Lunar Interferometric Radio Array: A Telescope Concept Uniquely Enabled by the Lunar Far Side

Zahra Khan\textsuperscript{1}, Phillip M. Cunio\textsuperscript{2}, Mark Avnet\textsuperscript{3}, Justin M. Colson\textsuperscript{4}, Christopher H. Tracy\textsuperscript{5}, Christopher L. Williams\textsuperscript{6}, Jim Keller\textsuperscript{7}, Richard A. Jones\textsuperscript{8}, and Olivier L. de Weck\textsuperscript{9}

Massachusetts Institute of Technology, Cambridge, MA, 02139

NASA’s plan to return to the moon by 2020 raises the possibility of conducting science specifically enabled by unique characteristics of the lunar surface. One such science objective is the study of the Epoch of Reionization in the formation of the universe, which has been given top priority by the 2001 National Research Council’s Astronomy and Astrophysics Decadal Survey. The “Epoch of Reionization” is the period of transition of the universe from its early state of close-to-perfect uniformity to one of galaxies and inhomogeneous structures, and is currently an area where data is much needed. This period is best studied in the radio waveband, especially at low frequencies, which are inaccessible to ground observatories. In addition, these low frequency waves offer a window on the universe that is unexplored at present. This increases the potential for new and unexpected discoveries. The lunar far side provides an ideal radio-quiet environment essential to observe this period in the universe’s history. Such an environment is unavailable on Earth or in near-Earth space. This paper presents the design of a lunar telescope facility that provides the capability to observe the “Epoch of Reionization” by placing a radio array on the far side of the moon. This array is envisioned to consist of 3440 simple radio dipoles, arranged in 215 clusters over an area 62 kilometers in radius, which provides a resolution of 12 arcminutes, to observe the Epoch of Reionization. Highlights of the design include a light-weight, self-deploying structure, a high data-rate wireless communication system, autonomous deployment, and high modularity of system elements. This project is designed to provide value to the exploration community in addition to the science community by leveraging planned lunar exploration architecture transportation elements, including the Ares V launcher, unmanned surface transportation rovers, and communications infrastructure. Additionally, the modularity of the design makes it highly robust from both a technical and a programmatic standpoint.

\textsuperscript{1} Graduate (SM ’08), Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, AIAA Student Member.
\textsuperscript{2} Graduate Research Assistant, Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, AIAA Student Member.
\textsuperscript{3} Graduate (PhD ’09), Engineering Systems Division, 77 Massachusetts Avenue, AIAA Student Member.
\textsuperscript{4} Graduate (SM ’08), Department of Aeronautics and Astronautics, 77 Massachusetts Avenue.
\textsuperscript{5} Graduate (SM ’07), Department of Mechanical Engineering, 77 Massachusetts Avenue.
\textsuperscript{6} Graduate Student, Department of Physics, 77 Massachusetts Avenue.
\textsuperscript{7} Graduate (SM ’08), Department of Aeronautics and Astronautics, 77 Massachusetts Avenue, AIAA Member.
\textsuperscript{8} Graduate (SM ’08), Department of Mechanical Engineering, 77 Massachusetts Avenue.
\textsuperscript{9} Associate Professor, Department of Aeronautics and Astronautics and Engineering Systems Division, 77 Massachusetts Avenue, AIAA Associate Fellow.
Nomenclature

\begin{align*}
EO & = \text{Epoch of Reionization} \\
HST & = \text{Hubble Space Telescope} \\
IR & = \text{Infra-Red} \\
LIRA & = \text{Lunar Interferometric Radio Array} \\
LOFAR & = \text{Low Frequency Array} \\
LRV & = \text{Lunar Roving Vehicle} \\
LSAM & = \text{Lunar Surface Access Module} \\
MIT & = \text{Massachusetts Institute of Technology} \\
MWA & = \text{Mobile Widefield Array} \\
NASA & = \text{National Aeronautics and Space Administration} \\
NRC & = \text{National Research Council} \\
RF & = \text{Radio Frequency} \\
RTG & = \text{Radioisotope Thermoelectric Generator} \\
SMAD & = \text{Space Mission Analysis and Design} \\
TRL & = \text{Technology Readiness Level} \\
XSP & = \text{ Extrasolar Planets} \\
\end{align*}

I. Introduction

This paper presents the results of a study conducted by members of the Space Systems Engineering class (16.89/ESD.352) at the Massachusetts Institute of Technology (MIT) in the spring of 2007. The challenge of the class was to design a lunar telescope facility that would deliver the most scientific value, while leveraging the crewed lunar transportation architecture proposed by NASA and ensuring both technical and budgetary feasibility.

