The Lunar Radio Array (LRA)

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1 Executive Summary

The Lunar Radio Array (LRA) is a concept for a telescope sited on the far side of the Moon with a prime mission of making precision cosmological measurements via observations of the highly-redshifted $\text{H} \text{I}$ 21-cm line. Technology development in the 2010–2020 decade is required for a successful start to the LRA in the 2020–2030 decade. Many of these technologies are applicable to other NASA missions, space missions conducted by other Government agencies, or commercial interests. A key issue is that, while other interests are developing these technologies, focused investments will be necessary to make them applicable to the LRA and for astrophysics missions, in general. The table below presents a prioritized list of these investments.

Hydrogen is the dominant component of the intergalactic medium (IGM), and the LRA potentially will provide precision cosmological measurements from observations of the state of the IGM prior to the formation of the first stars and unique information about the state of the IGM and large-scale structures after the first stars formed. Primary questions include: Does the standard cosmological model describe the Universe during the “Dark Ages,” before the first stars? How does the IGM evolve during this important time? What were the properties of high-$z$ galaxies? How did they affect the Universe? What is the nature of the field that drove inflation?

The LRA will be an interferometer, composed of a large number of science antennas. The LRA could usefully exploit the Constellation system, or components with similar capacity. The far side of the Moon is likely the only site in the inner solar system for these observations as significant obstacles exist to ground-based telescopes—distortions introduced by the Earth's ionosphere and heavy use of the relevant spectrum by civil and military transmitters.


<table>
<thead>
<tr>
<th>Technology</th>
<th>Duration</th>
<th>Cost</th>
<th>Heritage</th>
<th>Synergies</th>
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<tbody>
<tr>
<td>Low-frequency, wide-bandwidth, low-mass science antennas</td>
<td>7 years</td>
<td>$3M</td>
<td>Ground-based antenna development</td>
<td>NASA heliophysics missions</td>
</tr>
<tr>
<td>Ultra-low power, radiation-tolerant digital and analog electronics</td>
<td>7 years</td>
<td>$7M</td>
<td>NASA ST5; JPL GeoSTAR correlator</td>
<td>NASA missions; DoD; commercial</td>
</tr>
<tr>
<td>Autonomous low-power generation</td>
<td>5–7 years</td>
<td>$25M</td>
<td>Multiple spacecraft missions</td>
<td>NASA micro-sats, small lunar payloads</td>
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<tr>
<td>Low-mass, high-capability, autonomous rovers (DALI concept only)</td>
<td>7–10 years</td>
<td>$5M</td>
<td>Mars rovers, ATHLETE rover, DARPA competitions</td>
<td>NASA planetary, lunar exploration; DoD; commercial (human-hazard)</td>
</tr>
<tr>
<td>High data rate, lunar surface data transport</td>
<td>7 years</td>
<td>$3M</td>
<td>NRL-JPL free-space lasers; commercial radio wireless, optical fiber</td>
<td>NASA lunar exploration, satellite constellations</td>
</tr>
</tbody>
</table>

A potential staged approach is technology development, a single dipole in the lunar environment, successively larger arrays prototyping both the science and technology, to the LRA itself.
2 Science Objectives

2.1 Cosmology and Astrophysics with the Highly-Redshifted 21-cm Line

Modern cosmology has advanced rapidly in recent years owing to precision observations of the CMB (Komatsu et al. 2008); large data sets produced by wide field galaxy surveys (SDSS, Eisenstein et al. 2005; 2dFGRS, Colless et al. 2001); and observations of Type Ia supernovae (Riess et al. 1998; Perlmutter et al. 1998). This information has produced a standard model for cosmology. Yet significant questions remain

- Does the standard cosmological model describe the universe during the “Dark Ages,” before the first stars formed?
- How does the IGM evolve during this important time, ending with the reionization of hydrogen?
- What were the properties of high-z galaxies? How did they affect the Universe around them?
- What is the nature of the field that drove the universe during inflation?

Hydrogen is the dominant component of the IGM, and neutral hydrogen (H I) displays a hyperfine spin-flip transition at a frequency of 1420 MHz. The feasibility of observing this redshifted H I line has stirred significant recent interest precisely because it offers the chance to extend current data sets by orders of magnitude (Loeb & Zaldarriaga 2004; Furlanetto et al. 2006). Through detailed mapping of the H I line brightness temperature in space and frequency, it might be possible to determine the distribution of hydrogen throughout the Universe from the present day to a redshift z ~ 100. This unprecedented data set would constrain the properties of the inflation era, detect signatures of any exotic heating mechanisms before the first star formation (e.g., dark matter decay), and constrain the properties of “dark energy” and fundamental gravity by tracking the evolution of the angular scale of the baryon acoustic oscillations. It would also provide a wealth of astrophysical data on the first galaxies and their descendants, including the properties of the first stars, the birth of the first black holes, and their evolution towards mature galaxies.

Figure 1 shows the evolution of the global (all-sky averaged) H I signal after recombination; shown are the signals in three models chosen so that the astrophysical parameters yield a CMB optical depth to electron scattering of $\tau = 0.06$, 0.09, and 0.12, corresponding to the WMAP5 central and $\pm 2\sigma$ values. Three regimes are apparent. At high redshifts ($30 < z < 300$), collisions in the gas produce a broad absorption signal because the gas expands and cools at a faster rate than the CMB; this signal fades as the Universe continues to expand and collisions become more rare. Once the first stars form, they flood the Universe with Ly$\alpha$ photons, which produce a second, deep absorption feature ($15 < z < 30$). Finally, as the gas is heated above the CMB temperature (probably by X-rays from the first black holes), the absorption turns into emission, which eventually cuts off as reionization completes.

This global signature is currently an experimental target (Bowman et al. 2008). Although conceptually simple, these observations are experimentally challenging, because of the difficulty of separating the faint signal from the many other sources of emission, including Galactic synchrotron, free-free radiation, and the CMB as well as corrupting effects due to observing from the ground ($\S$2.3). Experimental detection relies upon a distinctive, step-like feature in frequency (Figure 1, left), which is not expected from the spectrally smooth foregrounds; current limits are over an order of magnitude short of theoretical expectations.
Figure 1. (Left) Evolution of the mean H I line brightness temperature $T_b$ as a function of redshift (bottom axis) or frequency (top axis) for three models of the first galaxies representing the range of astrophysical parameters consistent with CMB analyses (Pritchard & Loeb 2008). (Right) Redshift (frequency) evolution in one model for the angle-averaged H I line power spectrum $\Delta T$ at $k = 0.01$ (solid curve), 0.1 (dotted), 1.0 (short dashed), and 10.0 (long dashed) $\text{Mpc}^{-1}$. Reionization occurs at $z = 6.5$. Diagonal red lines show the strength of the combination of Galactic and extragalactic foregrounds reduced by indicated numerical factors.

An alternate, and ultimately more powerful, approach is through H I line fluctuations, conventionally parameterized with the power spectrum. Figure 1 (right) illustrates the redshift (frequency) evolution of the power spectrum $\Delta T = (k^3 P_T(k)/2\pi^2)^{1/2}$ at four comoving wavenumbers $k = 0.01, 0.1, 1, \text{and } 10 \text{ Mpc}^{-1}$. These wavenumbers span the range that might be observed: on small wavenumbers (large scales) we expect contamination from foregrounds to limit the detection of the power spectrum, while at large wavenumbers (small scales) thermal broadening of the H I line will smooth the signal.

The shape and amplitude of power spectra encode a great deal of information about the first sources of light and the processes modifying the IGM, and extracting the power spectra at different redshifts will allow the evolution of the IGM to be traced. Figure 2 shows model H I line fluctuation spectra at three different epochs; at $z = 15.7$, the dip at moderate $k$ indicates that X-rays from the first black holes are beginning to heat the IGM, transforming the signal to emission. H I line fluctuation spectra have the potential to distinguish between heating and ionizing sources (i.e., black holes and stars), determine the epoch(s) at which each became important, and constrain the luminosity function of the first galaxies.

This power spectrum approach motivates a number of current generation instruments: the Murchison Wide-field Array (MWA), the Precision Array to Probe the Epoch of Reionization (PAPER), and the Low Frequency Array (LOFAR), all of which focus on detecting the H I

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1 MWA: http://www.mwatelescope.org/
2 PAPER: http://astro.berkeley.edu/%7Edbacker/eor/
3 LOFAR: http://www.lofar.org/
Lunar Radio Array

power spectrum at redshifts $z = 7$, at which the reionization of the neutral IGM produces a large signal. While not directly motivated by EoR observations, the Long Wavelength Array (LWA)$^4$ has frequency coverage that overlaps with some of these instruments. These pathfinder telescopes will likely be followed by the Square Kilometre Array (SKA)$^5$ to perform even more sensitive measurements.

Foreground removal must be accomplished at a high level of precision for detection of the H I signal. Figure 1 (right) also shows $rT_{\sky}(v)$, for $r = 10^{-4}–10^{-9}$, with $T_{\sky}$ corresponding to the sum of the Galactic non-thermal emission in a dark region of the sky and extragalactic contributions. Lending confidence to the notion of high-precision foreground removal is that the foregrounds are generally *spectrally smooth*, while the H I signal has frequency structure. Further, exotic physics (e.g., energy injection by decaying dark matter, Furlanetto et al. 2006) can increase the H I signal strength and reduce the level to which foregrounds need to be removed.

![Figure 2](image)

Figure 2. Redshift slices of the H I line power spectrum, for one of the models in Figure 1: during the EoR ($z = 7.9$), during the transition phase ($z = 15.7$), and during the Dark Ages ($z = 30.2$). Also shown are the expected errors for three fiducial instruments, the MWA (red), the SKA (cyan), and a potential LRA (blue); the sensitivity of the LRA is also shown with its observing time split between 16 separate fields (blue dashed).

Figure 2 shows redshift slices, and signal-to-noise ratios, for the H I power spectrum for one of the models in Figure 1 at three fiducial epochs: during the EoR, during the transition phase, and during the Dark Ages. Signal-to-noise ratios are shown for three fiducial experiments: (i) a current generation experiment; (ii) the SKA; and (iii) an LRA concept (collecting area $\sim 3.6 \text{ km}^2$, 4-yr observing campaign). These labels primarily denote different scales of experimental effort, as the design for any array following the pathfinders will clearly be informed by their results. Clearly, though the current generation of instruments may detect the EoR H I signal, measuring detailed physics will require efforts comparable to the SKA, which also sets a target for the LRA.

### 2.2 Secondary Science

Examples of the secondary science that the LRA may enhance are the following:

**Extrasolar Planets:** The magnetic polar regions of the Earth and the solar system giant planets

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$^4$ LWA: [http://lwa.unm.edu/](http://lwa.unm.edu/)

host electron cyclotron masers generated by interactions between solar wind-powered currents and planetary magnetospheric fields. Empirical relations for solar system planets suggest that extrasolar planetary radio emission may be detectable. Magnetospheric emission would aid the understanding of extrasolar planets by providing information that will be difficult to obtain otherwise: The existence of a magnetic field constrains the interior of a planet while modulation of the emission can yield its rotation rate.

The Heliosphere and Space Weather: Within the inner heliosphere (2–10 solar radii) intense electron beams are produced; a significant fraction of solar wind heating occurs in the same region. Radio wave observations and spacecraft coronagraphs, notably those on the Solar Heliospheric Observatory (SOHO), have provided dramatic indications of the violent, magnetically driven activity of the Sun and its connection to particle acceleration. Because of its proximity and brightness, the inner heliosphere is one of the best places to study the fundamental physics of particle acceleration. Solar radio bursts are one of the primary manifestations of particle acceleration in the inner heliosphere: Type II bursts originate from shock-accelerated suprathermal electrons (~ 100 eV) and Type III bursts are generated by fast (2–20 keV) electrons, often driven by reconnection events. Previous space-based radio observations have been from single dipole instruments with no imaging capabilities.

Radio Transients: Transient sources are necessarily compact and usually are the locations of explosive or dynamic events, therefore offering unique opportunities for probing fundamental physics and astrophysics. A wide variety is known, ranging from extremely nearby to cosmological distances; motivated by analogy to known objects or applying known physics, there are a number of hypothesized classes of transients (e.g., extrasolar planets). Radio transients form a part of the key science case for all of the low-frequency ground-based arrays. A key limitation for ground-based arrays is radio interference (§4.1), which limits the available radio spectrum. The farside of the Moon presents an ideal platform from which to conduct searches for radio transients over the full frequency range that will be accessible to the LRA.

Spectral Lines at z = 0: The spectral universe below about 200 MHz is unexplored except in a few narrow (~ 1 MHz) windows. Not only are low frequency spectral lines interesting from the standpoint of secondary science, they may serve as a foreground contaminant to the cosmological signal. An example of a possible contaminant is the 178 MHz hyperfine transition of H I in its 2s quantum state, equivalent to the 1420 MHz hyperfine transition of the 1s quantum state. The 2s-1s transition is forbidden (Lyγ photons are 2p-1s transitions) and therefore conducive to the hyperfine 2s transition, which may therefore complicate cosmological H I observations.

Radio Recombination Lines: Radio recombination lines (RRLs) are abundant at low frequencies and can exhibit weak maser action. For example, H400α through H500α lie in the 50–100 MHz range with separations between lines of approximately 0.2 MHz near 50 MHz, comparable to the expected frequency signature of the H I signal, and can appear in absorption or emission, depending on the local conditions and background continuum illumination.

3 Mission Relevance and Significance

3.1 Expected Significance

The LRA samples a unique time in the early development of our Universe and its approach, imaging the H I gas as it begins to coalesce, is likely to be the only way to probe directly the
Dark Ages. Although numerous low-frequency arrays exist or are in development, including the MWA, PAPER, and the SKA, these all operate at higher frequencies and thus do not reach back to the Dark Ages. LOFAR may construct a “low band” component, but it is located in northern Europe, one of the worst RFI environments on Earth. The LWA’s frequency coverage of 20–80 MHz is appropriate for observing the H I signal at the required redshifts, but, like the other ground-based arrays, it will be limited by RFI and ionospheric disturbances. Two conceptual free-flying radio arrays, ALFA and SIRA, as well as the Radio Observatory for Lunar Sortie Science (ROLSS, a lunar-based radio observatory intended for solar observations) sample redshifts too far back in time (z ~ 150–1500; v ~ 1–10 MHz) and lack adequate sensitivity. The James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA) will only observe objects at lower redshifts, after the first stars have formed and reionization has occurred. CMB experiments target recombination, before the first baryonic structures form.

Scientifically, the goal of 21-cm cosmology studies is to extend the spectacularly successful CMB experiments, beginning with COBE and continuing with WMAP and soon Planck. The density fluctuations detected in the CMB observations will be followed forward in redshift, revealing the process of the structure formation they seeded. This process culminates in the formation of the first galaxies, and 21-cm studies will complement observations of very high redshift galaxies with the JWST, ALMA, and probes of high redshift gamma-ray bursts by Swift and follow-on missions. 21-cm cosmology studies will also extend matter density power spectra to smaller angular scales than possible with CMB studies (because of Silk damping), giving about $10^{16}$ independent pixels on the sky, rather than about $10^7$ with the CMB (Loeb & Zaldarriaga 2004). This enables new physics to be addressed, such as the nature of the inflaton field.

3.2 Relevance to NASA Programs

In characterizing the first structures in the Universe, the LRA responds to NASA Strategic Goal 3D, “Discover the Origin, Structure, Evolution, and Destiny of the Universe …”; NASA Science (Astrophysics) Goal, “The Origin and Evolution of Cosmic Structure”; and key problems identified in the NRC Report *Astronomy and Astrophysics in the New Millennium* including, “Study the dawn of the modern Universe, when the first stars and galaxies formed.” In addition, the NASA Advisory Council (NAC) “Workshop on Science Associated with the Lunar Exploration Architecture” Astrophysics Recommendation (Number: S-07-APS-1) recognized the value of the lunar far-side meter-wavelength radio environment, and the community workshop “Astrophysics Enabled by the Return to the Moon” identified “low-frequency radio observations from the lunar far side” as one of the two most promising aspects of lunar-based astrophysics.

One of the potential secondary science goals, studying the heliosphere and space weather, addresses NASA Strategic Goal 3B: “Understand the Sun and its effects on Earth and the solar system.” Another of the potential secondary science goals, detecting the magnetospheric emissions from extrasolar planets, addresses NASA Strategic Goal 3D, “… Search for Earth-like Planets”; NASA Science (Astrophysics) Goal, “The Origin and Destiny of Stars” including exoplanet exploration; and the key problem of understanding the “formation of stars and their planetary systems, and the birth and evolution of … planets” from *Astronomy and Astrophysics in the New Millennium*.

NASA Strategic Goal 6 is to “Establish a lunar return program having the maximum possible utility for later missions to Mars and other destinations.” The construction of a radio array on the
far side of the Moon will require techniques for deploying large structures, power and data transport infrastructure, and signal processing on the lunar surface. The technologies are relevant well beyond the immediate scientific goals of this project and are of utmost importance for human return to the Moon and travel to other destinations.

4 Technical Approach and Methodology

4.1 The Moon as an Astronomical and Cosmological Platform

The lunar farside is potentially the only site in the inner solar system for the LRA:

No Human-generated Interference: Civil and military transmitters make heavy use of the relevant frequencies ($\nu < 100$ MHz). The FM radio band is at 88–107 MHz, and Digital TV channels and myriad other signals also exist in this frequency range. Further, because of ionospheric refraction, interference in the HF band ($\nu < 30$ MHz) used for international communication is independent of location on Earth. Terrestrial transmitters can be orders of magnitude ($\sim 10^{12}$) stronger than the H I signals and are detectable even at remote locations on Earth (Figure 3). The Moon reduces such interference to a negligible level (Alexander & Kaiser 1976).

![Figure 3. Radio interference enabled by the Earth's atmosphere. (Left) An all-sky, 61-MHz image from the Long Wavelength Demonstrator Array in New Mexico. The Galactic plane slopes from the upper right to the lower left and the sources Cyg A and Cas A are visible as is a general enhancement toward the inner Galaxy. (Right) An image acquired seconds later. The dominant source (upper right) is a reflection off an ionized meteor trail from a TV station hundreds of kilometers away. The highest sensitivity astronomical observations will require shielding from such interference, shielding that can be obtained only on the Moon.](image)

No (Permanent) Ionosphere: The Earth's ionosphere produces phase errors that limit radio observations (in addition to simply reflecting interference from distant transmitters, Figure 3). These phase errors form a significant fraction of the error budget in the recent 74-MHz VLA Low frequency Sky Survey (Cohen et al. 2007), even after the development of new algorithms for ionospheric mitigation. While the Moon has a plasma layer due to solar irradiation during the lunar day, this ionized layer disappears during lunar night.
Shielding from Solar Radio Emission: The Sun is the strongest celestial source at these frequencies when it is bursting. Within the solar system, the only mitigation for solar radio emissions is physical shielding. Such shielding is readily accomplished by observing during lunar night; while the same is true for the surface of the Earth, interference and ionospheric effects continue to occur during terrestrial night.

4.2 Mission Description

Tables 1 and 2 summarize key scientific requirements, and derived technical requirements, for the LRA. Depending upon the results from ground-based arrays and the cost-performance achieved, different scientific goals are envisioned. A “nominal” LRA has modest overlap with the redshift range of ground-based arrays and its redshift coverage extends back to the epoch of the first star formation; a “dark ages” LRA has considerable overlap with the redshift range of ground-based arrays and its redshift coverage extends well into the Dark Ages.

<table>
<thead>
<tr>
<th>Table 1. LRA Scientific Requirements</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Redshift</td>
</tr>
<tr>
<td>Brightness Temperature Sensitivity</td>
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<tr>
<td>Angular Resolution</td>
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</table>

The LRA concept draws on the considerable experience from ground-based radio arrays. Multiple radio-receiving elements are operated together to collect radio signals from a particular region of the sky. In the LRA, each array element is composed of a multiple antennas. The individual antenna signals are aligned in time and summed, so that each element behaves as a single very sensitive antenna. The signals from each pair of elements are correlated with one another as an interferometer, and the different baselines between the various pairs sample the brightness distributions across the region of interest.

<table>
<thead>
<tr>
<th>Table 2. LRA Derived Technical Requirements</th>
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<tbody>
<tr>
<td><strong>Parameter</strong></td>
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<tr>
<td>Collecting Area</td>
</tr>
<tr>
<td>Frequency</td>
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<tr>
<td>Maximum Baseline</td>
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<tr>
<td>Lifetime</td>
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Two concepts are currently being explored for the LRA. Common to both concepts is that, once deployed, the LRA would have no moving parts. Individual aspects of both concepts are described further below. However, both concepts also share a number of common aspects. Command and control information and clock data must be transmitted to the elements from the central station. Digitized, filtered, frequency divided, multiple polarization science data are returned to the central processor and those signals are combined. Data are either correlated real-
time and stored at the central processing unit, or stored at the elements and transmitted and correlated during the lunar day.

The LRA will be located on the lunar farside, in a relatively flat area at least 10 km across. A nominal location is the Tsiołkovsky crater, which has been filled in by basaltic mare deposits making its floor relatively flat. LRA components will be delivered to the lunar farside using a heavy-lift vehicle (e.g., Ares V or similar) and lander (e.g., Altair cargo lander or similar). Unpacking, antenna distribution, antenna deployment, and array connection will be handled by rovers, such as the ATHLETE (All-Terrain Hex-Legged Extra Terrestrial Explorer). A central processing unit will remain on the lander and will serve as a control and communications center.

4.2.1 The Dark Ages Lunar Interferometer (DALI) Concept

The DALI concept is a hierarchical array, based on simple dipole or bowtie-like science antennas deposited on long strips of polyimide (e.g., Kapton™) film. The motivation for this approach is two-fold.

1. Both the hierarchical architecture and the antenna topology (dipole or bowtie) have considerable heritage from radio astronomy community. Many of the ground-based radio astronomy interferometers, either existing or under construction, use similar topologies for their science antennas and have similar hierarchical architectures.

2. Space-qualified Kapton has been used in many spacecraft applications and represents a promising low-mass substrate on which to form a science antenna. Even simple estimates suggest that the collecting area for pre-EoR and Dark Ages studies of the intergalactic medium will require thousands of science antennas, so that mass is likely to be a significant driver for the system design.

The hierarchical architecture for DALI consists of individual science antennas, which are grouped into “stations,” which form the overall array (Figure 4). In the current design, there are approximately 1500 science antennas per station and 300 stations in the full array.

A science antenna consists of two crossed, single polarization, dipoles or bowties deposited on polyimide film. The dipoles are entirely passive and nominal film dimensions are 100 m × 1.5 m × 20 µm. The film is flexible enough to be stored in a roll during transit and unrolled directly onto the lunar surface. Dust is not an issue for these antennas—it is an excellent thermal insulator and a thin coating could provide some protection from exposure.

