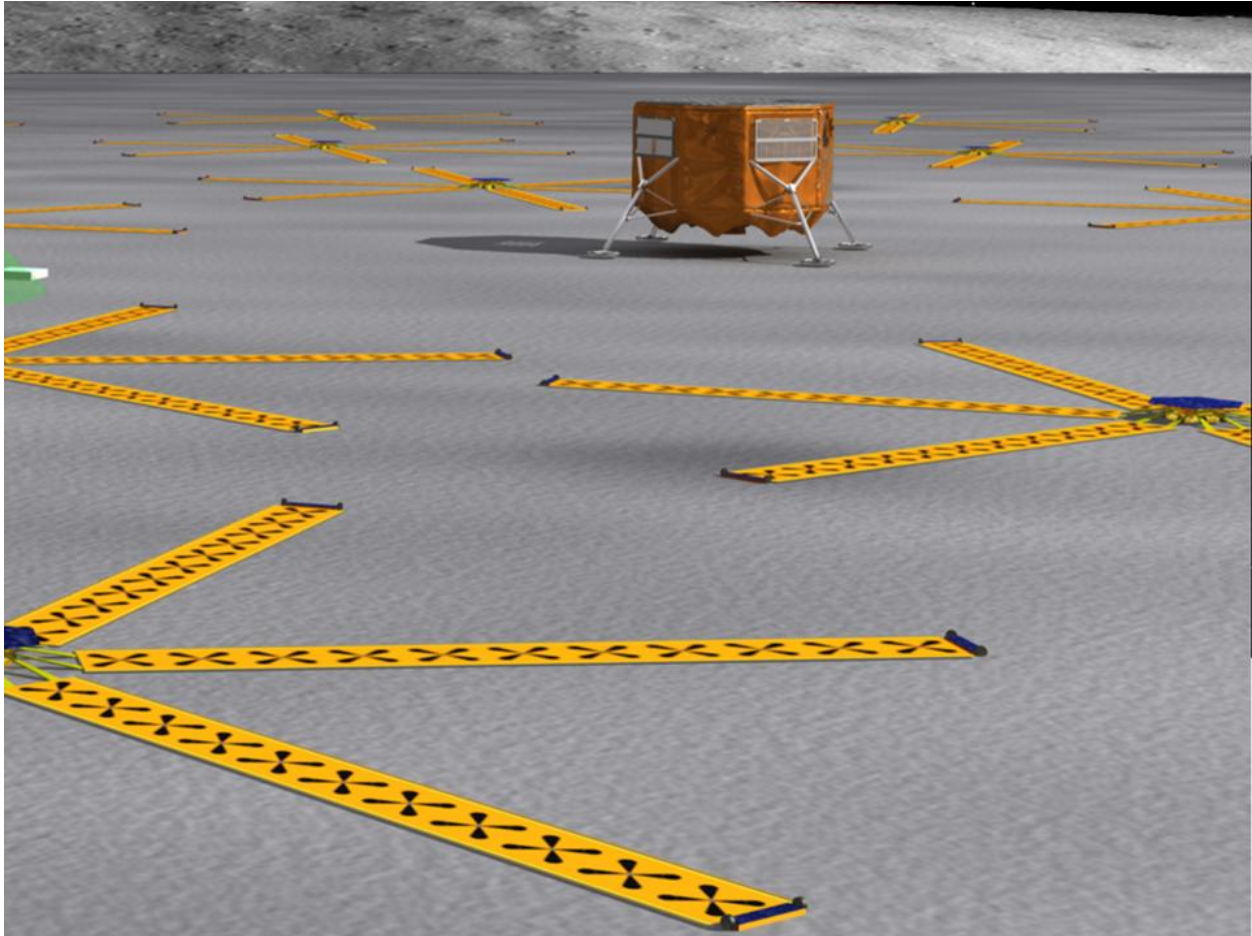


## The Lunar Radio Array (LRA)



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## 1 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 H 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 have applicability to other NASA missions, space missions conducted by other Government agencies, or potentially commercial interests.

Hydrogen is the dominant component of the intergalactic medium (IGM), and LRA observations potentially will provide information 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 form. Primary questions include, Does the standard cosmological model describe the Universe during the “Dark Ages”? How does the IGM evolve during this important time? What were the properties of high-*z* galaxies? How did they affect the Universe?

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.

This initial technology assessment originates from two concept studies funded under the Astrophysics Strategic Mission Concept Studies (ASMCS) program over the past year. 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.