For purposes of this study, locations considered for the lunar telescope facility included points on the surface of the Moon, as well as in space near the Moon or at a Lagrange point between the Earth and the Moon or the Earth and the Sun. Using science goals derived from the 2001 National Research Council Astronomy and Astrophysics Decadal Survey\textsuperscript{1} and a detailed stakeholder analysis, thousands of concepts for space telescopes were downselected to the one which is described in this paper. The subsystems developed for this design include instrumentation, electronics and communications, power, structures, and transportation/deployment. Detailed cost, mass, volume, and power assessments for all these systems are provided in a publicly available report, as is extensive background information on the downselection process, stakeholder analysis, and science goals chosen\textsuperscript{2}. This paper presents an overview of the design selection process and the telescope subsystems as well as cost estimates for the system.

II. Scientific Context and Programmatic Design Rationale

In order to select a telescope design which will deliver significant value to the scientific community, an analysis of the most appropriate and valuable scientific goals for the proposed lunar telescope facility was conducted in conjunction with research on the unique properties of cislunar space and the lunar transportation architecture. The goals were taken from concerns of the scientific community, NASA, and Congress. Details on stakeholder needs were drawn from the NRC Decadal Survey: Astronomy and Astrophysics in the New Millennium\textsuperscript{1}, and the Connecting Quarks with the Cosmos report\textsuperscript{3}, and a list of particular astrophysical science objectives that could be particularly enabled -- or at least significantly facilitated -- by the return to the Moon was developed.

The key science drivers identified as targets for this telescope concept include: the Epoch of Reionization (EOR), Extrasolar Planets (XSP), solar science, and serendipitous science. The Epoch of Reionization deals with the transition of the universe from its early state of close-to-perfect uniformity to one of galaxies and inhomogeneous structures is currently an area where data is much needed. This period is best studied in the radio waveband, especially at low frequencies, which are inaccessible to ground observatories. The Extrasolar Planets objective deals with long-standing questions about the existence and the formation of planets in other solar systems. Extrasolar Planets with magnetic fields may emit low frequency radio emission. However, observations above the Earth’s ionosphere such as those provided by a cislunar telescope facility are needed to detect emission from sub-Jovian mass planets\textsuperscript{5}. In addition to these major scientific objectives, another science goal is the study of particle acceleration and magnetic fields in the Sun. A radio observatory located above the Earth’s ionosphere would...
provide a unique imaging capability at low frequencies, giving a previously unseen look at these processes.

Serendipitous science is another important key goal that this telescope system will provide. Extremely low frequency radio astronomy is not possible due to the Earth’s ionosphere, and high sensitivity observations at these frequencies in the vicinity of the Earth are precluded due to the strength of the Earth’s own aural radio emission. Consequently the lunar far side provides a unique location that will allow high sensitivity observations at frequencies never before explored. As such, the conduction of serendipitous science, including the potential discovery of new astrophysical processes or objects, is a very real possibility with this telescope concept.

As mentioned above, for this project, the features of cislunar space were analyzed for potential advantages for telescopes. From this analysis, the far-side of the Moon’s surface emerges as a uniquely advantageous location in cislunar space for an astrophysical observatory. The low amounts of electromagnetic energy reaching the far side of the Moon results in a radio quiet environment ideal for observations in the RF regime. Other advantages include the lack of an atmosphere (which allows access to radio energy incoming from deep space which is blocked on Earth by the atmosphere) and the stable solid surface which permits deployment of telescope hardware with little risk of disturbance (preserving orientation for free and allowing a constant baseline for interferometry).

