon would entail a whole new set of challenges. Landing sites on the far side require a relay infrastructure to ensure adequate communications with the Earth. The ESAS report identified a number of suitable landing sites, of which two are on the far side. The two sites are the Central Far Side Highlands and South Pole-Aitken (SPA) Basin Floor [7] and they are shown on Figure 6 below.

Central Far Side Highlands (near Dante, 26°N, 178°E): This site is on the most ancient, primordial crust of the Moon and regolith here is rich in calcium and aluminum. Being on the far side, this site would require relay satellites for Earth communications. Observation of the low-frequency radio sky would be possible here.

SPA basin floor (near Bose, 54°S, 162°W): This site is on the floor of the SPA basin, which possibly exposes the lower crust or upper mantle of the Moon. This site would require a communications relay system for Earth contact and observation of the low-frequency radio sky would also be feasible here.

When choosing between the two sites, it is worth noting that the poles of the Moon have very unique environments. As the lunar spin axis is essentially normal to the ecliptic, the Sun is always near the horizon at the poles. This phenomenon thus creates permanently shadowed cold traps that may contain water ice. In contrast, high peaks and terrain elements near the poles may be in near-constant solar illumination. Such areas have great value for an outpost site due to the near-constant availability of solar power. Temperatures hover at –50°C ± 10°C, which falls within the operating temperature ranges for most space-rated avionics and components. However, little is still known about the terrains and geological composition at the poles of the Moon. Therefore, the prospect of finding water, ice and other minerals, and most importantly, exploring the unknown, increases the site's utility to science. Based on a projected higher utility to science, the SPA basin floor, located at 54°S, 162°W on the far side of the Moon has been chosen to be the landing site for this proposed mission.

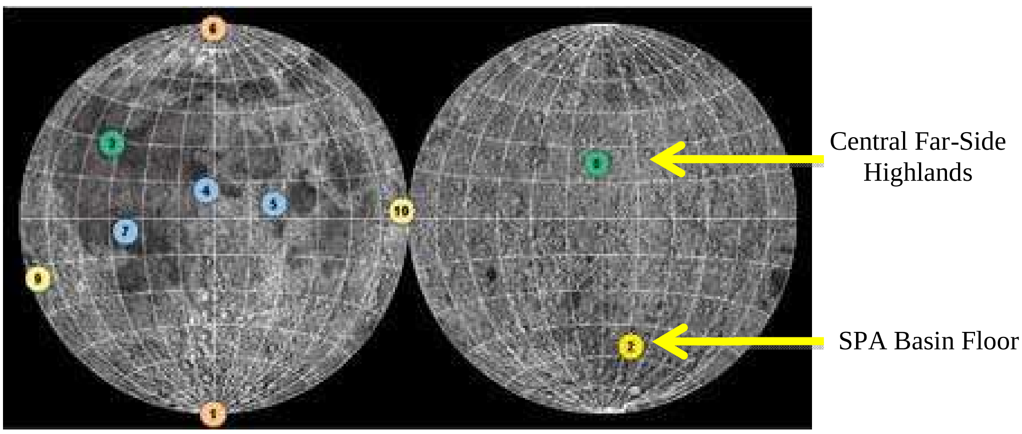

Figure 6: Prospective landing sites on the Far Side of the Moon. Adapted from [7].

IV. GUIDANCE, NAVIGATION AND CONTROL

After establishing the overall systems architecture, the next step is in developing the tools and technology that will take the entire system to lunar orbit, and facilitate the safe, accurate and reliable landing of the modified Centaur-based vehicle at its designated landing site on the Moon. This will be performed entirely by the Guidance, Navigation, and Control (GNC) system, which will provide active measurement and control of spacecraft position, velocity, and attitude in support of proposed mission objectives. Although the Altair spacecraft program was canceled, much study had been performed in academia to develop preliminary designs for the GNC system of Altair. As such, the GNC systems designed for Altair could potentially be applied to the modified Centaur-based lunar lander vehicle [14].

On the Altair, two sets of thrusters were present, one on the Ascent Module (AM) and the other on the Descent Module (DM) [15]. This thruster configuration can also be applied to the Centaur vehicle. On the Centaur, the DM thrusters will perform course correction burns during the Trans-lunar Coast while the AM thrusters will perform precise angular and translational controls of the AM in order to perform docking with the AM on Orion.

The Optical Navigation (OpNav) system aboard Altair comprises both a wide and narrow angle gimbal-mounted camera that will facilitate the rapid identification of landmarks in all directions without requiring the spacecraft to turn around as on the Apollo missions. Gimbal-mounted cameras can also be used for performing other functions such as star tracking for attitude determination as well as rendezvous and proximity phase navigation around the Orion vehicle [14]. This will be especially important since the Orion and Centaur vehicle would perform both an EOR and LOR during the mission. There would be a dedicated Central Processing Unit (CPU) onboard to process the images captured.