We have conducted two tests of the DALI antenna concept. The first test was a comparison of the feed point impedance of a polyimide-film based antenna laying directly on the ground. This test was conducted to verify that our simulations of the antenna concept were accurate and did not involve extrapolations of modeling software into a regime of parameter space for which they are not valid. The test consisted of a single antenna, two 8-m long segments each 30.5 cm wide, and composed of a 25 µm-thick Kapton® film with a 5 µm-thick Cu layer deposited on it. The feed point impedance was measured via a network analyzer, and the test was conducted at NASA/GSFC. The test scenario was simulated using the CST Microwave Studio 3D package, with various estimates of the ground characteristics at the NASA/GSFC site. The simulations were not complete, in that they did not attempt to model the small air gaps underneath the antenna where it did not rest flat on the ground, and the ground was only modeled to a depth of 15 m. Nonetheless, the agreement between simulation and measurement is considerable.
The second test consisted of exposing a polyimide film sample to a simulated lunar environment. Two space-rated polyimide film samples were acquired, each being a 10 cm diameter circular sample, 8 µm in thickness, with a silver coating on one side. These were placed in a small thermal vacuum chamber with an interior UV lamp. The chamber contained a platform on which a polyimide film sample could rest, and the temperature of the platform could be changed from −150° C to +100° C. The test plan focussed on the large temperature changes and UV exposure encountered over the course of a year. The test film was exposed to a total of 12 cycles over the course of 24 days, from hot (100° C) to cold (−150° C) and back to hot, at the maximum rate possible with the temperature control system, with the sample also exposed to a deuterium lamp while in the hot cycle. After the simulated year exposure to lunar conditions, the film sample was evaluated for tensile strength, electrical conductivity, and flexibility. No change in the film’s properties, typically to 5% precision or better, was found.

A secondary motivation for the use of stations is to co-locate antenna electronics and other electrical components in a central “box” for ease of thermal management, power generation, and electromagnetic shielding. Further, the stations are sufficiently large that multiple fields of view (“multi-beaming”) must be formed on the sky in order to acquire a sufficient cosmic volume. Within a station, the radio frequency (RF) signals therefore must be transmitted from the science antennas to the station “hub.” In the nominal design, the transmission leads to the station hub are also within/on the polyimide film. During the course of this ASMCS work, however, alternate transmission technologies were identified, including RF wireless and fiber optics. Further trade studies are needed to identify the optimum technology.
Stations would be deployed by autonomous rovers (Figure 5), and the linear pattern for polyimide film strips shown in Figure 4 would be relatively easy for rover deployment. A uniform distance between polyimide film strips is neither required nor desirable, as that would produce “grating lobes” in the station response. The effect of such grating lobes would be to make the calibration of the array more difficult. Thus, it would be acceptable for rovers to shift the deployment locations of polyimide film strips by small amounts in order to avoid local features (e.g., small boulders). Further trade studies include the number of stations that a rover would deploy. Options include one rover per station, one rover deploys multiple stations, or a hybrid approach in which multiple stations near the array center are deployed by a single rover while distant stations are each deployed by a rover.

4.2.2 The Lunar Array for Radio Cosmology (LARC) Concept

The LARC concept (Lunar Array for Radio Cosmology) combines three helical antennas into a single, autonomous phased-array element called a STANCE (Self-Tending Array Node and Communication Element). Preliminary results from trade studies indicate that the number of STANCEs needed for the LARC concept to be in the thousands. Given the sheer number of antennas, the following design considerations were implemented:

- Low Mass/Low Volume — antenna mass is the largest driver in the system;
- Autonomy — each STANCE is self-operable and will not impact array performance upon failure; and
- Ease of Deployment — each STANCE is self-deployable and will not require assembly.

Figure 6 illustrates the fully deployed configuration. Each helix is 1.2 m in diameter and attached to a hexagonal plate at its base. The fully-extended helix is 8.2 m high and supported by three vertical scissors-type truss assemblies (not shown). The ten-turn helices are separated by 1.8 m to meet the requirements for effective aperture and field-of-view. The antennas on a given STANCE are all sensitive to the same E-field polarization and are rotated such that the combined power results in a beam pattern, also shown in Figure 6, that has a high degree of circular symmetry. The central hexagon of the STANCE serves as a platform for the electronics canister, the DC power source, and the communications tower. Found inside the electronics canister are the low noise amplifiers, analog-to-digital converters, and digital signal processing unit.

![Figure 6. The STANCE concept. (Left) Sketch of the fully deployed configuration (support structure not shown). (Right) Simulated three-dimensional beam pattern at 90 MHz, calculated with CST Microwave Studio software.](image)

Each STANCE’s digital signal processing unit includes a polyphase filter bank that selects the 16 MHz band, trims the data to 4-bit complex samples and packetizes the header information.
The packets are passed to a laser transmitter that transmits the data to the 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 128 Mbs. We estimate that each STANCE will consume about 100 mW. Development of power storage technology appropriate for many of these small autonomous units on the Moon is critical.

While the final number of STANCEs will depend on the outcome of further trade studies, we adopt 10,000 LARC STANCEs, 5000 of each polarization, as a target. The total data rate to the correlator is over 1 Tb/s. To carry out complex correlation of all polarization products, over 40,000 Tops/sec are required. Scaling this computation load to the current performance of the GeoSTAR correlator (Lambrigsten 2006) implies that only 200 W of power will be required for the correlator. While the complexity of such a large correlator is a concern, already the remarkable advances in space-qualified ultra-low-power digital electronics enable the processing required for the large antenna array envisioned for the LARC concept.

STANCE deployment has been designed with the objective to eliminate low-mass rover and robotic technology development specific to the LRA. The ATHLETE system (funded by the Constellation Program) will be used both to offload the STANCEs from the Altair lander or similar vehicle and place them on the lunar surface. STANCEs will be loaded onto a cargo pallet on top of the Altair (Figure 7). After landing, the ATHLETE will unfold its legs, swing them down on the surface, extend and lift the cargo pallet, and “walk off” of the Altair to the deployment site. The ATHLETE will then use two of its legs to reach up, “grab” STANCEs using leg attachments, and lower them onto the surface. Once a STANCE has been placed, the ATHLETE will trigger its deployment mechanism.

Each STANCE in its packaged state is a single hexagonal plate consisting of four spring-loaded layers. When the deployment mechanism is triggered, three of the layers (the helical antennas) will unfold sequentially from a central hexagon. A communications tower will deploy from the center and establish a communications link. Cavity walls for each helical antenna will unfold “accordion-style” similar to solar panel deployment on ISS. Finally, the helical antennas will deploy to full extension by means of truss structures.

While optimal path planning will be used for actual deployment, current estimates for concentric circle and logarithmic spiral deployment indicate that on the order of a thousand STANCEs can be placed by an ATHLETE within a lunar day.

Figure 7. STANCE Packaging

4.3 **Operations Concept**

In both concepts, the array would be operated remotely from a lunar base or Earth, and data would be partially processed *in situ* before transmission to Earth. Observations would be conducted only during lunar night, to avoid solar interference. The correlated data would be returned to Earth, probably through a communications satellite, where processing and analysis will proceed using methods already in use (or being developed today) for ground-based arrays.
4.4 Technology Development

The program for the 2010-2020 decade is one of technology development and precursor missions in preparation for a mission in the 2020-2030 decade. Table 3 summarizes key technologies that have to be developed, heritage, trade studies, and potential synergies with other Government agencies. These technologies include low-mass science antennas, ultra-low power electronics, rovers, power generation and storage, and high data-rate lunar surface communications that can survive the punishing lunar environment.

4.5 Developing the Theoretical Tools

Much of the existing work on the thermal and ionization state of the IGM focusses on the EoR, at the end of the Dark Ages. The goal for the LRA is to probe deeper in redshift, so simulations and modeling are required in order to develop quantitative predictions for the HI signal in the pre-EoR era (z > 15) and to quantify the cosmological and astrophysical return from the LRA.

The Dark Ages requires treatment of two radiative processes in addition to the ionizing photons essential to the EoR: soft-UV photons, which couple the spin and kinetic temperatures of the gas, and X-rays, which heat the IGM. Both backgrounds exert important feedback—soft-UV photons (11.26–13.6 eV) dissociate H₂, the major coolant in the proto-galaxies where the first stars form, while X-rays produce free electrons and catalyze the formation of H₂, but they also heat the gas and prevent the formation of small galaxies. These radiation fields, and their effects on feedback and the HI field, must be modeled self-consistently. A combination of analytic, numeric, and “semi-numeric” approaches—in which galaxies are identified approximately in numerical realizations of large cosmological volumes through simple analytic tools—must be developed.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Requirement</th>
<th>Current State</th>
<th>Required (~ 2020)</th>
<th>Heritage</th>
<th>Synergies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency, wide bandwidth, low-mass</td>
<td>• ~ 20 – 150 MHz</td>
<td>DALI: proof-of-concept film</td>
<td>Prototype</td>
<td>Ground-based radio</td>
<td>NASA heliophysics missions</td>
</tr>
<tr>
<td>science antennas</td>
<td>• Easy deployment</td>
<td>antenna LARC: helical antenna concept</td>
<td>Deployment demonstration</td>
<td>astronomical arrays</td>
<td>NASA missions, DoD,</td>
</tr>
<tr>
<td></td>
<td>• Minimal mass, volume</td>
<td>design</td>
<td></td>
<td></td>
<td>commercial</td>
</tr>
<tr>
<td>Ultra-low power, ultra-low noise, radiation</td>
<td>• Low power budgets</td>
<td>• 130 nm process</td>
<td>• Prototype</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tolerant digital and analog electronics</td>
<td>• Analog amplifiers and ADCs</td>
<td>• ~ 1.3 V supply</td>
<td>• Deployment demonstration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Digital components</td>
<td>• Primary focus on digital</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Operate / survive lunar thermal extremes</td>
<td>• Limited temp. range</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Key LRA Technology Development
<table>
<thead>
<tr>
<th>Batteries:</th>
<th>RPUs:</th>
<th>Power beaming:</th>
<th>NASA micro-sat missions, small lunar payloads, commercial micro-sats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Li-ion ~3 kg/W for 300 hr; must charge at 270 K &lt; T &lt; 310 K</td>
<td>Available for &gt; 10 W or &lt; 10 mW</td>
<td>Terrestrial system studies</td>
<td>Multiple deep-space missions</td>
</tr>
<tr>
<td>&lt; 1 kg/W</td>
<td>~ 100 mW units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady 0.1 W for 300 hr at 100 K</td>
<td>Sufficient Pu-238?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge &gt; 310 K</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.6 Roadmap and Precursor Missions

Many ground-based radio arrays have been preceded by prototypes having a smaller number of antennas, but which were scientifically productive themselves, and scientific observations began with many of the ground-based arrays well before they reached their final complement of antennas.

A strawman illustration of the staged deployment of lunar radio interferometers follows. We do not discuss ground-based arrays here, but they provide important scientific pathfinding. Also, we illustrate a potential prime science mission, but each stage also could be used as a technological demonstrator.

**Stage 1:** One dipole (or a few) deployed on the near side or on a lunar orbiter. Key science would be searching for the global signature from the Epoch of the First Stars or probing the lunar ionosphere. A single dipole on the lunar surface could be deployed in a sortie scenario; an
example would be the Lunar Array Precursor Station (LAPS), a concept developed under the Lunar Sortie Science Opportunities (LSSO) program. A lunar orbiter could include a single dipole as part of the science payload.

**Stage II:** A small interferometer located on the near side. Key science would include particle acceleration in the inner heliosphere, and possibly in astrophysical sources. A target number of antennas is 100, which could be deployed in a sortie scenario. Deployment could be done either robotically or with astronaut assistance; an example would be the Radio Observatory for Lunar Sortie Science (ROLSS), a concept developed under the LSSO program.

**Stage III:** A modest-sized interferometer, possibly located on the far side of the Moon. Such an interferometer would be capable of verifying ground-based observations of the Epoch of Reionization and potentially capable of detecting the magnetospheric emission from brightest extrasolar planets. A target number of antennas is $10^3$. Deployment would be largely robotic, though possibly with astronaut oversight.

**Stage IV:** A fully capable interferometer located on the far side. Such an instrument would be capable of imaging tomography at least of the Epoch of Reionization and ideally deep into the Dark Ages. A target number of antennas is $10^4$, with deployment conducted robotically.

## 5 Management Approach

We describe activities outside of the ASMCS program. *These activities are, in and of themselves, insufficient to mature any of the LRA-specific technologies.*

### 5.1 Organization

Science and technology development for the Lunar Radio Array are currently being conducted in the Lunar University Network for Astrophysics Research (LUNAR), one of the inaugural seven teams in the recently instituted NASA Lunar Science Institute (NLSI). LUNAR consists of 19 institutions, including universities, NASA Centers, Federal laboratories, and the National Radio Astronomy Observatory (PI: J. Burns; Figure 8). LUNAR work will begin in the second half of FY09 and continue for 4 years. A key project in the LUNAR work is Low Frequency Astrophysics & Cosmology, involving

1. Development and refinement of theoretical tools for predicting and analyzing H I signals from the Dark Ages and Epoch of Reionization;
2. Array concept and algorithm development to test configurations and data analysis on existing data sets;
3. Science antenna technology development, including development and deployment of proof-of-concept antennas and stations.

The Low Frequency Cosmology & Astrophysics work within the LUNAR team in turn builds upon three design studies conducted over the past three years:

- **Radio Observatory for Lunar Sortie Science** (ROLSS; PI: J. Lazio), funded by Lunar Sortie Science Opportunities (LSSO) program, ROLSS would be a near-side precursor mission for the LRA.
- **Dark Ages Lunar Interferometer** (PI: J. Lazio), funded by the ASMCS program.
- **Lunar Array for Radio Cosmology** (PI: J. Hewitt), funded by the ASMCS program.
The LUNAR program will provide an intellectual base for future LRA technology development efforts, coordinating individual development projects and hosting regular conferences for exchange of information and presentation of results.

5.2 Activity Schedule

The proposed schedule consists of two components, technology development related to the LRA and the development of precursor missions. We describe both aspects of the program in terms of durations.

5.2.1 LRA Technology Development

A 7–10 year program will be required to mature technologies for the LRA to TRL 6.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Duration</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-frequency, wide-bandwidth, low-mass science antennas (unique to LRA)</td>
<td>7 years</td>
<td>Development within LUNAR NLSI team and follow-on; experience from ground-based antenna development (e.g., LWA)</td>
</tr>
<tr>
<td>Ultra-low power, radiation-tolerant digital and analog electronics</td>
<td>7 years</td>
<td>Experience from NASA ST5 flight, GeoSTAR program</td>
</tr>
<tr>
<td>Autonomous low-power generation</td>
<td>5–7 years</td>
<td>“Enabling Exploration with Small Radioisotope Power Systems” (JPL Pub 04-10)</td>
</tr>
<tr>
<td>Low-mass, high-capability, autonomous rovers (DALI concept)</td>
<td>7–10 years</td>
<td>Experience from JPL Rover group</td>
</tr>
<tr>
<td>High data rate, lunar surface data transport</td>
<td>7 years</td>
<td>Proposed data link development for Mars rovers</td>
</tr>
</tbody>
</table>

Technology relevant to the LRA consists both of technologies specific to the LRA (e.g., low-mass science antennas) as well as technology relevant more broadly (e.g., ultra-low power digital
electronics). Table 4 illustrates the development time scales required to bring technologies such as these to a TRL sufficient for the LRA. In some cases, more rapid advance may be possible because of the broad applicability of the technology.

**Low-frequency, wide-bandwidth, low-mass science antennas:** One low-mass science antenna concept (polyimide-film based dipoles) has already been tested in the field (at NASA/GSFC) under the Astrophysics Strategic Mission Concept Studies program. Work by the LUNAR NLSI team budgets a 4-year development and test program (starting in mid-FY09), including electromagnetic simulations, field testing, and thermal-vac chamber testing. We estimate that an additional 3 years of test and development will be required. This time scale is also comparable to that for the development of a new, broadband antenna for the ground-based Long Wavelength Array.

**Ultra-low power, radiation tolerant digital and analog electronics:** Ultra-low power electronics have flown on the NASA ST5 spacecraft and have been developed for the GeoSTAR\(^6\) correlator. The development program for these electronics was approximately 10 years. Although there is significant experience with this technology, the LRA will likely require different digital components, and less attention is being paid to analog electronics. We allot a similar duration for the development and test of other digital components.

**Autonomous low-power generation:** As an illustration of the development of new sub-Watt power sources, the development program for a sub-Watt radioisotope power system for a Scout-class mission was estimated to be 5 years in duration (“Enabling Exploration with Small Radioisotope Power Systems,” JPL Pub 04-10). We allot somewhat longer to allow for lunar surface considerations.

**Low-mass, high-capability, autonomous rovers:** Rover concepts have been developed under the Astrophysics Strategic Mission Concept Studies program, and JPL has the ATHLETE rover program in development currently. We estimate a development program of approximately 7–10 years to refine mass estimates for a rover, develop a proof-of-concept, verify its capability, and construct a prototype.

**High data rate, lunar surface data transport:** We use the development of an optical communication system based on a laser and modulated retroreflector as an example of a potential surface data transport technology, without necessarily asserting that the final LRA surface data transport would be laser optical communication. NRL and JPL have already demonstrated the use of laser optical communication in the field. Further development to TRL 6 for a Martian mission was proposed in a 4-year program. Allowing for initial trade studies to determine the best lunar surface data transport (laser optical vs. RF wireless vs. fiber optic) and additional development for higher data rates, we estimate a 7-year program would be required.

### 5.2.2 Precursor Missions

As described above, there are various precursor missions that could conduct scientific pathfinding for the LRA, serve as technology test beds, or both. We illustrate a precursor mission consisting of a single dipole to a lunar orbiter with the dual science goals of searching for the H I absorption feature due to the first stars at a redshift \(z \sim 15\) and characterizing the far-side radio environment (Table 5).

---

\(^6\) A microwave radiometer for Earth remote sensing.
Table 5. Illustrative Schedule for LRA Precursor Mission

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>3 months</td>
</tr>
<tr>
<td>Phase B</td>
<td>6 months</td>
</tr>
<tr>
<td>Phase C/D</td>
<td>20 months</td>
</tr>
<tr>
<td>Phase E</td>
<td>6 months</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35 months</strong></td>
</tr>
</tbody>
</table>

This schedule is given in durations because it is sufficiently short that such a mission could be flown either stand-alone (e.g., SMEX) or as part of a larger mission. The schedule itself was developed as part of a proposal for such an instrument on the Lunar Atmosphere and Dust Environment Explorer (LADEE). A longer schedule would be required if significant technology development was desired as part of the mission (e.g., the incorporation of ultra-low power electronics).

6 Cost Estimates

We describe cost estimates for a technology development program specific to the LRA (Table 6). We emphasize that in many cases the total program related to developing the technologies will be much larger than what we describe here, as many of these technologies have broader applicability than just the LRA, but we focus on the aspects specifically relevant to the LRA. Further, in some cases, the technology readiness level (TRL) of some sub-systems is high, but aspects relevant to the LRA make the effective sub-system TRL low.

Table 6. LRA Technology Development Program Costs

<table>
<thead>
<tr>
<th>Technology Component</th>
<th>Program Cost ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low frequency, wide-bandwidth, low-mass science antennas</td>
<td>3</td>
</tr>
<tr>
<td>Ultra-low power, radiation tolerant digital &amp; analog electronics</td>
<td>7</td>
</tr>
<tr>
<td>Distributed low-power generation</td>
<td>25</td>
</tr>
<tr>
<td>Low mass, high-capability, autonomous rovers (DALI concept)</td>
<td>5</td>
</tr>
<tr>
<td>High data rate, lunar surface data transport</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>43</strong></td>
</tr>
</tbody>
</table>

Low frequency, wide-bandwidth, low-mass science antennas: Our estimate of a $3M program is based on, but larger than, on the development programs for ground-based antennas. The LWA, MWA, and PAPER have all developed antennas that operate at frequencies below 250 MHz with frequency dynamic ranges of approximately 3:1. While the frequency coverage of these antennas is similar to what is envisioned for the LRA, mass has not been a significant design constraint for the ground-based antennas, the electromagnetic properties of the lunar regolith are different than that of terrestrial soil, and the lunar environment is far more harsh than the terrestrial. The combination of understanding the electromagnetic properties of the LRA antenna over the required bandwidth along with developing the mechanical and thermal
properties of it will require a greater effort than was required for the ground-based programs.

**Ultra-low power, radiation tolerant digital and analog electronics:** Our estimate of a $7M program is based on the experience from development of the GeoSTAR correlator and largely represents a *marginal* cost for the digital electronics development specific to the LRA; for reference, the first ultra-low power digital processor on the NASA ST5 spacecraft was developed for $2M. A variety of agencies (NASA, DARPA, NRO) have funded and are funding ultra-low power digital electronic development. We assume that this funding continues, at a rate consistent with previous experience, namely $2–3M per year. The current digital ultra-low power roadmap indicates that a 12 nm process will be reached on the relevant time frame. Development of LRA-specific digital could then build upon this work. We assume a level of effort for analog electronic development comparable to the development of the initial ultra-low power digital electronics.

**Autonomous low-power generation:** Our estimate of a $25M program is based on the experience of developing multi-mission radioisotope thermal generators (MMRTGs), such as that deployed on the Mars Science Laboratory (MSL). That particular power generator produces far more power than appears to be required for LRA interferometer elements, based on our current estimates. In general, the development of smaller RTG units is not necessarily cheaper. However, if an RTG or radioisotope heater unit (RHU) approach is optimal, there may be existing designs (~ 10 mW) that could be used as the starting point for the 0.1–1 W anticipated for the interferometer units. Power generation for the correlator will require engineering development, but available options for power generation appear to be sufficient to provide the required power for the correlator.

**Low mass, high-capability, autonomous rovers:** Our estimate of a $5M program is based on comparable experience from developing planetary rovers. Lunar rovers will have many of the same requirements as planetary rovers, and we expect that it will be possible to build upon developments in autonomous rover navigation and self-intelligence. Development work would aim to demonstrate a full station deployment sequence, including all mechanical, electrical, and optical connections, using only on-board autonomous rover control.

**High data rate, lunar surface data transport:** Our estimate of a $3M program is based on a proposed NRL-JPL effort to develop and demonstrate a free-space laser communication system for a Mars rover and upon NASA/ESMD assessments of a technology development program for high data rate lunar surface data transport. NRL has had an applied research (6.2) program in which a free-space laser communication system has been demonstrated, with data rates of order 10 Mbps. The proposed NRL-JPL effort was to advance this system to a TRL of 6. Additional funding is required in order to conduct trade studies to determine whether free-space laser, radio wireless, or fiber optic is the optimum intra-array communication method.

## 7 Technology Development

Sections 3.4 and 4.2.1 summarize a range of technology developments for the LRA. Much of that can either build upon work from, or has synergies with, other activities. However, one significant aspect of the LRA is unlikely to advance without a concerted effort by the astronomy community.

### 7.1 Low-frequency, wide-bandwidth, low-mass science antennas

The anticipated H I signals are extremely weak, requiring a sizeable collecting area to overcome
random noise. In addition, the instrument must have sufficient spatial resolution to localize foreground sources for extraction from the data while simultaneously maintaining a reasonable field-of-view. A large number of interconnected antennas spread over a distance of at least a few kilometers will be needed. Therefore, the mass of the collecting area per unit sensitivity becomes a critical design parameter. For instance, from the ASMCS review of the DALI concept, “The system mass [is] highly dependent on the development of [the antenna concept].”