<b>Technology</b>	<b>Duration</b>	<b>Cost</b>	<b>Heritage</b>	<b>Synergies</b>
Low-frequency, wide-bandwidth, low-mass science antennas	7 years	\$3M	Ground-based antenna development	NASA heliophysics missions
Ultra-low power, radiation-tolerant digital and analog electronics	7 years	\$7M	NASA ST5; JPL GeoSTAR correlator	NASA missions; DoD; commercial
Autonomous low-power generation	5–7 years	\$25M	Multiple spacecraft missions	NASA micro-sats, small lunar payloads
Low-mass, high-capability, autonomous rovers	7–10 years	\$5M	Mars rovers, ATHLETE rover, DARPA competitions	NASA planetary, lunar exploration; DoD; commercial (human-hazard)
High data rate, lunar surface data transport	7 years	\$1.5M	NRL-JPL free-space lasers; commercial radio wireless, optical fiber	NASA lunar exploration, satellite constellations

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 Key Science Goals

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

Relevant Science white papers: “Astrophysics from the Highly-Redshifted 21 cm Line” by Furlanetto et al. and “Cosmology from the Highly-Redshifted 21 cm Line” by Furlanetto et al.

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, e.g., **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?**

Hydrogen is the dominant component of the IGM, and neutral hydrogen (H I) displays a hyperfine spin-flip transition at a frequency  $\nu = 1420$  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

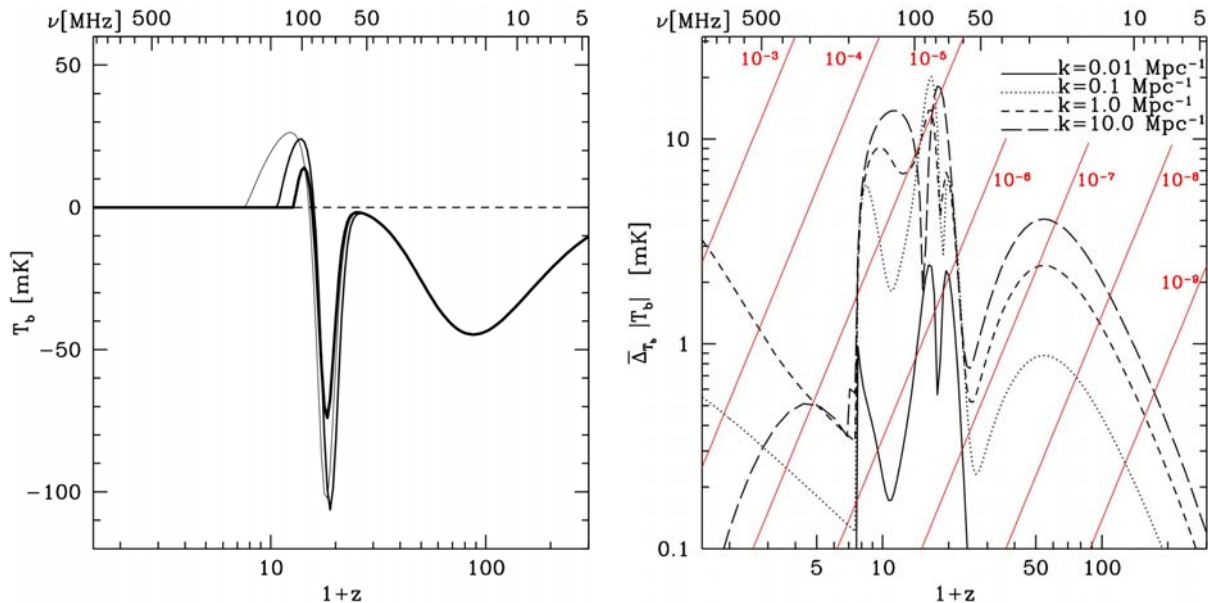
The neutral hydrogen (H I) hyperfine line has the potential to be the spectral equivalent of the powerful continuum CMB observations.

possible to determine the distribution of hydrogen throughout the Universe from the present day to a redshift  $z \sim 100$ . 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 (§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  $\Delta_T \equiv (k^3 P_T(k)/2\pi^2)^{1/2}$  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.

