Technology Development for The Lunar Radio Array

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1. Introduction: This document summarizes the technology development required in the 2010–2020 decade, for a successful start to the Lunar Radio Array (LRA) in the 2020–2030 decade. Many of these technologies have broad applicability to NASA astrophysics missions, to NASA missions in other disciplines, space missions conducted by other Government agencies, and potentially commercial interests.

This technology assessment originates from two concept studies funded under the Astrophysics Strategic Mission Concept Studies (ASMCS) program over the past year. This initial assessment has helped identify both key technologies as well as synergies with other programs. However, the duration of these concept studies has been less than 1 year and this assessment should be regarded as preliminary. A key aspect of continuing to develop these technologies is to monitor developments in other agencies and industries, build on technology developments in other sectors where possible, but making investments in order to make them useful for NASA astrophysics missions generally, and the LRA in particular.

A complementary Activity White Paper on the mission concept for LRA has been submitted to the Astro2010 Program Prioritization Panel.

1.1. Science Questions: The science goals of a Lunar Radio Array (LRA) are presented in two Science White Papers, "Astrophysics from the Highly Redshifted 21 cm Line" and "Cosmology from the Highly Redshifted 21cm Line" (both Furlanetto et al. 2009).

The LRA will exploit the highly redshifted 21-cm line of H I. Its observations will potentially provide information prior to the formation of the first stars and unique information about the state of the intergalactic medium (IGM) and large-scale structures after the formation of the first stars. Primary questions to be addressed by the LRA include, Does the standard cosmological model describe the Universe during the "Dark Ages"? 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?

1.2. Measurement approach: The LRA design is driven by the requirement to determine the power spectrum of fluctuations in the 21 cm (1.4 GHz rest frequency) line of H I between $30 > z > 6$. At these redshifts, the H I 21-cm line is redshifted into the meter-wavelength radio regime: at $z = 30$, the transition is observed at 46 MHz (λ6.5 m), and, at $z = 6$, at 203 MHz (λ1.5 m). The science requires sampling the Universe with a resolution of approximately 0.4 Mpc, or 3' at 90 MHz, over an area of order 100 Mpc^2 (11 deg.^{2}). The sensitivity of the desired measurement requires an effective collecting area of order 3 km^2.

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Ground-based arrays currently under construction are investigating this approach, but will likely be limited to the lowest redshifts of interest ($z \sim 7$, well after reionization has begun) by a combination of ionospheric and Radio Frequency Interference (RFI) constraints. These new arrays include the Murchison Widefield Array (MWA) and the Precision Array to Probe the Epoch of Reionization (PAPER) in Australia, the Low-Frequency Array (LOFAR) in The Netherlands and, to a lesser degree, the Long Wavelength Array (LWA) in New Mexico.

1.3. Reasons for a *lunar* observatory: Ground-based arrays are unlikely to be able to observe the early part of the Epoch of Reionization, or the Dark Ages, with sufficient sensitivity to answer the main science questions because of the severe physical restrictions of the ionosphere and human-produced RFI. The ionosphere, of course, covers the entire Earth, and at the earliest times ($z > 20$; below ~ 75 MHz), the Earth's ionosphere is heavily distorting or even opaque. Civil and military transmitters, which are orders of magnitude stronger than the desired signal, make heavy use of the relevant spectrum, and they can be detected, at some level, essentially everywhere on the Earth's surface. LOFAR (in northern Europe) is attempting to develop measures to counteract RFI, and the MWA and PAPER are being built in Western Australia, which is one of the most radio quiet regions on Earth. However, neither is expected to probe deep into the Dark Ages.

The mass of the Moon is an excellent RFI shield, if one is more than about 200 km around the limb from lunar nearside. Indeed, the farside of the Moon is likely the only place in the inner Solar System which is sufficiently "radio dark" to enable these measurements. In addition, the Moon has no ionosphere to distort or block low frequency measurements.

