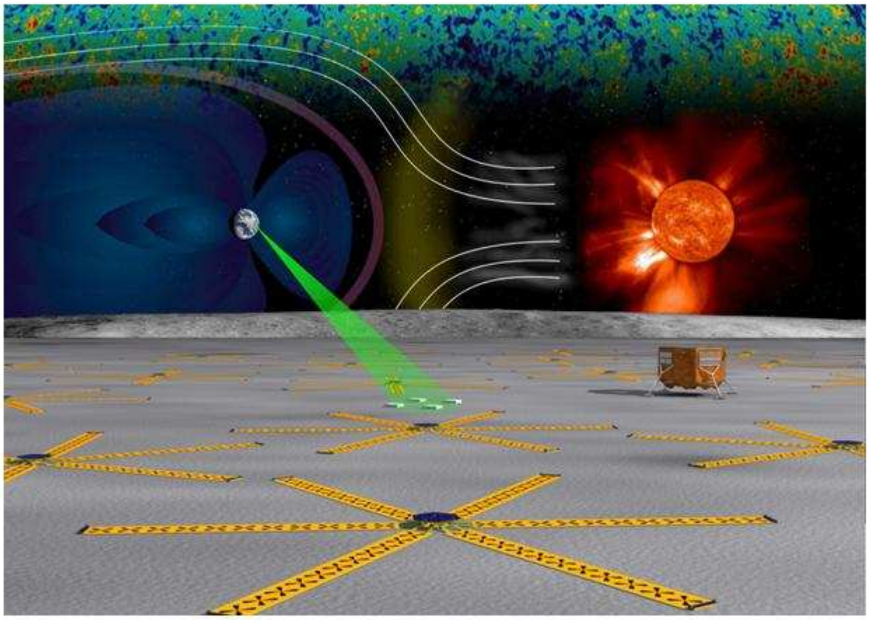

Lunar University Node for Astrophysics Research (LUNAR): Exploring the Cosmos From the Moon

A proposal submitted to the NASA Lunar Science Institute in response to the Cooperative Agreement Notice NNH08ZDA008C

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Contents

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1 Executive Summary

How can the Moon be used as a platform to advance important science goals in astrophysics and the physical sciences? This is one of the key questions posed by the NLSI and the NRC study *The Scientific Context for Exploration of the Moon.* The **Lunar University Node for Astrophysics Research (LUNAR)**, a consortium of top research institutions led by the University of Colorado, proposes a coherent and integrated plan for research, education and outreach, and community development to advance **Astrophysics From the Moon**. The LUNAR consortium proposes to create a national virtual node of the NLSI for astrophysical research and education that focuses on the key, unique instruments that most effectively take scientific advantage of sites on the lunar surface. LUNAR team members were selected based upon their cutting-edge research, their innovations in teaching and outreach, and their desire to develop a program of research from the Moon.

LUNAR will address fundamental questions about the cosmos *from the Moon* including gravitational physics, cosmology, and heliophysics.

Why the Moon and why now? The Moon is a unique platform for fundamental astrophysical measurements of gravitation, the Sun, and the Universe. Lunar Laser Ranging of the Earth-Moon distance provides extremely high precision constraints on General Relativity and alternative models of gravity. Lacking a permanent ionosphere and, on the farside, shielded from terrestrial radio emissions, a radio telescope on the Moon will be an unparalleled heliospheric and astrophysical observatory. Crucial stages in particle acceleration near the Sun can be imaged and tracked. The evolution of the Universe during and before the formation of the first stars can be traced for the first time, yielding high precision cosmological constraints. LUNAR will pioneer important new astrophysical research by "using the Moon as a unique platform"; it broadens the participation in the NLSI by incorporating physical sciences *from the Moon*; it combines astrophysics and the Moon, which are individually both compelling means of motivating students and the public at large; and the required technology development is synergistic with other lunar science programs. It is urgent to begin development of the lunar platform for astrophysics, given the technology and science programs that must be completed to guide the design of experiments that may be emplaced in only a decade.

Research

Our research efforts are composed of four Key Projects that provide structure under which individual research tasks are organized. Each Key Project also has a technology development component with relevance to the general deployment of scientific instrumentation on the lunar surface.

Key Project - Low Frequency Cosmology and Astrophysics: The Universe's Dark Ages occurred between the end of Recombination (when the Universe first becomes transparent, producing what we observe today as the Cosmic Microwave Background) and the beginning of Reionization (when the first stars and black holes form). Theoretical models have shown that highly redshifted neutral hydrogen signals from the first collapsing structures in the Dark Ages may be detectable with sensitive low frequency antennas operating below $\sim$100 MHz. The Moon's radio-quiet farside is likely the only viable location in the inner solar system for such sensitive observations. These radio data could be the richest of cosmological datasets that may constrain the nature of inflation, possible decay of dark matter, and the equation of state of dark energy. Three research tasks will explore the viability of a lunar farside low frequency telescope for cosmology and astrophysics: (1) A significant theoretical modeling effort to produce more realistic simulations of the Dark Ages that will determine

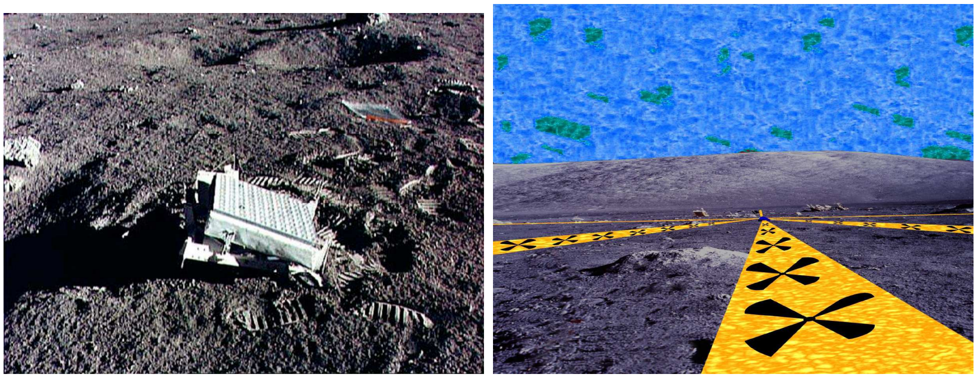


Figure 1: The unique attributes of the Moon for astrophysics are illustrated with two instruments. *Left:* The Apollo 14 laser ranging reflector package after installation at the Fra Mauro landing site, used in constraining models of gravity and the Moon's liquid core. *Right:* An artist's concept of the Dark Ages Lunar Interferometer (DALI) with polyimide foil and embedded low frequency dipoles (shown in yellow); a sky filled with redshifted neutral hydrogen signals from the first collapsing objects illustrates the early Universe to be studied by DALI.

the cosmological constraints achievable by various designs for the low frequency array; (2) An array concept and algorithm development project that will explore the telescope performance relative to the array configuration and test specific processing methodologies on existing radio astronomical data; (3) Technology development focusing on two key subsystems to reduce risk, low-mass science antennas and autonomous rovers for deployment, which has relevance to other NLSI lunar science efforts.

Key Project - Gravitational Physics and Lunar Structure: An enduring legacy of Apollo is the lunar laser ranging (LLR) package that has been used to test alternate theories to General Relativity (GR) and to probe the nature of the lunar core. Current alternate theories for gravity, including those that explain dark matter and dark energy, predict deviations from GR at a level that is potentially within the grasp of the next generation of LLR. LUNAR will design and test LLR array technologies that are capable of extremely high precision. Specifically, we will (1) Develop the science goals for higher precision LLR that incorporate new gravitational model frameworks as well as new constraints on the Moon's internal structure, simulating observations to explore the sensitivities and timescales of new LLR data to key physics parameters; (2) Assess two different approaches to corner cube designs for next-generation retroreflectors and a new transponder with the goal to improve the accuracy from the current $\approx$1 mm to $\sim$10 μm; (3) Investigate environmental issues for retroreflectors on the lunar surface, including dust and shading.

Key Project - Radio Heliophysics: The Sun is a laboratory for understanding how cosmic rays are accelerated to high energies - important in safeguarding astronauts on the Moon. Low frequency radio observations are an excellent diagnostic of electron acceleration because the emission process encodes information about the source region. LUNAR will study an array of short dipoles operating at $<$20 MHz deployed on the lunar nearside during an early science sortie mission. Our goals include (1) Developing a statistical characterization of the lunar radio environment using data from previous spacecraft to understand terrestrial RFI on the lunar nearside, the solar background, and the conditions on the farside; (2) Refining the heliophysics science and performance requirements to optimize the design of the array; (3) Examining antenna deployment strategies in conjunction with the cosmology Key Project; (4) Identifying and encouraging the development of ultra low power and ultra low temperature electronics for the lunar surface.

Key Project - Assessment of Other Astrophysics Enabled by a Return to the Moon: Other potentially interesting concepts for lunar-based telescopes have been proposed. These ideas include rotating liquid mirror telescopes, optical/IR interferometers, and cosmic-ray and neutrino

Science Theme	NASA Strategic Goal	Telescope/Instrument	Why the Moon?
Low Frequency Cosmology & Astrophysics	3D: Discover destiny of Universe	Long-baseline, low frequency (<100 MHz) array	unique radio-quiet of lunar farside
Gravitational Physics	3D: Origin of Universe	Lunar Laser Ranging	drag-free laboratory
Heliophysics & particle acceleration	3B: Understand Sun	Low frequency (<20 MHz) roll-out array	lunar surface structural support; interference reduction; very low frequency ionospheric cutoff

detectors. How viable are these potential telescopes and do they require the Moon? On behalf of the NLSI, we propose to assess potential concepts for lunar-based astrophysics via a small grants program. LUNAR will run a peer review of these proposals, provide year-long subcontracts funded via this NLSI grant, and then evaluate the results at our yearly scientific symposium.