Low-frequency radio astronomical detectors have a long history, as many of the first radio astronomy pathfinder instruments (§2.1) focus on the expected HI signal from \( z = 6 \) (\( \nu = 200 \) MHz), but both the LWA and LOFAR have antennas that operate to \( \nu = 20 \) MHz \((z \sim 70)\), though neither would have the sensitivity to detect the expected HI signal. Figure 9 shows a prototype LWA antenna, for operation in the frequency range \( \nu = 20–80 \) MHz \((70 < z < 20)\). The final antenna design has manufacturability as a criterion, but it will not be significantly smaller. Its mass is lower, but remains unacceptably high for a space mission, and the LWA antennas need to tolerate only modest changes in temperature. The antenna designs for all of the other ground-based telescopes suffer similar shortcomings with respect to operation in the lunar environment.

The current antenna concepts for LRA are very different, and each needs extensive further development.

**DALI-type antennas:** Dipole antennas and transmission lines are deposited on thin sheets of Kapton (or similar material), which are delivered in rolls of 100+ antennas per roll and are deployed by unrolling on the lunar surface. Development is needed on the manufacturing, handling, and deployment of the metal-on-film antennas; the properties of transmission lines deposited on the film; and whether an entirely passive antenna suffices or if amplification at the antenna is needed.

**LARC-type antennas:** Three helical antennas, grouped in autonomous units called STANCEs, are delivered in foldable, flat packages and erected using ultra-lightweight trusses. Development is needed in the electromagnetic performance of the antennas, in the design of a lightweight structure, and in correlator design.

Figure 9. A prototype Long Wavelength Array antenna. This antenna is sensitive to the frequencies relevant for probing the Dark Ages. The final antenna design has manufacturability as a criterion in its design, and will be somewhat lower in mass, but remain too massive for a lunar mission. In the background are the antennas of the Long Wavelength Demonstrator Array.
8 References

Alexander, J. K., & Kaiser, M. L. 1976, JGR, 81, 5948

The work described in this report was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.
Appendix

Over the course of the ASMCS work, a number of memos on more detailed technical aspects of the design were written. In some cases, the results of these memos influenced the conclusions of the study, so that the content of these memos is dated with respect to the final study report. Nonetheless, for completeness, we include these here in their entirety. Some of these sections refer to the Radio Observatory for Lunar Sortie Science (ROLSS), a concept developed under the Lunar Sortie Science Opportunity (LSSO) program.
**DALI Report: Ultra-Low Power Electronics**

Gary Maki and Sterling Whitaker (CAMBR, University of Idaho)

**Current State-of-the-Art**

Commercial fabrication processes have been following Moore’s Law and enabling considerable processing enhancements over the years. Shown in Table 1 are relative advantages from 350 nm to 45 nm in commercial electronics.

<table>
<thead>
<tr>
<th>Process nm</th>
<th>Vdd</th>
<th>Density</th>
<th>Speed</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>3.5</td>
<td>1</td>
<td>75 MHz</td>
<td>1</td>
</tr>
<tr>
<td>250</td>
<td>2.5</td>
<td>2.0</td>
<td>125 MHz</td>
<td>1.96</td>
</tr>
<tr>
<td>180</td>
<td>1.8</td>
<td>3.8</td>
<td>250 MHz</td>
<td>3.78</td>
</tr>
<tr>
<td>130</td>
<td>1.3</td>
<td>7.2</td>
<td>500 MHz</td>
<td>7.25</td>
</tr>
<tr>
<td>90</td>
<td>1.0</td>
<td>15.1</td>
<td>1 GHz</td>
<td>12.25</td>
</tr>
<tr>
<td>65</td>
<td>1.0</td>
<td>29.0</td>
<td>2 GHz</td>
<td>12.25</td>
</tr>
<tr>
<td>45</td>
<td>1.0</td>
<td>60.5</td>
<td>5 GHz</td>
<td>12.25</td>
</tr>
</tbody>
</table>

From Table 1, the density (number of transistors per unit area) increases by a factor of 60 from the 350 nm to 45 nm process nodes. This effectively enables 60 times the logic to be incorporated on a die of the same size. The speed also is greatly improved, but not a major consideration in the DALI program. The power factor is also greatly improved. From this table, one can either increase the speed (clock) on a given amount of circuitry by a factor of 12.25 or increase the amount of circuitry by 12.25 and operate at the same speed and keep the power at the same level. Therefore, the commercial fabrication migration has allowed significant improvements in capability.

The current radiation hard electronics has designs being created at the 90 nm node with some very preliminary activity at the 45 nm node. The 90 nm electronics is fabricated at IBM with the following expected radiation results:

- No latch up at LET < 100
- SEU requirement LET = 15 (goal = 20)
- Speed approximately 250 MHz
The latch up results are fine, however the SEU tolerance is only 50% of the current standard levels. It is not clear how flight programs are going to integrate electronics with only half of the radiation tolerance required for flight programs. In addition, the clocking speed is limited in current Radiation Hard By Design (RHBD) technologies to somewhere near 250 MHz. Since DALI will operate near the 200 MHz rate, current RHBD technologies are adequate. The primary value for DALI is density to achieve as many correlators per chip as possible.

The current processing nodes being used for new radiation tolerant designs range from 0.25 microns to 90 nm. Progress is just starting at the 90 nm node, and as noted above, there still are serious unresolved issues. However, it is the author’s belief that a solution to these problems is forth coming. Current new designs are being implemented and manufactured at the 0.25 micron node with a good history of success in radiation testing, performance (power and speed), and reliability. However, the requirements of DALI will require utilization of a process below the 90 nm node, most likely the 23 nm or 12 nm nodes. The best commercial process today is 45 nm and the 23 nm node is likely in 18 months. It is not clear when the 12 nm node will be available, but it is reasonable that it will be ready when the DALI design is required.

Low Power Operation

From Table 1, significant power reductions by a factor greater than 10 are achieved in migrating to smaller feature sizes. However, current process technology does not allow the supply voltage to drop much below 1.0 V.

Ultra low power technology can be important in the DALI electronics, given the desire to perform operations during the lunar night. The only known ultra low power electronics known to achieve both low power and reasonable performance (speed) is CULPRiT (CMOS Ultra Low Power Radiation Tolerant), a program created by NASA and the NRO. The key element in reducing total power is lowering the supply voltage; power decreases as the square of the ratio of supply voltages when comparing two processes. CULPRiT utilized a 0.35 micron CMOS process at AMIS and successfully produced flight electronics flown on ST-5. The power savings was reported in the ranges of 40X to 100X. DARPA is funding another CULPRiT type activity with CAMBR to demonstrate ultra low power operation at the 130 nm SOI node with American Semiconductor. The program has just begun and initial results are encouraging. However, the 130 nm processing node will not meet DALI needs due to density. The key element in a future CULPRiT program is access to a foundry which will allow process changes to achieve CULPRiT performance. The CULPRiT paradigm is unique and opposite from the traditional foundry philosophy to produce low power. The typical approach to low power is to reduce leakage current as much as possible. However, this approach ignores the primary source of power in modern chips, namely dynamic power, not static power. Reducing leakage current does nothing to dynamic power. If one takes a typical process and attempts to reduce static power, which is fine for high voltage operation, but then reduces the supply voltage, the result is a disaster in terms of speed.

The data shown next illustrates the power/speed issue. The American Semiconductor 130 nm AS130FF process was designed to minimize static power (leakage current) and hence represents the traditional means to produce low power circuits. Initial SPICE
models have been created and used to produce the following power and time delay estimates. The 0.35 µm bulk CMOS CULPRiT and 130 nm SOI Flexfet AS130FF processes are compared. The simulation circuit consists of 280K minimum sized transistors operating at 28 MHz with 100% activity at various supply voltages. The chart in Figure 1 shows power for the AS130FF 130 nm process as a function of supply voltage. Notice that the power levels drop as a function of supply voltage, but the power is dominated by dynamic power.

![AS130FF Power vs Vdd](image)

**Figure 1: AS130FF Power vs Vdd**

Figure 2 shows the same circuit simulation for the 0.35 µm bulk CMOS CULPRiT process under the same conditions. By modifying the back gate voltage, the effective threshold voltage of the channel can be modified. Thus, the performance of the device can be enhanced by lowering $V_t$ at the cost of increasing leakage. Of course, if the device’s performance can be enhanced then the power supply voltage can be decreased while maintaining the frequency. So the performance gain garnered by lowering $V_t$ is balanced with the performance loss caused by lowering the supply voltage. This decreases dynamic power, which is a strong function of power supply voltage, while increasing static (or leakage) power. Careful balancing of these two can lead to dramatic overall power savings by finding the optimal operation point. Note that the static power grows as a percentage of total power as the supply voltage is reduced.
From Figure 3, it appears that AS130FF is superior to CULPRiT. But this is only half the story. Figure 4 shows a comparison between 0.35 μm bulk CMOS CULPRiT and AS130FF in terms of gate delay in ns. When the supply voltage is high (1.3 V), the AS130FF process is faster than CULPRiT (3.14 ns vs. 5.82 ns or 85% faster), again as
should be expected when comparing 0.35µm bulk CMOS to 130 nm SOI. However, at 0.4 V, CULPRiT is faster (12.54 ns vs. 42.71 ns or 240% faster). However, the baseline AS130FF Flexfet process has been optimized for 1.2V operation. While this certainly does qualify as traditional ultra low power process, the native transistor thresholds are still too high and even the enhanced threshold tunability is not enough to operate the baseline AS130FF process in a regimen consistent with the findings of Stanford’s Ultra Low Power (ULP) CMOS Project as implemented in bulk CMOS under the CULPRiT program.

![CULPRiT vs AS130FF](image)

**Figure 4: Speed comparisons**

A true CULPRiT process requires adjustable, near zero threshold voltages. American Semiconductor has begun development of an ultra low power 130 nm Flexfet process, called AS130ULP, specific to meeting the CULPRiT goals for highly active, high performance, ultra low power microcircuits. The initial AS130ULP process has been designed and simulated using Silvaco’s Athena and Atlas programs to generate SPICE models targeted for operation at 0.5 V. Shown in Figure 5 is the total power comparison between CULPRiT, AS130FF, and the projected AS130ULP process at the maximum speed for each process. AS130ULP shows a total power of 29 mW, slightly lower than the 31 mW for CULPRiT and nearly twice as much as the 15 mW for the baseline AS130FF process. However, the most interesting result is in the speed comparison.
Figure 5: Power at Maximum Speed

As shown in Figure 6, at 0.5 V and the selected back gate operating point (non-optimized) AS130ULP is 49% faster than CULPRiT and 141% faster than AS130FF.

Figure 6: Maximum Speed Comparison
Ultra Low Power Roadmap

The key to achieving high density (45nm to 12 nm) CULPRiT technology is gaining access to a commercial foundry partner that is willing to allow one to modify the process to achieve near zero voltage threshold transistors. Such transistors along with CULPRiT design techniques, would enable highly dense CULPRiT circuits to be designed that would be of great interest to DALI type missions. The key is a willing foundry partner. The technology could be created today at the 45 nm process node and would take less than two years to implement, complete with radiation hard circuits and a library that can be used to synthesize custom processors. The amount of funding to establish the first CULPRiT program was only $2,000,000 which resulted in a flight processor for ST-5. CULPRiT at the 45 nm node would cost more, but only due to the fabrication costs. With success at the 45 nm node, CULPRiT technology could follow IBM to smaller feature sizes all the way to the 12 nm node, desirable for DALI. Table 2 summarizes the various technology developments and available expected dates.

Table 2: Technology Development with foundry process

<table>
<thead>
<tr>
<th>Process Node</th>
<th>Commercial</th>
<th>RHBD</th>
<th>ULP</th>
<th>DALI Correlator</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 nm</td>
<td>Now</td>
<td>Low Speed</td>
<td>2010(^1)</td>
<td></td>
</tr>
<tr>
<td>90 nm</td>
<td>Now</td>
<td>Started(^2)</td>
<td>2010(^3)</td>
<td></td>
</tr>
<tr>
<td>65 nm</td>
<td>Now</td>
<td>Skip(^3)</td>
<td>Skip(^4)</td>
<td></td>
</tr>
<tr>
<td>45 nm</td>
<td>Beginning</td>
<td>2011(^5)</td>
<td>2013(^1)</td>
<td>Test Chip 2014</td>
</tr>
<tr>
<td>23 nm</td>
<td>2011</td>
<td>2012(^5)</td>
<td>2013(^1)</td>
<td></td>
</tr>
<tr>
<td>12 nm</td>
<td>2015</td>
<td>2016(^1)</td>
<td>2013(^1)</td>
<td>Chip 2017</td>
</tr>
</tbody>
</table>

Notes:
1. DARPA funded with American Semiconductor
2. RHBD program initiation but results fail to meet current objectives in SEU tolerance and speed
3. Projected DARPA funded effort, a priority to DARPA/MTO
4. This node is being skipped by most government programs with a focus on the 45 nm node instead.
5. Can be solved to achieve commercial density and speed with $2M funding complete with synthesis library; estimate does not include fabrication costs.

Correlator Calculations

Assumptions

- 10 signals per station
- 8 bit data
- 300 stations
- 200 MHz data rate
- 64 second sample time
- Beam forming is accomplished by analog means. A digital solution appears to require a very large number of transistors, depending on the accuracy required.

The number of signals for cross correlation is 10 x 300 = 3000. The number of cross correlations is 3000 x 2999/2 ~ 4.5 million.
Accumulator length per correlator = 200 MHz x 64 seconds = 1.28 x 10^{10} samples. Each sample of 8-bits multiplied by another 8-bit sample can result in a 16 bit result; if so 2^{16} x 12.8 x 2^{30} \approx 2^{50}, or a 50 bit register is needed.

An existing design in the 90 nm process has approximately 10K correlators in a custom design in an area of 20 mm^2, which represents a chip with 4.5 mm on a side. Shown in Figure 5 is the layout of 289 correlators in the IBM 90 nm process that operates at 1 GHz. The following table scales correlator area over the process geometries:

<table>
<thead>
<tr>
<th>Process Node</th>
<th>Area per 10K correlators</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 nm</td>
<td>20 mm^2</td>
</tr>
<tr>
<td>65 nm</td>
<td>10 mm^2</td>
</tr>
<tr>
<td>45 nm</td>
<td>5 mm^2</td>
</tr>
<tr>
<td>23 nm</td>
<td>2.5 mm^2</td>
</tr>
<tr>
<td>12 nm</td>
<td>1.25 mm^2</td>
</tr>
</tbody>
</table>

The 23 nm process is under development today. Using the 23 nm process node, 8 times the number of correlators can be placed on an equivalent area as the current 90 nm design, or 80,000 correlators per 20 mm^2 chip. The total number of 20 mm^2 chips needed for 4.5M correlators = 4.5M/80K \approx 57 chips. For the 12 nm process, approximately 29 20 mm^2 chips are needed.

**I/O Considerations**

The dominant problem in the DALI circuit is the number of I/O signals input to the chip. The number of I/O signals is dominated by the input signals. For a 23 nm design with 3,000 8-bit inputs, the number of I/O’s = 24,000 signal lines. If one uses existing flat package technology with 50 um pad spacing (current spacing is 70 um), the total pad length would (24 x 10^3) x (50 x 10^{-6}) meters = 1.2 meters or a package 300 mm on a side. (Note, modern foundries process 300 mm wafers.) Using a bump grid array with a 50 um
pitch (today’s pitch is 60 um), the area per 100 pads is $25 \times 10^{-8} \text{um}^2$. For 24K signal lines, the area is $(24 \times 10^3)/100 \times (25 \times 10^{-8}) = 6,000 \times 10^{-6} \text{ sq meters}$ or a chip with 77 mm on a side. There is little room for circuitry in this configuration hence this is not a solution even if a 77 mm chip could be manufacturable. If the bump grid array had a 10 um pitch, then the area for 24K signal lines is $(24 \times 10^3)/100 \times (1 \times 10^{-8}) = 2.4 \times 10^{-6} \text{ um}^2$ or a chip with 1.55 mm on a side. A layout challenge is needed to partition circuitry and the I/O pads, which also have active devices. Circuitry and I/O need to be partitioned on the die surface which may be possible in a 12 nm process. Clearly packaging technology needs to advance beyond the current technology to achieve this result. However, a new emphasis exists today in the research area of nano package technology, therefore it is reasonable to expect such breakthroughs in the near future.

It is unlikely event that nano package technology will solve the problem of interfacing 3000 pins on a single chip. It is envisioned that a custom design be implemented, taking care to integrate the I/O package requirements with the design if a bump grid array is utilized. The circuitry must be partitioned among the I/O. It is likely a custom design is implemented with sets of I/O devoted to each correlation function. Another unique challenge within the chip is the means to pass all the signals to be correlated to all the correlators in an area efficient manner. One possible design has all input signal registers (8-bits) configured as a large shift register with 3000 8-bit data words passed between correlators. A similar output structure can be configured to output the final 34 bit values with one output port needed.

The following expands on the notion to buffer the 3000 input signals. There is design which balance the number of pins and the amount of circuitry that can be placed on the chip. If there are $N$ signal pins per chip, then the number of chips needed to meet the input constraints alone are $3000 \times 8/N$. If $N = 800$, then 30 chips are needed. Let $3000 \times 8/N = C$, $C$ is the number of chips. With $N = 800$, 100 8-bit inputs can be presented to a chip at any one time. A system level solution would store $N/8$ samples on each chip to perform correlation with this data, and provide a means to shift the internal data from each chip to the other chips such that all the data is shifted among the $C$ chips during the 64 second sample time. With this scenario, each chip would have the means to store $N/8$ samples in an internal buffer. At least two such internal buffers are needed, one to store a set of $N$ values which are used for cross correlation of all samples, and the second buffer to store the shifted versions that are passed among the chips.

The bump grid array has issues that must be considered in a flight program. One desires to visually inspect each connection, which would be difficult with today’s technology. If it is impossible to achieve such a high pin count package, then it might be necessary to design a buffer between the stations and correlator where signals are input sequentially. This requires more hardware to store the data. More time is also needed to perform the correlation.

### Power Calculations

The correlator core shown in Figure 5 modified for an 8-bit input signal would consume 500 microwatts per correlator when operating at 200 MHz. For 4.5 million correlators, the total power in the 90 nm process would be $500 \times 10^{-6} \times 4.5 \times 10^6 = 2250 \text{ W}$. Table 4 shows power scaling for 4.5 million correlator over the various processes and ultra low
power processes. There is significant power scaling in the transition between commercial 90 nm and 65 nm due to voltage scaling. However, the only scaling between 65 nm to 12 nm is assumed due to a reduction in capacitance; a 10% power reduction between process nodes is assumed. ULP power reduction is due to voltage scaling and two ULP processes are shown, namely a 0.5 volt supply and a 0.25 volt supply. At the 12 nm node, a 0.10 volt ULP process is assumed. The power shown in Table 4 is only internal correlation power consumed and does not account for I/O power or buffer power consumed.

Table 4: Power consumption in watts for 4.5 million DALI correlators @ 200 MHz

<table>
<thead>
<tr>
<th>Process Node</th>
<th>Commercial Process</th>
<th>ULP 0.5 v</th>
<th>ULP 0.25 v</th>
<th>ULP 0.10 v</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 nm</td>
<td>2,250</td>
<td>390</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>65 nm</td>
<td>1,124</td>
<td>280</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>45 nm</td>
<td>1012</td>
<td>254</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>23 nm</td>
<td>912</td>
<td>282</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>12 nm</td>
<td>820</td>
<td>205</td>
<td>51</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Hardware Conclusion
Based on the current work being implemented for GEO STAR IIP at the 90 nm node, and the calculations above, it is possible to realize a DALI correlator at the 23 nm or 12 nm node, however likely only with a custom design. An Field Programmable Gate Array (FPGA) is likely not to be able to realize a correlator function given the fact that an FPGA is about 100 times less dense than a custom design and dissipates many times more power than a custom design. The attractive portion of an FPGA design is that much less time is required to create the high level design and verify functionality with a simulator of a DALI correlator. Partitioning the correlation function among numerous FPGA is a major challenge. Loading the desired number of correlators into a FPGA chip is a more significant task if one desires a FPGA high utilization. Realizing the power specification would be the largest challenge for the designer has little control over power consumption.

Table 5 is a summary for an estimated number of chips and power per chip required to meet the DALI correlator needs. The chip size is assumed to be 100 mm² or 10 mm per side, which is not a huge chip. Note that the Table 2 discussion assumed a 20 mm² size chip. The number of chips is calculated from Table 1 data to determine the total area per feature node. The power per chip was derived from power given in Table 2 divided into the number of chips. Table 4 can be used as a guide the final design to balance number of chips, power per chip and number of I/O’s per chip.

Table 5: DALI Correlator chip number and power per chip

<table>
<thead>
<tr>
<th>Process</th>
<th>No. Chips</th>
<th>Pow/chip Commercial</th>
<th>Pow/Chip 0.5 ULP</th>
<th>Pow/Chip 0.25 ULP</th>
<th>Pow/Chip 0.1 ULP</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 nm</td>
<td>90</td>
<td>25 w</td>
<td>4.3 w</td>
<td>1.1 w</td>
<td></td>
</tr>
<tr>
<td>65 nm</td>
<td>45</td>
<td>25 w</td>
<td>6.2 w</td>
<td>1.6 w</td>
<td></td>
</tr>
<tr>
<td>45 nm</td>
<td>23</td>
<td>45 w</td>
<td>11.2 w</td>
<td>2.8 w</td>
<td></td>
</tr>
<tr>
<td>23 nm</td>
<td>12</td>
<td>81 w</td>
<td>20.2 w</td>
<td>5.1 w</td>
<td></td>
</tr>
<tr>
<td>12 nm</td>
<td>6</td>
<td>146 w</td>
<td>36.4 w</td>
<td>9.1 w</td>
<td>1.46 w</td>
</tr>
</tbody>
</table>
It is proposed that the data path be radiation protected only against latchup and not SEUs. However, the control should be protected for all radiation effects.

The bump grid array has issues that must be considered in a flight program. One desires to visually inspect each connection, which would be difficult with today’s technology. If it is impossible to achieve such a high pin count package, then it might be necessary to design a buffer between the stations and correlator where signals are input sequentially. This requires more hardware to store the data. More time is also needed to perform the correlation.

**Estimated Cost**

Shown in Figure 6 is a depiction of the technology costs for various programs needed to support the DALI program; technology programs will support the entire space electronics program also.

The ULP development program seems to be a priority to DARPA/MTO, which is currently funding an 130 nm ULP effort. NASA, NRO and DTRA have funded Radiation Hard By Design (RHBD) efforts over the years. Not included are fabrication costs (at least $1,000,000) but could be different if DALI can partner with other government agencies and submit fabrication under the TAPO program for example. Packaging cost is very difficult to estimate since such packages are not available yet.