The OpNav system comprises mainly the Optical Navigation Sensor System (ONSS), which would essentially model and extract landmark positions on the lunar surface to process and collect vital geometric navigation knowledge. Different landmarks on the Moon are used by the OpNav depending on the proximity and angle of approach of the Centaur-vehicle to the lunar surface. Concurrently, the onboard navigation system on the Centaur vehicle would be getting continuous state updates and estimates from the ground-based navigation systems to perform attitude determination and control. This would be especially important for powered descent and precision landing operations. OpNav also serves as a backup navigation system in the event that ground support is lost. Without continuous updates from the ground, the Centaur vehicle's state vector would begin to lose accuracy and controllability. As such, the OpNav system would take passive optical pictures of stellar, solar system celestial objects, and surface landmarks continuously using the ONSS so that there would be reference points available [16]. In addition to the ONSS, Altair also has a Terminal Descent Radar System (TDRS) that will be used to estimate its surface-relative altitude and velocity [14]. Likewise, GNC technology on Altair can be transferred to the Centaur vehicle.

Inertial Measurement Units (IMUs) will also be present to measure non-gravitational accelerations and attitude rates using a combination of accelerometers and gyros [16]. For maneuvers that occur prior to the descent sequence the IMU is used to control the commanded delta-V of a burn and will cut off the burn when the desired delta-V has been achieved. However, for descent and landing the IMU accelerometer data is coupled with the other navigation sensor data in the navigation filter to produce current state position and velocity solution state vectors that drive the guidance and control to achieve the desired landing position. Finally, Altair also has a Terrain Hazard Detection Sub-System (THDSS) that measures the local topography [14]. The system will assess the local terrain for hazards and recommends a trajectory divert to a new safe landing site when a hazard is detected. With further progress in technology, a more advanced THDSS would be available and can be installed onboard the Centaur vehicle to enhance safety considerations.

A combination of onboard autonomous navigation systems, ground-based control, enhanced optical navigation systems and availability of human input thus constitutes the GNC system for the vehicle and it would be extensively deployed to ensure safe and accurate maneuvers during the course of the mission.

V. POWER

Numerous power source options have previously been studied for lunar missions, ranging from batteries and fuel cells to full-scale nuclear reactors. Generally, lunar missions that have actually flown have deployed with either batteries or solar cells depending on the mission duration. However, for this mission, solar panels appear to be the most attractive choice in the trade space. Unlike RTGs, solar panels do scale well to smaller sizes, making it cost effective to make many small solar arrays to power numerous dispersed stations such as those present in this mission. Their renewability (coupled with batteries to store energy for the lunar night) makes them more attractive than batteries or fuel cells alone. Finally, they are well understood, have a long history of use in spaceflight applications, and are appropriate for this mission which is not particularly power-intensive unlike, for example, missions which feature drilling or the use of high-power lasers.

In order to size the solar arrays, an estimate of the system power is required. The LARC concept assumes that each STANCE consumes about 250 mW, which can translates into a requirement of 300 mW with a 20% margin. Assuming the use of the most modern and efficient solar cell types, GaAs, an efficiency of approximately 22% can be achieved. Solar array sizing is a complicated function of expected panel alignment and solar insolation angles; therefore, here it will be made an estimate for the mass, the most important element by far, by using the rule of thumb of 20 W/kg and $3000/W, which is accurate for advanced space solar power systems. Using these numbers, we derive a mass of less than 1 kg and $900 per panel for each STANCE. Such a low mass value should not surprise, because here the assumption has been made that the solar panel will be directly mounted on one of the flap covers of the box containing one of the antennas comprising each STANCE. Assuming 43 STANCEs, equivalent to 300 antennas, on the mission, the total solar-array mass will be about 40 kg and the cost will be around $250,000 for the entire apparatus. The correlator is estimated to consume about 200 W, which adds 10 kg to the solar power system. The mass will, however, be driven up by the power conditioning equipment and especially the batteries necessary to store energy for the lunar night. We can derive an estimate for the lunar night batteries, assuming an energy density of 200 Whr/kg. To maintain the antennas at 100% power loading through the lunar night, this would require batteries massing 117 kg, which are much heavier than the solar panels, though still a relatively small fraction of the overall system mass. Therefore, the power system is unlikely to be a major technical or cost risk driver using currently available and well-understood technology.

The other elements of the proposed mission plan, including an Orion-derived spacecraft, have already had solar panels included into their design, with fuel cells in the case of Altair and batteries in the case of the LRV. The Orion solar panels measure approximately 5 meters across; no cost estimates breaking out the solar panels from the rest of the spacecraft are presently available. Altair is specified to have hydrogen/oxygen fuel cells and the LRV can use the successful battery heritage of the Apollo LRV since it is primarily needed only during the deployment phase.