Education and Public Outreach

We propose to (1) create two Planetarium shows, both in English and Spanish, that will be piloted at our Fiske Planetarium and then distributed nationally - a general audience program that illustrates the Constellation system and expected science of/on/from the Moon, and a show based upon the award-winning children's book *Max Goes to the Moon*; (2) Compile existing material and then distribute nationally new program content for "Science on a Sphere", including displays of high resolution images of the Moon; (3) Conduct workshops for teachers from urban and rural school districts, with particular outreach to underserved communities in the state. E/PO is <2% of the budget but will be matched dollar-for-dollar by Colorado.

Broad-based Contributions of LUNAR to the Objectives of NLSI

Training: Colorado has established an innovative three-course undergraduate curriculum dedicated to space and lunar science, exploration, and space policy. Classes include guest lectures from NASA project managers and scientists, and the lunar science community. Through hands-on projects, students will be challenged to examine problems facing LUNAR Key Projects, stimulating innovation within LUNAR and training of the next generation of lunar scientists and explorers.

Community Development: Our plan to help develop the lunar science community consists of (1) Conducting multidisciplinary technology-themed workshops, involving a cross-section of the NLSI, to explore "tall pole" issues such as mass and power for instruments on the Moon; (2) Holding a yearly science symposium dedicated to the four Key Projects and to our E/PO program resulting in published conference proceedings; (3) Having a monthly colloquium series among our LUNAR institutions with speakers addressing topical issues in lunar science of/on/from the Moon.

Institutional Commitments: LUNAR institutions have strong commitments to developing astrophysics, gravitational physics, and heliophysics *from the Moon*. We are committing significant institutional resources including salary for students (RA/TA), postdoctoral fellows, academic year release time for Co-Is, equipment, administrative support, and office/laboratory space. In addition, our industry partners, Lockheed-Martin and Ball Aerospace, will provide mentorship to students, guest lectures in classes, and assistance in developing our Planetarium programs. In total, the dollar equivalent value of resources contributed by the LUNAR institutions is over $1 million.

Management: Overall oversight will be provided by the P.I./Director and the University of Colorado. Each Key Project and the E/PO will be managed by a small team of senior scientist Co-Is and funded via subcontracts. The P.I., Assistant Director, and Key Project lead scientists together form a steering committee. The P.I. has final authority and responsibility over all expenditures, subject to the rules and regulations of U. Colorado and NASA.

2 Summary of Personnel, Commitments, and Costs

3 Research and Management Plan

3.1 Introduction

Community-based reviews consistently identify fundamental astrophysics and physics - in the form of cosmology, solar science, and testing theories of gravity - as priorities that should be advanced by lunar-based observations. The LUNAR Consortium proposes to address these multifaceted astrophysics themes via a unifying scientific connection: **answering fundamental questions about the cosmos from the Moon.** Among the scientific questions that we will pursue in the LUNAR research program are:

- Was Einstein right about gravity? Do we need Dark Energy to explain the large scale Universe?
- Do low frequency radio observations of the Universe's Dark Ages contain clues to the nature of inflation, dark energy, and the decay of dark matter?
- How are high energy cosmic rays accelerated by the Sun and can bursts of these particles be predicted via low frequency radio observations to enhance safety of the astronauts on the lunar surface?
- What can we learn about the Moon's liquid core?

LUNAR will create a virtual node of NLSI to advance the key science uniquely enabled by astrophysical observations *from the Moon*.

Coupled with the science investigations, LUNAR will pursue focused technology development driven by technological "tall poles" identified by initial concept studies. An innovative education and public outreach effort will be coupled to the proposed astrophysics research. These components of LUNAR are focused on NLSI's goal of using the Moon as a unique platform for scientific investigations of the cosmos and are synergistic with NLSI's plans for lunar science and exploration. As a prominent university in space astrophysics and educational innovation, U. Colorado will lead a national virtual NLSI node for astrophysics research *from the Moon*.

The Moon as a Platform for Astrophysics Research

The *Vision for Space Exploration* has stimulated new interest in astrophysics enabled by a return to the Moon. A 2006 conference at STScI, chaired by M. Livio, with this same title was attended by over 100 scientists. Participants identified key attributes of the Moon that will permit unique classes of astrophysical observations and measurements: a farside free of terrestrial radio interference and a drag-free laboratory for precise laser ranging.

Lunar Low Frequency Array: The 2007 NRC study entitled *The Scientific Context for Exploration of the Moon* singled out a low frequency radio telescope emplaced on the lunar surface as a particularly important scientific instrument. The report stated that such a telescope on the "extraordinary radio-quiet sites on the lunar farside" would be a "powerful tool in investigating the "dark ages" of the universe, before the reionization era, in which highly redshifted 21 cm (1420 MHz) emission from neutral hydrogen would reveal the earliest structures in the universe before the first phase of nuclear enrichment." The NRC study went on to say that "a low-frequency radio interferometer with simple dipole elements spread out on a kilometer scale of the lunar surface has synergistic value to both priority astrophysical and heliophysical research," particularly in understanding particle acceleration mechanisms. The NRC panel urged that "near-term studies should be started to improve the understanding of the requirements and possible limitations of such a low frequency radio interferometer effort, perhaps defining near-term site survey experiments that would help clarify the potential."

The NRC committee further described the potential of imaging radio emissions from solar corona mass ejections and solar flares using a low frequency array by stating "the Moon offers a large, stable surface on which to build a large, capable low-frequency radio array for the purpose of imaging solar sources at wavelengths that cannot be observed from the ground, an array that is well beyond the current state of the art for antennas in space."

Lunar Laser Ranging: The NRC Committee described Lunar Laser Ranging (LLR) as another uniquely enabled experiment for the lunar surface. They stated that LLR reflectors "provided important data on the lunar orbit and are now challenging (our) understanding of basic physics." These LLR data are used to constrain deviations from General Relativity as well as the nature of the Moon's core. Recent observations of supernovae, galaxy clusters, large-scale structure and the cosmic microwave background have led to an unexpected paradigm shift in our understanding of the universe: that 95% of the mass-energy content of the universe is in an exotic form, dubbed dark matter and dark energy. Is it possible that our framework for describing the dynamics and evolution of the universe—General Relativity (GR)—is itself deficient? When coupled with the fact that we have not yet successfully unified the theories of GR and quantum mechanics, it is imperative that we subject Einstein's model for gravity to the utmost scrutiny. Lunar laser ranging has been and will continue to be on the front line of such tests. Recent advances using the Apache Point Observatory in New Mexico have achieved 1 mm precision (Murphy *et al.*, 2008). Current measurements are inadequate to further test alternate gravity models. LUNAR proposes deployment of next-generation LLR reflectors that will improve the accuracy to ∼0.01 mm, enabling confirmation or rejection of several gravity models.

The LUNAR Consortium Approach

It is clear that the Moon is a prime destination for particular classes of telescopes and instruments for fundamental astrophysical measurements. The NLSI has recognized this in defining lunar science within the Institute's mission to include "use of the Moon as a platform for performing scientific investigations including observations of the Earth and other celestial phenomena that are uniquely enabled by being on the lunar surface." LUNAR will be a key node for NLSI in bringing broad-based representation from the physical sciences, in complementing the scientific scope brought by the lunar geological sciences, and in researching topics at the very frontier of astrophysics. There has been a gap of nearly 20 years since the last serious studies of lunar-based observatories so we urgently need to engage a new generation of space scientists trained in the HST-era to define the science program, develop the technologies, and build a constituency for *Astrophysics From the Moon* that will potentially begin in only a decade.

Our LUNAR Consortium is composed of recognized scientific leaders, along with their students and postdocs, who have experience in developing the scientific goals and instruments required to grow a vigorous program of astrophysics research from the Moon. Partner institutions in this consortium (Section 2) include 10 universities, 3 NASA Centers, the Smithsonian Astrophysical Observatory, the National Radio Astronomy Observatory, and the Naval Research Laboratory. LUNAR will bring together expertise in each of the key science areas to focus on the most important research issues, and to create a program of training the next generation of citizens, scientists, and technologists through undergraduate, graduate, and postdoctoral programs.

As the lead institution, Colorado plays an important role in implementing the science, technology evaluation/development, and education/outreach goals summarized in Table 1. P.I. Burns has over two decades of experience working with the astrophysical, the lunar science, and the exploration communities in designing telescopes for the Moon, and managing large teams as a university administrator.