![Figure 6: Technology Development Funding Estimate.](image-url)
**DALI Array Deployment Considerations**

Dayton Jones (JPL)

A low-frequency radio array needs to have a large number of individual antennas to provide an appropriate combination of sensitivity, angular resolution, and image dynamic range. Consequently, the process of deploying antennas over an extended area is not a viable job for astronauts; a number of autonomous rovers will need to carry out this task in parallel if it is to be completed in a reasonable amount of time. Fortunately, rover technology is advancing rapidly, especially in mobility over difficult terrain, high dexterity manipulation, and on-board intelligence. We can leverage much of this work for lunar applications. Nevertheless, the harsh lunar surface environment and the critical need to minimize the ratio of rover mass to deployed array mass will require focused rover technology development.

A primary requirement for rovers intended for lunar array antenna or station deployment is low mass, because a large number of deployment rovers may be needed. For a given payload mass (antennas, electronics, receivers, etc., for the array), the rover must be as small a fraction of the payload mass as possible. We will take full advantage of the low lunar gravity, but nevertheless careful attention to the rover mechanical and power systems will be necessary. In particular, we need to investigate the optimal combination of solar arrays and on-board batteries for rover power, and the minimum required manipulation capability for deployment of array elements. The question of whether each rover should continue to serve as a central electronics and data relay site for multiple array antennas, or should be designed to function only through the deployment stage, is an important system-level trade that will affect the scale of electronics located at each antenna. A similar high-level trade is the number of separate array stations that may be deployed by an individual rover, and the impact of this on rover speed, total distance, and reliability.

The basic requirements on an array deployment rover are:

- Transport an array station (multiple antennas, an electronics/data relay box, solar cell array, and battery) from the lunar lander to a site up to 10(? km away, during a lunar day
- Navigate autonomously to pre-selected station site
- Verify suitability of site (surface smoothness, lack of large obstacles) and adjust station location is necessary
- Mechanically deploy station antennas
- Electrically connect antennas (and solar array) to station electronics box
- Deploy mast for data transmission to lander
- Return to lander if necessary and repeat deployment process for other stations
- Survive lunar night if array deployment takes multiple lunar days to complete
Based on these general requirements, and the existing state of the art for planetary rovers, the following areas will require technology development funding to enable rovers capable of deploying a large low-frequency radio array on the far side of the Moon:

A. High specific capacity batteries able to operate at +125 C and survive -200 C
B. Rover mechanical systems that can survive lunar night without active heaters
C. Increased rover traverse speeds under autonomous navigation
D. High dexterity manipulation of RF and power connectors
E. Significant increase in payload/rover mass ratio

The first of these technology areas is obviously of direct benefit to many potential lunar-based instruments and facilities. However, the deployment rovers and array stations differ from most other applications in that they cannot afford the mass penalty associated with continuous thermal control of a significant battery mass.

The following illustrates a potential deployment sequence.
LARC/DALI/ROLSS Thermal Issues

Pam Clark (NASA/GSFC)

Based on our experience in the development of concepts and participation in integration exercises for the lunar surface instrument packages (Clark et al, 2009), thermal issues are a principal driver of mass and power requirements when conventional design approaches are used. The use of lightweight multiple thin fiberglas layers combined with a gravity siphon heat pipe for connecting the radiator system (placement varying as a function of latitude) during the day, battery placement in the interior, low temperature operating components, and a limited duty cycle (in lieu of active heating) during the long, cold lunar night helped to reduce such requirements (mass) by a factor of 5 (from 500 to 100 kg) in the case of our study of an environmental monitoring package deployed near the lunar poles where darkness was limited to up to one week approximately once a year. We anticipate that with the use of Ultra Low Temperature/Ultra Low Power components (electronics, power supplies, sensor heads) we will be able to deploy a similar size package anywhere on the Moon experiencing a normal diurnal cycle. The incorporation of a more efficient and flexible solar film technology and distributed power are also under consideration.
On the other hand, astrophysics observatory packages, in this case DALI, LARC, and ROLSS, present special challenges not present in in-situ lunar surface instrument packages, including greater data rates independent of diurnal cycle which drive power requirements, particularly during periods of dark, either as a result of the greater need for processing in place or more frequent or higher bandwidth communication. In fact, the need for development of more efficient antennas and ULT/ULP components in receivers, CPU, and correlators, and data storage have been identified as areas in need of development, as indicated in the table below (Lazio 2008). Development of such components would all assist in reducing thermal requirements, and thus mass and power for astrophysical observatories. In fact, we are currently studying the potential for using the regolith for thermal control (heat source/sink), via heat pipe technology. Incorporation of ionic liquids, which have appropriate properties (low temperature melting points, liquid over large range, high thermal conductivity) shows some promise in this application, in producing stand-alone thermal support, or even geothermal power, stations which could help to reduce power required for active heating.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Sub-system</th>
<th>Required Technology (baseline)</th>
<th>Required TRL 6 Product</th>
<th>Heritage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rovers</td>
<td>Deployment</td>
<td>Autonomous navigation and antennas deployment up to 30 km from landing site</td>
<td>Lunar-qualified rover</td>
<td>Mars rover, ATHLETE development</td>
<td>Relevance to both human- and robotic lunar exploration; significant JPL rover experience, possible DARPA synergies</td>
</tr>
</tbody>
</table>

Correlator Development

Justin Kasper & Jonathon Weintraub (SAO)

The design of a fieldable correlator for the Murchison Widefield Array (MWA) (Cappallo, 2007; Lonsdale et al., 2009) demonstrates that, for a terrestrial application, construction of a dual polarization wideband correlator for up to 1k stations using current FPGAs is feasible now at moderate cost. The essential parameters of the MWA are at least roughly comparable to DALI. One difference is that DALI will operate in a lower frequency band, 10 to 100 MHz, corresponding to a redshift range $z$ of approximately 15 to 150 and wavelengths about ten times larger than MWA. Another difference is that the moon rotates 30 times slower than the Earth, so the rate at which the projection of physical baselines changes is slower. Critical interferometer parameters such as the fringe rate are a function of a combination of wavelength, lunar or terrestrial rotation, and the maximum physical baseline. These factors tend to cancel, and MWA and DALI do have similar fringe rotation rates.

Other similarities between DALI and MWA include the use of phased arrays of crossed dipoles, and a comparable number of dual polarization stations to be correlated. There are critical additional challenges to making a correlator operate in space. In considering how to modify a terrestrial correlator such as the one for MWA we must also consider issues of radiation hardening low power design, and general operability in space. For example, ground based correlators typically use forced air for cooling, which would not work in vacuum. Hardware for ground operations is not radiation tolerant, either to total damage or single event upsets (SEU) or latching, because components can be replaced and continuous operation is less critical to the health of the instrument. The purpose of this section is to identify general technological aspects of MWA that may carry over to DALI and to comment on space specific additional work.

Radiation Tolerance

In studying how the MWA correlator could serve as a guide for a space-based correlator, it is interesting to note that Xilinx already offers the Virtex 4 line of the FPGAs which are used in the MWA correlator, in a radiation hardened version. While radiation tolerant versions of processors tend to lag the leading edge of capabilities of ground based hardware, it is reasonable to expect other aerospace needs to drive the radiation qualification of the chips needed for a correlator.

Power Consumption

While very capable FPGAs are available in radiation hard formats, power considerations lead us to the conclusion that custom ASICs may be required for a lunar correlator. Based on a survey of the literature, it seems likely that the benefits of ultra low power (ULP) design could better be accessed with an implementation using ASICs. Current state-of-the-art in ultra low power (ULP) ASIC design is 0.5 V 0.35 micron radiation tolerant CMOS (Maki, 2009). A Reed-Solomon encoder design (CULPRiT) has been successfully flown on the NASA ST-5 technology demonstrator mission with minimal radiation induced errors and low power consumption due to lower operating voltages. The correlator for DALI has been estimated as a 400 TFLOP computational load. A 1 kW system, feasible for lunar deployment, would require ULP technology with a computational efficiency of about 2.5 Watt/TFLOP. This should be contrasted
with the current state of art, which suggests that either a great deal of development will need to take place to improve the efficiency of these ASCIs or the correlator must be simplified or more power made available.

Tradeoff studies on the correlator are clearly possible to optimize the design in light of limited computational or power resources. In an FX correlator design the F portion scales as \( m \times N \log m \), where \( N \) is the number of antennas and \( m \) is the number of frequency channels. The corner turn is of size \( N \times m \). The X part scales as \( N^2 \), though for a two-bit correlator the multiplier can be small though dynamic range considerations may require more bits even in the low RFI lunar environment). All portions scale linearly with bandwidth. The above scaling suggest a possible optimization exercise in resource allocation between the linearly cost scaling array elements, and the back end, whose scaling, while not quite \( N^2 \) is scales faster than \( N \).

References
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http://gsfctechnology.gsfc.nasa.gov/CULPRIt.html
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Specifications for a Lunar radio telescope to study cosmic reionization and the Dark Ages

Chris Carilli (NRAO) & Greg Taylor (UNM)

1. Introduction

This document presents initial estimates of telescope design requirements for a Lunar array to study cosmic reionization, and potentially the higher redshift ‘dark ages’. The requirements are derived from the science document of Loeb & Zaldarriaga (2008), with some of the initial numbers drawn from the LARC design study proposal to NASA (Hewitt 2008). This has been supplemented by additional studies by S. Furlanetto.

The document is organized as follows:

A. Introduction
B. Assumptions
C. A table detailing the scientific requirements specifications for a nominal Lunar array to study reionization and the end of the Dark ages, plus a second, more ambitious array that could perform detailed studies of the Dark Ages. In NASA terminology, the former could be considered a ‘spec’, and the latter a ‘goal’.
D. A table with the technical requirements which flow down from the science requirements.
E. Explanatory remarks on each parameter.
F. A list of design trade-offs and coupled parameters.

The current values for the specifications are, at best, rough estimates, and in many cases, just place-holders. These will evolve with time, depending on theoretical and observational understanding of the evolution of the neutral IGM, and depending on technical lessons learned with the current ground-based arrays. Hence, this report should be considered a ‘living document’, of which this is one iteration. We recommend this document eventually be reformatted into a web-based project book that can be edited and refined, as information becomes available, under appropriate change control.

2. Assumptions

The array is assumed to be placed on the far side of the moon, and to have no radio interference (of either solar or human origin) by observing during the long lunar night. The array is assumed to be observing at zenith so that no dimunition of the collecting area occurs by projection. The array is assumed to consist of N roughly circular stations of diameter, D, distributed over a flat surface. The stations are comprised of M dipoles which can be used to form B beams on the sky. These beams are transmitted to a central location, or to the Earth, for correlation. The final product of the array is visibility measurements which can be transformed to create images or analyzed directly. The deployment of the array is assumed to be carried out by one or more rovers.
Location is assumed to be in the vicinity of the lunar equator. This implies a duty cycle of about 50% (no observing possible during the long lunar night), and requires that multiple fields (~10) are available for study.

Not considered yet are using other receiving elements than dipoles. These could have more gain, and possibly give more collecting area/kg.

The array is assumed not to require any maintenance by human intervention. Humans could be remotely involved in the deployment, either from Earth or from a lunar base.

3. Table 1 of Scientific requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal Array</th>
<th>Dark Age Array</th>
<th>Design⁹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redshift range</td>
<td>( z = 30 ) to 8.5</td>
<td>( z = 50 ) to 6</td>
<td></td>
</tr>
<tr>
<td>Dynamic range requirements</td>
<td>( 10^5 ) to ( 10^6 )</td>
<td>( 10^6 ) to ( 10^7 )</td>
<td>Calibration</td>
</tr>
<tr>
<td>Angular Resolution @ 90 MHz</td>
<td>3'</td>
<td>1.4'</td>
<td>Config and redshift</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>10 ms</td>
<td>10 ms</td>
<td>Correlator, Calibration</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>8 MHz</td>
<td>&gt; 8 MHz</td>
<td>Correlator</td>
</tr>
<tr>
<td>Sensitivity in 1000 hr at 90 MHz</td>
<td>2 ( \mu )Jy for 8 MHz bandwidth</td>
<td>0.2 ( \mu )Jy for 8 MHz bandwidth</td>
<td>FE, area, bandwidth</td>
</tr>
<tr>
<td>Brightness sensitivity in 1000 hr at 90 MHz</td>
<td>10 mK</td>
<td>4 mK</td>
<td>resolution, sensitivity</td>
</tr>
<tr>
<td>Polarization</td>
<td>Dual Circular</td>
<td>Dual Circular</td>
<td>Correlation, Calibration, antenna</td>
</tr>
<tr>
<td>Field-of-View (total at one time) @ 90 MHz</td>
<td>11 sq degrees</td>
<td>11 sq degrees</td>
<td>Station diam, No. beams</td>
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</table>

⁹Design implications

4. Table 2 of Technical Requirements

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<th>Parameter</th>
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<th>Design⁹</th>
<th>Type⁰</th>
</tr>
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<td>Frequency range</td>
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<td>30 – 200 MHz (( z = 50 ) to 6)</td>
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<td>D (from redshift range)</td>
</tr>
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<td>Total instantaneous bandwidth</td>
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<td>Full range, 170 MHz</td>
<td>IF transmission, correlator</td>
<td>D (from redshift range)</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
<td>Unit</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Frequency resolution</td>
<td>12.2 kHz (8192 channels)</td>
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<tr>
<td></td>
<td>1 kHz ?? 10.4 kHz (16384 ch)</td>
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<tr>
<td></td>
<td>Correlator, real-time processing, telemetry</td>
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<td></td>
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<tr>
<td></td>
<td>D (from size scale)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Baseline</td>
<td>5 km</td>
<td></td>
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<tr>
<td></td>
<td>10 km</td>
<td></td>
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<tr>
<td></td>
<td>IF transmission</td>
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<tr>
<td></td>
<td>D (from ang resol)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Configuration</td>
<td>Emphasis on short spacings, 2D array</td>
<td></td>
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<tr>
<td></td>
<td>Uniform coverage of ((u,v)) plane, 2D</td>
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<tr>
<td></td>
<td>IF transmission</td>
<td></td>
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<tr>
<td></td>
<td>D (from PS or imaging analysis)</td>
<td></td>
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</tr>
<tr>
<td>Station Diameter</td>
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<tr>
<td></td>
<td>150 m</td>
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<td></td>
<td>Deployment Config</td>
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<tr>
<td></td>
<td>D (from station FoV and sens.)</td>
<td></td>
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</tr>
<tr>
<td>Number of Beams, B</td>
<td>9</td>
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<tr>
<td></td>
<td>9</td>
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<td></td>
<td>Config</td>
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<td></td>
<td>D (from station FOV and sens.)</td>
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<tr>
<td>Antenna elements per station, M</td>
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<td>1500</td>
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<tr>
<td></td>
<td>D (from sensitivity)</td>
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<tr>
<td>Number of stations, N</td>
<td>30</td>
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<tr>
<td></td>
<td>300</td>
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<td>Deployment Config</td>
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<td>D (from sensitivity)</td>
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</tr>
<tr>
<td>Calibration requirements</td>
<td>phase errors &lt; 0.23° to 0.023°</td>
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<td>phase errors &lt; 0.023° to 0.0023°</td>
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<td></td>
<td>Real-time processing</td>
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<tr>
<td></td>
<td>D (from DNR)</td>
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</tr>
<tr>
<td>Allowed RFI level (self generated)</td>
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<tr>
<td></td>
<td>FE</td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration time</td>
<td>&lt; 15 min</td>
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<tr>
<td></td>
<td>&lt; 15 min</td>
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<tr>
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<td>Correlator</td>
<td>D</td>
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<tr>
<td>Receiver Temp</td>
<td>10 dB less than Galactic Noise</td>
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<td></td>
<td>10 dB less than Galactic Noise</td>
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<tr>
<td></td>
<td>D (sens)</td>
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<tr>
<td>Antenna Field of View</td>
<td>30°</td>
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<tr>
<td></td>
<td>45°</td>
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<td></td>
<td>Antenna</td>
<td>D</td>
<td></td>
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<tr>
<td>Dipole Sidelobes</td>
<td>TBD</td>
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<tr>
<td></td>
<td>TBD</td>
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<tr>
<td></td>
<td>D (DNR)</td>
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<tr>
<td>Antenna Gain</td>
<td>G ~ 4 @ 90 MHz</td>
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<td></td>
<td>G ~ 4 @ 90 MHz</td>
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<tr>
<td></td>
<td>Antenna</td>
<td>D</td>
<td></td>
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<tr>
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<td>D (sensitivity)</td>
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<td>Number of bits for Sampling, S</td>
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<tr>
<td></td>
<td>Communication</td>
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<td>D (DNR)</td>
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<td>Lifetime</td>
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<td></td>
<td>20 years</td>
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<td>E</td>
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<td></td>
</tr>
<tr>
<td>Monitor and Control</td>
<td>Remote Operation from Moonbase</td>
<td></td>
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<td></td>
<td>Remote Operation from Moonbase</td>
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<tr>
<td></td>
<td>Communication</td>
<td>E</td>
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</tr>
<tr>
<td>Temperature Survival</td>
<td>100 to 400 K</td>
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<td></td>
<td>100 to 400 K</td>
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<tr>
<td></td>
<td>FE, antenna</td>
<td>E</td>
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<td></td>
</tr>
<tr>
<td>Meteorite impact survival</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>IF transmission</td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data rate from station--correlator</td>
<td>50 Gbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>75 Gbps</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Communication</td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D (bandwidth, nyquist, sampling, pol, B: BW<em>2</em>S<em>pol</em>B)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5. Explanation of parameters

**Collecting area:** The nominal spec will allow for imaging of some of the larger structures during reionization (clustered galaxy formation, bright quasar CSS), and for power spectral studies of the end of the dark ages. The expanded array spec will allow for imaging of typical structures during reionization, and for power spectral studies during the dark ages. Collecting area $A = N*\lambda*M*A_e$ where $N$ is the number of stations, and $M$ is the number of dipoles in a station, and $A_e$ is the effective collecting area of the dipole given by $A_e = G*\lambda^2 / 4\pi = 6.76 \text{m}^2$. total $A_e$ is multiplied by $M$.

Image sensitivity for the array:

$Gain = M*A_e / 2 k = 3.67 \text{K/Jy}$ for each station; see Wrobel (1999)

$SEFD = 1200 \text{K}/3.67 \text{K/Jy} = 330 \text{Jy}$ for each station

$rms = 330 / \sqrt{(N*(N-1)*8 \times 10^6*3.6 \times 10^6)} = 0.2 \mu\text{Jy}$ for 1000 hours, 8 MHz bandwidth

$T_{b,\text{min}} = 2 \ln 2/\pi * \lambda^2 / k * \text{rms/\theta}^2 = 4 \text{mK}$, where $\theta = \text{resolution} = 1.4'$

**Frequency range:** Nominal spec is set by requirement to study the HI 21-cm signal from the end of the dark ages ($z \sim 30$) through the peak of reionization ($z \sim 8$ to 10). Expanded array spec is set by desire to study the HI signal in linear regime of structure formation out to $z \sim 50$, and down to the very end of reionization at $z \sim 6$. The redshifts come from Figure 1 in Loeb & Zaldarriaga (2008).

**Total instantaneous bandwidth:** The array should aim to correlate the full bandwidth in both renditions.

**Frequency resolution:** The nominal spec is set by the need to resolve structures in redshift space (depth) on a scale of $\sim 0.4 \text{Mpc}$ (comoving; see equ. 23 in Tegmark & Zaldarriaga 2008). The expanded array spec allows for real-time, narrow-band RFI excision techniques to be applied.

**Maximum Baseline:** The nominal spec allows for $4'$ resolution at the lowest frequency, corresponding to a comoving scale of $0.4 \text{Mpc}$ at $z = 30$ ($1 \sim 2700$). The expanded array spec allows for similar angular resolution down to $30 \text{MHz}$ (see Figure 6 in Loeb & Zaldarriaga 2008).

**Configuration:** The nominal specification emphasizes shorter spacings to improve power spectral sensitivity, as recommended in Lidz al. 2008. The expanded array spec will provide improved imaging capability.

**Field of view:** The nominal spec provides adequate statistics for study of the power spectrum during early reionization, and at the end of the dark ages. The expanded array spec improves the statistics. See Furlanetto al. Field of view is set by the size of the station and the number of beams.

**Dynamic range:** Dynamic requirements are dictated by the ratio of the brightest source expected in the field relative to the required imaging rms (Carilli 2007).
**Calibration requirements:** The calibration requirements flow-down from the dynamic range requirements, based on standard synthesis array DNR equations (Carilli 2007). The calibration accuracy being considered here corresponds to the phase errors that remain after the standard self-cal procedure and frequency differencing, i.e., the residual channel-dependent phase errors across the spectrum.

**RFI levels:** Ultimately, a limitation on self-generated RFI will be required, which will flow down to a shielding requirement for electronics in the array.

**Temporal Resolution:** The minimum dump time out of the correlator. Should be short in order to allow for calibration schemes requiring rapid switching around the sky, and for RFI excision.

**Tsuy:** We would like to be Galactic Noise Dominated over the entire frequency range by some amount, perhaps by as much as 10 dB. $T_{sky} \sim 180 \text{ K} (v/180 \text{ MHz})^{2.6}$ (Furlanetto et al. 2006)

**Dipole Sidelobes:** These will affect our ability to achieve the required dynamic range.

**Polarization:** Dual polarization observations are likely to be required for calibration of foregrounds.

**No. Bits for Sampling:** Driven by RFI concerns and gain slope variations over the passband. Probably could be less than 6 bits.

**Lifetime:** Depends on integration time required to get the results. Currently ~8 years.

**Monitor and Control:** How the array is to be controlled. Is there a moonbase or is it all done remotely by telemetry back to Earth? Where is the correlator?

**Meteor Impact Survival:** Need to calculate the probability of a meteor impact taking out a dipole, or a communication line. May require some redundant systems.

**6. Trade-offs and coupled parameters, and open questions**

Here is a list of issues that arise due to the close inter-relationship between science requirements and multiple array specifications.

A. The total number of dipoles goes like $N\times M$, where $N = \text{Number of stations}; M = \text{Number of dipoles/station} \sim D^2$ (if close packed); $D = \text{Diameter of the station};$ And we have chosen $A = 3 \text{ km}^2,$ independent of $D$. So $N\times M = 3 \times 10^6 \text{ m}^2/ 6.8 \text{ m}^2 = 444,000$ dipole pairs. For $D = 50 \text{ m}; \text{FOV} = 3.4 \times 3.4 \text{ deg.}^2$ and can be covered by a single beam ($B=1$); Computation ($X$) is going to depend on cross correlating the station beams and the computation at the individual station to form the beams out of the M dipoles in each station: $X = B\times N\times (N-1)/2 + B \times M$; where $B = \text{number of beams} \sim D^2; \text{ and recall } M \sim D^2;$ simplifying a little we get $X = D^2 N^2 + N \times D^4$. Communications requirements scale as $D^2$.

B. There is presumably some minimum number of stations, $N$, set by the need for high fidelity imaging. Each station has some overhead (power, communications, beamformer, shelter and shielding).

C. In the end it all comes down to weight. A proper minimization analysis needs to be done considering the weight required for computations (including power).
D. Deployment needs to be better understood and reflected in the technical requirements. How many rovers will deploy how many stations each?

E. Increasing frequency range affects dipole design, and may imply lower efficiency overall. It also implies higher data rates into the correlator.