2. Concepts for the LRA: The electrical concept for the LRA is similar to many existing and planned ground-based radio arrays. Multiple radio-receiving antennas are operated together as an interferometer to form one or more high sensitivity beams that collect signals from a particular region of the sky. In the LRA, multiple antennas are coherently combined to form a "station," and then multiple stations are coherently combined to form the full array. The different baselines between the various station pairs sample many Fourier components of the region of interest, and the Fourier components can be transformed or analyzed in standard methods for ground-based arrays.

Two concepts are currently being explored for the LRA, under the support of the Astrophysics Strategic Mission Concept Studies (ASMCS) program:

The **Dark Ages Lunar Interferometer** (DALI: PI J. Lazio) concept combines approximately 1500 individual antennas into a single station and then combines about 300 stations to form the full interferometer. DALI envisions simple dipole antennas deposited as thin metallic films on space-qualified polyimide film (e.g., Kapton™) sheets, which are about 100 m × 1 m × 10 μm and can be easily rolled out by rovers. The signal transmission lines from the dipole antennas to a central station hub would also be deposited on the polyimide film. Communications between stations and a central array correlator would be done through fiber optic cables or ribbons, possibly with local concentrator nodes.

The **Lunar Array for Radio Cosmology** (LARC: PI J. Hewitt) concept combines four helical antennas to form a station or "stance," with each helix being 1 m in diameter and 8.2 m high. The four helices on each stance are attached to a flat base and are separated by about 3.2 m. There are 10,000–20,000 LARC stances. Signals are collected at local communications nodes, and then relayed along trunk communication lines to a central array correlator. A major electronics/signal processing challenge for the LARC concept is correlating the $N*(N-1)$ signals from more than 10,000 elements.

In both concepts, command and control information and clock data must be transmitted to the stations from the central hub. The digitized signals from each station must then be returned to the central processor hub where cross-correlation of all station pairs is performed. The correlated data are returned to Earth, probably through a satellite link (shared or dedicated, depending on other lunar development).

The LRA will be located on the lunar farside, at least 200 km around the limb from the Earth, in a flat area at least 20 km across. Observations will be conducted only during lunar night, to avoid solar radio interference. Data will be either correlated in real-time and stored at the central correlator hub, or stored at the stations and then transmitted during the lunar day to the central hub for correlation when solar power is available.

LRA components will be delivered to the lunar farside using a heavy lift vehicle (e.g., Ares V or similar capacity) and an Altair-derived or similar capacity cargo lander. Rovers will handle the unpacking, antenna distribution, antenna deployment, and array connection. The central processing hub will remain as part of the cargo lander and serve as a control and communications center.

3. Engineering and Technical Challenges to Building the LRA: Although there will be many technical and engineering challenges involved in building the LRA, the DALI and LARC concept studies have identified five areas ("technology tall poles") that demand special attention. These issues are common to the LARC and DALI concepts as well as being applicable to other astrophysics needs and other space mission concepts.

3.1. Ultra Low-Mass Components: The LRA requires an effective collecting area of about 3 km^2. Current studies suggest this implies 10^4–10^6 individual radio antennas (dipoles, helices, or equivalent), local transmission lines to connect each antenna to its station, electronics, a low-level power sources for each station (with possibly a requirement for low-level power sources for individual stances or dipoles as well), and a communications infrastructure for connecting the stations to the central array hub where the correlator is located. Because of the high cost of transporting mass to the Moon and landing it on the lunar surface, every component of the array must be small and ultra lightweight to save mass and, thereby, reduce the overall cost of launch, landing, and deployment.

3.2. Clean Signal Handling and Environment: The pristine lunar farside is an incredibly valuable resource—it is likely to be the only location in the inner Solar System where the Dark Ages signal can possibly be detected against the cosmic background without ionospheric or RFI degradation. In accordance with International Telecommunications Union (ITU) recommendations (ITU-R RA.479-5), this resource must be protected for the LRA. Consequently, the LRA must be optimized to avoid self-generated RFI. Doing so will require both careful design and shielding of digital components.

3.3. Autonomous, Low Wattage (~ 1 W) Power Supply: Each station of the array, at a minimum, will need its own localized power source. These sources will need to provide steady power for the duration of the 300-hour, 125 K lunar night. In order to minimize this power requirement, the stations and individual antenna electronics will need to be ultra-low-power. The central correlator hub will, of course, require much higher power levels and may only be able to operate during the lunar day when solar power is available.