Our approach in addressing the science themes for astrophysics from the Moon is to support fundamental research with 4 Key Projects including:

- Precise tests of General Relativity and alternative models of gravitation, and physical constraints on the lunar interior using Lunar Laser Ranging,

Table 1: LUNAR Projects

Key Project	**Science Drivers**	**Technology Development**
Low Frequency Cosmology & Astrophysics	high precision cosmology via observations of universe's Dark Ages	low-mass antennas; deployment; rovers
Lunar Laser Ranging	tests of General Relativity (e.g., Equivalence Principle); interior structure of Moon	next-generation retroreflectors & laser transponders with $\sim 10\mu$m accuracy.
Radio Heliophysics	coronal mass ejections; high energy particle acceleration; astronaut safety	sortie-deployable antennas; low temperature, low power electronics
Assessment of Other Astrophysics Enabled by a Return to the Moon	e.g., optical interferometer; cosmic ray & γ-ray telescopes	via LUNAR grants program
Education & Public Outreach	undergraduate student projects; public multilingual planetarium shows	Design dipole deployment mechanism

- Precise cosmological measurements utilizing highly redshifted signals at low frequencies (< 100 MHz) from neutral hydrogen during the pre-reionization or Dark Ages of the Universe,
- Heliophysics of solar eruptions and particle acceleration in the inner solar system at low radio frequencies (< 20 MHz),
- Critical evaluations of the scientific potential and uniqueness of other astrophysics observations and experiments enabled by the Constellation infrastructure.

Our consortium will promote cross-disciplinary interactions with the astrophysics, lunar science, and lunar exploration communities, both formally and informally, among the Co-Is and their research groups, and between LUNAR participants and other researchers both within the NLSI and outside of it, in order to address interdisciplinary and multidisciplinary questions. We will use the Co-Is and this program as a means of connecting to a larger group of faculty and researchers both at LUNAR institutions and nationally who are involved in lunar science research, in order to leverage NLSI support into a much larger program.

Using these concepts as broad guidelines, we have developed a research and E/PO program to take best advantage of the expertise within the LUNAR consortium. Our approach in developing our proposed programs is as follows:

- To focus research on Key Projects in order to maximize cohesiveness and collaboration,
- To evolve our program during the 4 year lifetime of this NLSI grant, taking advantage of developments in both the science and technology,
- To include evaluations and development of promising technologies in each of the Key Projects in order to help the NLSI and the lunar science community as a whole to build an integrated strategy for lunar research,
- To provide an innovative, hands-on education experience for students in lunar science and exploration in conjunction with the Colorado Space Grant Consortium, and novel multilingual public outreach via nationally distributed planetarium shows.

3.2 Key Project: Low-Frequency Cosmology and Astrophysics from the Moon

Lead scientists: J. Lazio (NRL), J. Hewitt (MIT), C. Carilli (NRAO)

The Dark Ages represent a new frontier in cosmology, the era between the genesis of the cosmic microwave background (CMB) at recombination and the formation of the first stars (Figure 2). During the Dark Ages—when the Universe was unlit by stars—and into the Epoch of Reionization (EoR), there may be a detectable signal from neutral hydrogen (H I) in the intergalactic medium (IGM). This H I signal represents potentially the richest of all cosmological data—for a portion of the Dark Ages, the physics is sufficiently simple that the H I signal can be used to constrain

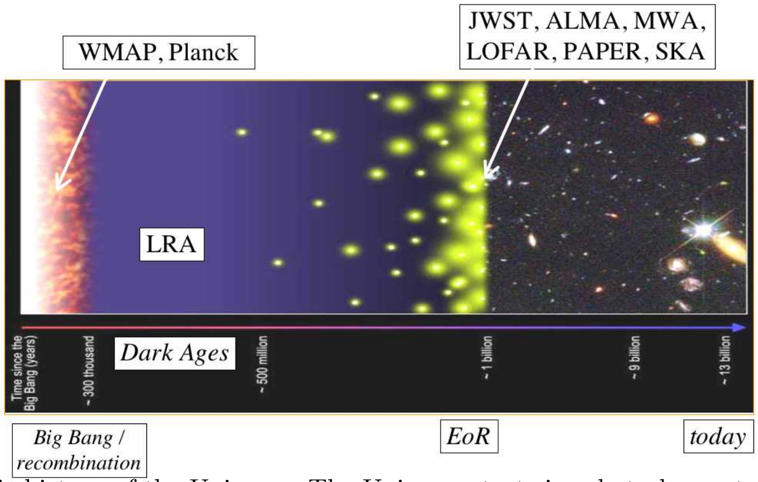


Figure 2: A schematic history of the Universe. The Universe starts in a hot, dense state after the Big Bang, and cools as it expands with the cosmic microwave background (CMB) forming at recombination. The Dark Ages last until stars and galaxies form, reionizing the Universe at the Epoch of Reionization (EoR). A Lunar Radio Array (LRA) is shown in relation to other telescopes and missions.

fundamental cosmological parameters in a manner similar to that of CMB observations, but the spectral nature of the signal allows the evolution of the Universe as a function of redshift (z) to be followed. However, the Moon is likely the only site in the inner solar system for Dark Ages observations as significant obstacles exist to ground-based telescopes, including heavy use of the relevant portion of the spectrum by both civil and military transmitters, distortions introduced by the Earth's upper atmosphere (ionosphere), and solar radio emissions.

The proposed work is to (1) Develop in greater quantitative detail our understanding of the IGM in the Dark Ages and preceding the EoR; (2) Explore the constraints that the lunar farside will have on a lunar cosmology telescope and demonstrate the robustness of the proposed measurements; and (3) Begin technology development of key subsystems in an effort to reduce the risk associated with a lunar cosmology telescope. The proposed work addresses directly concerns raised in the reviews of the Dark Ages Lunar Interferometer (DALI) and Lunar Array for Radio Cosmology (LARC), two of the concepts funded for one year under the Astrophysics Strategic Mission Concept Studies (ASMCS) program. For generality, we shall refer to a **Lunar Radio Array (LRA)** concept. This team contains members of both the DALI and LARC teams, and those concept studies will be completed by the time the proposed work begins.

3.2.1 Key Science

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, such as Sloan Digital Sky Survey (Eisenstein *et al.*, 2005) and the 2-degree Field Galaxy Redshift Survey (Colless *et al.*, 2001); and observations of Type Ia supernovae (Riess *et al.*, 1998; Perlmutter *et al.*, 1998). This information has allowed, for example, within the standard model a precise determination of the age of the Universe and the overall distribution of matter in the local Universe. Yet significant questions remain, e.g., when did the first stars and galaxies form, and how did they affect the IGM? What is the correct theory of inflation? What is dark energy and how does it evolve in time?

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 in size (Loeb & Zaldarriaga, 2004; Furlanetto *et al.*, 2006a). Through detailed mapping of the H I line brightness temperature in space and frequency, it might be possible to

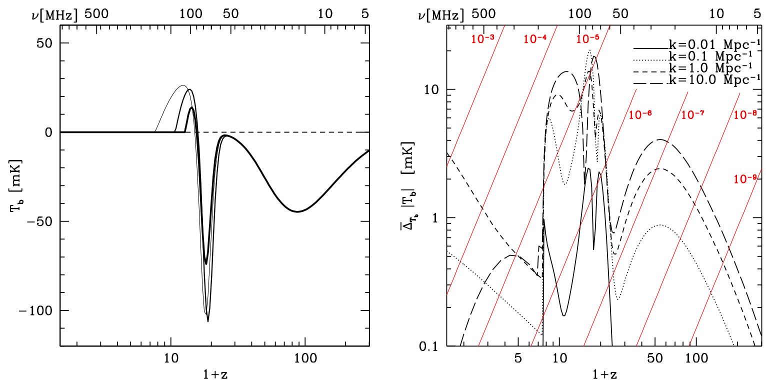


Figure 3: (*Left*) Evolution of the mean H I line brightness temperature T_b as a function of redshift (bottom axis) or frequency (top axis) for three models of the first galaxies representing the range of astrophysical parameters consistent with recent CMB analyses. (*Right*) Redshift (frequency) evolution in one model for the angle-averaged H I line power spectrum $\bar{\Delta}_{T_b}$ at $k = 0.01$ (solid curve), 0.1 (dotted), 1.0 (short dashed), and 10.0 (long dashed) 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.

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 begins (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 the mature galaxies.

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

For completeness, we begin by describing the evolution of the global (all-sky averaged) H I signal after recombination (Pritchard & Loeb, 2008). Figure 3 (left) plots the mean signal for 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, respectively (corresponding to the WMAP5 central and $\pm 2\sigma$ values, Komatsu *et al.*, 2008). Three regimes are apparent. At high redshifts ($30 < z < 300$), collisions in the gas produce an initial 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 rarer. Once the first stars form, they flood the Universe with Lyα photons, which produce a second, deep absorption feature ($15 \lesssim z \lesssim 30$). Finally, as the gas is heated above the CMB temperature $T_{\rm CMB}$ by X-rays (probably from the first black holes) the absorption turns into emission, which eventually cuts off as reionization completes.

This global signature is currently the target of multiple experiments (Chippendale *et al.*, 2005; Bowman *et al.*, 2008). Although such observations are conceptually simple, they are experimentally challenging, because of the difficulty of separating this 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 (§3.2.3). Experimental detection relies upon T_b changing rapidly (Figure 3, left), leading to a distinctive step-like feature in the frequency direction, which would not be expected to be produced by the spectrally-smooth foregrounds; current limits are over an order of magnitude short of theoretical expectations.

An alternate, and ultimately more powerful, approach is through H I line fluctuations on the sky, conventionally parameterized with the power spectrum (the variance of the signal when it is smoothed on wavenumber $k = 2\pi/R$). Figure 3 (right) illustrates the redshift (frequency) evolution of the power spectrum $\bar{\Delta}_{T_b} \equiv \sqrt{k^3 P_{T_b}(k)/2\pi^2}$ (i.e., the rms H I line brightness temperature fluctuations) at four comoving wavenumbers $k = 0.01$, 0.1, 1, and 10 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 (Lidz *et al.*, 2007).