F. Do we need some longer baselines for calibration? Also, is there a minimum station size (D), for calibration?

G. Power consumption requirements are clearly a major concern for receivers, communications, and correlation.

References:

Carilli 2007, PAPER memo 2 (dynamic range and calibration requirements)
Hewitt 2008, LARC memo 1 (proposal to NASA)
Loeb & Zaldarriaga 2008, LARC memo 2 (science requirements)
Tegmark & Zaldarriaga 2008 astroph 0805.4414
Farside Sites for the Lunar Radio Array

J. Burns and A. Dove (University of Colorado)

The Lunar Orbiter missions from the pre-Apollo era gave us initial insight into topography of the lunar surface, but most of these data are from imaging. Subsequent Apollo missions supplemented the imaging observations, but still lacked global detailed coverage. Currently, the best data available on which to base our exploration of the lunar surface is from the Clementine mission, flown in 1994. Clementine made great advances in mapping the mineralogy, in producing a topographic reference for the surface, and in providing higher resolution imaging of the majority of the lunar surface (Table 1). Unfortunately, even these highest resolution observations of the majority of the lunar surface are inferior to the excellent topographic and imaging resolution we have of the Martian surface.

While the Apollo missions were technologically constrained to the equatorial region on the lunar nearside, future robotic (and manned) missions will certainly be placed in widely differing locations on the surface. Thus, high-resolution imaging, LIDAR, and radar coverage of the entire lunar surface, especially regions such as the poles and the farside, will be necessary for optimal site selection. LIDAR and radar (such as the bistatic radar used to image a section of the south polar region) can inform us of elevation changes and finer scale topography and surface roughness. Additionally, bistatic radar is useful in the search for water ice. Chang’e, Chandrayaan-1, SELENE, and LRO all have laser ranging equipment, as well as optical camera systems to map and take stereographic images of the global lunar terrain. Although not currently planned, a radar experiment would be also be advantageous to improve understanding of surface roughness in many regions.

Since it was first observed, Tsiolkovsky crater has received much attention because it stands out so distinctly on lunar farside. This crater is one of the few features on the farside that has been filled-in by basaltic mare deposits that are prevalent on the nearside. Photographs of the region have been taken by the Lunar Orbiters, with both medium- and high-resolution cameras, by cameras used during the Apollo missions, and by several astronauts with 70mm Hasselblad cameras. Although the topographic resolution of Clementine data is low, photographs and stereographic images of Tsiolkovsky crater show that the basaltic floor is relatively flat. As such, it is an example of an ideal location for the placement of a radio telescope array, which will necessarily be located in a radio-quiet farside region. The deployed array could be contained within the immense crater floor, and the topographically high central peak is an ideal relay station for communication between the dipole array elements and remote sources. Further research should be done to determine the most advantageous spacing and positioning of the array in this region, as well as the most feasible situation for robotic insertion into the crater and dipole deployment.

In the draft International Lunar Network (ILN) Final Report, the Science Definition Team (SDT) outlines its rationale and goals for development of a network of geophysical nodes on the lunar surface. They identify, in order of importance, seismometry, measurements of the lunar heat flow, electromagnetic sounding, and laser ranging as the primary elements to be considered in any plans for geophysical measurements on the Moon. An ideal deployment of this network would place a seismometer node on the lunar farside in order to maximize the potential for identification of both shallow and deep moonquake epicenters, and to monitor the modification
of seismic waves as they travel through the lunar interior. Additionally, measurements of lunar heat flow will benefit from sensor placement in unique terrain in “regions that are topographically smooth so that shadowing does not influence surface temperature” (ILN Final Report, p. 30). Tsiolkovsky crater offers advantages for both seismometer and heat flow measurements, as it provides a smooth surface that is relatively unique to the lunar farside, at greater depth than the average elevation of the feldspathic highlands that dominate the farside. The fourth focus in the ILN report is on laser ranging, which is a key component of the NLSI LUNAR team's focus on astrophysics from the Moon. Thus, it would be useful to form a synergistic relationship not only to identify a site, such as Tsiolkovsky crater or near the south pole, that would maximize the science return for both groups, but also to benefit from technological developments (i.e. corner cube design for LLR, long term power supplies such as the ASRG or the DASRG) and instrument deployment techniques (i.e. autonomous rover deployment).

Several several drivers for utilizing robotic exploration as a precursor to a manned presence on the Moon were outlined in the 2007 LEAG annual meeting final report. Strategic knowledge, programmatic milestones, emplacement of assets, and site precedence can all be gained by small precursor robotic missions to explore the lunar surface and environment. Additionally, surface missions can assess the enviroment in situ, and thus provide insight into the processes that affect the surface in regions, such as the south pole or the farside, whose environments need to be better understood to both optimize potential instrumentation and set the stage for human presence on the Moon.

Table 1. Past Lunar Orbiter Missions

<table>
<thead>
<tr>
<th>IMAGING Mission</th>
<th>Instrument</th>
<th>FOV (º)</th>
<th>Ground Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar Orbiter (I-V)</td>
<td>high-res: 610-mm focal length</td>
<td>20.4 x 5.16</td>
<td>~1m (from 46 km)</td>
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<tr>
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<td>med-res: 80-mm focal length</td>
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**Receiver Considerations for the Dark Ages Lunar Interferometer (DALI)**

Steve Ellingson (Bradley Dept. of Electrical & Computer Engineering, Virginia Polytechnic Institute & State University)

I. Introduction

The Dark Ages Lunar Interferometer (DALI) is a NRL-led design concept for a radio telescope array, located on the far side of the Moon, intended primarily for the exploration of the “Dark Ages” epoch of the Universe ($z \sim 50$ to $6$) by imaging the redshifted 21 cm line of hydrogen over the frequency range $v \sim 30$ MHz to $200$ MHz. A more conservative design has also been proposed for which the frequency range is reduced to $50$ MHz to $150$ MHz ($z \sim 30$ to $8.5$). DALI consists of “stations.” Each station consists of many dipole-like antennas which are combined into beams; the beams are subsequently correlated with corresponding beams from other stations, and the resulting products are used to form images.

The purpose of this report is to document some of the considerations in the design of the receivers for DALI (§§ III and IV), propose a design concept (§ V) and to identify corresponding issues that require attention in future studies (§ VI). A related project—the Lunar Array for Radio Cosmology (LARC)—is an MIT-led design concept with similar goals, and some of what is discussed in this document should be applicable to that system as well.

In the DALI concept, the antennas and transmission lines are printed on thin sheets, which are delivered to the Moon in rolls. These are unrolled onto the lunar surface by rovers, which also connect the ends of the transmission lines to a “station hub” containing the receiver electronics. The very large fractional bandwidth (219% and 115% for the two frequency ranges identified above) makes a “direct sampling” receiver architecture a natural first choice to consider (Ellingson 2005; Taylor 2006). A direct sampling receiver is one which consists solely of gain, filtering, and digitization. The resulting architecture is thus

1. A completely passive dipole-like antenna lying directly on the surface of the Moon.
2. A long transmission line, also lying directly on the surface of the Moon, connecting the antenna terminals to the input of the receiver located in the station hub. Because dipole-like antennas produce balanced outputs, the transmission line is also balanced; e.g., twin-lead as opposed to coaxial.
3. An analog receiver which amplifies the signal and delivers it to the input of an analog-to-digital converter (ADC). The gain is nominally applied with sufficiently low noise temperature such that the signal presented to the ADC is dominated by the ubiquitous Galactic synchrotron radiation background. The gain is nominally sufficient such that Galactic noise dominates over the quantization noise (including any non-white spurious products) in the ADC output.
4. The ADC. All subsequent processing—including beamforming and channelization—is digital.

It should be noted that this is not necessarily the only possible architecture, or even the optimal one. For example, one might consider an alternative architecture in which there is some...
combining of antennas before digitization. This approach reduces the number of digitizers (which is likely to reduce power consumption) but also constrains the field of view for beam pointing and results in bulkier analog electronics. Another architectural variant involves redistributing some portion of the analog gain from the station hub closer to the antennas. This makes it possible to overcome transmission line attenuation using amplifiers with higher noise temperature, but also greatly complicates the deployment of the station. While these are all important considerations, the overarching issues can be identified by considering first the simple architecture described above; this information can then be used in a subsequent study to guide the exploration of alternative architectures.

II. Assumptions

Some assumptions about the DALI station architecture are described above. In this section, some more specific assumptions are made in order to facilitate the analysis in later sections.

Antennas

A reasonable characterization of the antenna impedance and antenna efficiency (in this case, collecting area relative to collecting area for the same antenna in free space) is required to determine the corresponding receiver specifications. However, suitable characterization of the proposed DALI on-surface antenna design is not available.

In order to proceed, we shall instead assume that the antenna can be modeled as a “fat” cylindrical dipole in free space. This allows the antenna impedance to be obtained from a simple circuit model (Tang, Tieng, & Gunn 1993). For this study, the dipole length is 2.3 m and the radius is 5 cm. Such a dipole will have approximately the same impedance as a flat dipole which is 20 cm wide (Stutzman & Thiele 1998).

Is it reasonable to assume free space conditions when modeling the antenna? As a qualitative demonstration to reveal the relevant receiver design issues, the answer is probably “yes,” but with some important caveats as follows. If we assume that the surface of the Moon can be modeled as a lossless dielectric half-space, one effect of placing an antenna directly on the surface will be to reduce the frequency of resonance. However, the behavior of the antenna self-impedance is otherwise quite similar. Thus, in terms of self-impedance, we are in effect modeling the performance of a smaller antenna on the surface using a larger antenna in free space. Collecting area is a somewhat different matter. The effect of placing the antenna directly on the surface is likely to be a reduction in collecting area presented toward the sky, relative than the same antenna in free space. This is due to the tendency of antennas placed at a boundary between free space and dielectric half-spaces to become directive into the dielectric half-space. For the specific case of the currently-proposed DALI antennas placed on the lunar regolith, the resulting reduction in usable collecting area is unknown. However, the impact of significantly reduced collecting area, should it exist, is easy to anticipate in the analysis described in Section III.

Transmission Lines

Transmission lines will range in length from a few meters for the closest antennas, to hundreds of meters for the antennas furthest from the station hub. This implies possible requirements for variable gain (to equalize transmission line losses) and for compensation for variable amounts of dispersion (Ellingson 2008).
Just as antennas are affected by the presence of the regolith, so to will there be an effect on the characteristic impedance $Z_0$ and possibly other properties of the transmission line. While it is not reasonable to ignore the effect of the regolith, it is straightforward to account for this in the design of the transmission lines. It is assumed that any reasonable $Z_0$ can be achieved.

In terms of receiver design, the relevant characteristics of the transmission line are $Z_0$, loss due to length, and noise contribution due to loss. The loss due to length of any transmission line can be characterized in terms of the gain (always less than 1, of course)

$$G(\nu, l) = \exp[-2\alpha_0 l (\nu / \nu_0)^{1/2}]$$

where $\nu$ is frequency, $l$ is length, and $\alpha_0$ is the attenuation constant (having units of inverse length) measured at $\nu = \nu_0$. A previous study by NRL and NASA for the ROLSS lunar array concept suggested a design for which $\alpha_0 = 0.00553$ m$^{-1}$ (~0.048 dB/m) at $\nu_0 = 10$ MHz; this incidentally is approximately the same loss/length as RG-58 coaxial cable.

The contribution of the transmission line to the system noise temperature, referenced to the output of the transmission line, is

$$T_{\text{tl}} = [1 - G(\nu, l)] T_{\text{amb}}$$

where $T_{\text{amb}}$ is the ambient (physical) temperature of the transmission line. Assuming this is the same as the surface temperature, $T_{\text{amb}}$ will range between 120 K (night) and 380 K (day).

**External Noise and Interference**

External noise at the frequencies of interest is nominally dominated by the Galactic synchrotron background. This background is well characterized at the relevant frequencies (Cane 1979; Ellingson, Simonetti, & Patterson 2007). It should be noted however that (Cane 1979) is specific to the Galactic polar regions, whereas the region of the sky “seen” by a dipole-like antenna at any given time also includes significant portions of the brighter Galactic disk or Center regions. As a result, the model in Cane (1979) corresponds approximately to the minimum antenna temperature—and consequently the worst case for receiver design—whereas the maximum value can be as much as approximately a factor of two greater (Ellingson, Simonetti, & Patterson 2007). This report assumes the minimum antenna temperature, derived directly from expressions in Cane (1979).

It is assumed in this study that the Moon provides sufficient shielding that radio frequency interference (RFI) from sources on Earth or in Earth orbit are negligible, and that any other sources of RFI (e.g., from sources on the Lunar surface or in Lunar orbit) are also negligible.

**III. Analysis of the Input to the Receiver**

Figure 1 shows what we can expect at the input of a receiver located in the station hub, given the assumptions above. The top curve shows the Galactic noise power spectral density (PSD), expressed in equivalent temperature, as a function of frequency and plotted for three cases:

1. “Sky @ Ant Out”; i.e., PSD at the antenna output, assuming perfect (and unachievable) conjugate matching.

2. “Sky @ TL In”; i.e., PSD transferred to the input of the transmission line assuming $Z_0 = 50\Omega$. The PSD is reduced due to the impedance mismatch between antenna and transmission line, and reflection from the opposite end of the transmission line is neglected.
3. “Sky @ TL Out” i.e., PSD appearing at the output of the transmission line assuming $l = 100$ m and the ROLSS-type (-0.048 dB/m) transmission line.

Also shown is “TL @ TL Out”; i.e., the self-noise of the transmission line measured at the same point as (3), assuming the worst case (daytime) ambient temperature.

![Figure 1. An analysis of the input to the receiver assuming 100 m transmission lines of the 50 $\Omega$ type proposed by the ROLSS study.](image)

The situation shown in Figure 1 is an unacceptable starting point not only for receiver design, but also for DALI station design generally. The response is nowhere dominated by Galactic noise and is instead everywhere dominated by transmission line noise. Furthermore, the resulting sensitivity is relatively narrowband; strongly peaked around the frequency at which the antenna is resonant. Even during night, when the transmission line noise temperature can be expected to approach 120 K, the output remains dominated by transmission line noise. The only way to improve the situation (short of changing the architecture to put gain closer to the antenna) is to reduce transmission line loss. This can be achieved either by reducing transmission line length, or loss/length. Assuming that the former is unacceptable, we now consider the latter.

More reasonable performance can be achieved using a transmission line with higher $Z_0$ and lower loss. Such transmission lines are well known and commonly available; for example, $600 \Omega$ twin lead in free space achieves $\alpha_0 = 3.4 \times 10^{-4}$ m$^{-1}$ (-0.003 dB/m) at $\nu_0 = 10$ MHz in free space. Figure \ref{ff2} shows the results of the same analysis described above, substituting this new transmission line. First, note the higher impedance results in a flattening of the response. This comes at the expense of peak transfer gain but, because the total transmission loss is so much
less, the combined result is a desirable broadbanding of the antenna + transmission line combination. Furthermore, the reduced transmission line loss dramatically reduces the self-noise injected by the transmission line. In the resulting signal at the output of the transmission line, Galactic noise dominates over transmission line noise by a factor of 6 dB or greater between 17 MHz and 99 MHz. With some adjustment in the antenna dimensions, it is probably safe to assume that this could be shifted to cover 30 MHz to about 170 MHz, making this a reasonable fit to the frequency range requirements discussed in the first paragraph of this document.

![Figure 2](image)

**Figure 2.** Same analysis as in Figure 1 using lower-loss transmission line with $Z_0 = 600\Omega$.

Recall that this analysis assumes the antenna presents the same collecting area to the sky as the same antenna in free space. If this is not true, the “Sky @ TL in” and “Sky @ TL out” curves in Figures 1 and 2 will be proportionally less. With respect to the Figure 2 result, a reduction by as little as a factor of 2 would probably make this performance unacceptable. Thus, the collecting area efficiency of antennas is critically important to both the design of receivers as well as the overall performance of the station.

**IV. Derived Receiver Requirements**

If we assume that the performance shown in Figure 2 can be achieved, then we can derive requirements for receiver noise temperature and gain. The receiver noise temperature $T_R$, when combined with the transmission line self-noise, should not significantly increase the system noise temperature. From Figure 2, $T_R = 70$ K would increase the system noise temperature by about 3 dB, which is probably unacceptable. $T_R = 20$ K would increase the system temperature by
about 1 dB, which is probably borderline acceptable. Note that any reduction of collecting area from the nominal values assumed above would have dire consequences for receiver noise figure requirements, unless the transmission losses were reduced accordingly.

The required gain depends on what power level is needed at the input of the ADC. The total power delivered to the receiver input in the useable frequency range of interest, based on the analysis of Section III, is about -93 dBm. Modern ADCs digitize full scale somewhere between 0 dBm and +10 dBm. If this is also true for DALI ADCs, then the nominal receiver gain G_R is about 83 dB, assuming 0 dBm full scale and 10 dB headroom. A useful topic for future study would be to determine if the ADC full scale level could be significantly reduced, so that the required analog gain could also be reduced; thereby reducing power consumption.

Estimating the power consumption of the required analog gain stages is difficult. The theoretical minimum power consumption for analog gain is easily determined from conservation of power considerations to be about 100 mW, assuming the operating conditions described above. Receivers in contemporary low-frequency arrays (e.g., LWA) do much worse than this, achieving between 10 and 40 dB of useable gain for each watt of power consumed; i.e., several watts per antenna. This is primarily because terrestrial RFI imposes linearity requirements that in turn dramatically increase power consumption; presumably the RFI situation will be very different on the far side of the Moon. Modern CMOS RFIC-based receivers do much better; on the order of 100's of milliwatts for a comparable amount of gain; i.e., relatively close to the theoretical minimum. CMOS is an especially compelling technology for arrays due to its ability to accommodate tight integration of RF, ADC, and digital processing functions within a single chip, and also due to its ability to accommodate many channels simultaneously on a single chip. However, the design of RF on CMOS is presently quite difficult, and present day temperature are orders of magnitude greater than those required for DALI. An analogous technology capable of delivering lower noise temperatures will be required.

We now consider the ADC specifically. For direct sampling, we nominally sample at a rate f_s which is 2.5 to 3 times greater than the highest frequency of interest. This is significantly greater than the Nyquist sampling criterion in order to accommodate the anti-aliasing filters, which we would prefer to be of very low order (i.e., slow to roll off) so as to improve mechanical stability, which in turn reduces the tendency for gain to vary with temperature. For a z = 10 (150 MHz) requirement, the resulting range of reasonable sample rates is 375 MSPS (million samples per second) to 450 MSPS. For a z = 6 (200 MHz) requirement, this is 500 MSPS to 600 MSPS. Such ADCs are commercially available now, but require power in the range of hundreds of milliwatts to 10's of watts (Le et al. 2005). This will have to be dramatically reduced to meet the anticipated power budget for DALI stations.

It is natural to seek a requirement for number of bits N_b used in digitization, but this is not straightforward in this case. If the instrumental frequency response is perfectly flat, then digitization with just a few levels might be adequate. Using N_b = 4 (16-level) digitization provides quantization dynamic range of roughly (6 dB)N_b = 24 dB, which is still about 2 bits effective after leaving 10 dB or so for headroom. The value in leaving a generous margin for headroom is that this reduces the need for fine control of gain in response to the diurnally-varying antenna temperature (§ III) and may allow identically-configured receivers to accommodate varying cable losses (due to varying lengths or unequal wear) without gain

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1 RFIC = Radio frequency integrated circuit; see Lee (2004) for background on CMOS RFIC technology.
equalization. Increases in \( N_b \) reduce sensitivity to non-linear quantization errors (that would otherwise require van Vleck correction), subtle quantization distortions due to gain variations over the passband (Carlson & Perley 2004; Thompson & Emerson 2005), and accommodate even larger headroom for gain and signal level variations. The disadvantage in increasing \( N_b \) is increasing power consumption. A simple and general relationship between \( N_b \) and power consumed is not available because this depends on the specific architecture of the ADC (Le et al. 2004). For the purposes of baseline design, an interim conservatively-large value of \( N_b = 8 \) bits is suggested.

V. Receiver Design Concept

Figure 3 summarizes the receiver design concept that follows from the considerations above. In this concept, gain is divided across two stages, where one also serves as an impedance match to the transmission line, and the other also serves as an impedance-buffered ADC driver. Between them is the anti-aliasing filter, which also serves to (1) suppress any signals below the low edge of the desired frequency range (thereby limiting the impact of second-order intermodulation due to RFI in this range); and (2) equalize (level) the passband frequency response, which may improve spectral dynamic range after digitization (Carlson & Perley 2004).

![Figure 3. Design concept for DALI receiver following the “all gain in station hub” direct sampling architecture outlined in Section I.](image)

Also indicated in Figure 3 is that the receiver is completely differential; i.e., all connections between stages are balanced, as opposed to “single-ended” connections. Since the transmission line is balanced, and since ADCs are typically designed for balanced inputs (generally resulting in improved dynamic range), resorting to single-ended design anywhere in the signal path would necessitate the use of multiple baluns. Baluns are best avoided in this case as they are inevitably bulky and difficult to incorporate into integrated circuits.

VI. Summary of Findings

The principal findings of this study which follow from the assumptions cited in Sections I and II are as follows:

1. The efficacy of the receiver design—and perhaps the feasibility of the DALI concept in total—depends critically on the collecting area efficiency of individual antennas. This efficiency is currently unknown. If this efficiency is significantly less than 100%, it will be
impossible to design a system whose sensitivity is Galactic noise-limited. Even if the efficiency is slightly reduced, it may become impossible to design receivers with sufficiently low noise temperature ($T_R$).

2. It is essential to use transmission lines with high characteristic impedance $Z_0$ and low loss. The proposed transmission line from the previous (ROLSS) design study is not suitable. $Z_0 = 600\Omega$ and loss of $-0.003\,\text{dB}$ was found to be suitable in this study.

3. The required receiver noise temperature $T_R$ is about 20 K in order to avoid contributing significantly to the system noise temperature, which is nominally dominated by Galactic background noise. $T_R = 70\,\text{K}$ will approximately double the system noise temperature.

4. The power consumption of the receiver depends on the level that must be presented to the ADC. Assuming conventional existing devices and design approaches, the theoretical minimum power consumption will be on the order of 100 mW per antenna for analog gain, and a few hundred mW per antenna for digitization. A best guess for a highly-optimized (for power consumption) design using existing technology would be therefore about 300 mW per antenna. The keys to reducing this will be to (1) reduce the power level required for full-scale digitization in the ADC from the present day value of roughly 1 mW, and (2) reduce the power consumption of the ADC.

5. The sample rate for digitization should be somewhere in the range 375 MSPS to 600 MSPS depending on desired frequency range (mainly, lowest $f$ of interest) and extent of oversampling required to accommodate a (desirable) low-order antialiasing filter.

6. The number of bits $N_b$ required for digitization is difficult to determine. The optimal answer depends on the specific ADC architecture and instrumental frequency response. A simulation study might be of value to verify that the necessary spectral dynamic range can be achieved assuming a given $N_b$.

In summary, the architectural constraints described in Section I impose some rather severe requirements on antennas and receivers, resulting in considerable uncertainty as to the efficacy of this approach. Alternative architectures (including the two variants identified in Section I) should be considered. Also, an architecture employing analog channelization followed by digitization of the reduced-bandwidth channels should be considered, as this might lead to reduced power consumption.