3.4. Remote Deployment and Assembly: The LRA will need to be a minimum of 200 km around the limb from direct Earth view for shielding from Earth-generated RFI. Current studies suggest that a near-equatorial region, such as the Tsiolkovsky Crater on the lunar farside, is likely to be the preferred location, mainly because of topological and surface properties. The large number of stations will require that deployment be conducted largely via autonomous, intelligent robots, possibly without direct real-time human control.

3.5. Thermal Environment: Lunar surface temperatures range from 125 K to 400 K between lunar night and day, each of which are about 300 hours long. The LRA components must be able at least to survive, and possibly operate, at both extremes. The antenna and station electronics must be able to operate during the lunar night and survive the lunar day, and the correlator will probably need to be able to operate during the lunar day and survive the lunar night.

4. Specific Technologies Needing Development: There are five technology areas (§4.1–4.5) that are needed for the LRA and that will not be of sufficient maturity in ten years without a focused development effort beginning now. Many of these technologies have broad applicability, beyond merely the LRA.

4.1. Low frequency, wide bandwidth, low-mass science antennas: The LRA requires an effective collecting area of about 3 km^2 covering the approximate frequency range between 30–200 MHz (z = 50–6), which means tens to hundreds of thousands of individual antennas. The LRA also requires full polarization imaging observations to remove foreground emission such as that from the Galaxy, Jupiter, galaxy clusters and other cosmic radio emitters. While many of the other technologies described in this document may benefit from synergies with other interests (other NASA missions, other Government agencies, commercial), the science antennas require focused development by the astronomical community.

The two current antenna concepts for LRA are very different and each concept needs extensive further development and testing. The DALI concept proposes dipole-like antennas and transmission lines which are deposited on very thin sheets of Kapton (or similar material). These are delivered in rolls of 100+ antennas per roll and are deployed by unrolling on the lunar surface. The LARC concept assumes helical antennas, grouped in “stances” of four helices, which are delivered in flat packages and erected using ultra-lightweight trusses.

DALI-type antennas: Development work is needed on the manufacture, 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: Development work is needed in the electromagnetic performance of the antennas, the design of a lightweight structure, and in the deployment of the helices.

Both concepts need further work to understand the antenna response when deployed on the lunar regolith.

Table 1. Key Technology Development

Technology	Requirement	Current State	Required (~ 2020)	Heritage	Synergies
Low frequency, wide bandwidth, low-mass science antennas	• ~ 20 – 150 MHz • Easy deployment • Minimal mass, volume	DALI: proof-of-concept film antenna LARC: concept design	• Prototype • Deployment demonstration	Ground-based radio astronomical arrays	NASA heliophysics missions
Ultra-low power, ultra-low noise, radiation tolerant digital and analog electronics	• Low power budgets • Analog amplifiers and ADCs • Digital components • Operate / survive lunar thermal extremes	• 130 nm process • ~ 1.3 V supply • Primary focus on digital • Limited temp. range	• 12 nm process or better • < 1 V supply • General purpose chips and components	NASA ST5 spacecraft, GeoSTAR correlator	NASA missions, DoD, commercial
Autonomous low-power generation and storage	• 100s to 10,000s of individual station sinks • ~ 100 mW through lunar night • < 1 kg per station	*Batteries:* Best Li-ion ~3 kg/W for 300 hr; must charge at 270 K < T < 310 K	• < 1 kg/W • Steady 0.1 W for 300 hr at 100 K • Charge > 310 K	Planetary spacecraft, rovers	NASA micro-sat missions, small lunar payloads, commercial micro-sats
		RPUs: Available for > 10 W or < 10 mW	• ~ 100 mW units • Sufficient Pu-238?	Multiple deep-space missions	
		Power beaming: Terrestrial system studies	Lunar infrastructure, ~ 10× efficiency		
Low-mass, high capability rovers	• High payload / rover mass ratio • Autonomous navigation, antenna deployment	• ~ 850 kg • kW power • Payload / rover mass ratio ~ 3 • 10 cm/s	• 10s of kg • ~ 100 W power • Payload / rover mass ratio ~ 5 • > 1 m/s	Mars rovers, ATHLETE rover, DARPA competitions	NASA planetary, lunar exploration; DoD; commercial (human-hazard activities)