This power spectrum approach motivates a number of current generation instruments, including the Murchison Wide-field Array (MWA),[1] the Precision Array to Probe the Epoch of Reionization (PAPER),[2] and the Low Frequency Array (LOFAR),[3] all of which focus on detecting the H I power spectrum at redshifts $z \approx 6$–12, 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 Kilometer Array (SKA)[5] to perform even more sensitive measurements.

Foregrounds at these frequencies present a substantial challenge to measurements. Figure 3 (right) also shows $rT_{\mathrm{sky}}(\nu)$, for $r = 10^{-4}$–10^{-9} and with T_{sky} corresponding to the sum of the Galactic nonthermal emission in a dark region of the sky and the expected extragalactic contributions (Furlanetto *et al.*, 2006a). Clearly, foreground removal must be accomplished at a high level of precision for detection of the H I signal. 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.*, 2006b) can greatly increase the expected H I signal strength and reduce the level to which foregrounds need to be removed.

Even after removing the foregrounds, noise remains. Figure 4 shows redshift slices, and signal-to-noise ratios, for the H I power spectrum for one of the models in Figure 3 (Pritchard & Loeb, 2008). The redshift slices represent three fiducial epochs: during the EoR, during the transition phase, and during the Dark Ages. The shapes of these power spectra hold a great deal of information about the first sources of light: for example, 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. The signal-to-noise ratios are shown for three fiducial experiments to measure the power spectrum: (i) a current generation, pathfinder-class experiment like the MWA; (ii) the SKA; and (iii) an LRA concept (with a collecting area ~ 3.6 km^2 and a $\sim$ 4-year observing campaign). The above labels are meant primarily to denote different scales of experimental effort, as the design parameters for any array following the pathfinders will clearly be informed by their results. Moreover, one of the foci of the proposed work is to constrain better the design parameters for the LRA. Clearly, though the current generation of instruments can hope to detect the H I signal during the EoR, measuring detailed physics will require efforts comparable to the SKA, which also sets a target for the LRA.

3.2.2 Secondary Astrophysics

As a secondary goal, we also aim to quantify other possible astrophysical observations for the LRA. Three examples of the kind of 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 host intense electron cyclotron masers generated by interactions between solar wind-powered currents and planetary magnetospheric fields (Figure 5). Empirical relations for solar system planets suggest that extrasolar planetary radio emission may be detectable (e.g., Farrell *et al.*, 1999).

[1] `http://www.haystack.mit.edu/ast/arrays/mwa/`
[2] `http://astro.berkeley.edu/%7Edbacker/eor/`
[3] `http://www.lofar.org/`
[4] `http://lwa.unm.edu/`
[5] `http://www.skatelescope.org/`

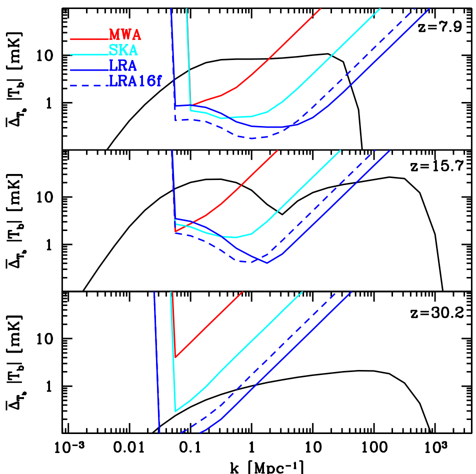


Figure 4: Redshift slices of the H I line power spectrum, for one of the models in Figure 3: during the EoR ($z = 7.9$), during the transition phase ($z = 15.7$), and during the Dark Ages ($z = 30.2$). Also shown are the expected errors for three fiducial instruments, the MWA (red), the SKA (cyan), and a potential LRA (blue); the sensitivity of the LRA is also shown with its observing time split between 16 separate fields (blue dashed).

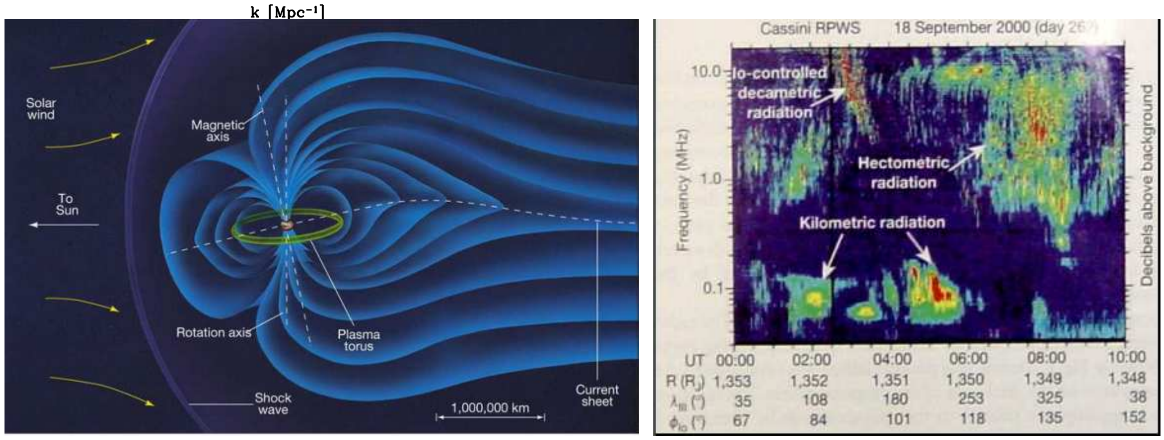


Figure 5: Radio emission from planetary magnetospheres. (*Left*) A schematic of the Jovian magnetosphere. Various observations are beginning to suggest that extrasolar planets may have substantial magnetospheres, which might also generate intense radio emissions. (*Right*) Jovian radio emission, as detected by the *Cassini* spacecraft during its cruise phase to Saturn. The abscissa is time, the ordinate is frequency, and the color scale is logarithmic.

Magnetospheric emission can 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. For a terrestrial planet, a magnetic field may be important for habitability, shielding its surface from the harmful effects of energetic charged particles (e.g., Grießmeier *et al.*, 2005).

Radio Transients: Jovian radio emission is quite "bursty," and, more generally, the LRA may be a powerful means of detecting 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. Transients can also be powerful probes of intervening media owing to dispersion, scattering and Faraday rotation that modify the signals. Searches for radio transients have a long history, and a wide variety are known, ranging from extremely nearby to cosmological distances. In addition, motivated by analogy to known objects or applying known physics, there are a number of classes of hypothesized classes of transients (such as 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 (§3.2.3), which limits the available radio spectrum. The farside of the Moon, shielded from the human-generated emissions from the Earth and, for half of its orbit, from solar radio emissions, 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. Possible contaminants include atomic hyperfine transitions, radio recombination lines, and molecular masers; it is also possible for molecules to absorb CMB photons, mimicking redshifted H I absorption.

An example of an atomic hyperfine transition 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 (Lyα photons are between the 2p and 1s states) and therefore conducive to the hyperfine 2s transition. However, 2s-1s transitions can occur via 2-photon emission with total energy equal to a Lyα photon. Thus, the hyperfine 178 MHz line will compete with 2-photon emission and will require study to determine its expected strength and width.

3.2.3 The Moon as an Astronomical and Cosmological Platform

The lunar *farside* is potentially the only site in the inner solar system for the LRA, for the following reasons:

No Human-generated Interference: The LRA frequency range ($\nu < 100$ MHz) is used by both civil and military transmitters. The FM radio band (88–107 MHz), and Digital TV channels and other signals also exist in the Dark Ages frequency range. Further, because of ionospheric refraction, interference in the HF ($\nu < 30$ MHz) band used for international communication is essentially independent of location on Earth. Terrestrial transmitters can be MUCH ($\sim 10^{12}$) stronger than the H I signals and are detectable at some level even at remote locations on Earth (Figure 6). The Moon reduces such interference to a negligible level (Alexander & Kaiser, 1976a).

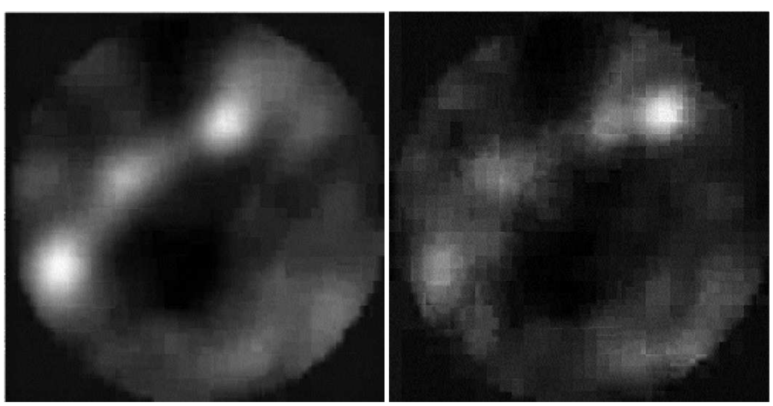


Figure 6: Radio interference enabled by the Earth's atmosphere. (*Left*) An all-sky, 60 MHz image acquired by the Long Wavelength Demonstrator Array in New Mexico. The Galactic plane slopes diagonally from the upper right to the lower left and the sources Cyg A and Cas A are visible as is a general enhancement 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.*

No (Permanent) Ionosphere: The Earth's ionosphere is sufficiently dense that density variations within it induce phase errors that limit radio observations (in addition to simply reflecting interference from distant transmitters, Figure 6). These phase errors form a significant fraction of the error budget in the recent 74-MHz Very Large Array (VLA) Low frequency Sky Survey (VLSS, 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.