References


Optimization of the DALI array configuration minimizing sidelobes

G. B. Taylor (Dept. of Physics & Astronomy, Univ. of New Mexico; National Radio Astronomy Observatory) & C. Rodriguez (Dept. of Physics & Astronomy, Univ. of New Mexico)

Abstract

The goal of this report is to explore array design options for the Dark Ages Lunar Interferometer (DALI), which includes assessing the number and the location of stations, as well as the number of dipoles per station. We apply the algorithm of optimization of an array configuration minimizing side lobes designed by Leonid Kogan. We consider several possibilities for the station configuration of this telescope by varying the number of elements on each station, the minimum separation between the elements, and the diameter of the station.

We arrived at a viable option for the array design consisting of 919 dipole antennas, inside a circle of 120 m diameter and having a minimum spacing between the dipoles of 3 m. The array consists of 469 of such stations, inside a circle of 10 km diameter, with minimum spacing between stations of 125 m. The total collecting area for this array is 3 km² at 90 MHz at the zenith.

Introduction

The Dark Ages Lunar Interferometer (DALI) is a telescope designed to study highly-redshifted neutral hydrogen (HI) signals from the Universe's Dark Ages, namely, the epoch between recombination and the formation of the first luminous objects. The array is assumed to be placed on the far side of the moon, and to have no radio interference (of either solar or human origin) by observing during the long lunar night. The array is assumed to be observing at zenith so that no dimunition of the collecting area occurs by projection. The array is assumed to consist of N roughly circular stations of diameter, D, distributed over a flat surface. The stations are comprised of M dipoles which can be used to form B beams on the sky. These beams are transmitted to a central location, or to the Earth, for correlation. The final product of the array is visibility measurements which can be transformed to create images or analyzed directly. The deployment of the array is assumed to be carried out by one or more rovers.

The array will observe at 1.5–10 m wavelengths (30–200 MHz; redshifts 6 < z 50) in two polarizations using crossed dipoles. The dipoles will be grouped into stations. For more details on the requirements see Carilli & Taylor (2009).

Our goal is to explore array design options for this telescope, which includes assessing the number and the location of stations, as well as the number of dipoles per station. We use the algorithm of optimization of an array configuration minimizing side lobes designed by Leonid Kogan (2000). The algorithm minimizes the biggest side lobe in a given area of optimization on the sky. The algorithm is coded into AIPS task CONFI I and the most important input parameters are the number of antennas on the array, the area of optimization on the sky, the maximum size of the array, and the minimum spacing between the antennas.
Collecting Area

The sensitivity of an interferometer is generally determined by the system temperature of its component receivers, and its total collecting area. The sky at the low frequencies considered is bright. Even far from the Galactic plane, in the coldest regions the sky is 3500 K at 45 MHz (Alvarez et al. 1997). This emission has a steep spectrum and in general we can characterize the system temperature as:

\[ T_{\text{sys}} = 2000 \left( \frac{\nu}{74 \text{ MHz}} \right)^{-2.6} \text{ K.} \]

For this reason, there is little benefit to building low temperature receivers, and the only way in which we can improve the sensitivity is to increase the collecting area. The collecting area is just set by \( N \cdot M \cdot A_c \) where \( N \) is the number of stations, each of which has \( M \) dipoles each with an effective collecting area \( A_c \). The collecting area for a Hertz dipole is

\[ A_c = \frac{3}{8\pi} \lambda^2 \]

The modified dipole of the DALI station is assumed to have a collecting area of 7 m\(^2\), based on analogy with that achieved for the Long Wavelength Array. Details of the dipole design will be presented elsewhere.

At 90 MHz, we estimate \( T_{\text{sys}} \) to be 1200 K, the total collecting area of a station to be 3200 m\(^2\), for an SEFD of 1030 Jy in each polarization. The total collecting area (both polarizations) is 3 km\(^2\), and the sensitivity of the array over an 8 MHz bandwidth is 0.3 mJy beam\(^{-1}\) in 1 second, and 0.076 \( \mu \)Jy beam\(^{-1}\) in one year (observing during the lunar night only). This corresponds to a brightness temperature sensitivity of 0.4 \( \mu \)K in one year (lunar night only). This meets the 0.2 \( \mu \)Jy beam\(^{-1}\) in 1000 hours sensitivity requirement specified by Carilli & Taylor (2009).

Station configuration

We started the optimization with an initial configuration of a hexagon. We set the size of the antenna station as a circle with diameter 50 m. We carried out the minimization at the highest DALI frequency of 100 MHz (\( \lambda = 3 \) m), considering that the effective circle of optimization on the sky will be even larger at longer wavelengths. We chose a radius of optimization on the sky of 30°, and we consider a station phased to zenith. We performed the optimization for different values of the number of antennas as well as for the minimum spacing between them. In Table 1, we list the maximum side lobe level in the optimization region reached for each case considered.

There are two important factors to consider when designing the station configuration: having as many antennas as possible and achieving the minimum side lobe levels. For this reason, among the cases that we studied, we considered the case of 169 antennas with minimum separation of 3 m as the more desirable scenario for a 50 m diameter station. Figure 1 shows the initial station configuration for this case and Figure 2 shows the station configuration after optimization. Figure 3 shows the two dimensional beam pattern obtained and Figure 4 shows a one dimensional slice of the beam pattern.
Table 1. Results of configuration optimization for stations 50 m diameter

<table>
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<th>Number of antennas</th>
<th>Minimum spacing between antennas (m)</th>
<th>Maximum side lobe level (%)</th>
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<tr>
<td>91</td>
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<td>0.58</td>
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<tr>
<td>91</td>
<td>4</td>
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<td>91</td>
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<tr>
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<tr>
<td>169</td>
<td>3</td>
<td>0.13</td>
</tr>
<tr>
<td>217</td>
<td>3</td>
<td>0.46</td>
</tr>
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</table>
Figure 1. Hexagonal station configuration used as a starting point for the optimization of 169 antennas inside a circle of diameter 50 m. A minimum spacing of 3 m between the elements was used.
Figure 2. Configuration after optimization of a station consisting of 169 antennas located inside a circle 50 m diameter with minimum spacing of 3 m.
Figure 3. Two dimensional beam pattern created as a result of the optimization of a station consisting of 169 antennas located inside a circle 50 m diameter with minimum spacing of 3 m.

Peak flux = 1.0000E+00 JY/BEAM
Levs = 1.000E-02 * (0.135, 10, 20, 50, 90)
While a 50 m diameter station provides the desired wide field of view (11 square degrees at 90 MHz), to achieve the desired sensitivity (collecting area) requires 2550 stations. We therefore considered next a larger station diameter.

We explored designing a station consisting of 919 antennas\(^2\) with a minimum separation between them of 3 m inside a circle 120 m diameter. This case is equivalent to the case of 169 antennas inside a 50 m diameter circle up to a scaling factor. Table 2 lists the maximum side lobe level in the optimization region reached for this case. Figure 5 shows the initial station configuration for this case, and Figure 6 shows the station configuration after optimization. Figure 7 shows the two dimensional beam pattern obtained, and Figure 8 shows a one dimensional slice of the beam pattern.

\(^2\)919 was the maximum number of antennas we considered because of software limitations.
Table 2. Results of configuration optimization for a station 120 m diameter

<table>
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<th>Number of antennas</th>
<th>Minimum spacing between antennas (m)</th>
<th>Maximum side lobe level (%)</th>
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<tbody>
<tr>
<td>919</td>
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<td>0.15</td>
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</table>

Figure 5. Hexagonal station configuration used as a starting point for the optimization of 919 antennas inside a circle of diameter 120 m. A minimum spacing of 3 m between the elements was used.
Figure 6. Configuration after optimization of a station consisting of 919 antennas located inside a circle 120 m diameter with minimum spacing of 3 m.
Figure 7. Two dimensional beam pattern created as a result of the optimization of a station consisting of 919 antennas located inside a circle 120 m diameter with minimum spacing of 3 m.
Array configuration

The next step in our exploration of array design options was to pick a station configuration, among the many options considered. We decided on the station consisting of 919 antennas inside a circle 120 m diameter with a minimum separation between the elements of 3 m.

We performed the optimization of 469 of such stations, which comprises the entire array, inside a circle of diameter 10 km, and minimum spacing between the stations of 125 m. A radius of optimization on the sky of ~ 1° was used, corresponding to the field of view of a 120 m diameter station. The total number of stations was decided based on the total collecting area requirements of 3 km². Similarly to the optimization of each station, we started with an initial array configuration of a hexagon. Table 3 lists the maximum side lobe level reached in the optimization region. Figure 9 shows the initial array configuration and Figure 10 shows the array configuration.
configuration after optimization. Figure 11 shows the two dimensional beam pattern obtained, and Figure 12 shows a one dimensional slice of the beam pattern.

Table 3. Results of the array optimization. Total size of the array 10 km.*

<table>
<thead>
<tr>
<th>Number of stations</th>
<th>Minimum spacing between stations (m)</th>
<th>Maximum side lobe level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>469</td>
<td>125</td>
<td>0.68</td>
</tr>
</tbody>
</table>

*Each station consists of 919 antennas, inside a circle 120 m diameter, with a minimum spacing of 3 m.

Figure 9. Hexagonal array configuration used as a starting point for the optimization of 469 stations inside a circle of diameter 10 km. A minimum spacing of 125 m between the stations was used.
Figure 10. Configuration after optimization of an array consisting of 469 stations located inside a circle 10 km diameter with minimum spacing of 125 m between stations.
Figure 11. Two dimensional beam pattern created as a result of the optimization of an array consisting of 469 stations located inside a circle 10 km diameter with minimum spacing of 125 m between stations.

Peak flux = $1.0000E+00$ JY/BEAM
Levs = $1.000E-02 \times (0.650, 10, 20, 50, 90)$
Summary and Future Plans

We have demonstrated that an array with the desired sensitivity can be designed using 469 stations of 919 dipoles each. This can be accomplished by deploying 431,000 dipoles which requires that each dipole be extremely lightweight. Alternatively, if the effective area for each dipole can be increased then the total number of dipoles could be reduced.

Future studies should be carried out to examine the trade-offs between number of stations and number of dipoles in each station. This may require some modification of the software that has been used as we are currently up against a limit of less than 920 dipoles per station. This trade is linked to the desired field of view, to the number of beams that can be formed simultaneously for each station, and to the computation and communication needs of the array.
Another area of study for the future is to include realistic toplogical constraints for a specific site. We also plan to analyze how the beamshape and sensitivity degrades as stations are removed. Furthermore, it is desirable to simulate the response of the array to a realistic sky, using the dipole power patterns rather than the approximations used in this memo.

**Acknowledgements**

We thank L. Kogan for instructions on how to use his CONFI task for the configuration simulations.

**References**


**Polyimide Film Antenna Testing**

Robert MacDowall (NASA/GSFC), Kenneth Stewart, Brian Hicks, & Carl Gross (NRL)

We tested a prototype thin film dipole antenna by comparing its measured and calculated feedpoint impedance between 1 and 10 MHz. The antenna was constructed from a 25-μm thick kapton film with a 5 μm thick Cu layer deposited on it, with dimensions shown in Figure 1. Each arm was 8 m long and 30.5 cm wide. At the feedpoint the arms were separated by approximately 10 cm. The inner 1 m of each arm tapered to a point at the feedpoint where a 1:1 wideband balun was attached. Coaxial cable connected the balun to an AIM4170 vector impedance antenna analyzer. The effects of the cable were removed from the measurements shown below. Measurements without the balun were similar and are not shown.

![Figure 1. Antenna, with dimensions in meters.](image)

The feedpoint impedance was measured for two different antenna positions. For the first test the dipole arms were laid out on top of an asphalt road. The measurements were repeated after the antenna was moved onto the dry, sandy soil next to the road, as shown in Figure 2. Stones were placed along the edges of the antenna to prevent it from blowing away in the wind.
CST Microwave Studio 3D electromagnetic simulation software was used to model the performance of the antenna on different types of ground. The dielectric constant and conductivity of the ground were adjusted to give the best fit to the measured data. The best values found so far are listed in Table 1.

### Table 1. Best-fit values for ground dielectric constant and conductivity

<table>
<thead>
<tr>
<th></th>
<th>Dielectric Constant</th>
<th>Conductivity (mS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>11</td>
<td>0.8</td>
</tr>
<tr>
<td>Soil</td>
<td>6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The feedpoint impedances calculated using these values, along with the measured data, are plotted in Figure 3 and Figure 4.
Figure 3. Measured and calculated impedance of the antenna on an asphalt-covered road.

Figure 4. Measured and calculated impedance of the antenna when placed on sandy, grass-covered soil.
Possible sources of disagreement between theory and measurement are:

- The simulated volume around the antenna was necessarily finite. In particular, the depth of the ground was limited to 15 m in order to give reasonable memory requirements and calculation times. This caused the increasing discrepancy at low frequencies.

- The thicknesses of the Cu and kapton films were such a small fraction of the wavelength that the tiny mesh size required for the finite-element algorithm in the volume around the antenna reduced the simulation accuracy.

- The simulations assumed perfect contact between the kapton substrate and the ground surface. In reality, the film was a small, varying distance above the ground due to gravel, grass, etc. The effects of a small air gap between the antenna and ground were not modeled. This probably resulted in lower effective ground dielectric constant and conductivity.

Given these possible sources of error the agreement between theory and measurement is remarkably good, and increases confidence that models using ground properties appropriate for the lunar surface will give reasonably accurate predictions of antenna performance.
**Hubble Space Telescope (HST) Solar Array Design and Applicability to DALI Design**

L. Demaio (NASA/GSFC)

The original solar arrays for Hubble Space Telescope (HST) were two double-roll-out wings (2.3 m × 12 m) generating a total of 5000 W (Beginning Of Life [BOL]).

The flexible array varies in thickness from 0.21 mm for the substrate to ~ 0.7 mm at the cell.

**Figure 13 Cross Section Of Interconnected Hubble Solar Cells**

HST neither, had solar panels sticking together (blocking) or, have bending requiring a detensioner/counter-roller. The ROLSS antennae array is a magnitude thinner (roughly 0.02 mm total thickness) than the Hubble solar array. Therefore, the Hubble lack of blocking and bending is probably not applicable to DALI.

Edward Gaddy (2008, private communication), a space power systems engineer, at GSFC explained the two significant failures to the original Hubble solar arrays were not related to the DALI antennae. The first failure was of the bi-stemmed push-outs deployment mechanisms during deployment. The second failure was vibration due to thermal snapping of the taunt array as it would enter and exit shadow. Both of these do not apply to DALI as DALI doesn’t have bi-stemmed push-outs or a taunt array on a frame.
REFERENCES:
L. Gerlach, Hubble Space Telescope Solar Generator Design For A Decade In Orbit, Photovoltaic Specialists Conference, 21-25 May 1990, Kissimmee, FL, USA
Appendix: Polyimide Film Environmental Testing

Jack Burns (U. Colorado)

Overview:
Polyimide films (Kapton and many other trade names) have had much success in a myriad of spacecraft related applications. Kapton in particular, has been used on many vehicles; the Apollo Lunar Lander and the Spirit and Opportunity mars rovers have used Kapton polyimide films in the critical environment of space with excellent service history. The material properties of most polyimide films have been well studied for almost forty years, showing excellent mechanical, electrical, and durability characteristics at extremes of temperature. The novel use of silver coated polyimide as the primary antenna of a lunar-based radio telescope, however, requires additional testing to assure that a polyimide based material is indeed capable of maintaining the excellent mechanical and durability characteristics it is known for, while simultaneously performing well as a radio antenna.

The testing carried out at the Astrophysics Research Lab (ARL) of CASA at the University of Colorado was intended to provide further data on the durability of a sheet of polyimide film in the thermal and ultraviolet radiation conditions of the lunar surface. We conclude from these initial tests that this novel use of polyimide-based films is potentially feasible, and we provide preliminary evidence that the film could withstand the lunar environmental effects.

The lunar environment presents two primary conditions that would likely have the largest adverse effect on the film: large temperature changes (~150 C to 100 C) and ultraviolet exposure from the sun (e.g., Dever et al. 2001, AIAA, AIAA-2001-1054, 39th AIAA Aerospace Sciences Meeting). (Cosmic ray radiation is not considered in this laboratory study.) These two factors form the primary focus of this initial testing. Interaction between the silver coating and polyimide layer will also be examined as a secondary focus (stiction, delamination etc.).

Polyimide Sample:
Two 4” by 4” polyimide film samples, manufactured by MannTech SRS Technologies, were delivered to ARL. Each film sample (Figure 1) was 8 microns thick and had vapor deposited silver on one side; the silver side simulating the eventual dipole that would be present on the flight DALI antenna arrays.

Figure 1- Silvered polyimide sample
Cutting of Large Samples into Test Coupons:

Since the total quantity of test polyimide film was limited due to costs, one of the two original film samples was cut into several test coupons for initial outgassing and sticktion testing. The film was cut with an X-acto blade on a teflon surface in a particulate clean environment using a metal straight edge (Figure 2). After the cuts were made, the edges of each coupon were examined and saw-tooth effect was present (Figure 3 and Figure 4). Even with the extreme sharpness of the blade, it appears that the film was occasionally being torn instead of cut. Further testing will be necessary to reliably create small samples without this edge effect.

Figure 2 - Cutting of test coupons

Figure 3 - Saw tooth edge effect under 7x magnification. (Dark side in left image is the film, the white fibrous material is a clean room wipe.)
Initial Physical Testing / Stiction:
Three samples were cut from one of the large 4” by 4” films and placed into a small vacuum chamber (Figure 5).

The two small samples were folded in half, one silver side together and one polyimide side together, and placed inside the chamber underneath precision cleaned teflon blocks. The long coupon was placed silver side up in the chamber and was held in place with two cylindrical aluminum slugs and one block of Teflon on the corners (Figure 6). The three samples were then baked at 100° C for 24 hours while under high vacuum (< 10⁻⁵ Torr) to check for excessive outgassing and or breakdown of the film (Figure 7 for a photo of the bakeout setup).
The samples’ masses were recorded pre and post bake and showed no significant change (Table 1).

The folded film with the polyimide side together showed no visual evidence of stiction, while film with the silver side together did show some evidence of stiction. When the silver sided together coupon was unfolded some silver was removed from one portion of the film leaving an optically transparent section (Figure 8).

**Subjective Initial Bakeout Results/Conclusions:**

In order to prevent out-gassed volatiles from contaminating the turbo-molecular pump of the bakeout setup, a liquid nitrogen cold trap was located in the foreline. This cold trap is maintained at cryogenic temperatures during the duration of any the bakeout cycles and will condense most volatiles preventing back contamination. If the item being baked releases large quantities of volatiles, a residue will typically collect on the cold trap. The cold trap post bakeout of the three test films showed no visual signs of accumulated residues (Figure 9), nor did the trap have a perceivable odor; another warning sign of large volume outgassing. These subjective results along with the mass change results showed that the film would not contaminate
the primary thermal vacuum chamber during the extended test profile, and that out-gassing / material breakdown was similar to other Kapton polyimide films.

Table 1 - Initial Bake out Mass Delta Results

<table>
<thead>
<tr>
<th></th>
<th>Small Strip #1</th>
<th>Small Strip #2</th>
<th>Large Strip</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre Bake</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial 1 (grams)</td>
<td>0.0102</td>
<td>0.0098</td>
<td>0.0210</td>
</tr>
<tr>
<td>Trial 2 (grams)</td>
<td>0.0102</td>
<td>0.0100</td>
<td>0.0210</td>
</tr>
<tr>
<td>Trial 3 (grams)</td>
<td>0.0101</td>
<td>0.0099</td>
<td>0.0209</td>
</tr>
<tr>
<td><strong>Average Mass Prebake</strong></td>
<td>0.01017</td>
<td>0.009900</td>
<td>0.020967</td>
</tr>
</tbody>
</table>

|                  |                |                |             |
| **Post Bake**    |                |                |             |
| Trial 1          | 0.0101         | 0.0098         | 0.0211      |
| Trial 2          | 0.0104         | 0.0097         | 0.0208      |
| Trial 3          | 0.0102         | 0.0098         | 0.0209      |
| **Average Postbake** | 0.01023       | 0.009767       | 0.020933    |

|                  |                |                |             |
| **Mass Loss (grams)** | -0.00007     | 0.00013        | 0.00003     |
| **Percent Change**  | -0.656         | 1.347          | 0.159       |

Figure 8 – Probable stiction of the silver coating on the silver side together folded sample. (Left Image is 1x under stereo microscope)
Thermal Vacuum Test Profile:
Since Kapton’s performance at both high and low temperatures is well known, the test profile carried out inside the thermal vacuum chamber focused on the large temperature changes that will be encountered from lunar day to lunar night. The test film was exposed to a total of 12 cycles over the course of 24 days, from either hot (100 C) to cold (−150 C), or cold to hot, at the maximum rate possible with the temperature control system. This cycling will simulate one year worth of lunar temperature cycles.

Generating solar flux across all wavelengths in a laboratory environment is extremely difficult. For simplicity and cost reduction, UV flux will be used to simulate solar flux on the film during the mission. Generating sufficient flux proved to be a problem as the deuterium lamp output was less than 1% of the flux that the Sun creates from 150 to 400 nm (Figure 9). The figure shows 4 different days of SORCE data from 150 to 400 nm and the total flux when integrated. The deuterium lamp is the red trace and shows a total flux of 30 μW cm⁻². Thus the lamp will remain on during all “HOT” days of the test, a total of 288 hours of exposure.

Thermal Vacuum Test Setup:
The primary testing required construction of a small thermal-vacuum chamber capable of holding the polyimide film sample at −150 C to 100 C, and the ability to expose the film to UV light. The final set up is shown in Figure 10, and includes the chamber and all associated peripherals.

The main chamber of the thermal-vacuum setup was an 8” diameter ConFlat “T” section made from stainless steel. This section of high-vacuum tube created a chamber with an inside diameter of approximately 6”, and an overall length is 13”. Access to the chamber came from a ConFlat Window View Port, made of Borosilicate glass, which allowed visual inspection of the film during the duration of the test.

The top flange had a compression mount that held a Heraeus-Noblelight deuterium lamp with a magnesium fluoride (MgF₂) window.
Figure 9 - Solar flux compared to lamp flux (SORCE data courtesy of Tom Aryes @ CU http://lasp.colorado.edu/sorce/index.htm)
Figure 10 - Primary Thermal Vac Setup

Figure 11 - Solid model of thermal vacuum chamber
The back flange consisted of one 2 3/4" CF half nipple that was connected to a 2 3/4" CF Cross. Attached to this cross were a fluid feed-through (Item 1 in Figure 14), a thermocouple feed-through (2), as well as a 2 3/4-inch CF tee. An electrical feed-through (3) and the turbo-molecular vacuum pumps and associated rough pump (4) were also attached to the tee.

Inside the chamber, an aluminum shelf provided a thermally isolated mount point for the test sample. This shelf was five inches wide by ten inches long by 3/4 inch thick, and was thermally isolated from the rest of the chamber by four G-10 legs.