High data rate, lunar surface data transport	• > 400 Mbps • Low mass • Low power • Operate / survive lunar thermal extremes • Non-RFI generating (ITU compliant)	*Free-space laser* 10 Mbps	*Free-space laser* > 400 Mbps	NRL-JPL demonstrations	NASA lunar exploration, satellite constellations
		RF wireless 600 Mbps	*RF wireless* Non-RFI generating	Commercial RF wireless	
		Optical fiber 1 kg/km	*Optical fiber* 0.1 kg/km	Commercial optical fiber	

<u>4.2 Ultra-low power, ultra-low noise, radiation tolerant, digital and analog, electronics</u>: The reduction of power requirements for electronic components would be useful to a broad suite of space missions—for NASA, the DoD, and commercial users. Success is being achieved in reducing the power consumption of digital components, but comparable levels of effort need to be directed toward reducing the power consumption of analog components.

The LRA will have hundreds to thousands of stations, each composed of multiple (4 to 1000) radio antennas (dipoles and helices are currently being considered). Each station will combine the signals from its member antennas. Current designs strongly favor the use of passive antennas and transmission lines to bring the signals to a central station location for amplification, combination, and conversion from analog to digital with an analog-to-digital-converter (ADC). It is not yet clear if the signal combination will be accomplished via analog or digital techniques. At a minimum, each station will have to have low-noise amplifiers, receiver chains, signal combiner, digitizer, and filters; digital components will have to be shielded to prevent self-RFI generation. In the worst case, each individual antenna (dipole or helix) will require active gain *in situ*. If each individual antenna does require local signal processing, ultra low-power, ultra low-noise, radiation tolerant, thermally tolerant electronic components, particularly analog components, will be critical items. Power savings of 40–100× for digital components have already been demonstrated with the CMOS Ultra-Low Power Radiation Tolerant (CULPRiT) technology onboard the NASA ST5 spacecraft, in a program funded jointly by NASA and the National Reconnaissance Office (NRO). A similar effort is required for analog components (e.g., ADCs).

The LRA will also require a correlator at its central hub to combine signals from the hundreds to tens of thousands of stations. The correlation of all unique pairs of N stations [$N(N-1)/2$ * 4 Stokes polarization parameters * number of beams] quickly leads to extraordinarily correlator requirements. Even if is feasible to store-and-forward station data—storing the individual station data locally during the 300-hour lunar night and forwarding it for correlation during the lunar daytime when solar power is available—it is still required that the correlator consume minimal power.

Correlators have traditionally been huge power users. Fortunately, this situation is changing since the capability of the requisite sampler and multiplier chips is doubling approximately every 18 months. Space-qualified correlators (e.g., GeoSTAR) have already been built with ultra-low power chips, which also demonstrate excellent radiation-hard properties. The computing, communications, and gaming industries are also pushing digital electronics to smaller and less power hungry designs in order to extend battery life and reduce heat. This trend is expected to continue, suggesting that while the correlator will be a formidable challenge, the technology will be available to support it in 10 years. However, development work needs to be applied to push towards still lower power consumption units that are space capable and can survive in the harsh lunar environment.

Less work is currently ongoing in building ultra-low-power, thermally resilient *analog* electronics (ultra-low-noise amplifiers, A/D converters). A few groups are beginning to build such components, but rapid, directed, sustained technology development in ultra-low-power analog electronics is crucial to LRA progress.

4.3 Autonomous low-power (~ 1 W) generation or storage: Most space missions—NASA, DoD, and commercial—could realize large benefits from improvements in power generation and storage technology, particularly light-weight, high capacity, and long service lifetime.

The LRA will require a few hundred to tens of thousands of stations. Each station will house an electronics package including, at a minimum, low-noise amplifiers, receivers, A/D converters, and digital processing systems. While the station design is still being optimized, it is likely that other electronics components will be needed at each station such as filters, beam formers, data storage units, and intra-array communications modules. Therefore each station will require a small amount of power (~ 0.1 W), either distributed from a central location or *in situ*. The array will observe only during the lunar nighttime, so the power source must be capable of sustained, steady operation for 300 hours in an environment that is dark and cold (~ 125 K). Finally, the power sources or energy storage units must be extremely lightweight because there are so many of them.