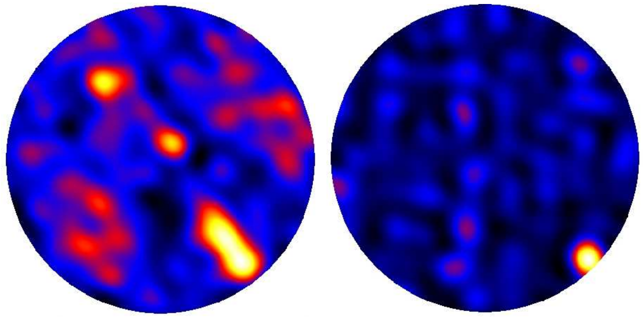


Figure 7: The Sun as a radio source. (*Left*) An all-sky image from the Long Wavelength Demonstrator Array in New Mexico at 74 MHz. In this image, the Galactic plane slopes diagonally from the upper left to the lower right, the inner Galaxy is to the lower right, Cyg A is in the center of the image, and Cas A is toward the upper left. This image was acquired in December, when the Sun was in the constellation Sagittarius (toward the inner Galaxy). (*Right*) The sky later the same day during a solar flare. Due to the finite dynamic range available, the only source visible is the Sun.

Shielding from Solar Radio Emission: The Sun's proximity makes it the strongest celestial source at these frequencies when it is bursting (Figure 7). Solar radio bursts are many orders of magnitude stronger than the Dark Ages H I signals. Within the solar system, the only mitigation for solar radio emissions is physical shielding. A free-flying mission could not be shielded from the solar radio emission (nor from human-generated terrestrial interference). Such shielding is readily accomplished by observing during lunar night and, while the same is true for the surface of the Earth, interference and ionospheric effects continue to occur during terrestrial night.

3.2.4 Technical Approach / Methodology

The proposed work consists of three work packages—developing the theoretical tools to predict the characteristics of the expected H I signals, optimizing the array concept and analysis methods for the LRA, and conducting technology development on key subsystems. This last major thrust will be closely coordinated with the Radio Heliophysics and E/PO sections of this NLSI node. Further, for all three of these work packages, while we will build on the heritage of ground-based radio interferometers, we focus on characteristics of an LRA that are not under development for ground-based arrays.

We describe the work packages individually. Table 2 summarizes the work packages and the contributions of various team members. The team includes representatives from all of the major ground-based arrays as well as from both the DALI and LARC teams.

Work Package #1—Theoretical Tools: *Much of the existing theoretical work on the thermal and ionization state of the intergalactic medium (IGM) focusses on the Epoch of Reionization (EoR), at the end of the Dark Ages. The major theoretical goals are to develop quantitative predictions for the H I signal in the pre-EoR era ($z > 15$, $\nu \lesssim 90$ MHz), the study of which is unlikely to be approached from the ground, and to quantify the cosmological and astrophysical information that an LRA can provide.*

The Dark Ages requires careful treatment of two radiative processes over and above 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. Complicating matters, both backgrounds exert important feedback effects—soft-UV photons (11.26–13.6 eV) dissociate H_2, the major coolant in the protogalaxies thought to form the first stars, while X-rays produce free electrons and so catalyze the formation of H_2, 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, and must be modeled self-consistently.

Existing analytic models are limited to simple source models and linear theory (Barkana & Loeb, 2005; Pritchard & Furlanetto, 2007; Pritchard & Loeb, 2008), while numerical simulations find these feedback processes difficult to incorporate because such codes are typically pure N-body simulations

Table 2: Expected Contributions: Key Project: Low-Frequency Cosmology and Astrophysics

Work Package	**Summary**	**Personnel**
1. Theoretical Tools	Develop and extend tools to predict the H I signal from the Dark Ages; quantify other astrophysics observations.	Co-I: Furlanetto, Loeb, Burns, Darling, Hallman, Hewitt, Lazio, Jones, Taylor, Weiler; Collaborator: Carilli, Bowman, Falcke, Mesinger, Pritchard, Visbal, Wandelt
2. Array Concept & Algorithm Develop.	Quantify array configuration impact; test proposed processing algorithms.	Co-I: Hewitt, Lazio, Taylor, Weiler; Collaborator: Carilli, Bowman, Falcke, Neff, Ulvestad
3. Technology Development		
3.1. Science Antennas	Develop proof-of-concept science antenna.	Co-I: Burns, Hewitt, Lazio, Jones, Taylor, Weiler; Collaborator: Bradley, Neff, Stocke
3.2. Deployment & Rovers	Demonstrate feasibility of autonomous deployment.	Co-I: Jones, Burns; Collaborator: Bradley, Neff

that cannot self-consistently include the feedback nor achieve sufficient dynamic range to resolve the tiny galaxies over the enormous scales relevant to H I studies (though see Ahn *et al.* 2008 for a first attempt). We will use 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 (Bond & Myers, 1996; Mesinger & Furlanetto, 2007).

Our study will approach these issues from two major directions: (1) Methods to study the feasibility and science return of lunar observing strategies, and (2) Detailed predictions for the H I signal in the pre-EoR era when the first astrophysical sources appear. Our work plan is:

Year 1: *Extend existing computer codes to include a realistic model for the thermal noise and the sky foregrounds, efficient calculation of the H I power spectrum, and Fisher-matrix–based constraints on cosmological parameters.* Our approach is to develop tools similar in concept to those that already exist for CMB analyses (e.g., `CMB-fast`) and will build on model skies already developed under LWA and MWA work (e.g., de Oliveira-Costa *et al.*, 2008).

Modify analytic and semi-numeric methods currently tuned for use during reionization to the redshifts of interest to the LRA. These include tools to identify proto-galaxies efficiently and to study fluctuating radiation fields, already applied to the ionizing background (Meiksin & White, 2004; Mesinger & Dijkstra, 2008) that can be extended to the soft-UV and X-ray backgrounds critical for predicting the H I signal at the end of the Dark Ages.

Year 2: *Combine noise, foreground, signal, and error estimation codes, both existing and to be developed in Year 1, to a master code that will determine the cosmological constraints achievable by different LRA designs.* Studies will include the achievable constraints on (1) Cosmological parameters, including the equation of state of the dark energy, and the value and running of the spectral index of the matter power-spectrum; (2) Exotic energy deposition from measurements of the global H I signal (Furlanetto *et al.*, 2006b; Valdés *et al.*, 2007; Khatri & Wandelt, 2008; Mack & Wesley, 2008); and (3) Inflationary parameters.

Use these tools to compute H I line images and statistics for a variety of simple source models, excluding feedback. We will study how realistic source distributions, source histories, and nonlinearities affect the features predicted by simple analytic models (Barkana & Loeb, 2005; Pritchard

& Furlanetto, 2007). We will explore statistics that are best-suited to extract the complicated physics of this era, such as an angular decomposition of the signal. We will produce maps of sufficient quality to pass through simulations of foreground removal algorithms described below.

Years 3 and 4: Continue the study of achievable constraints using the *master code*, exploring in particular exotic physics during the Dark Ages.

Optimize specifications for the LRA to measure the power spectrum $P(k)$ in the range $z = 20$–50 ($\nu = 30$–70 MHz). This study will build on the codes developed above and will examine the technological trade-offs and scientific benefits of observing at the lowest frequencies.

Study the importance of radiative feedback on these first generations of structure. We will explore how the inhomogeneous soft-UV and X-ray backgrounds interact to affect the formation of early galaxies and black holes and self-consistently include feedback in generating H I signal predictions. We will identify any robust signatures of feedback and, in combination with the parameter estimation code, develop strategies to measure these qualities. Finally, we will also work to develop simplified analytic models describing the principal features of the full results.

Work Package #2—Array Concept and Algorithm Development: *The LRA will face constraints not generally encountered for ground-based telescopes, such as limitations on the ability to modify the site and the ability to conduct maintenance. Further, while suggestions exist in the literature for how to process the data to be acquired by the LRA, little has been done to date to test processing methods on existing radio astronomical data acquired at relevant frequencies. We will explore the sensitivity of the array configuration to its performance and test specific processing methodologies on existing data.*

A standard aspect of design for ground-based radio astronomical arrays is the configuration, i.e., where antennas are to be located (Thompson *et al.*, 1986, Chapter 4). The array configuration has an impact on various aspects of its performance, such as calibration and dynamic range achievable, and potentially the amount of computational power required to process the data. Various metrics exist for quantifying the performance of an array given a particular configuration, and the construction of a ground-based array is procedeed by simulations designed to produce, in some sense, an "optimal" array configuration (e.g., Kogan & Cohen, 2005; Bowman *et al.*, 2006).

A key assumption for a ground-based array is that the site is largely under the control of the project, often allowing for large-scale modification of the site. For example, the VLA and Atacama Large Millimeter/submillimeter Array (ALMA) projects constructed significant infrastructure, and the LOFAR project plans to re-terrace about 1 km^2.