VI. LUNAR SURFACE OPERATIONS

Once on the surface, the astronauts' primary task will be to deploy the 198 antenna units over the first six days of their stay, equating to 33 antenna units per day. To do this, the astronauts will do buddy-pair deployment each day, with the exact details of each EVA left to the discretion of the crew in order to meet the goal of deploying 198 units by the end of the sixth day. While the antennas are being deployed, two astronauts will remain back inside the Centaur module, receiving and checking diagnostic feedback from the deployed antennas. To assist in antenna deployment, the astronauts will utilize a lunar rover vehicle and trailer attachment with the combined capability of transporting up to 750 kg (7 antenna units) in one load. In addition to antenna deployment, it will also be the responsibility of the astronauts to deploy the assistant robot vehicles by Day 6, which will remain on the lunar surface once the astronauts leave in order to maintain the entire LRA. The Centaur's design allows for easy cargo access at chest level, which can easily lowered to the surface via simple mechanical design.

Following the successful deployment of all antenna units and assistant robots, the final day will be used for final diagnostic checks of the LRA and support equipment, in addition to preparing for the journey back to Earth.

When the crew is ready to leave, or even if the crew must make an early or emergency ascent, the Ascent module tanks will be brought up to pressure, with the option for moving the remaining propellants from the Descent module into the Ascent one if needed by the crew. The Ascent module first thrusts up to 35% power to obtain a "small positive upload at the separation interface" between the Ascent and Descent modules as it cautiously navigates away from the surface. Once well clear of the Descent module, the Ascent one provides 0.35 g of thrust during initial descent, finishing with 1 g of thrust at the end of ascent [12].

If envisaged in the future, the astronauts might also set up a real lunar outpost and perform other types of scientific experiments to further explore the Moon, contribute to our understanding of its properties and history, and think of how to use the Moon to advance space exploration and reach farther destinations.

VI.I Implications and Constraints

The degree of autonomy of the observatory and its antennas is largely dictated by the difficulty associated with the tasks required to build, operate, and maintain such an infrastructure and the ability of rovers or robots to cope with it. In addition, given the large dimensions of the observatory itself, defining ways of guaranteeing quick and effective serviceability becomes crucial in order to keep the downtime of the whole infrastructure, or just part of it, at a minimum. This was envisioned to be accomplished by using a large number of robots deployed at several stations, so that they could reach the malfunctioning elements within a reasonable time and repair them. However, robots themselves might be subject to failures, thus increasing the risk of keeping the observatory inoperative for too long. It becomes obvious at this point that humans will play an important supervisory role and step in every time high-level skills are required to perform tasks that robots will not be able to do.

Astronauts will also expedite maintenance operations thanks to their ability of executing such tasks much more quickly and possibly with the help of external vehicles that they can drive to reach the points of failure. Finally, a system so complex as this one, made of a fully automated observatory with hundreds of antennas and robots spread over an area of at least ten kilometers across, is intrinsically subject to systematic failures. These, along with supporting human activities on the Moon at the beginning of the mission and in subsequent phases when direct human intervention will be directly needed, will drive up the operations costs in a dramatic manner. In order to support this mix of humans and robots, one should not forget that the two afore-mentioned criteria, i.e., robots' technological capabilities and overall cost, represent two major constraints and drivers for all future missions in space.

As far as developments in robotics are concerned, the only proved technology in space has been Robonaut 2. While it possesses dexterity, it can only perform very simple tasks and has not been approved for use in the vacuum of space yet, which will require a further upgrade of the entire robot in the next few years. Depending on the timeframe envisioned for establishing a lunar radio array, robotics may not yet be a viable substitute to humans, whose level of performing complex tasks with ease and quickly still remains unparalleled. Investments in robotics would therefore be highly recommended in preparation to such a challenging mission.

Recently, NASA has been under extremely tight budgetary conditions, which are likely to worsen in the coming years. Budget cuts have already hindered many missions and led to the cancellation of many others. Several-billion-dollar flagship missions or programs will not be pursued by NASA in the near future unless dramatic changes occur in the current economic and political environment, which will move large amounts of funding toward the Agency as was done for the Apollo program.

VII. MISSION COST ESTIMATES

An attempt was made to provide an estimate for the cost of mounting the proposed mission. The biggest driver of most space mission costs is launch, and this mission is no exception: a single SLS launch as required for our mission is estimated at $500 million, while the Falcon 9 is at least $128 million, though given that this number is several years old it too is likely to skyrocket to a higher value. A conservative estimate of $200 million for the Falcon 9 launch will therefore be assumed. The cost of the Orion spacecraft and Centaur are not generally broken out separately from their launch vehicles, so they will be assumed to be included in these launch costs. Given the early stages of the designs of such vehicles, such cost estimates do not include the development costs.