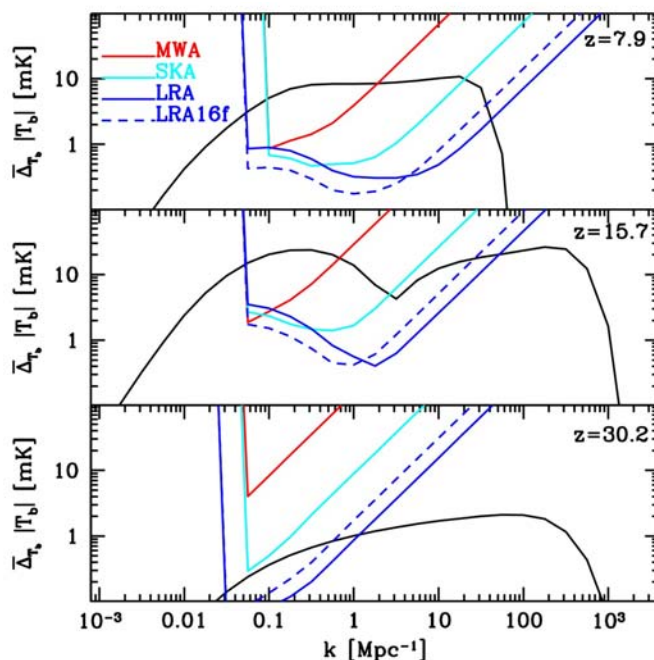
This power spectrum approach motivates a number of current generation instruments: the Murchison Wide-field Array,<sup>2</sup> the Precision Array to Probe the Epoch of Reionization,<sup>3</sup> and the

<sup>2</sup> MWA: <http://www.mwatelescope.org/>

<sup>3</sup> PAPER: <http://astro.berkeley.edu/~%7Edbacker/eor/>

Low Frequency Array,<sup>4</sup> all of which focus on detecting the H I power spectrum at redshifts  $z \approx 7$ , at which the reionization of the neutral IGM produces a large signal. While not directly motivated by EoR observations, the Long Wavelength Array<sup>5</sup> has frequency coverage that overlaps with some of these instruments. These pathfinder telescopes will likely be followed by the Square Kilometre Array (SKA)<sup>6</sup> 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  $rT_{\text{sky}}(\nu)$ , for  $r = 10^{-4}$ – $10^{-9}$ , with  $T_{\text{sky}}$  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.** 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 Astrophysics

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

<sup>4</sup> LOFAR: <http://www.lofar.org/>

<sup>5</sup> LWA: <http://lwa.unm.edu/>

<sup>6</sup> SKA: <http://www.skatelescope.org/>

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

**Radio Transients:** Transient radio 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 to all of the ground-based arrays is radio interference (§2.3), 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 ( $\sim 1$  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 ( $\text{Ly}\alpha$  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,  $\text{H}400\alpha$  through  $\text{H}500\alpha$  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.

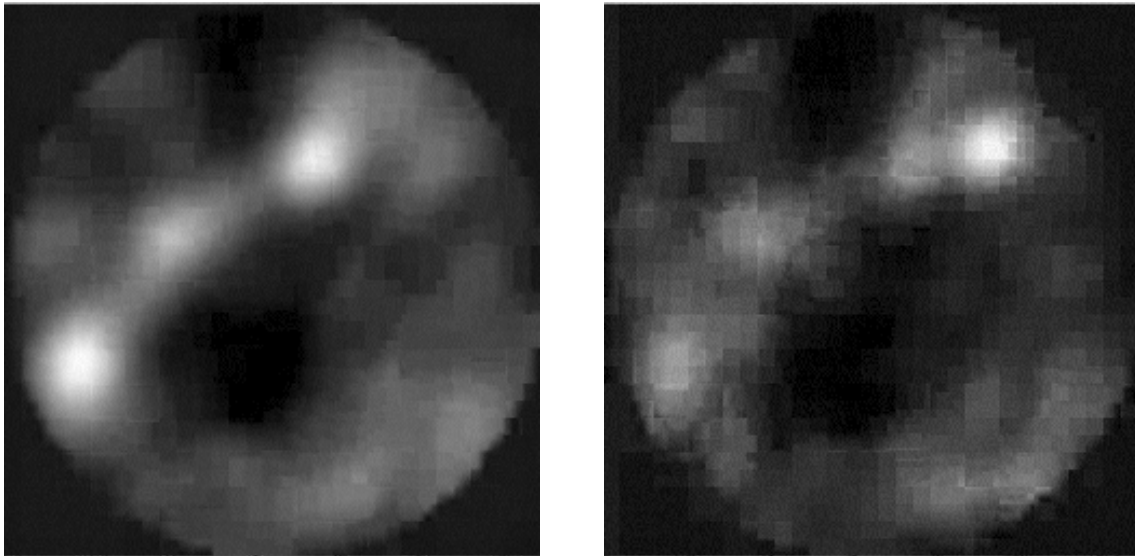
### **2.3 The Moon as an Astronomical and Cosmological Platform**

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 5). The Moon reduces such interference to a negligible level (Alexander & Kaiser 1976).