Large-scale site modification is extremely unlikely to be possible for the LRA. Moreover, if deployment depends exclusively on robotic rovers (§3.2.4), it is possible that a few rovers will fail to position antennas at the desired locations. Interferometers degrade gracefully, and ground-based arrays operate routinely in the presence of the complete failure of a small fraction of their antennas. Nonetheless, the deployment and antenna positioning for the LRA are likely to be in a different regime from ground-based arrays. We propose to assess the impact of array configuration and related issues (calibration, computation, ...) on the performance of the LRA.

The second focus of this Work Package is to use *existing* radio astronomical data to verify the extent to which existing treatments of *astrophysical foregrounds* are accurate. As Figure 3 illustrates, *astrophysical foregrounds*—such as the Galactic nonthermal emission (including its polarization effects), low-frequency RRLs, and discrete extragalactic sources—will be a challenge for the LRA. Much of the effort to date in assessing the degree to which these foregrounds can be removed has been numerical modeling of their effects on the desired signal. Further, a common assumption has

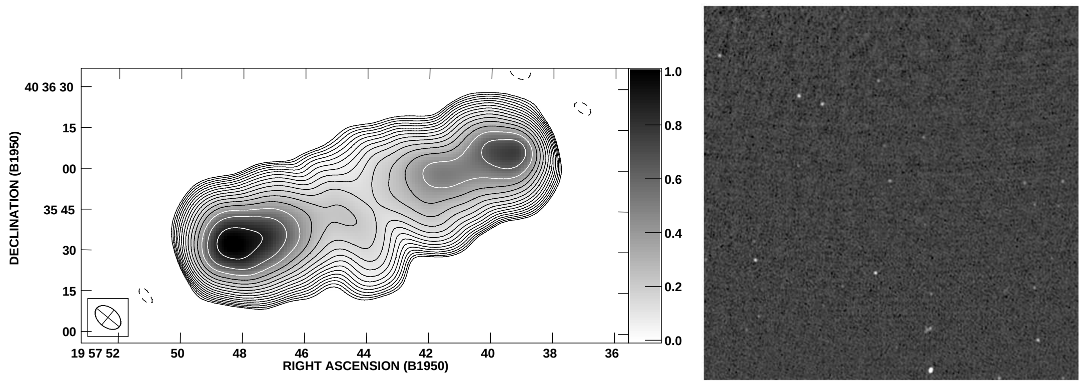


Figure 8: Illustrations of the data available to test potential LRA algorithms. (*Left*) Cygnus A at 74 MHz (Lazio *et al.*, 2006). The VLA Archive contains observations of sources sufficiently strong that radio interference and ionospheric effects are minimal and can be used to assess possible analysis techniques for dealing with astrophysical foregrounds. For this figure, the gray scale is linear between 0 and 1 kJy, and the contours are 0.97 Jy $\times$ -5, 5, 7.070, 10, ... The beam is in the lower left corner. (*Right*) A $3.5^\circ \times 3.5^\circ$ portion of the 74 MHz ($z \approx 20$) sky from the VLSS (Cohen *et al.*, 2007, `http://lwa.nrl.navy.mil/VLSS/`). The numerous sources visible in the VLSS will allow foreground source subtraction methods to be evaluated.

been that many of these foregrounds are *spectrally smooth* (Gleser *et al.*, 2008; Liu *et al.*, 2008). We propose to use actual data in an effort to reduce the dependences on models.

We will use data in the publicly-accessible National Radio Astronomy Observatory's (NRAO) VLA Archive[6] as the VLA has two data acquisition systems at frequencies close to or in the range relevant for the EoR and Dark Ages (330 MHz, $z \approx 3$, and 74 MHz, $z \approx 20$). Also available is the recently published and publicly-accessible 74 MHz VLSS[7] (Cohen *et al.*, 2007). In one sense, the VLA is less than optimal in that the eventual configuration of the LRA is unlikely to be the `Y`-shape of the VLA. However, the VLA offers the promise of existing, publicly-accessible data on which to begin testing algorithms for the eventual use of the LRA.

While ground-based data are often afflicted with the effects of interference and ionospheric distortions, there are a small number of discrete extragalactic sources that are sufficiently strong so that these corrupting effects are unimportant. Examples include Cygnus A (Figure 8), Cassiopeia A, Virgo A, and Taurus A. Moreover, the typical archival observation is at a spectral resolution comparable to or better than that required for EoR and Dark Ages observations (< 0.1 MHz).

Specific tests to be conducted include probing the degree to which existing data constrain the spectral smoothness or indicate design parameters for the LRA. We envision at least three approaches to this issue. The first is to calibrate and subtract the response from a strong source at a particular frequency and assess the extent to which any residuals in the resulting spectrum at nearby frequencies could be due to the spectral behavior of the source itself.[8] The second approach is similar, but exploits the large field of view at low frequencies. Sufficiently strong sources (e.g., Cyg A and Cas A) effectively can be detected whenever they are above the horizon. Thus, we can compare the extent to which the spectral behavior of Cas A can be detected in residual data from Cyg A.

The third approach is to assess foreground source subtraction methods. Low frequency antennas naturally respond to large sections of the sky; for example, the VLA field of view is approximately 10°, and antenna concepts for the LRA (§3.2.4) might very well have even larger fields of view. As Figure 8 illustrates, even a small fraction of this field of view can contain many foreground sources,

[6] `https://archive.nrao.edu/archive/advquery.jsp`; the NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[7] `http://lwa.nrl.navy.mil/VLSS/`

[8] An illustration of potential data for this test is the 74 MHz observation of Cyg A on 2001 September 12.

and, as Liu *et al.* (2008) discuss, the precision to which these foreground sources can be subtracted may ultimately determine the accuracy to which the H I line signal can be probed. Moreover, the LRA is likely to be much more sensitive than the VLA, so that even more sources would be visible in an LRA image. Of particular concern is the frequency dependence of both the antenna parameters and the source spectra. An approach similar to those described above will be used, namely, an assessment of the degree to which foreground subtraction leaves frequency-dependent residuals. The difference for this third approach is that we will now be considering many, much weaker sources. A statistical evaluation may be necessary, but such a statistical evaluation is consistent with methods being considered for the LRA.

Our work plan is:

Year 1: We will begin assessment of the array configuration and the impact of variations of the configuration on the desired measurements. We will develop metrics for this comparison—including the requirements for calibration and imaging—and identify classes of configurations to compare. This study will include an exploration and leveraging of existing data processing software being employed on ground-based arrays. As an illustration of the kinds of comparisons to be undertaken would be a comparison between the Fast Fourier Transform Telescope (FFTT, Tegmark & Zaldarriaga, 2008) and a traditional u-v plane sampling criterion (Boone, 2002). We will begin identifying VLA data suitable for algorithm tests.

Year 2: We will conclude the assessment of the array configuration. Though our primary goal is to assess the array configuration and its impact on the EoR and Dark Ages measurements, a secondary consideration will also be the impact on other astrophysical measurements (§3.2.2). We will begin the spectral dynamic range tests and foreground subtraction tests, utilizing existing VLA Archive and VLSS data. We will also assess, based on the work being conducted in Work Package #1, whether other aspects of astrophysical foregrounds can be tested using VLA Archival data.

Years 3 and 4: We will continue and conclude the spectral dynamic range and foreground subtraction tests. If other astrophysical foreground tests can be conducted on VLA Archival data, these will be initiated with the goal of also finishing them during these years.

Work Package #3—Technology Development: There are a number of challenges for the LRA, including but not limited to antenna design, array configuration, electronics, deployment, power generation and storage, thermal management, and data communication. We have identified the science antenna and deployment as subsystems that present unique requirements relative to many other lunar surface activities and as ones that this team is uniquely positioned to address. Nonetheless, through the ROLSS and DALI/LARC concept studies, we are in contact with groups working on other design aspects (e.g., power, thermal), and we will maintain those contacts and discussions.

Science Antennas: *We will develop a proof-of-concept for a low-mass science antenna for the LRA. The antennas developed for the ground-based antennas have not had mass or volume constraints imposed on them. Further, the lunar environment presents differences (e.g., the dielectric constant of the lunar regolith) relative to the traditional design assumptions of ground- or space-based antennas.*

The anticipated level of the H I signals is extremely weak, requiring a sizeable collecting area to overcome random noise and systematic effects. 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. Large numbers ($\gtrsim 10^4$) 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 that must be minimized. 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. A prototype LWA antenna operating in the frequency range ν = 20–80 MHz ($70 \lesssim z \lesssim 20$) has been fabricated. 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.

We have examined various antenna configurations as part of the DALI and LARC initiatives. In both cases, the instrument is composed of antenna clusters that form "stations" in the larger array. Field-of-view requirements impose limits on the maximum gain (collecting area) for a station. The station configurations may be grouped into two basic categories: (1) clusters of low gain antennas such as dipoles that are phased together to form two-dimensional, broad-side arrays; and (2) clusters of end-fire antennas such as Yagi-Uda or helicals that involve three-dimensional structures. Subtle design details will greatly affect the performance and physical characteristics of the antennas which, in turn, will influence the instrument configuration and deployment strategy. Therefore, both categories will be studied within the context of the lunar environment and transport options so that the attributes of each can be compared and contrasted properly with regard to critical design criteria.

Our team has extensive experience in the development of low-frequency radio astronomical antennas, from the LWA, PAPER, and the MWA projects, all of which demonstrate useful attributes that can be adopted for the LRA. Lessons learned from these projects are reflected in the notional designs of DALI and LARC, thus forming a solid foundation on which the LRA design will be based.