Additionally, as described later, this telescope design provides value to the space exploration community by leveraging existing elements of the NASA’s Constellation lunar architecture, including the use of transportation elements such as the Ares V cargo rocket and the lunar rover, as well as the human lunar base, which may serve as a transmission relay point for telescope sensor data.

III. Instrument Design

The basic form of the instrument is an interconnected array of low frequency (10 to 130 MHz) dual-polarization dipole antennae. The dipoles will be grouped into clusters, which will then each be connected to a central digital correlator to interfere these signals and produce radio measurements of the sky. The size/geometry of the antenna was assumed to be equal to 0.75 meters (1/4 wavelength at 100 MHz) and the antennae were spaced with 0.45 meters between their tips (0.15 times the wavelength at 100 MHz). In order to determine the number of dipole antennae required for the array, the chief science driver – being able to observe the Epoch of Reionization (EOR) – was considered.

The size of clusters used in the array is determined by the field of view desired. The antennae in each cluster are phased in realtime with delay lines to act as a single effective antenna from the point of view of the correlator. The diameter, $D$, of the array is determined by the required maximum angular resolution, $\theta$. It is important to note that this resolution is the maximal resolution of the telescope, which is different than the resolution at which the instrument will make the EOR measurement. The EOR signal will only be detectable on larger spatial scales than the instrument is capable of making.

The antenna system was given an “efficiency” of 80%, which corresponds to the percentage of incident radiation that is coupled into the telescope system (for comparison, a value of 60% was used for radio array estimates by Carilli, Hewitt & Loeb). Additionally, it was also assumed that the electronics draw 0.5 W for the amplifiers in each antenna, and that each cluster beamformer draws 3 W.

The final specifications of the instrument were determined through an optimization process as described in the next section.

IV. Optimization of Telescope Design

The main driver for this telescope concept, the observation of the EOR signal, places the following requirements on the telescope: wavelength range of 2 m to 30 m, minimum angular resolution of 10 arcseconds, and field of view of 900 sq. deg. Cost concerns dictate that the entire system payload be capable of launch with a single booster, chosen to be Ares V as described in Section IV. In order to define the specifications of the telescope system, e.g. the number of array dipoles, an analysis was conducted to characterize and maximize the system’s science output per unit cost.

A scientific figure of merit which would encapsulate the value of the science the array can produce was defined to allow an optimized design for the array to be calculated. In order to quantify the scientific value of a particular design, the metric was developed with an aim to be similar to the “discovery efficiency” metric used by the Hubble space telescope and other similar instruments. This type of figure of merit attempts to estimate the amount of science that can be performed with a telescope by analyzing its sensitivity and viewable area of the sky. For the figure of merit for LIRA, this concept is modified to incorporate the value of having greater EOR resolution. The
A figure of merit is as follows:

\[ FOM = \text{Constant} \times \log \left( \frac{1}{t_{\text{survey}}} \sqrt{\frac{1}{\theta_{\text{EOR}}}} \right), \quad (\text{Eq. 1}) \]

where \( t_{\text{survey}} \) represents the time it takes for a survey of half of the sky to a target sensitivity over the entire frequency band and \( \theta_{\text{EOR}} \) is the EOR resolution. The survey time is calculated by determining the field of view at enough frequencies to fully cover a 10-130 MHz bandwidth with 32 MHz observations, and calculating both the field of view and sensitivity at these frequencies. The survey time then becomes the sum of the number of observational hours required to get down to a target sensitivity of 10 milliJansky (mJy) for half of the sky. The square root and logarithm are used to balance the components and reflect the fact that incremental increases in the capability become less important as the instrument becomes more capable. This figure of merit includes a constant multiplicative factor to make the scale of the values easier to work with.

An optimization trade study was conducted by dividing the figure of merit by the total system cost (discussed later in this paper) and calculating this quantity over a range of input parameters. The two parameters used were EOR resolution and field of view, with the other relevant parameters given assumed values. The tradeoff surface, seen in Figure 1, shows a pronounced maximum, which was taken as the optimal value of the system.