**No (Permanent) Ionosphere:** The Earth's ionosphere produces phase errors that limit radio observations (in addition to simply reflecting interference from distant transmitters, Figure 5). 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.



**Figure 5. 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.***

**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.

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### 3 Technical Overview: Mission Concept & Technology Development

The scientific objective of the LRA is to exploit the highly redshifted hyperfine transition of neutral hydrogen (21-cm H I line) to probe as early in the Universe's history as possible. Precision cosmological and astrophysical measurements would be extracted from a power spectral analysis of the H I line fluctuations on the sky, in a manner analogous to the continuum measurements of the cosmic microwave background (CMB).

Initial concept studies for the LRA have been funded under the NASA Astrophysics Strategic Mission Concept Studies program. These concept studies have identified a number of technologies that need to be developed and matured over the next decade in order for the LRA to be realized.

A companion white paper on technology development has also been submitted.

#### 3.1 Mission Summary

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 1. LRA Scientific Requirements**

<b>Parameter</b>	<b>Nominal LRA</b>	<b>Dark Ages LRA</b>
Redshift	8.5–30	6–50
Brightness Temperature Sensitivity	10 mK	4 mK
Angular Resolution	3'	1.4'

**Table 2. LRA Derived Technical Requirements**

<b>Parameter</b>	<b>Nominal LRA</b>	<b>Dark Ages LRA</b>	<b>Scientific Driver / Technology</b>
Collecting Area	0.36 km <sup>2</sup>	3 km <sup>2</sup>	Brightness Temperature Sensitivity Low-mass antennas
Frequency	50–150 MHz	30–200 MHz	Redshift Electronics, Power
Maximum Baseline	5 km	10 km	Angular Resolution Rovers, Data transport
Lifetime	3 yr	5 yr	Brightness Temperature Sensitivity Power

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.

Two concepts are currently being explored for the LRA:

*The DALI concept* (Dark Ages Lunar Interferometer) combines ~ 1500 individual antennas into a single interferometer element or “station.” DALI envisions simple dipole-like antennas and transmission lines deposited on long strips of polyimide (e.g., Kapton™) film, ~ 100 m × 1 m × 20 micron. Each station also includes a “hub” for digitization and transmission of the signals to the central correlator. The stations are sufficiently large that “multi-beaming” is required in order to acquire a sufficient field of view. There are about 300 stations.

*The LARC concept* (Lunar Array for Radio Cosmology) combines four helices into a single interferometer element or “stance.” Each helix is 1 m in diameter and 8.2 m high, the four helices 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. The major electronics / signal processing job for the LARC concept is correlating the  $N \times (N-1)$  signals from more than 10,000 elements.

In both concepts, 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 must be returned to the central processor and those signals must be combined. Observations are conducted only during lunar night, to avoid solar interference. 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 correlated data are 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.

The LRA is located on the lunar farside, in a relatively flat area at least 10 km across. LRA components are 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 is handled by rovers. The central processing unit remains on the cargo lander and serves as a control and communications center.

### **3.2 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 H I 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 H<sub>2</sub>, the major coolant in the proto-galaxies where the first stars form, while X-rays produce free electrons and catalyze the formation of H<sub>2</sub>, but they also heat the gas and prevent the formation of small galaxies. These radiation fields, and their effects on feedback and the H I 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.

### 3.3 Technology Development

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, high data-rate lunar surface communications that can survive the punishing lunar environment.