The unique lunar environment together with limitations imposed by transportation and deployment will present several challenges. While vacuum-induced outgassing, UV-enhanced material deterioration, thermal stresses, and abrasive particulates impose design constraints, the lack of an atmosphere, the low gravitational field, and the low loss dielectric regolith have distinct advantages that can be exploited. In addition, various types of technologies and innovations such as memory metals, lightweight materials, polyimide films, etc., will be examined as potential solutions to the basic engineering challenges.

The proposed work also builds upon the Radio Observatory for Lunar Sortie Science (ROLSS) concept study being conducted under the Lunar Sortie Science Opportunities (LSSO) program. ROLSS is an antenna array in which the concept antennas are metals deposited on polyimide film. The primary science mission of ROLSS is particle acceleration in the inner heliosphere, but it could also serve as a pathfinder toward the LRA. Candidate ROLSS antennas have been designed, and thermal-vacuum chambers tests are being conducted. However, the duration and scope of that study are too short to enable a sufficiently in-depth exploration of the parameter space for LRA antennas.

The work plan presented here will be conducted in close collaboration with the Radio Heliophysics portion of this Institute node.

Year 1: We will conduct detailed simulations of the performance of antenna topologies. Candidate topologies, identified in the ROLSS and DALI/LARC studies, include dual-polarization dipoles constructed by depositing a conducting substance on polyimide film (e.g., Kapton) and self-deploying helical antennas. Simulations will focus on the antenna performance as a function of frequency, geometry, and polarization and be conducted with commercial and customized modeling software that can determine the current distributions and radiation patters of multiple antenna, following techniques developed for testing LWA, MWA, and PAPER antennas. The effect of mutual coupling between antennas will be studied in addition to individual antenna designs.

Year 2: Guided by the simulation work, we will construct proof-of-concept models and verify their performance. These performance tests will focus on two aspects of the antenna. One is its electrical behavior, such as the impedance as a function of frequency, and the second is its ability to withstand the lunar environment. A suite of standard antenna performance tests has been developed as part of the LWA, MWA, and PAPER antenna development, and the LRA proof-of-concept antenna must demonstrate similar capabilities.

The second aspect is to demonstrate that the antenna can withstand the lunar environment. The Center for Astrophysics & Space Astronomy (CASA) at the U. Colorado has a sufficiently large vacuum chamber that could accomodate a nearly full-scale model, and considerable experience on simulating the lunar environment (both thermal and UV exposure) has been developed as part of the ROLSS study. While both polyimide film and "memory metals" have spaceflight heritage, the lunar environment is sufficiently different (e.g., the range of temperature fluctuations) that we intend to test the robustness of the proof-of-concept material in a thermal-vacuum chamber.

Year 3: We will continue the proof-of-concept antenna testing. Based on experience from the LWA, MWA, and PAPER antenna development, 3 years is the requisite amount of time to take an antenna concept from simulation to initial verification. Our goal, however, is that by the end of Year 3 we will be able to conduct a downselect to the most promising antenna topology.

Year 4: Construct a second proof-of-concept model and demonstrate interferometric fringes. Possible targets include Cas A, Cyg A, or the Sun. These sources have been observed by PAPER and LWA hardware. Assuming suitable progress, we would seek to deploy this proof-of-concept interferometer and demonstrate its performance against other low-frequency antennas (e.g., at the LWA site in New Mexico, at the PAPER site in Green Bank, WV, or the Goddard Decametric Radio Observatory site in Maryland).

Deployment and Rovers: *We will demonstrate the feasibility of autonomous deployment of LRA components. A cosmology telescope will ultimately have a large number of individual science antennas in order to provide the appropriate sensitivity. Consequently, the process of deploying antennas over an extended area is not a viable job for astronauts; multiple, autonomous rovers will be needed to carry out this task in parallel if it is to be completed in a reasonable amount of time. This technology development will also be coupled to the E/PO component of this Institute node.*

Semi-autonomous rovers have been or are being developed for Mars missions (e.g., *Spirit*, *Opportunity*, and *Mars Science Laboratory*). Rover technology is advancing rapidly, especially in mobility over difficult terrain, high dexterity manipulation, and on-board intelligence (Figure 3.2.4). Beyond NASA applications, there are other agency interests in autonomous rovers, e.g., DARPA. We will leverage this work for LRA development. Rover development will reduce a key risk for the LRA; from the ASMCS review of the DALI concept, a "tall pole" was considered to be, "designing a rover that can 'walk' over an unknown landscape and [deploy antennas]."

A primary requirement for rovers intended for deployment of LRA components is low mass for their mobility and manipulation capabilities. For a given payload mass, the objective is to maximize the fraction devoted to science hardware (e.g., science antennas, receivers). While the rover could be used to house parts of the science hardware (e.g., receivers), components of the rovers that do not contribute directly to the reception and processing of the celestial signals result in a reduced sensitivity or processing capability, even if those rover components are necessary for emplacing the science hardware.

As an example of a rover concept, a scaled-down, 0.5-meter version of JPL's ATHLETE rover, with a pair of articulating arms and multiple solar array petals, could carry and deploy several

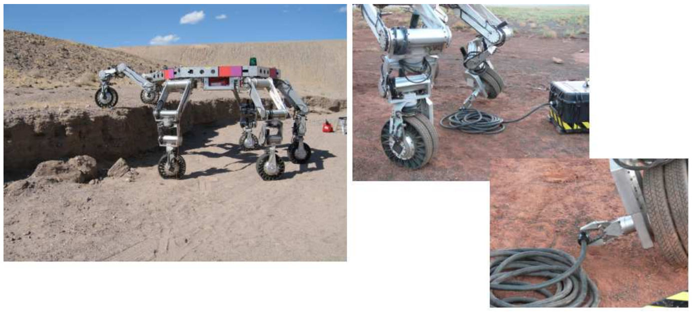


Figure 9: An illustration of recent rover developments, showing tests of JPL's ATHLETE rover manuevering over rough terrain and engaging in precision manipulation. Efforts are also directed toward developing mini- and micro-rovers.

tens of kilograms of antenna mass. After antenna deployment, the rover could serve as the central signal processing and transmission hub for an antenna "station." A primary goal of this activity is to determine a rover mass estimate based on a full-scale (but not flight qualifiable) rover that has demonstrated the needed level of mobility, stability, and dexterity.

We will coordinate with groups at JPL working on advanced rover development to determine which areas of performance relevant to lunar arrays are being addressed and which will require a focused effort through the NLSI. Our goal is to develop a rover design at a sufficient level of detail to allow useful estimation of mass, reliability, and cost. Our work plan is:

Year 1: We will conduct a trade study on the number of antennas to be deployed by a single rover, produce an antenna deployment process concept definition, and produce initial estimates of rover size, power, and mass. These tasks are critical for the over-all system design if the LRA is to have any appreciable size, and consequently these tasks need to begin early.

Year 2: We will focus on tasks that are essential to the rover capabilities, other than the actual antenna deployment. These include developing the mobility and autonomous navigation concept; defining the level of required imaging, on-board intelligence, and communications; and developing a concept for wideband data relay and associated rover hardware.

Year 3: The goal is to transition the general rover concept into a more specific hardware form (proof-of-concept) to allow verification of the mobility and deployment concepts. Likely tests of the proof-of-concept rover include conducting a test of the deployment process; demonstration of the integration of antenna payload and deployment mechanism onto a rover; and demonstration of rover stablity with a realistic mass and volume payload.

Year 4: We will construct a to-scale deployment rover for testing, demonstrate rover mobility and navigation with full test payload, and demonstrate the complete antenna deployment sequence.

3.3 Key Project: Gravitational Physics and Lunar Structure

Lead Scientists: T. Murphy (UCSD), D. Currie (Maryland), S. Merkowitz (GSFC)

3.3.1 Key Science from Lunar Laser Ranging

Lunar laser ranging (LLR) has contributed to a broad sweep of science over the decades since the Apollo astronauts placed reflectors on the lunar surface. The time series of range measurements between stations on the Earth and the lunar reflectors provide our most precise knowledge of the shape of the lunar orbit and lunar orientation, and also contributes to knowledge of Earth orientation. Together, these data allow us to probe the fundamental nature of gravity as well as physical properties of the lunar interior and tidal dissipation on Earth (Williams *et al.*, 1996; Dickey *et al.*, 1994).

At present, based on centimeter-accuracy data, LLR provides the strongest constraint on the equivalence principle, with a fractional acceleration sensitivity of $\Delta a/a < 1.3 \times 10^{-13}$—translating to a constraint on the *strong* equivalence principle of $\eta < 4.5 \times 10^{-4}$, describing how gravity pulls on gravitational self-energy (Nordtvedt, 1968; Williams *et al.*, 2004). The time variation of the gravitational constant is constrained to $\dot{G}/G < 10^{-12}$ per year, and geodetic precession is measured to 0.6% accuracy (Williams *et al.*, 2004). Gravitomagnetism is seen to play a role in shaping the lunar orbit at the level expected by general relativity (Murphy *et al.*, 2007). Additionally, LLR provides the best test of the inverse square law, to $< 10^{-10}$ times the strength of gravity at 10^8 m scales (Adelberger *et al.*, 2003). It is also seen via centimeter-level LLR that the Moon has a liquid core (Khan *et al.*, 2004), though confidence in this statement has room for improvement. By placing reflectors on the Moon capable of providing range information at the 10 μm level, we will open the door to science investigations exceeding the current limits by up to three orders of magnitude. More importantly, we will extend the scientific scope to include new theoretical frameworks heretofore inaccessible to LLR techniques.