The results of the trade study analysis yielded the optimal configuration for LIRA. This optimal configuration had properties as follows:

**Characteristics**
- Frequency Range: 10-130 MHz
- Instantaneous Bandwidth: 32kHz
- Number of Dipoles: 3440
- Number of Clusters: 215
- Array Diameter: 62 km

---

**Figure 1: Scientific Figure Of Merit/Cost trade study surface.**
Capabilities
- EOR Resolution: 12 arcminutes
- Max Resolution: 9.2 arcseconds (at 130 MHz)
- Sensitivity: 3.6 mJy at 10 MHz, 0.6 mJy at 130 MHz
- Field of View Diameter: > 25 degrees

This resulting array configuration provides the strongest scientific value per dollar for the LIRA concept.

This optimal point is calculated under the assumption that 3440 dipoles will be sufficient to resolve the EOR signal and thus achieve the desired scientific goal of the telescope. This point design provides a good baseline on which to evaluate the science goals which the point design can perform, a detailed assessment which is left for future work. If it becomes necessary to scale up LIRA by adding more dipoles, the total system cost and the scientific FOM will both be affected. The relationship between the number of dipoles and the total system cost is discussed in Section V.

Finally, comparing the optimized LIRA concept to other instruments provides a gauge of how useful LIRA will be in the context of planned/existing telescopes and their capabilities. Figure 2 compares the sensitivity and angular resolution of LIRA with the Mileura Widefield Array (MWA) and the LOFAR radio telescope, two radio instruments currently being developed to observe the EOR.

As can be seen in these figures, LIRA’s performance is similar to these other cutting edge instruments where the edges of their bandpass overlap, and LIRA in fact extends these high performances to previously unexplored low frequencies. In this aspect, LIRA provides essentially a low frequency complement to the Earth-based systems currently in development.

V. Telescope Subsystem Design

A. Cluster Structure Subsystem
The cluster structure provides packaging for the radio dipoles, cluster communications system, and cluster power system. In addition, it deploys the dipoles from its compact launch and lunar transportation envelope stowed into the large envelope dimensions of a fully-activated dipole cluster.

Specifications for the LIRA telescope design are 215 clusters, with 16 dipoles per cluster. The deployed area of a cluster is 24 square meters and each dipole has a length of 0.75 meters. The total array has a diameter of 62 km and contains 3440 individual dipoles. Each dipole was assumed to have a length density of 0.1 kg per meter of dipole length. The base mass of the structure was estimated to be 1 kg per square meter of deployed area. Cost for the structure system is estimated at $10,000 per kg of cluster structure. Results of the cluster design are a 30.8 kg cluster mass, not including power and communication mass. The cost for each cluster comes to $308,000 per cluster.

The mechanical design of each cluster packages stows the dipoles in a 1.6 by 1.6 meter thin square-shaped volume. This compact volume allows for easy packing for launch and lunar transportation. Illustrations of the folded and deployed clusters are shown in Figure 3. Sixteen dipoles fold out from the four corners via a lightweight foldable structure. The final deployed area is a 4.8 by 4.8 meter square.

Figure 2. Sensitivity and angular resolution of LIRA.
Batteries are stored at the base of the square footprint for stability. The cluster rests on the corners of the 1.6 by 1.6 meter footprint and includes a capability to level the dipole cluster on an uneven surface. It is desired that the entire array of clusters be coplanar.

Figure 3. Folded (left) and deployed (right) LIRA clusters.

B. Electronics Subsystem

The electronics subsystem comprises all of the command and data handling (C&DH) functions of the central processing unit. Each 16-antenna cluster will have an associated command and data handling unit which has been designed into the structure of the cluster and is not a part of this analysis. The electronics subsystem receives raw observation data from each cluster via a laser communication network. The output of the system is processed data, on which interferometry calculations have been performed. This data is passed to the downlink communications network.

A number of processors from Broad Reach Engineering provide the 14 Gbps data processing requirement while operating near their capacity of 1.575 Gbps. The assumption was made that the data inputs to the electronics modules could be directly connected to the data processing cards to provide this high processing capacity. The amount of data stored by the system is only that required to allow for brief periods of signal interruption with the Earth base station.

For large arrays of dipoles, there is a non-trivial power level needed to process the data before it is transmitted and stored. This power requirement is proportional to the number of distinct paths between dipole clusters of an interferometer, which is proportional to the number of array clusters squared. For a total of 215 clusters, this results in a power requirement of approximately 4.6 kW.