**Table 3. Key LRA Technology Development**

Technology	Requirement	Current State	Required (~ 2020)	Heritage	Synergies
Low frequency, wide bandwidth, low-mass science antennas	<ul style="list-style-type: none"> <li>• ~ 20 – 150 MHz</li> <li>• Easy deployment</li> <li>• Minimal mass, volume</li> </ul>	DALI: proof-of-concept film antenna LARC: concept design	<ul style="list-style-type: none"> <li>• Prototype</li> <li>• Deployment demonstration</li> </ul>	Ground-based radio astronomical arrays	NASA heliophysics missions
Ultra-low power, ultra-low noise, radiation tolerant digital and analog electronics	<ul style="list-style-type: none"> <li>• Low power budgets</li> <li>• Analog amplifiers and ADCs</li> <li>• Digital components</li> <li>• Operate / survive lunar thermal extremes</li> </ul>	<ul style="list-style-type: none"> <li>• 130 nm process</li> <li>• ~ 1.3 V supply</li> <li>• Primary focus on digital</li> <li>• Limited temp. range</li> </ul>	<ul style="list-style-type: none"> <li>• 12 nm process or better</li> <li>• &lt; 1 V supply</li> <li>• General purpose chips and components</li> </ul>	NASA ST5 spacecraft, GeoSTAR correlator	NASA missions, DoD, commercial
Autonomous low-power generation and storage	<ul style="list-style-type: none"> <li>• 100s to 10,000s of individual station sinks</li> <li>• ~ 100 mW through lunar night</li> <li>• &lt; 1 kg per station</li> </ul>	<i>Batteries:</i> Best Li-ion ~3 kg/W for 300 hr; must charge at $270\text{ K} < T < 310\text{ K}$	<ul style="list-style-type: none"> <li>• &lt; 1 kg/W</li> <li>• Steady 0.1 W for 300 hr at 100 K</li> <li>• Charge &gt; 310 K</li> </ul>	Planetary spacecraft, rovers	NASA micro-sat missions, small lunar payloads, commercial micro-sats
		<i>RPU:</i> Available for > 10 W or < 10 mW	<ul style="list-style-type: none"> <li>• ~ 100 mW units</li> <li>• Sufficient Pu-238?</li> </ul>	Multiple deep-space missions	
		<i>Power beaming:</i> Terrestrial system studies	Lunar infrastructure, ~ 10× efficiency		
Low-mass, high capability rovers	<ul style="list-style-type: none"> <li>• High payload / rover mass ratio</li> <li>• Autonomous navigation, antenna deployment</li> </ul>	<ul style="list-style-type: none"> <li>• ~ 850 kg</li> <li>• kW power</li> <li>• Payload / rover mass ratio ~ 3</li> <li>• 10 cm/s</li> </ul>	<ul style="list-style-type: none"> <li>• 10s of kg</li> <li>• ~ 100 W power</li> <li>• Payload / rover mass ratio ~ 5</li> <li>• &gt; 1 m/s</li> </ul>	Mars rovers, ATHLETE rover, DARPA competitions	NASA planetary, lunar exploration; DoD; commercial (human-hazard activities)

High data rate, lunar surface data transport	<ul style="list-style-type: none"> <li>• &gt; 400 Mbps</li> <li>• Low mass</li> <li>• Low power</li> <li>• Operate / survive lunar thermal extremes</li> <li>• Non-RFI generating (ITU compliant)</li> </ul>	<i>Free-space laser</i> 10 Mbps	<i>Free-space laser</i> > 400 Mbps	NRL-JPL demonstrations	NASA lunar exploration, satellite constellations
		<i>RF wireless</i> 600 Mbps	<i>RF wireless</i> Non-RFI generating	Commercial RF wireless	
		<i>Optical fiber</i> 1 kg/km	<i>Optical fiber</i> 0.1 kg/km	Commercial optical fiber	

### 3.4 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 is the following. 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 could also be used as a technological demonstrator.

**Stage I:** 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 robotically, 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  $10^5$ , with deployment conducted robotically.

## 4 Technology Drivers

Section 3 summarizes 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.

### 4.1 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 measurements were made in the Dark Ages frequency band. The EoR pathfinder instruments (§2.1) focus on the expected H I signal from  $z \approx 6$  ( $\nu \approx 200$  MHz), but both the LWA and LOFAR have antennas that operate to  $\nu \approx 20$  MHz ( $z \sim 70$ ), though neither would have the sensitivity to detect an H I signal at these frequencies. Figure 4 shows a prototype LWA antenna, for operation in the frequency range  $\nu = 20\text{--}80$  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 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:** Helical antennas, grouped in “stances” of four, which are delivered in flat packages and erected using ultra-lightweight trusses. Development is needed in the electromagnetic performance of the antennas, the design of a lightweight structure, and in their deployment.