Distributing power by wire from a central power source to the hundreds to thousands of stations spread over a radius of 10 km is considered infeasible for several reasons, two of which are that RFI could be self-induced by distributing power through long cables and the mass of such power cables is prohibitively large.

Three technologies worthy of further consideration and development are

1) *High specific capacity batteries:* Using current battery technology, we would require a mass of 10s of kg per station (not even counting insulation or other thermal protection requirements) to provide power through the 300-hr lunar night. We anticipate a major push in battery technology in the consumer electronics and automotive industries, which will certainly be helpful. However, these efforts will not be concerned with performance in extreme thermal environments and technology developments directed towards lunar surface applications must be monitored and encouraged.
2) *Small Radioisotope Power Units (RPUs)*: These have been studied by NASA's Glenn Research Center, among others. Current units include devices that provide more than 10 W and small units that produce less than 0.01 W. Development of units that provide an intermediate level power source will require directed effort. A major problem anticipated for RPUs is political, not technical: it is not clear that sufficient Pu-238 will be available in the future. Also, there are serious concerns about launching significant amounts of Pu-238.
3) *Beamed power distribution:* This concept is much discussed but little developed to date. Beaming is often discussed as a possible option for significant mass reduction in constellations

of micro-satellites and it is being studied for the NASA Constellation (human presence on Moon) program. However, in order to become a reasonable possibility for LRA, this option will require significant space infrastructure spending, a 5–10 times increase in efficiency, and careful attention to design in order not to generate RFI during power transmission.

4.4 Low-mass, high capability, autonomous rovers: Rovers or autonomous distributed robotics benefit NASA planetary exploration, lunar exploration, and human spaceflight; DoD, and potentially commercial users (in industries with significant human hazards).

The LRA requires a very large number of individual antennas. These may be grouped in small numbers (LARC) or large aggregations (DALI), but either way they will need to be deployed over an extended area. This large number of deployments probably demands multiple autonomous rovers—probably no fewer than 10, even if each rover uses many lunar day-night cycles for multiple deployments, and possibly hundreds if each rover is designed to only do a single deployment during a single lunar day.

As with other components of the mission, each rover will need to be ultra lightweight and have the lowest possible ratio of rover mass to rover-deployed mass. The low-mass requirement will, in turn, pose severe constraints on the rovers' mechanical and power systems. If the rovers need to perform multiple station deployments, they may have to survive the extremely cold lunar night.

Each rover will need to transport antennas to their desired locations, possibly as far as 10 km from the landing site, without active human intervention. Doing so will require autonomous navigation across the lunar terrain and around obstacles. Once at the desired location, the rover must use its site evaluation capabilities to assess the suitability of the site and adjust the location if necessary.

Even if each rover deploys a single station, it will have to deploy many antennas by erecting them in stances or by unrolling sheets of antennas across the lunar surface. They may need to deploy ribbons or cables to connect the stations together or to deploy mast antennas and/or free-space laser systems to link the station data to the central correlator hub. These tasks will require strength, high dexterity manipulation, and (probably) a gentle touch.

The LRA requires rover technology development work in a number of areas. These include:

1) Significant increase in the payload/rover mass ratio;
2) Increased rover traverse speeds (currently the best is ~ 10 cm s^{-1} for small rovers and LRA deployment will need at least 1 m s^{-1});
3) High dexterity manipulation capability for unrolling coated polyimide film or erecting an 8-m tall truss structure, making RF and power connections, and possibly for optical fiber connections; and
4) Potentially mechanical systems that can survive the lunar night.