C. Power Subsystem

Two separate power subsystems were designed for the LIRA telescope: a larger system for the central processing unit, and a smaller system for each of the clusters. The central unit power system will provide power chiefly for the central processing unit as well as the communications system in the central unit, which collects signals from the clusters and transmits processed data to the radio downlink station. The cluster power system will provide power to the amplifiers of each antenna, the beam combiner electronics, and the communications systems on each cluster. Systems with solar panels and batteries were chosen in the end, but Radioisotope Thermoelectric Generators (RTGs) were also studied as an alternative.

The final design of the central processing unit power subsystem is a solar panel system with batteries that will deliver the required 230 W continuously under 70% sunlight availability (assumed for the location of the telescope). The final design of the cluster power subsystem is a solar panel system with batteries, which will deliver the required 12 W continuously under 70% sunlight availability. The power system, especially the batteries, is a significant portion of the cost of the clusters and the whole telescope array. Any improvement in battery technology will have significant positive effects on the total system.
Table 1. Final power subsystems design values (solar-powered).

<table>
<thead>
<tr>
<th>System Type</th>
<th>Mass</th>
<th>System Cost</th>
<th>Total Cost w/ Transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Processing Unit Power System</td>
<td>396 kg</td>
<td>$145,301.00</td>
<td>$27.87 $M</td>
</tr>
<tr>
<td>Cluster Power System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Cluster</td>
<td>19 kg</td>
<td>$7,078</td>
<td>$1,337,078 $M</td>
</tr>
<tr>
<td>215 Clusters</td>
<td>4085 kg</td>
<td>$1.52 $M</td>
<td>$287.5 $M</td>
</tr>
</tbody>
</table>

D. Communications Subsystem

The communications system consist of three parts: the interior system, which carries data between clusters and the central processing station; a relay chain, which carries data to the Earth downlink station; and the downlink station itself, which communicates with Earth ground stations. The interior system interfaces with the electronics at the clusters and at the central station, where data preprocessing is carried out, and interfaces with the deployment systems for the purpose of laying the relay chain.

The relay chain is a laser-based system that feeds data to a radio transmission station on the Moon’s limb. The selection of laser communications technology eliminates interference issues associated with radio transmissions spanning the far side of the Moon near LIRA’s location. Other options considered include fiber optic relays and a constellation of communication satellites. These were eliminated due to mass, cost and complexity.

The following subsections describe some of the more challenging aspects of this system design including the laser communication system sizing and the relay chain design.

1. Laser system design

The communications system is sized according to the downlink data rate since that is envisioned to be much higher than the uplink data rate. The downlink rate is assumed to be tens of gigabits per second based on the data rates for the JWST\textsuperscript{9,10} and the Spitzer space telescopes\textsuperscript{11}. This data rate is the source of the initial consideration given to laser communications technology. Within the timespan allocated to design and implementation of this telescope, it was assumed that laser communications systems, which are currently approaching the necessary Technology Readiness Levels for use in large-scale space systems, will be sufficiently developed that they can be included in the communications system. For this study, scaling of laser communications systems was based on Hemmati et al.\textsuperscript{12}, and the figures used were for the largest system considered in Hemmati et al.\textsuperscript{12}.

Additionally, a trade study was conducted to investigate whether it would be cheaper to process the data on site or to simply downlink it all to Earth. It was found that there is not a major component cost difference between the two approaches. However, a laser communications system large enough for the predicted raw data rate has a Technology Readiness Level of no more than 3, while the lower-data-volume system has a TRL of approximately 6. Development costs inherent to reducing this gap in TRL may be significant. Furthermore, a lower data rate system results in savings in power that translate to mass savings for the telescope.
2. Relay system design

The relay elements of the system were designed to be collapsible, self-sufficient, and reliable. Accordingly, each deploys from a 1-m high storage mode to a 3-m high transmission mode, as seen in Figure 5 and 6 below. The outer shell and the structural elements are titanium alloy, chosen for strength, weight, and resistance to temperature changes; the interior sections are sealed and contain batteries and a suite of motors and acquisition-pointing-tracking (APT) mechanisms. The uppermost section, which telescopes out of the lower two, is covered with miniature solar arrays to provide power when needed, and crowned by an optical laser lens.