The shelf’s temperature was controlled by 1/4-inch stainless steel tubing snaked underneath the shelf in a serpentine pattern through which either liquid nitrogen (LN₂) or heated gaseous nitrogen (GN₂) flowed (Figure 14). The tubing was installed in grooves machined into the bottom of the shelf for more efficient heat transfer, and both were secured together by small aluminum clips.
As stated above, the shelf was thermally controlled by pumping in LN$_2$ or hot GN$_2$. Liquid nitrogen was supplied by a dewar, while the heated GN$_2$ was supplied from ARL’s house line after passing thru a Chromalox GCH-2155 circulation heater.

In order to monitor the temperature inside the chamber four thermocouples and a pair of Minco Thermal-Ribbon Sensors were used. The temperature controller’s feedback was provided by a thermocouple attached to the inlet tube. Two thermocouples were placed on either end of the shelf; the two Minco sensors were adjacent to the thermocouples. The final thermocouple was left unattached to monitor ambient chamber temperature. Lastly, small copper alligator type clips were used to measure the films conductivity during the duration of the test.

**Test Film Installation:**

The polyimide sample was installed onto the table and held in place with two precision cleaned Teflon blocks. The copper alligator clips were attached to opposite corners (measuring across the diagonal of the square film sample). Figure 15 shows the film just prior to closing the chamber, and the underside of the film in the folded over portion is visible just below the central Teflon block.

**Subjective Visual and Tactile Results:**

After temperature cycling and UV light exposure per the test profile, the film was removed from the chamber and photos were immediately taken (Figure 17). A white haze was present on the film and was evenly distributed on the silvered surface in all locations other than the folded over...
portion. Figure 18 shows that some haze was present underneath the fold as well. The sample was then immediately massed and had gained approximately 0.5% of its original mass. This positive mass change is likely due to condensation of out-gassed volatiles when the film is being held at low temperatures, turning the film itself into a trap. The chamber and film are then heated redistributing any volatiles that have not chemically reacted / bound to film and the process repeated for the remaining cycles.

The experimenters noticed no perceivable change in the flexibility when the film was handled post-test. The film did not seem to have become excessively brittle or more fragile post exposure.

**Electrical Conductivity:**

The resistance across the diagonal of the film sample was measured with a Fluke multimeter during the entirety of the test, however a faulty solder joint was found on one of the connections. To assure no bias in the result due to this problem the first half of this conductivity data was discarded. No appreciable change in conductivity was present in the uncorrupted data collected (see Figure 19 and Figure 20). In future testing, conductivity needs to be measured with higher resolution as the measurements taken could only be resolved to 0.1 Ω.
Figure 18 - Unfolded film post test

Figure 19 - Conductivity vs. Time

Polyimide conductivity over time

Fit line = $-0.00048(\pm 0.00013) \times \text{Time} + 1.78(\pm 0.01)$, Reduced $\chi^2 = 4.2$
Tensile Strength Testing:

In order to quantify any reduction in strength from the environmental conditioning coupons were cut from both the conditioned film sample and some unconditioned control polyimide and then tensile tested.

Samples were prepared for tensile testing as follows: 5 samples from the two material conditions were cut with dimensions of 60 mm × 10 mm. The ends were encapsulated in two layers of cellophane tape and two reflective strips were applied to each sample with an approximate gauge distance of 15 mm. Each sample was installed into the clamps on an MTS Insight 2 tensile tester and then preloaded to 0.6 N (Figure 21). At this load the initial extension from a laser extensometer was recorded and used as the gauge length for all strain measurements. The samples were then loaded at a fixed rate (mm/min) until failure.

The conditioned (environmentally cycled and UV exposed) coupons did not show a statistically meaningful change in strength when compared to the control samples. Figure 22 shows stress vs. engineering strain, with blue traces from the control coupons and red traces from the conditioned coupons. These results, along with the basic statistical results shown in Table 4, show that the conditioning had little or no effect on the films strength. It is important to note that the edge effects from cutting the films likely created stress concentrations that could have led to premature failure, however all samples contained these flaws. In future testing, reduction of these edge effects will likely reduce scatter on break loads and strains.
Figure 21 - Insight tensile tester with film installed and a post break photo (Note the bright reflections off of the laser extensometer strips)
Table 4 – Maximum Stress Statistical Comparison

<table>
<thead>
<tr>
<th>Sample</th>
<th>Peak Stress Control Samples (MPa)</th>
<th>Peak Stress Conditioned Samples (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>159.753</td>
<td>140.31</td>
</tr>
<tr>
<td>Sample 2</td>
<td>159.345</td>
<td>139.444</td>
</tr>
<tr>
<td>Sample 3</td>
<td>159.503</td>
<td>160.776</td>
</tr>
<tr>
<td>Sample 4</td>
<td>158.921</td>
<td>156.07</td>
</tr>
<tr>
<td>Sample 5</td>
<td>151.823</td>
<td>155.693</td>
</tr>
<tr>
<td>Sample 6</td>
<td></td>
<td>162.893</td>
</tr>
<tr>
<td>Average</td>
<td>157.869</td>
<td>152.531</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.393</td>
<td>10.183</td>
</tr>
</tbody>
</table>

Conclusions:
At the end of this relatively simplistic material testing, we can conclude that silver coated polyimide is a good candidate for use as an antenna and backbone as proposed. However, a
second phase of testing where more definitive numerical values for material properties are measured is needed. Multiple material lots exposed to higher flux UV light that extends to below a wavelength of 100 nm for longer time periods more closely matching solar flux present on the lunar surface would allow more confidence for the lifetime of the array. A more accurate method of measuring the conductivity of the film is also necessary and could provide a baseline for expected calibration curves of electrical properties during the mission.
Lunar Array for Radio Cosmology

LARC Team

April 23, 2009
This Appendix to the NASA ASMCS report presents the Lunar Array for Radio Cosmology (LARC) as a concept of the Lunar Radio Array (LRA). Included here are basic technical details of the LARC concept, the autonomous array element, the correlator hardware and firmware, system modeling and trade studies, and deployment strategy.

1 LARC Concept

The factors that influenced the LARC design are presented in this section. Topics include instrument functionality, engineering issues, and deployment challenges.

1.1 Instrument Functionality

The nature of the 21 cm spatial and spectral structures associated with EoR and Dark Ages cosmology requires a highly specialized instrument that is designed to detect, characterize, and image the signals in the presence of strong Galactic and extra-Galactic foregrounds and terrestrial-based radio interference (RFI). Instrument collecting area, array baseline size and orientation, instantaneous field-of-view, operational frequency and bandwidth, and integration time are all fundamental design parameters that flow directly from the science goals. Our trade studies have clearly shown that the LRA must consist of thousands of rather sizable, antenna elements to achieve its objectives.

The technical requirements for an LRA are defined by the science: observing frequencies must be in the range of 90 MHz (for EoR redshift $z = 15$) to 45 MHz (for Dark Ages redshift $z = 30$), the field of view must accommodate as large an area away from the Galactic plane as possible ($\theta_{\text{FOV}} \approx 30^\circ$), interferometric baseline lengths should be no longer than 3 km to image large-scale structures, and sensitivity to $\approx 10$ mK signals must be achieved. Preliminary results indicate that an LRA capable of studying the EoR would require 1,000 antenna elements each with $\theta_{\text{FOV}} \approx 30^\circ$; an array capable of studying the Dark Ages or a possible first generation of active galactic nuclei would require about 15,000 of the same antenna elements. In principle such large arrays could be achieved by deploying light-weight wire antennas on the Moon, and by taking advantage of the continuing rapid improvement in the capability of ultra-low power digital electronics to carry out the analysis of all the signals.

Deploying the array on the far side of the Moon will significantly reduce radio interference provided this region remains radio quiet [1] for the du-
ration of the experiment. Furthermore, the instrument should be located away from limb-diffracted terrestrial signals. This can potentially be modeled to within the accuracy needed for array placement. Most importantly, the Moon provides us with an ideal environment for the experiment since it is the only venue near the Earth where the effects of solar noise, terrestrial RFI, and ionospheric distortions are all mitigated, simultaneously.

The sidereal day on the moon is 27.322 earth-days [2] which has two important implications. For a fixed pointing of the array, this relatively slow apparent motion (about 0.55 degrees per hour) permits deeper integrations per scan. In addition, the array will be in darkness for about 13 consecutive days (about 300 hours) requiring a long lasting power source to permit operation during this prime observing time.

Some foreground contaminants such as Galactic synchrotron contain polarized regions. The array must have dual orthogonal E-field sensitivity for the proper measurement and subtraction of such signals.

1.2 Engineering Issues

What we have witnessed over the past decade regarding advances in signal processing techniques will undoubtedly continue throughout the next decade. Such advances are linked to technology enhancements in signal processing hardware capability, memory capacity, and process speed. In addition, distributed computing and high speed networking are expected to continue expanding in both functionality and performance.

While it will certainly be convenient and efficient to convert signals to the digital domain at the antenna where full advantage can be had from these developments, it also highly desirable from a systematic standpoint. Locating the low noise electronics as close to the antenna as possible will improve sensitivity and stability. Therefore, the development of a compact, antenna-based module that effectively integrates both the analog receiver and the digital signal processor would be an important step toward realizing this array configuration.

Packetized digital data communications via fiber or free space should be employed in place of analog transmission systems. Data rates of such systems could exceed 40 Gb/sec, easily handling the data rates from the antennas. For example, one such optical system could simultaneously stream data from over 200 antennas sampling at 50 MS/sec with 4-bit (16-level) quantization. In addition, optical isolation of the array elements will prevent unwanted ground loops.

Infrared metrology systems have replaced conventional surveying equip-
ment. Low cost, rugged theodolites employing this technology together with retroreflectors are commonplace, only recently are they being replaced by GPS-based systems in certain applications. Laser diodes and mirrors can be easily manipulated using modern stepper motors linked to microcontrollers. This technology could be used in conjunction with the optical/infrared communication system to provide a means of reckoning the locations of antennas.

The capability and speed of computing hardware is also advancing rapidly. Correlators of the future will be built from Application Specific Integrated Circuits (ASICs). Routing of bits via cables and multiplexers are being replaced by packet switching techniques enabling fast, efficient distributed computing architectures. In addition, if the array is located in a low radio frequency interference environment such as the far side of the moon, significantly fewer bits would be required for correlation due to the pure Gaussian nature of the signals.

The instrumentation must be well-engineered to handle the extreme lunar environment. Protection from cosmic rays, solar particles, thermal extremes, high vacuum, micrometeorites, etc. must be included. Mechanical joints and bearings can lose lubrication due to out-gassing.

The lunar regolith is dominated by silicates and oxides having a density ranging from 1 to 2 g/cm³. From [3], the real and imaginary parts of the relative permittivity range from \( \epsilon' = 2 \) to 4 and \( \epsilon'' = 0.003 \) to 0.05, respectively, depending on the percentages of titanium oxide and ferrous oxide present in the lunar samples. This is consistent with values used by Jin et al. in modeling radar pulse echos [4]. The wave attenuation in a lossy dielectric is given by [5],

\[
\alpha = \frac{\omega \sqrt{\mu \epsilon}}{\sqrt{2}} \left[ \sqrt{1 + \left( \frac{\epsilon''}{\epsilon'} \right)^2} - 1 \right]^{\frac{1}{2}} Np/m. \tag{1}
\]

At 100 MHz, the loss can be as high as 0.026 Np/m or 0.228 dB/m. Antennas placed directly in contact with the regolith will tend to favor a beam pattern that is directed into the material exhibiting a larger dielectric constant. This phenomenon is exploited in the design of silicon dielectric lenses [6]. The regolith is also a rather poor ohmic conductor thereby reducing its effectiveness as a primary ground plane for an array.

The regolith can easily acquire an electrostatic charge when disturbed. The weak gravitational force and the vacuum environment will result in particle suspension above the lunar surface that will remain for long periods of time.
The temperature of the lunar surface will range from 150 K to nearly 400 K during dark and lighted periods in the cycle [7]. Some parts of the antenna will be in direct sunlight while others will be shaded, leading to rather larger thermal gradients.

1.3 Deployment and Assembly Considerations

There are both advantages and disadvantages to deploying structures on the Moon. In this section, several issues affecting antenna deployment activities are examined.

The gravitational constant on the moon is 4,902.8 km$^3$/sec$^2$ [2], which is a factor of 81.3 less than on the earth. Therefore, the force of gravity on the moon relative to that of the earth is

$$\frac{f_m}{f_e} = \frac{1}{81.3 \left( \frac{r_e}{r_m} \right)^2} = 0.165 \approx \frac{1}{6},$$

(2)

where $r_m = 1738$ km and $r_e = 6371$ km are the mean radii of the moon and earth, respectively. This is a significant advantage in the deployment of vertical structures such as towers that can be erected using less force than is required on earth. Folding truss structures that depend on counter-torques for lifting can be made of lightweight materials since the magnitudes of the forces are less.

Unlike the Earth and Mars, the Moon lacks an atmosphere and hence no weather patterns to affect tall mechanical structures. Antenna towers placed on the regolith will remain in place for many years. Thus, large vertical structures on the Moon can be quite practical due to the low gravitational field and lack of atmospheric forces.

It would be difficult to perform precise surveying and leveling activities on the moon. To circumvent these problems, antenna packages need only be positioned in the vicinity of the desired location by a rover. The antennas should be capable of measuring precise distances to other antennas or reference markers.

1.4 Functional Components

A top-level block diagram is shown in Fig. 1. Many antennas will be required to achieve the desired collecting area. Here, an *element* is defined as a small group of antennas on a single platform that are phased together to form a non-steerable beam.

A high speed optical communications link consisting of a number of local nodes that interface directly with the array elements nearby and a trunk
network of such nodes feed the data to the Data Processing Center (DPC). The DPC, which would house the correlator electronics and array control computers, might be located either on the lunar surface some distance away from the array or perhaps even on-board a spacecraft. Array monitor & control (m/c) can be performed via an Earth communications link to the DPC. Data transfer may require a separate Earth link for optimum efficiency.

Figure 1: Top level functional description of the LARC concept.

2 Autonomous Element

The LARC autonomous array element is the Self Tending Array Node and Communications Element (STANCE). It is a highly compact, low-mass structure that makes use of three helical antennas to produce about 40 m² of collecting area. The fully-deployed configuration is illustrated in Fig. 2. It consists of a set of three, tall helical antennas, each being supported by a vertical, scissor-type truss assembly (not shown). The hexagonal base of each antenna structure is attached to a hexagonal central frame which serves as a platform for the STANCE electronics and DC power source. Ensnconced within the electronics canister are the low noise amplifiers, receivers, analog-to-digital converters, and digital signal processing unit. Towering above it is the communications module; a wide bandwidth data transfer system that directs the time-tagged bits of information acquired from each STANCE to
the central array correlator for further processing. This primary STANCE functionality is represented in the block diagram of Fig. 2b.

Figure 2: The STANCE concept; a) Sketch of the fully-deployed configuration (helical support structure not shown, and b) functional block diagram.

Since it is anticipated that several thousand such STANCEs will be needed on the Moon for Dark Ages science, it is imperative that the entire structure be designed with transport and deployment procedures in mind. The antennas and truss assemblies are folded neatly into a very compact, quasi-planar configuration that can be efficiently stowed for the flight to the lunar surface. Once there, a robotic rover, most likely the NASA ATHLETE which is currently under development, will be used to first remove the entire pallet of STANCE structures from the lander’s payload bay and then transport and place each STANCE at its prescribed location on the regolith. The level platform will serve as a base from which the spring-loaded antenna structures will unfurl, automatically. It is anticipated that over 2,000 STANCEs could be packed into a single Ares V vehicle.

2.1 Helical Antenna

As mentioned earlier, significant gain per element is required to provide enough collecting area for detection. The directivity or gain $D$ of an antenna is related to its collecting area through the fundamental relation

$$D = \frac{4\pi A_e}{\lambda^2},$$

where $A_e$ is the effective area and $\lambda$ is the wavelength. Assuming 80 % efficiency, the required antenna gain per station at 90 MHz ($\lambda = 3.33$ m) is about 71 or 18.5 dBi.
There is simply no substitute for collecting area. While many dipoles may be used for this purpose, the inefficiency, cross-coupling, and feeding problems associated with large dipole arrays will seriously compromise this option. As an alternative, end-fire arrays are attractive due to the higher gain per antenna that can be achieved. One can think of such antennas as simply a vertical array of fundamental radiating structures such as a dipoles or loops.

While Yagi-Uda and quad-loop antennas come to mind when pondering end-fire options, the need for 16 MHz or more of bandwidth essentially rule out such structures. Wide bandwidth antennas, such as a log-periodics, are useful, but the gain is compromised and a significant amount of metal would be required. However, an antenna that does provides significant gain over a reasonable bandwidth in a lightweight structure is the wire helix. An empirical study is given in [8].

One interesting advantage of the wire helix is that it can be collapsed into a relatively small volume during transport and erected easily in the field. A single, one-meter diameter helix with a 10 degree pitch has 10 turns over an 5.5 m length. From [8], the gain is about 13 dBi at 90 MHz. Four such antennas spaced 1.2λ apart [9] would yield 17 dBi with a half-power beamwidth of 40 degrees. Grating lobes would be somewhat attenuated due to the higher gain of the antenna as compared with a dipole, but more study is needed here. A helix is elliptically polarized (nearly circular). Counter-wound helical pairs may be used in close proximity to obtain dual polarization capability.

At 45 MHz, a two-meter diameter helix with 10 degree pitch has 9 turns over a 10 meter length. This antenna provides about 13 dBi of gain or, from [8], 70 m² of collecting area.

The feed point impedance of the helical antenna is about 180 ohms and unbalanced. This antenna could easily feed a low noise unbalanced (coaxial) amplifier located in an enclosure directly under the ground plane. The upper sections of the helix are sometimes tapered to reduce the frequency-dependent variation of feed-point impedance.

The gain of a helix usually peaks at the design frequency and drops monotonically with decreasing frequency over a 30 % bandwidth. The end-fire mode has a relatively sharp cutoff at the high frequency end as the radiation mode changes from end-fire (axial) to broadside (normal). The side-lobes are conical about the axis of the helix and can be engineered to have a gain of -15 dB or less relative to the main lobe.

For the LARC STANCE, the basic helical antenna design is illustrated in Fig. 3a. It consists of ten turns of #24 gauge (nominal) copper wire
wound in the form of a 1.2 m diameter fixed pitch helix, but slightly tapered to allow for the wire to fold into itself when furled. Fully extended, the helix is 8.2 m high.

Figure 3: a) Scale drawing of the 90 MHz single helix showing the wire, tapered cavity, and slab of lunar regolith, and b) simulated beam pattern of the single helix at 90 MHz.

The helix requires a ground at one end to force unidirectivity. In order to reduce the overall size of the STANCE, the ground plane is replaced here by a multi-sectioned metallic shroud that encircles the helix, extends to a height of 1.2 m, and is tapered outward at an angle of 30 degrees from vertical. There is also metal directly under the helix. The base metal and the tapered walls form an electromagnetic cavity. The basic dimensions for the helix and cavity were derived from [8], where the gain of each STANCE is set by the 30-degree field of view requirement.

The antenna shown in Fig. 3a was modeled using the well-proven CST Microwave Studio software [10]. This is a time domain electromagnetic simulation package that has been in use for over ten years. The accuracy of the simulation is under the control of the user in terms of spatial resolution and response decay amplitude. Cross coupling among the antennas and the effects of the lunar regolith [3] are included in the simulation.

The simulated beam pattern of the helix at 90 MHz is presented in Fig. 3b. The response is circularly polarized along the antenna’s bore sight with a gain of 13.9 dBi and Z=180 ohms. The circularly symmetric side lobes have a response that is 12.5 dB below that of the primary beam. Table I contains the antenna parameters for the single helix over 70-100 MHz.
Table I: Single Helix Data

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Wavelength (Meters)</th>
<th>Gain (dBi)</th>
<th>Area (m²)</th>
<th>Field of View [Degrees X Y]</th>
<th>Side Lobe Level (dB below max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>4.28</td>
<td>9.9</td>
<td>14.2</td>
<td>55.7 56.1</td>
<td>-10.6</td>
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<tr>
<td>80</td>
<td>3.75</td>
<td>12.0</td>
<td>17.7</td>
<td>44.6 44.8</td>
<td>-12.5</td>
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<tr>
<td>90</td>
<td>3.34</td>
<td>13.9</td>
<td>21.8</td>
<td>35.9 36.0</td>
<td>-13.0</td>
</tr>
<tr>
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<td>4.00</td>
<td>13.3</td>
<td>15.3</td>
<td>29.4 29.6</td>
<td>-8.0</td>
</tr>
</tbody>
</table>

2.2 Three Antenna Phased Array

A sketch of the tri-helix configuration is shown in Fig. 4a. Imposing Cartesian coordinates, we see that the antennas are spaced at 120-degree intervals and a radial distance of 1.8 m from the STANCE center. The three helices are excited simultaneously during the simulation process, and the resulting beam pattern at 90 MHz is shown in Fig. 4b.

Figure 4: a) Scale drawing of the 90 MHz tri-helix, and b) simulated beam pattern of the tri-helix at 90 MHz with the antennas fed in phase.

The beam pattern is beautifully circular having a width of about 25 degrees (close to the desired 30-degree field-of-view). The side lobes are better than 15 dB below the level of the primary beam over the 70-90 MHz band. The beam phase center is located at the geometric center of the three antennas (the proposed location of the communications and metrology tower). Table II contains the antenna parameters for the quad helix over the 70-100 MHz band.
Table II: Tri-Helix Data

<table>
<thead>
<tr>
<th>Frequency MHz</th>
<th>Wavelength Meters</th>
<th>Gain dBi</th>
<th>Area m²</th>
<th>Field of View Degrees [X Y]</th>
<th>Side Lobe Level dB below max</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>4.28</td>
<td>13.9</td>
<td>35.8</td>
<td>33.0 33.5</td>
<td>-18</td>
</tr>
<tr>
<td>80</td>
<td>3.75</td>
<td>15.9</td>
<td>43.5</td>
<td>27.6 27.9</td>
<td>-19</td>
</tr>
<tr>
<td>90</td>
<td>3.34</td>
<td>16.7</td>
<td>41.5</td>
<td>23.4 23.2</td>
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<td>13.4</td>
<td>15.7</td>
<td>29.4 30.1</td>
<td>-10</td>
</tr>
</tbody>
</table>

All of the helical antennas on a given STANCE will have the same polarization sense, i.e. either left- or right-handed. STANCEs of both types will be interspersed throughout the array to provide dual-polarization capability. While both polarizations will be required for foreground detection and subtraction, the signals from all of the STANCEs will be combined for the detection of the neutral hydrogen power spectrum since this signal is believed to be randomly polarized.

2.3 Folding Support Truss

A sketch of the fully deployed, three single-polarization antenna STANCE was shown in Fig. 2a. Each antenna consists of the helical wire, a plastic support tower (not shown), and a multi-sectioned, tapered cavity made from a metalized polymer. The inner surface of the sides form metallic walls that are needed by the helix while the outside surface might support solar cells. The bottom edge of the fan-folded sides attach to a hexagonal metal framework that serves as part of the electromagnetic cavity and a carrier for the helix and tower. Three such assemblies are connected together to form the STANCE. A small tower containing the signal processing and optical communication electronics is located at the phase center of the composite beam of the tri-helix structure.