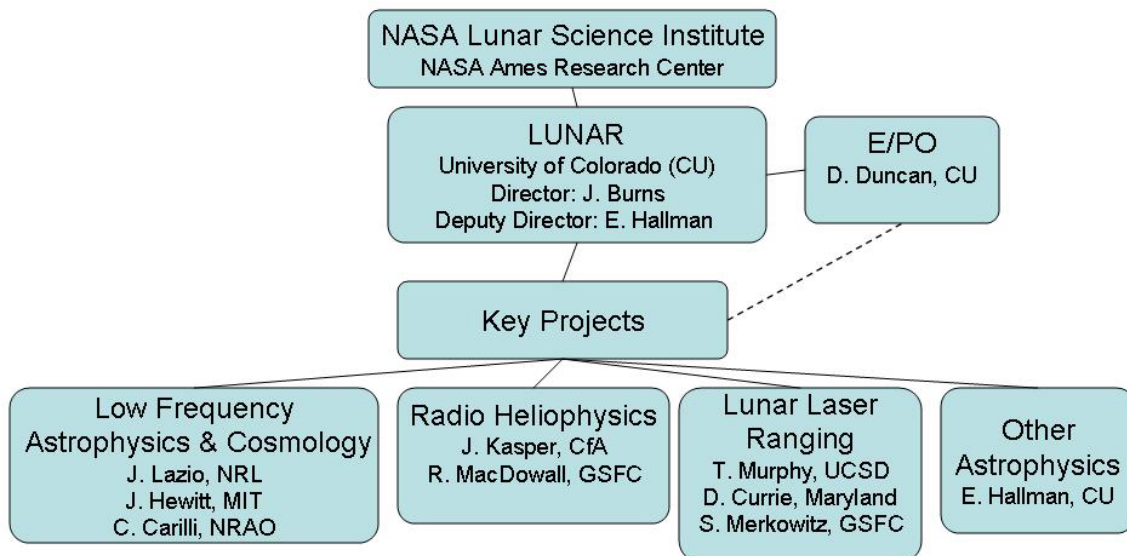


**Figure 4. A prototype Long Wavelength Array antenna. This antenna is sensitive to the frequencies relevant for probing the Dark Ages. The final antenna design has manufacturability as a criterion in its design, and will be somewhat lower in mass, but remain too massive for a lunar mission. In the background are the antennas of the Long Wavelength Demonstrator Array.**

## 5 Activity Organization, Partnerships, and Current Status

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 5). 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 Cosmology & Astrophysics, 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.



**Figure 5. Organizational structure of LUNAR. Only key team leaders are identified.**

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 (DALI; PI: J. Lazio)**, funded by the Astrophysics Strategic Mission Concept Studies (ASMCS) program, DALI would be a farside, polyimide-film based dipole array for cosmological studies.
- **Lunar Array for Radio Cosmology (LARC; PI: J. Hewitt)**, funded by the ASMCS program, LARC would be a farside, freestanding helical array for cosmological studies.

## 6 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.

### 6.1 LRA Technology Development

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

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 1 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. Additional discussion of and justification for each technology follows Table 1.

**Table 4. Illustrative LRA Technology Development Program**

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

**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<sup>7</sup> 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.

**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

<sup>7</sup> A microwave radiometer for Earth remote sensing.

to that for the development of a new, broadband antenna for the ground-based Long Wavelength Array.

**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.

## 6.2 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. Illustrative Schedule for LRA Precursor Mission**

<b>6.2.1 Phase</b>	<b>6.2.2 Duration</b>
Phase A	3 months
Phase B	6 months
Phase C/D	20 months
Phase E	6 months
<b>Total</b>	<b>35 months</b>

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 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).

## 7 Cost Estimates

We describe cost estimates for a technology development program specific to the LRA. 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**

<b>Technology Component</b>	<b>Program Cost (\$M)</b>
Low frequency, wide-bandwidth, low-mass science antennas	3
Ultra-low power, radiation tolerant digital & analog electronics	7
Distributed low-power generation	25
Low mass, high-capability, autonomous rovers	5
High data rate, lunar surface data transport	1.5
<b>Total</b>	<b>41.5</b>

**Low frequency, wide-bandwidth, low-mass science antennas:** Our estimate of a \$3M program is based, 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 ( $\sim 10$  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 \$1.5M program is based on a proposed NRL-JPL effort to develop and demonstrate a free-space laser communication system for a Mars rover. 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.