The optical package requires no power. It simply accepts the laser beam from the previous relay, refocuses it, bends it slightly around the curvature of the Moon’s surface, and sends it on to the next relay. Power is required for extension during deployment, initial acquisition, and aiming adjustments after disturbances (e.g., meteor impact nearby). The power requirement is minimized by allowing for passive optical packages, although the internal mirrors are equipped with powered aiming systems, to allow for tight refocusing of the incoming beam and thus increase overall robustness of the relay chain. The fact that the laser relays will transmit through vacuum, and thus not be required to compensate for atmospheric attenuation, adds to the ability of the relay chain to successfully transmit data to the downlink station.

Figure 4. Interior (left) and relay chain (right) communications system arrangements.

Figure 5. Storable mode, front and top views.
Figure 6. Fully-deployed relay.

The estimated power, mass, dimensions, and cost of a relay appear in Table 2. The deployed height allows a spacing between relays of 6.45 km.

Table 2. Relay properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>26 kg</td>
</tr>
<tr>
<td>Power</td>
<td>0.5 W or less each</td>
</tr>
<tr>
<td>Cost</td>
<td>$27,750 each</td>
</tr>
<tr>
<td>Upper tube diameter</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Middle tube diameter</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Leg diameter</td>
<td>0.075 m</td>
</tr>
<tr>
<td>Stored height</td>
<td>1 m</td>
</tr>
<tr>
<td>Deployed height</td>
<td>3 m</td>
</tr>
</tbody>
</table>

E. Transportation Subsystem

In order to leverage the lunar exploration architecture developed by NASA, transportation of telescope components from the Earth to the lunar surface is assumed to be provided by the Ares V launch vehicle and the Lunar Surface Access Module as described in the Exploration Systems Architecture Study\textsuperscript{13}. The total mass of components that can be landed on the moon with one launch is estimated to be 18 mT. Currently, the total mass of all telescope components, including the communications and deployment systems, is 17.2 mT. Therefore, a single launch is required for transportation of the entire telescope to the Moon.

Note that it was assumed that a variant of NASA’s Lunar Surface Access Module, capable of transporting prepackaged cargo in an unpressurized container, would be available for use by this project. Additional considerations for this subsystem included offloading of cargo from the LSAM. For this project, a simple system composed of a ramp and a winch would suffice to unload telescope elements packaged together into a large container attached to the winch. For purposes of this project, it was assumed that the cargo version of the LSAM would have such a system, or one with similar characteristics, and this project would be able to utilize it with
minimal modifications.

Finally, it is envisioned that the Trans-Lunar Injection stage left in lunar orbit before descent to the surface would be outfitted with a simple radio communications system, in order to provide contact between the telescope on the lunar surface and ground controllers on the Earth before the laser communications system has been set up.

F. Deployment Subsystem

The deployment subsystem is responsible for positioning of array elements and communications relays on the lunar surface. Since these elements are spread over a distance of several hundred kilometers across the lunar surface, it was not considered feasible to land the components separately from each other. Rather, it is envisioned that the transportation system will place a single module on the lunar surface containing all telescope components. Each of these components will then need to be positioned at the proper location on the lunar surface through a surface transportation system.

Since one of the objectives of this project is to leverage the lunar exploration architecture developed by NASA., this system tries to use elements from the lunar exploration architecture wherever possible. The Exploration Systems Architecture Study and the Lunar Architecture Team’s study both mention plans for an unpressurized rover at the human lunar outpost. It is assumed, therefore, that these rovers would be available for use in the deployment of this telescope concept. Note that the cost of these rovers is still counted in the cost of the telescope system. Also, it is assumed that these rovers have a range of several hundred kilometers and a rechargeable power system.

These rovers will be modified from NASA’s design in several important ways including equipment to load and unload cargo, a gimbaled laser receiver to enable tracking of the communications system laser during the deployment of communications relays, automated navigation, interface for automated recharging from telescope power system and a radio system to communicate with the Trans-Lunar Injection stage left in lunar orbit to ensure contact with the Earth. The maximum payload capacity of each rover is assumed to be 480 kg based on the Apollo Lunar Roving Vehicle (LRV). For calculation of deployment times, the speed of the rovers is taken to be 2 km/h.