The helix is attached to a scissor-truss tower made from several pieces of polymer-based rectangular hollow bar stock of 10 mm x 5 mm x 1.2 m (nominal). During transport to the Moon, the thin pieces are folded in a zig-zag fashion so that the entire tower structure is contained in a volume of approximately 1.2 m x 1.2 m x 1 cm. The joints of the polymer tubes are spring loaded so that the tower can self-extend to full height when released. Photographs of the hinge joint assembly are shown in Fig. 5. The tapered cavity is made from fan-folded sheets of metalized polyester or Kapton. This material is quite flexible and can be folded tightly during transport.

The configuration of the antenna during transport to the lunar surface is shown in Fig. 6. The three antennas are simply folded inward to form a
Figure 5: Photographs of our prototype, spring-loaded, low-mass hinge assembly for the helical support truss showing both closed and open configurations.

stack surrounding the central electronics canister and data communications systems. Once in position on the Moon, the STANCE package would be triggered to open by the rover. The three platforms holding the compact helical antennas would fold open, one at a time. The communications tower would rise and the STANCE would be powered. It would find its location based on information gathered by the metrology system, check vital system operation, and confirm that the antennas are level. The telemetry is sent to the DPC. If all is well, the STANCE would be instructed to unfurl the three helical antennas to complete the deployment.

Figure 6: Sketch of the three antennas relative to the central platform before the antennas and communications tower are extended. The three antenna platforms are folded on top of the central platform during transport.
2.4 STANCE Electronics

The electronics canister forms the heart of each STANCE. Within the confines of its compact cylindrical housing are the analog and digital electronic subsystems needed for data acquisition and monitor/control functions. It will need to interface mechanically with the STANCE’s platform truss assembly and electrically with the dc power distribution, antennas, and communication systems. Thermal issues will also be studied.

The analog subsystem includes a 20 dB gain, low noise amplifier for each helical antenna followed by a power combining network to form a single radio frequency (RF) channel centered at 90 MHz. The RF then enters the receiver where it is band-limited to 16 MHz and amplified by another 60 dB or so before feeding the data sampler.

The analog-to-digital converter samples the data at 40 MSps to digitally downconvert the 90 MHz to baseband. The signal processing unit, based on the successful CASPER IBOB architecture [11], will implement the Hilbert transform and polyphase filter operations. As a result, the amplitude and phase of the signal represented by the bit stream will be channelized into 4096, 4 kHz wide, complex frequency bins. A few seconds of astronomical data are acquired and assimilated with STANCE metadata, which includes a time stamp and array element identification, before being packetized and sent to the communications module for transmission to the central correlator. Monitor and control functions will be handled through a separate communications link.

The major engineering challenges facing the design of the electronics canister centers around RF shielding. Since over 80 dB of amplification is required at the same RF frequency, care must be taken to prevent power at the output of the receiver from coupling back into the earlier RF stages. Otherwise, unwanted oscillations may occur due to signal regeneration; a well-known, feedback mechanism that was discovered back in the early days of radio. An additional effort will be required to adequately shield the digital electronics to prevent it from radiating unwanted noise into the RF components. This broadband interference would otherwise reduce the receiver’s overall sensitivity.

The sampling clocks must be synchronized via an external time distribution system, the details of which are to be determined upon careful analysis of decorrelation loss due to unresolved delay offsets. A time standard capable of maintaining the required accuracy (in terms of coherence time) between synchronization marks will be required at each STANCE [12].
2.5 Data Communications

The output of the polyphase filter must be combined with time tags and STANCE housekeeping data and transmitted to the central correlator without substantial loss. We shall not use an RF system, both because it would be unable to support the bandwidth from a large array of STANCEs, and because a single malfunctioning transmitter might generate sufficient RFI to ruin the operation of the entire array until the fault is located. However, we do propose to develop RF communications channels to the STANCEs, because the bandwidths are very much smaller and, aside from the possible need for timing signals, the links need not be activated while the array is in operation.

Optical fiber and free-space laser beams are being considered for the high-bandwidth STANCE-to-correlator communications. Sending the STANCE signals through optic fibers, either directly to the correlator, or from one STANCE to another and from the last STANCE to the correlator, shouldn’t present any special problems, and can be rapidly prototyped. In this case, fiber can be used to send commands and timing signals back into the STANCE.

For free-space laser communication from each STANCE to a central correlator, a system which is probably be more scalable to large lunar arrays than one that employs fiber optics, a link is needed that modulates a low-power solid-state laser, pointing at a receiver at \( \sim 100 \) m range that uses a small lens or mirror to focus the light onto an avalanche photodiode (APD) operating either in linear or Geiger (single-photon) mode. The laser transmitter will be attached to a pair of small servo motors. A closed-loop pointing system would employ a low bandwidth signal that the APD receiver can detect from the light that leaks out from the off-pointed laser beam. The receiver will send commands back to the motors until the laser’s milliradian beam points directly at the APD.

2.6 DC Power

The LARC design has two reference power design requirements. The first is for a (single) central hub which requires hundreds of watts during daytime operation and thermal control power at night; this is a common requirement of lunar missions, and will require no more than current technology to solve. The thermal aspects of maintaining the hub at reasonable temperatures through the day/night cycle is a topic already successfully addressed by a number of authors. It will take much effort to provide a deliverable solution, but, again, current technology is adequate.
The second LARC reference power design is for a large multitude – many hundreds – of autonomous cells whose power requirements are less than 100 milliwatts continuous during the night and little more during the day. Based upon current technology we can require the relatively minimal electronics in these cells to operate over a temperature range of 100K - 350K. Power storage is another matter, however. Extrapolations of current technology rely upon chemical energy storage, e.g.: batteries. This leads to two complementary problems: a) keeping the batteries warm enough, above 230K, during the night to provide the 100 milliwatts; and b) keeping the batteries cool enough, below 310K, during the day to accept charge. Previous reference designs have shown it to be difficult to solve the first problem with less than a 1 watt dissipative thermal control; the actual electronics power requirement is thus much less than that of the thermal. Keeping the batteries cool during the day may or may not be a problem, depending upon the latitude of deployment, but some mechanisms may well be required – and that in the presence of a hostile dust environment. (At high latitude one probably has to track the sun to gather enough charging energy; at low latitude one may have to deploy shades.)

3 Data Handling Considerations

There are three legs to the data flow, each with different data masses and rate requirements:

1. Receiver data passed from the individual antenna elements to the central correlator;

2. Data transport from the array site on the lunar dark side to a relay station with direct line of sight to the Earth;

3. Downlink to Earth ground station.

In terms of difficulty, the first two legs present technological challenges that will be discussed below.

3.1 Intra-array communication

The array will contain hundreds /thousands of elements within several square kilometers, with each antenna reporting data with a minimum bandpass of 8 MHz; at 4 bit resolution, a minimum of 128 Mbps is generated from each antenna (phase information included). The data flow is central, as all data
from each antenna must eventually reach the correlator either directly or
passed through a network (with other antennae acting as conduits of data
flow). The total data flow coming into the correlator can reach 2-3 Tbps.

Given the number of array elements, simple and remotely deployable
links are desired to reduce risk. The same deployment machinery that erects
the antennas can be tasked to establish and activate the links, i.e., small
rovers will spool out cable while bringing the antenna to its spot, or aligning
the laser as part of deployment. Suitable (sub)systems for lunar applications
are already nascent in some commercial applications, and we consider a few
of these.

In such a relatively dense environment (especially near the central core of
the array), wireless systems working at RF frequencies will have inadequate
bandwidth to accommodate all antennas, besides potentially cluttering the
pristine radio environment that brought the array to the moon in the first
place.

Optical systems have a main advantage of allowing large bandwidths,
and can be highly directional with little danger of introducing RF or cross
interference. The technology is fast developing, given the present growing
appetite for video streaming. These can be fielded with either fiber optic
cable, or with direct laser communications, each with pros and cons.

Fiber optic cables are lightweight and have a high tensile strength, but
they have to be spooled out and physically connected. They also contribute
a non-negligible mass contribution to the payload given the kilometer scale
size of the array. Most of the mass is contained in the cladding surrounding
the fiber optic, but this can be minimized given the absence of activity
beyond deployment. Near the correlator, additional attention must be paid
by the rovers/astronauts to avoid snagging/fouling the hundreds of lines.

Laser links avoid the mass penalty and deployment issues with cables,
but pose a different set of challenges. Foremost among these is the ability
to align a laser to its corresponding receiver at the correlator. Small, low
power lasers and pointers are achievable with present technology. Detectors
such as Avalanche Photodiodes (APDs), which can detect single photons,
already exist and are used in IR sensing and laser altimetry. These solid
state versions of photomultiplier tubes can handle up to 100 Mbps. One
possible implementation of this system is to have a 5mW laser pointer
beam the data stream across the array field to a central receiving tower.
The tower (shown in the figure mounted on an ATHLETE lunar explorer
used in deployment) can have large panels or netting bearing arrays of small
APDs, each receiving a signal from an antenna.
3.2 Communication link from the Dark side to Relay Station

The output of the correlator after processing the antenna inputs and integrating the output visibilities, is estimated to have a data rate as high as 14Gbps. Optimal lunar sites on the dark side preclude any direct-line-of-sight communications to the Earth, and thus a relay link will be necessary to bring the processed data to a position visible from the Earth.

Large scale lunar activity may allow relay link towers connecting to a Moon base to be established, although the number of such towers are likely to be prohibitive (e.g., a 5000km traverse requires 130 towers 100m tall). An automated lunar rover to lay down fiber optic cable on such distances will be a similar engineering and surveying challenge, but the problem becomes more tractable if more Moon stations are established along the path from the array to the Moon base.

An alternative approach is to place a relay satellite in an orbit around a Moon-Earth Lagrange point. This relay satellite can be launched on a separate rocket with a lower payload mass to reduce costs. The L4/L5 Lagrange points have a disadvantage of not being in the line-of-sight of portions of the lunar dark side, as well as the longer relay paths. Lunar site selection will determine whether this option is feasible. A satellite placed in a halo orbit around the L2 Lagrange point may be more suitable.

Again, an optical laser link may provide the answer. The detector technology will require high speed detectors that are preferable to APDs. For example, Niobium nanowire technology allows detection of single photons at Gbps rates. Such detectors however, are cryogenically cooled, requiring liquid Helium as a consumable aboard the spacecraft.

3.3 Downlink from relay station to Earth

This is the most developed portion of the communications problem, and there are options offered by present technology. For a relay satellite, multiple stations on the Earth can provide continuous reception during the two-week lunar night when data is being generated. For example, one could consider a 3m Ka-band dish on the satellite transmitting 100W, and 3x18m earth stations located at different locations on the earth. Such a system could readily do 14 Gbps, sufficient for the Black Hole physics target. Conversely, if the satellite has memory storage sufficient to store 12 hours of data (77 Tbytes), then a single large (25m) dish will be sufficient to download a day’s worth of data during the time the Moon is visible to the station.

The correct architecture will depend on the available future technology.
providing the best cost-effective solution (the cost of on-board memory versus adding smaller ground stations). If future advances in laser communications (in particular high speed detectors) allow 2-3 Tbps data channels, the full transmission of the raw (uncorrelated) data becomes possible. For example, with a 100W laser and 1m dish on the Moon, and a similar system on a relay satellite in L2/L4/L5 orbit, one can trade off the power consumption used to calculate the correlations, as these can be performed conveniently on the Earth.

4 Correlation Hardware and Firmware

LARC requires a very large correlator. Given the requirement of extreme dynamic range with extremely low systematics, it makes sense to consider only digital correlators. Historically, digital correlators are power hogs. Power in space is doubly expensive: not only must the power system be larger, but also mass increases. As a result, to date there have been no large correlators in space.

This situation is changing. Driven by wireless communications and gaming (not by radio astronomy!), the capability of sampler and multiplier chips is doubling every 18 months or so. Earth science missions are leading the way in the application of this commercial technology to cross-correlators for Fourier synthesis interferometry, especially the Geosynchronous Earth Orbit Synthetic Thinned Aperture Radiometer (GeoSTAR), a microwave atmospheric sounding experiment in geostationary orbit. GeoSTAR will have 50 km spatial resolution 15 50–60 GHz for temperature sounding and 25 km resolution at 183 GHz for water vapor sounding. The baseline design has a $3 \times 112$ element array at 50 GHz and a $3 \times 196$ element array at 183 GHz. There are six spectral channels at 50 GHz and four at 183 GHz, with bandwidth per channel 200–1,000 MHz.

The GeoSTAR multiplier/accumulator uses a 90 nm, 0.5 V, CMOS ASIC process. (ASIC foundries are now producing 28 nm chips, two generations later than the 90 nm used for GeoSTAR; however, the design rules for the later generations are not generally available to outside designers during the commercial equivalent of a “proprietary period.”) It is designed to produce complex cross-correlations of all possible pairs of 196 In-Phase and 196-Quadrature Phase 2-bit input signals, clocked at 1400 MHz, while drawing 1.68 W of DC power. Scaling from these chips, the power for multiplier/accumulators for a CMB application given current mature technology would scale as
For 1.4 GHz IF bands, the digitizer needs to run at 2.8 GHz for Nyquist sampling. Low-voltage digitizers that operate at this clock speed have not yet been demonstrated, but a 1-bit digitizer clocked at 392 MHz has been demonstrated that dissipates 4 mW. Assuming that the power dissipation scales with clock speed, the power dissipation would be

\[ P = 40 \left( \frac{N_{el}}{2} \right) \left( \frac{\Delta \nu}{19.8 \text{ GHz}} \right) \text{ W.} \]

(5)

We can use these expressions to get a very rough estimate of the power that LARC would dissipate, based on current technology. We can start with the most ambitious configuration of LARC that has been considered: 20,000 elements and \( \Delta \nu = 16 \text{ MHz} \). We also assume 8 bit correlation, which might be required to realize enough dynamic range to cover both the synchrotron foreground and the neutral hydrogen emission. Ignoring any difficulty of getting the narrow-band LARC signals into the multiplier chip, then we have

\[ P = 98 \left( \frac{N_{el}}{196} \right)^2 \left( \frac{\Delta \nu}{19.8 \text{ GHz}} \right) \left( \frac{n_{\text{bits}}}{2 \text{ bits}} \right) \text{ W.} \]

(6)

\[ = 98 \left( \frac{2 \times 10^4}{196} \right)^2 \left( \frac{16 \times 10^6 \text{ Hz}}{19.8 \times 10^9 \text{ Hz}} \right) \left( \frac{8 \text{ bits}}{2 \text{ bits}} \right) \text{ W} \]

(7)

\[ = 3.3 \text{ kW.} \]

(8)

Similarly, for the samplers:

\[ P = 40 \left( \frac{N_{el}}{2} \right) \left( \frac{\Delta \nu}{19.8 \text{ GHz}} \right) \text{ W} \]

(9)

\[ = 40 \left( \frac{2 \times 10^4}{2} \right) \left( \frac{16 \times 10^6 \text{ Hz}}{19.8 \times 10^9 \text{ Hz}} \right) \text{ W} \]

(10)

\[ = 323 \text{ W.} \]

(11)

Correlation dominates sampling, of course, because it depends on \( N_{el}^2 \) rather than \( N_{el} \). By historical standards these are very low powers indeed. In fact, they are no doubt too low, for two reasons. First, because a correlator is more than simply a collection of sampler and multiplier chips. Second,
and more importantly, we have ignored the problem of how to bring many narrow-bandwidth signals from individual elements into inherently broadband sampler and multiplier chips, a significant issue that can only be addressed by a proper correlator design.

Nevertheless, even if this underestimates the power requirement by an order of magnitude, the speed of chips is increasing rapidly and power consumption is going down a factor of 2 every 18 months. On the timescale of LARC, correlator power would not be a problem. We emphasize again that this increase of capability with time does not depend on radio astronomy funding!

We can therefore draw an important conclusion: the LARC correlator will be large, complicated, and hard, requiring detailed engineering and careful design, but it will not be the mission-limiting factor, and power consumption will not be a mission driver.

5 System Modeling and Trade Studies

An end-to-end model was developed for the LARC concept to quantitatively evaluate system performance and design trades. The model is based on the latest estimates and relationships given by the subsystem developers. User inputs to the model are representative of design trades and high-level metrics correspond to system performance.

A functional block diagram was created early in the project to understand the LARC system and its component subsystems include

- Antenna
- Correlator
- Communication, Local
- Communication, Earth
- Deployment
- Power

Relationships were defined both within and across subsystems to capture parameters such as mass, volume, and data rate. These parameters, when enumerated at the system level, are used to calculate metrics such as total mass, total volume, and the number of launches required for deployment. The thermal uncertainty of the HI line in the 1-D power spectrum (at z
(\textit{eq} = 15)\) is used to quantify scientific performance, where the desired thermal uncertainty (or “good design”) is an order of magnitude below the theoretical prediction. The model is written in Excel and MATLAB.

A handful of design trades for the LARC system were closed by decision (based on subject matter expert opinion) early in the project, though they may be revisited in the future.

- \textbf{Helical Antenna} vs. Dipole Antenna
- \textbf{Optical Communication} vs. Radio Communications
- \textbf{Robotic Deployment} vs. Human Deployment
- \textbf{Solar Power} vs. Nuclear Power

The remaining trades are built into the system model as user inputs, and are evaluated with respect to the performance metrics mentioned above:

- Correlate by Day vs. Correlate by Night
- Number of Stations (STANCES) vs. Thermal Uncertainty vs. Deployment Time

A technology input is also built into the model to reflect system mass and power if the LARC system is to use current technology vs. future technology available 1-20 years from now. The ability to resolve the open trades is highly dependent on what assumptions are used for these "improvement factors".

A range of parameters and their values were explored to address uncertainty in the model and to identify the LARC system drivers.

First, combinations of the parameters shown in Table III were run in the model to evaluate their impacts on thermal uncertainty over a range of angular wavenumbers \((k = 0.01 - 10 \text{ [Mpc-1]})\). The results are presented in Fig. 7.
Table III: Science Trade Studies

<table>
<thead>
<tr>
<th>Science</th>
<th>Nominal</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Step</th>
<th>Units</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Stations</td>
<td>20,000</td>
<td>1,000</td>
<td>20,000</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Collecting Area</td>
<td>40</td>
<td>20</td>
<td>60</td>
<td>10</td>
<td>$m^2$</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>16</td>
<td>8</td>
<td>16</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Station Distribution</td>
<td>$1/r^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Station Spacing</td>
<td>1.25</td>
<td>1</td>
<td>1.5</td>
<td>0.25</td>
<td>$m$</td>
</tr>
<tr>
<td>Integration Time</td>
<td>12,000</td>
<td>6,000</td>
<td>18,000</td>
<td>6,000</td>
<td>hours</td>
</tr>
<tr>
<td>Maximum Baseline</td>
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<td></td>
<td></td>
<td></td>
<td>$km$</td>
</tr>
<tr>
<td>Epsilon</td>
<td>0.5</td>
<td></td>
<td></td>
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</table>

The sawtooth-like features in the plot correspond to increasing the number of stations by 1,000 (from left to right). The highlighted blue section represents 10,000 stations and all other combinations of parameters and values.

Figure 7: Thermal Uncertainty versus Theoretical Prediction for k=1.

There are two conclusions that can be drawn from this set of results. First, thermal uncertainty does not significantly decrease for numbers of stations greater than 10,000 (that is, less "bang-for-the-buck"). Second, varying other parameters, such as increasing integration time, can serve as
an alternative to increasing the number of stations

Using the same "science" parameters, a set of "system" trade studies was performed to assess ranges of antenna mass and volume against the number of launches. These are listed in Table IV and the results are presented in Fig. 8.

<table>
<thead>
<tr>
<th>Table IV: System Trade Studies</th>
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<tbody>
<tr>
<td>Science</td>
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<tr>
<td>Redshift</td>
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<tr>
<td>Number of Stations</td>
</tr>
<tr>
<td>Antenna Mass</td>
</tr>
<tr>
<td>Antenna Volume</td>
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<tr>
<td>Bandwidth</td>
</tr>
</tbody>
</table>

The number of launches is extremely sensitive to the number of stations and the values used for station mass and volume. While this is due to the number of multiplications involved, the masses of the correlator and data storage systems are not comparatively insignificant.

Combining the "science" and "system" trade studies resulted in the ability to identify the optimal design space for competing metrics. If both metrics are weighted equally, then the optimal design has 11,000 stations and requires three launches (blue point).

Figure 8: Thermal Uncertainty versus Theoretical Prediction for k=1.
If the number of launches is constrained to a single Ares V cargo launch, then the number of stations is limited to 2,328. This number is the result of a detailed packing and deployment analysis using dimensions for Ares V payload fairing, usable Altair deck area, and ATHLETE leg length. Fig. 9 shows that such a design can resolve the theoretical power spectrum at values of $k = 0.5$ and below.

![Thermal Uncertainty versus Theoretical Prediction](image)

Figure 9: Thermal Uncertainty versus Theoretical Prediction.

The results thus far are only as valid as the assumptions and data used in the systems model. Future work would include an effort to complete, update, and validate the systems model for further analysis. These updates will be implemented as subsystems are developed, while also reflecting the latest understanding in technology assumptions.

Once the systems model is mature, future trade studies will capture the impact of additional parameters and their values against new metrics. These proposed metrics include total cost (development, production, and operations), total deployment time, and total downlink data rate. Updates from the Constellation Program and plans for lunar communication infrastructure will be used to apply realistic constraints to the design space. The ultimate goal is to establish "target" values for system parameters that are indicative of the areas in which future technology investments should be made.
6 Deployment

Preliminary results from trade studies indicate the number of STANCEs for the LARC concept to be in the thousands. Given the sheer number of antennas, the following design considerations were implemented:

- Low Mass/Low Volume (antenna mass is the largest driver in the system)
- Autonomy (each STANCE is self-operable and will not impact array performance upon failure)
- Ease of Deployment (each STANCE is self-deployable and will not require assembly)

STANCE deployment was designed with the objective to eliminate low-mass rover and robotic technology development specific to the LRA. The ATHLETE system (funded by the Constellation Program) will be used to both offload the STANCEs from the Altair lander and place them on the lunar surface.

Figure 10: STANCE Packaging

STANCEs will be loaded on a cargo pallet on top of the Altair as shown in Fig. 10. After landing, the ATHLETE will unfold its legs, swing them
down on the surface, extend and lift the cargo pallet, and "walk off" of the
Altair to the deployment site. The ATHLETE will then use two of its legs
to reach up, "grab" STANCEs using leg attachments, and lower them onto
the surface. Once a STANCE has been placed, the ATHLETE will trigger
its deployment mechanism.

Each STANCE in its packaged state is a single hexagonal plate consisting
of four spring-loaded layers. When the deployment mechanism is triggered,
three of the layers (the helical antennas) will unfold sequentially from a
central hexagon. A communications tower will deploy from the center and
establish a communications link. Cavity walls for each helical antenna will
unfold "accordion-style" similar to solar panel deployment on ISS. Finally,
the helical antennas will deploy to full extension by means of truss structures.

While optimal path planning will be used for actual deployment, current
estimates for concentric circle and logarithmic spiral deployment indicate
that STANCEs on the order of a thousand can be placed by an ATHLETE
within a lunar day.
References