A robust rover development effort is associated with NASA's planetary exploration program. These rovers are expected to require optimized dexterity and autonomy but are unlikely to be designed to withstand the extreme thermal range found on the Moon. We also expect that there will be a healthy rover development program associated with the return of humans to the Moon. That effort will certainly focus on working in the harsh lunar thermal environment but is unlikely to address the LRA's requirement for low mass coupled with large carrying capability. The DoD also supports autonomous vehicle development, e.g., DARPA's Grand Challenge program for autonomous vehicles. The LRA need for very delicate rover work, such as needed for fiber deployment, would benefit many NASA programs, and possibly also be of use in medical applications or in human-hazardous locations such as in nuclear reactors, volcanoes, and the deep ocean.

4.5 High data rate, lunar surface data transport systems: High data rate communications have significant commercial drivers, but systems for space or hostile Earth environments are need for NASA missions (particularly satellite constellations) and DoD missions.

The LRA stations will be distributed over an area about 10 km in diameter with all of the stations needing to communicate with the central control/correlator hub. Data rates from each station could exceed 400 Mbps. Correlation may occur real time, or the data may have to be stored through the night and transmitted for correlated during lunar day when solar power is available. In either case, each station will be transmitting 400 Mbps or more continuously, for about 300 hours at a time. The resulting correlated data will then need to be transmitted to Earth.

If current data storage technology trends continue, we do not expect data storage to be an issue, although the data storage units will need space qualification and testing for extreme thermal tolerance. Similarly with the digital correlator hardware (§4.2), if current trends continue, we expect that the correlator will require engineering but not major new technology development.

The intra-array communication is challenging and requires substantial technology development. Hundreds to thousands of stations must be able to communicate with the central hub.

- Communication by radio or microwave links is a well-known technology (e.g., 802.11g) but could disturb the pristine lunar farside radio environment (per International Telecommunications Union recommendation ITU.R RA.479-5), unless significant attention is paid in the design to out-of-band emissions. There is significant commercial interest in improving wireless radio communication, but it is unlikely that such development would include considerations such as the harsh lunar environment and the out-of-band emissions.
- Free-space laser links from individual stations to a central hub could be a solution. Such links can be very low power if used with avalanche photodiode single photon detectors and lenslet arrays. Free-space laser communication at data rates greater than 10 Mbps has been demonstrated by a Naval Research Laboratory-JPL team, and lasers present a natural method for communicating with a low probability of interception. How free-space links might be aligned requires further study, further development is required to increase the data rates, and contamination from electrostatically charged lunar dust could be a serious obstacle.
- Fiber optics are also a well-known technology. Typical fiber distances would be only of order 1 km, depending on array layout, but deployment of a web of cables would be a major technical challenge, particularly for fragile fibers and multiple rovers. Shielded cable is unlikely to be an option because of its high mass. Current fiber densities are of order 1 kg km^{-1}, though much of this is protective coating that may not be needed on Moon.

Data transport will also be required from the central control/correlator hub to Earth. This requires lunar infrastructure or a dedicated communications satellite, but does not require any unusual technology development.

5.0 Conclusion: The LRA will provide a unique, high precision cosmological and astrophysical probe of an unexplored realm of the early Universe, via observations of the highly redshifted 21-cm line of neutral hydrogen (from redshifts $6 < z < 50$). The methodology required for this study is extremely challenging and requires substantial technology development. If this technology work occurs in the decade 2010–2020, the LRA can be ready to move into development in the 2020–2030 decade.

The technology development required for LRA can be grouped into five main areas (or “tall poles”):

- **Low frequency, wide bandwidth, low-mass science antennas**;
- **Ultra-low power, ultra-low noise, radiation tolerant, digital and analog, electronics**;
- **Autonomous low-power (~ 1 W) generation or storage**;
- **Low-mass, high capability, autonomous rovers**; and
- **High data rate, lunar surface data transport systems**.

Many of these technologies also are likely to have broad applicability to space missions, both those undertaken by NASA as well as those of the DoD and commercial interests. We expect some of these technologies to enjoy some development driven by other interests, however each area requires specific technology development for the success of the LRA.

This initial technology assessment is based on two concept studies funded under the Astrophysics Strategic Mission Concept Studies (ASMCS) program over the past year. Over the next decade, on-going investments in these technologies in other areas (DoD, commercial) must be both monitored as well as leveraged to produce implementations suitable for NASA astrophysics missions and the LRA.