The number of rovers employed is dependent on the mass of the telescope as well as the payload capacity of each rover. The deployment limiting factor is the total mass of the communications relays, 650 kg. For better efficiency, all the relays need to be carried aboard the rovers to avoid having to drive back and forth from the landing site to retrieve relays. For this reason, two rovers each having a payload capacity of 480 kg, are landed with the telescope. Thus, the current design entails the use of two rovers, which provides both payload margin for the deployment of relays and redundancy in the deployment system, but still results in a total mass below the payload limit of the LSAM.

The rovers are capable of deploying elements over a maximum range of 255 km in any direction on a single charge and returning to the telescope location for recharging. The total mass of these rovers is 1192 kg. Assuming a rover speed of 2 km/hr, deployment of all telescope components takes at least 20 days, plus time required for offloading of the telescope elements and recharging of the rovers.

VI. Cost Estimation

When dealing with a space system as complex as a lunar observatory, accurate cost estimation is an important program driver. Here an attempt is made to provide an accurate, yet conservative, estimate of the overall budget for all project phases including a generous allocation for research and development (R&D). Estimates are based on existing or predicted technology. Where existing technology or predictions are not available, costs are estimated based on SMAD, or using analogies to components of the Apollo program and where appropriate, learning curves are applied. Additional margins and accounting for inflation are also applied to subsystems. Integration costs are estimated using a 25% margin, which is intended to account for any subsystems not included in the initial design and any increased complexity of current subsystems.

The total cost of the LIRA telescope facility is estimated to be $1.987 billion. The estimate for the system itself is $726.2 million. For transportation costs, the Ares V launch cost estimate of $1.26 billion, is used. A breakdown of the system cost and mass is provided in Table 3. All costs are in 2010 U.S. dollars. Complete details of the cost estimation process may be found in the detailed report for this project. However, some details of the more challenging cost estimation aspects are provide in following subsections.
Table 3. Subsystem mass and cost breakdown for the LIRA concept over the entire development timeline.

<table>
<thead>
<tr>
<th>LIRA Subsystem Mass and Cost Estimation</th>
<th>Mass (kg)</th>
<th>Component Cost (M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>58.2</td>
<td>28.2</td>
</tr>
<tr>
<td>Communications</td>
<td>826.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Power</td>
<td>4,546.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Structures and Mechanisms</td>
<td>7,149.5</td>
<td>71.5</td>
</tr>
<tr>
<td>Deployment</td>
<td>1,007.3</td>
<td>256.6</td>
</tr>
<tr>
<td>Integration and Other</td>
<td>3,396.9</td>
<td>91.1</td>
</tr>
<tr>
<td>Software and Ground Segment</td>
<td>--</td>
<td>270.7</td>
</tr>
<tr>
<td>Subsystem Total</td>
<td>16,984.5</td>
<td>726.2 (M$)</td>
</tr>
</tbody>
</table>

Figure 7. Spreading of the $1.987 billion development cost for LIRA over a notional development timeline.

A. Software cost estimation

For the number of total lines of code for the telescope, it was assumed that the level of complexity of a lunar surface program would be approximately half that of a free space telescope program, as no code would be needed for attitude control or orbital guidance and the reduced complexity needed to recover from pointing failures. LIRA is estimated to have approximately half the software lines of code (SLOC) as HST. There will also not be a need to keep all software space-certified, resulting in lower complexity and cost. The HST has approximately 500 thousand lines of code (KLOC), so LIRA was estimated to have on the order of 250 KLOC, with only 1/3 of the code needing flight certification. From SMAD, this results in a software cost estimation of approximately $80.2 million. Also from SMAD, this number can be used to calculate total ground segment cost as a function of KLOC. From this, the total ground segment development cost for LIRA is estimated to be $270.7 million.\(^{17}\)

B. Operations cost estimation

From SMAD, the operating and maintenance costs for LIRA were estimated on a per-year basis, assuming no major upgrade or servicing missions are performed\(^{17}\). These costs cover ground operations and support after the
completion of the telescope. The day-to-day operations of the telescope facility is expected to require approximately 25 government employees and 50 contractors. Including a per year maintenance cost equivalent to 10% of the cost of software, equipment, and facilities, the total yearly operating cost of the telescope is estimated at $31.03 million per year.