The LARC study evaluates the technology development cost at $41 million for this type of mission [2]. Considering the envisioned timeframe of launching in the 2030s, this preliminary estimate for development will be projected into the future to about $100 million. Cost estimates for the antennas themselves are not available, but since the launch estimates for the SLS class boosters generally include the recurring cost of the payload (such as Orion), it is unlikely to be significantly more than the cost already quoted. Therefore, $250 million are conservatively added for reserve and recurring manufacturing costs, for a total estimated mission cost of approximately $350 million, putting this mission in NASA's New Frontiers class.

VIII. CONCLUSIONS

With renewed interests in human space exploration, there is a stronger impetus to establish sustainable robotic and human exploration programs in the solar system. This project proposes a new-generation integrated human-robotic mission to the far side of the Moon to establish a lunar radio array that will function as a Moon-based space observatory in future. The emergent Lunar Array for Radio Cosmology (LARC) concept is chosen as the basis of the science mission, where thousands of antenna units would be deployed on the Moon by both human and robotic means. Each antenna unit contains a Self-Tending Array Node and Communication Element (STANCE) and several STANCEs would form a station; the combination on the lunar surface of thousands of them would form the actual observatory. To establish the entire array, multiple trips to the Moon would be required. The pioneer trip of this program was the focus of this paper and it will be an integrated human-robotic mission. Subsequent missions have been envisioned to be entirely robotic with optimistic projections of technological advancement and financial capacities.

The overall systems architecture necessary for the launch, deployment and return phases recommended in this work are chosen based on a practical approach by using a combination of existing technologies and Commercial-Off-The-Shelf (COTS) products. A 1.5-launch EOR-LOR mission architecture is recommended, where a Block II Cargo

130-mT Space Launch System (SLS) will serve as the heavy-lift Cargo Launch Vehicle (CaLV) and a 53-mT Falcon 9 Heavy as the lighter Crew Launch Vehicle (CLV). The Orion spacecraft is recommended as the Crew Exploration Vehicle (CEV), which will have the capacity to harbor and support 4 astronauts required for the mission. For the lunar lander, the Centaur has been proposed for modification to develop a reusable Lunar Surface Access Module (LSAM) or Lunar Lander. The modified Centaur vehicle will perform a horizontal landing on the Moon instead of the traditional vertical landing as in the Apollo program.

The Centaur vehicle has been designated to carry cargo required for the science mission while the Orion will carry the crew. Once the Orion spacecraft and Centaur vehicle arrive at LEO, they will perform an Earth-Orbit Rendezvous, where the Centaur will dock with the Orion and the EDS from the SLS. The combined Centaur-Orion will then perform a Trans-Lunar Injection (TLI) to reach lunar orbit. After the crew transfers from the Orion to the Centaur, the Centaur vehicle will then undock from the Orion and performed a powered descent to the lunar surface. The proposed landing site on the far side of the Moon is the South Pole-Aitkin (SPA) Central Basin, as it is relatively unexplored and has the potential to offer the highest utility to science.

Upon safe landing, the astronauts will then execute the proposed science mission over a period of 7 days. With the aid of the onboard LRV, the astronauts will deploy individual or groups of antenna units at their assigned locations. This science mission will last for a maximum of 7 days, where the astronauts will take turns in pairs to drive the LRV and deploy the antenna units. The other pair will remain on the Centaur vehicle, performing tests and checks to determine if the antenna units are operating as desired. After completing the science mission, the crew will return to the Centaur vehicle, which will then perform a powered ascent to return to lunar orbit. It will then dock with the unmanned Orion spacecraft that remained in lunar orbit throughout the mission duration. The crew will then return safely to Earth in the CEV via a water landing. Inclusive of the return trips to the Moon, the entire duration of this proposed mission is approximately 14 days.

Apart from proposing the systems architecture and sequence of operations, a GNC system designed for the Altair lunar lander is proposed for modification and adaptation for the Centaur vehicle. Coupled with advancements in state estimation and optimal control in future, the GNC will be able to provide the necessary guidance, navigation and control to take both the Orion and the Centaur vehicle through LEO, TLI, LLO, descent and landing.

The sequence of science operations on the Moon is also discussed. In terms of infrastructure, power sources are discussed and a variety of platforms are available for providing an efficient and reliable power supply during the mission. Cost estimates are also performed to project the likely expenditure incurred if this project were undertaken. With an in-depth discussion and analysis of the mission plan, systems architecture, science mission, infrastructure and costs, this proposed mission is determined to be feasible and ultimately aligned to NASA's long-term goals and strategies for space exploration.

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