C. Cost spreading

Space missions take several years to develop, so the costs must be spread across the entire development timeline. The cost spreading function in common use by the U.S. space program is used to develop Figure 7. Accordingly, it can be seen that the peak annual cost over the notional 15-year development timeline is about $220 million for LIRA.

D. Effect of array design on cost estimation

As explained in Section II, the number of dipoles used in the point design chosen for this study could be increased in future design iterations. Increasing the number of dipoles, however, will have a direct effect on the estimate for the total cost of the system. To account for this, Figure 8 shows the effect of the number of dipoles on overall system cost, indicating the location on the curve of the present design.

![Figure 8. Effect of number of dipoles on total system cost. The steps in the graph result from the discontinuous cost increase that comes with each additional launch needed as the total mass of all dipoles increases. The location of the point design discussed in this study is indicated by the red dot.](image)

VII. Conclusions and Recommendations

The LIRA telescope design leverages the uniquely radio-quiet environment of the lunar far-side to observe key targets of interest to the science community including the Epoch of Reionization, Extrasolar Planets and low frequency solar science. Since extremely low frequency radio astronomy is not possible on Earth or in near-Earth space due to the Earth’s ionosphere, and its own aural radio emission, the lunar far side provides a unique location that will allow high sensitivity observations at frequencies never before explored. As such, the conduction of serendipitous science, including the potential discovery of new astrophysical processes or objects, is a very real
possibility with this telescope concept as well.

Additionally, this telescope design provides value to the space exploration community by leveraging existing elements of the Constellation lunar architecture, including the use of transportation elements such as the Ares V cargo rocket and the lunar rover, as well as the human lunar base, which may serve as a transmission relay point for telescope sensor data.

While the LIRA telescope has the potential for breakthrough astronomy, it requires further analysis in some areas including deployment, optical communications and exact telescope location.

Autonomous deployment of 215 clusters of radio dipoles would require a sophisticated system of rovers, communications, and planning. Deployment by human power alone would likely strain the abilities and usefulness of astronauts on the Moon, and even automated deployment represents a stretch for existing capabilities. The design of a capable deployment rover, and the tradeoffs of complexity and cost between the rover and other elements of the telescope concept are important issues.

A second major consideration is the transmission of high data rates using laser relays on the far side of the Moon. The main objective is to avoid emitting radio waves, which may interfere with the astronomical measurements being done; it was deemed desirable to keep the far side of the Moon radio-quiet. This drove the design to include an optical relay system, the cost of which was found to be less than that of an orbiting satellite. However, the Technology Readiness Level of a laser-relay communications system such as this is still low, and further investigation into this problem is suggested to justify the choice or generate alternatives for the communications system.

Finally, a significant driver in cost is the exact location of the LIRA telescope. First, the attenuation of radio noise from Earth needs further study to determine the distance behind the limb of the Moon necessary to achieve the sensitivity required for the primary science goal, observing the Epoch of Reionization. This choice impacts areas such as communications, power, and deployment, and consequently, cost.

Acknowledgments

The student authors as a group thank the following people:

Professor Edward F. Crawley and Professor Olivier L. de Weck, MIT Department of Aeronautics and Astronautics  
Mr. Mark Baldesarra, MIT Department of Aeronautics and Astronautics  
Professor Jacqueline Hewitt, Kavli Institute for Astrophysics and Space Research at MIT  
Professor Jeffrey Hoffman, MIT Department of Aeronautics and Astronautics  
Dr. Tupper Hyde, NASA Goddard Space Flight Center  
Dr. Gary Mosier, NASA Goddard Space Flight Center  
Ms. Sarah Shull, MIT Department of Aeronautics and Astronautics  
Dr. Massimo Stiavelli, Space Telescope Science Institute

References

16 Lecture notes for Satellite Engineering course (16.851). Fall 2006, Massachusetts Institute of Technology.