We stand at a crossroad in physics: astrophysical observations, when interpreted within the framework of general relativity, tell us that 95% of the mass-energy content of the universe is of unknown form. Dark matter and dark energy could indeed represent new particles and fields in physics. But it is also possible that our model for how gravity works is incomplete or wrong. Taken together with the fundamental incompatibility between gravity and quantum mechanics, we have a strong motivation to test gravity to the greatest precision possible. LLR gravitational physics has traditionally been cast in the Parameterized Post Newtonian (PPN) framework (Will & Nordtvedt, 1972; Will, 1981). But because new developments in gravitational theory—including attempts to unite gravity and quantum mechanics—are likely to abandon purely geometric (called metric) formulations, it is important to push LLR into new theoretical paradigms, and to new levels of precision.

Next generation retroreflectors with accuracy of ~10 μm will set unprecedented limits on alternate gravity models and define the nature of the Moon's liquid core.

Recently, a number of alternatives to general relativity have emerged that justify further testing in the solar system. For instance, Dvali, Gabadadze & Porrati offered a gravitational alternative to the accelerating universe interpretation of the supernova data that would result in an anomalous precession of the lunar orbit (Deffayet *et al.*, 2002; Dvali *et al.*, 2003; Lue & Starkman, 2003). The Standard Model Extension (SME) framework for Lorentz-violation has seven parameters that may be constrained by lunar range observations (Bailey & Kostelecky, 2006). And finally, the covariant version of Modified Newtonian Dynamics (MOND), called TeVeS (Bekenstein, 2004), should be testable using the lunar orbit. It is important to push opportunities to test these alternative theories in any way possible so that we may either eliminate blind alleys or discover new physics that could revolutionize our way of thinking about gravity.

3.3.2 Next-Generation Lunar Laser Ranging

The scientific deliverables from LLR have continued to progress despite the fact that the reflector arrays were designed when laser pulse widths exceeded several nanoseconds, dominating the error budget relative to the contribution from the small but finite size of the reflector arrays. Today, laser pulse widths in the tens of picoseconds can pack enough photons to produce a detectable return signal. But the ~ 0.5 m size of the arrays—when tilted by the lunar libration angle measuring up to 10°—contributes several hundred picoseconds of random uncertainty to the photon arrival time. In order to make a one-millimeter precision range measurement (6.7 ps of round-trip time), one must knock the 200–300 ps spread from the array down by a factor of 30–50, requiring the collection of 900–2500 photons in a short run. Until 2006, the record return counts for a single run on the Apollo 11, 14, and 15 arrays (100, 100, and 300 corner cubes 38 mm in diameter, respectively) was 172, 213, and 603 photons, respectively. Thus the millimeter goal remained elusive until very recently, with

Figure 10: *Left:* APOLLO LLR shooting the Moon from Apache Point, NM. *Right:* Prototype 100 mm next-generation corner cube next to a 38 mm Apollo engineering model corner cube.

the APOLLO project (the Apache Point Observatory Lunar Laser-ranging Operation; Murphy *et al.* (2008)) achieving photon counts of 4288, 5100, and 8937 on the three Apollo reflectors (see Fig. 10).

There is virtually no incentive at present to improve ground-station performance, other than by increasing the sheer photon yield. Improvements in laser pulse width, timing electronics, etc. are all swamped by the temporal spread of the arrays. Scaling the size of the array on the Moon produces no gain: doubling the physical dimension doubles the temporal spread, requiring four times as many photons—which is exactly what a doubled linear size provides.

One solution is to separate corner cubes into a sparse arrangement so that each cube can be individually resolved in the time domain with present laser systems. As a result, there would be a strong impetus to improve the performance of ground stations, since the lunar reflector array would no longer contribute to statistical timing error. We propose here to optimize the design of next-generation lunar reflectors (both passive reflectors and active transponders), test them in a simulated environment, and converge on the overall best choice.

Since LLR began, ground capabilities have improved by more than a factor of 100. Our goal is to design an apparatus capable of 10 μm performance, supporting similar advances on the ground in the coming decades, and anticipate the science that may be delivered as a result.

Our LLR Key Project has several issues in common with the low frequency array and the necessary technologies will be pursued collaboratively. First, both projects involve emplacement of arrays of detectors over large areas of the lunar surface. Second, both require innovative deployment strategies using humans and/or robotic rovers.

3.3.3 Technical Approach / Methodology

We propose to advance the state of the art of LLR on a variety of fronts, following the four work packages outlined in Table 3.

Work Package #1—Theoretical Tools

LLR Science Development (1.1): In Section 3.3.1, we describe the new science that may be pursued using next-generation LLR. We will seek to develop a complete picture of scientifically relevant alternatives to general relativity and their associated phenomenologies that LLR can test.

Table 3: Proposed Work: Next-generation Lunar Laser Ranging

Work Package	**Summary**	**Personnel**
1. **Theoretical Tools**		
1.1 LLR Science	Develop new LLR science goals	Nordtvedt, Currie, Merkowitz, Murphy, Dvali (consultant)
1.2 Analysis Package	Identify and adapt analysis framework for next-generation LLR	Merkowitz, Murphy
1.3 Simulations	Quantify LLR performance expectations: time scales; data quality; systematic influences	Merkowitz, Murphy, Currie, Nordtvedt
2. **Corner Cube Design**	thermal stability; 10 μm goal	
2.1 Solid CCR Design	Design and test prototype	Currie
2.2 Hollow CCR Design	Design and test prototype	Merkowitz, McGarry, Zagwodzki
3. **Transponder**	Develop lunar transponder concept; applications to interplanetary ranging and communication	Merkowitz, Murphy
4. **Placement**		
4.1 Array Layout	Geometry and range signature	Currie, Merkowitz, Murphy, McGarry
4.2 Environment	Dust mitigation, shading, anchoring	Currie, Merkowitz, Murphy, Carrier

We will develop estimates of the sensitivities to which LLR can test these ideas, and estimate adequate observing timescales.

Range Analysis (1.2): In addition to relativistic effects, the time series of range measurements from Earth stations to lunar reflectors is imprinted with gravitational effects from solar system bodies, body-orbit and body-body torques, tidal deformation, interior dynamics (core-mantle interactions, plate tectonics), loading from atmosphere, ocean, and ground water, as well as propagation delay of the laser signal through the Earth's atmosphere. Extracting the relevant science from the raw data requires an extensive model parameterizing every relevant effect that is known. Few models currently exist worldwide that are up to the task, and all of these require substantial work to even take advantage of the newly-available one-millimeter quality data.

The two packages that offer the most promise—in no small part due to their unrestricted availability—are the Planetary Ephemeris Program (PEP) and GEODYN. The former has been used extensively for solar system and lunar ranging analyses, and the latter is the primary tool used in satellite laser ranging (SLR) analyses. PEP would need to incorporate many Earth surface effects not currently implemented (present in GEODYN), though it is built in a relativistic framework in the solar system barycenter (SSB) frame. GEODYN is formulated in a geocentric frame, which may be difficult to relate to the asymptotically flat metric space of the SSB.

Science Simulations (1.3): Having identified an analysis package suitable for high-accuracy lunar range data, we will be able to produce simulated data sets to explore the sensitivities of new LLR data to physics parameters. Part of this effort will involve modeling the effects of new physics paradigms and getting a realistic sense of the observation quality and duration necessary to push these theories to interesting levels.

Because the science analysis essentially works like a least-squares fit of observed-minus-calculated ranges, one of the model's key jobs is to produce "simulated," or calculated, range values. It is therefore straightforward to use the analysis package to generate mock data at a realistic cadence and with appropriate random noise and unmodeled systematic offset. One may then explore the ability of the model to separate effects, estimating sensitivities and correlations. By doing this, it is possible to estimate the requisite duration of observations, data quality, the impact of unmodeled systematics, and the "feed-through" of particular effects (does the amplitude recovered match the amplitude injected, or is power distributed into other frequencies?).

Years 1-4: The theoretical tools will be developed uniformly across all years. The exception is that the simulations must await initial functioning of the analysis package, later progressing in parallel. Efforts at CfA and at U. Maryland to update PEP and GEODYN, respectively, for millimeter-level LLR capability are currently proposed or underway under separate funding sources. We will collaborate with the respective developers to produce an analysis framework capable of accommodating existing and future LLR data sets. We will consult with G. Dvali regarding new developments in gravitational theory.

Work Package #2—Corner Cube Design: The corner cubes placed on the Moon thus far followed two different designs, both based on solid cubes of glass. The Apollo reflectors are 38 mm diameter fused silica cubes with a circular face, employing total internal reflection (TIR) rather than reflective coatings for reduced thermal absorption. The French-built Lunokhod reflectors are triangular-faced large cubes (110 mm sides) with silver coating. The French cubes are unavailable for ranging during the lunar daytime owing to large thermal distortions. The Apollo cubes suffer little variation from incident sunlight. A different option exists in the form of hollow cubes. We propose to develop mature studies of the properties of both solid and hollow designs as part of this program, ultimately converging on the best overall approach.

The design of corner cube reflectors (CCRs) of either solid or hollow architectures share some common considerations:

- **Scaling**: The cross section (peak intensity of diffraction pattern) of a CCR scales as the fourth power of the linear size. For a solid cube, the mass increases as the cube of the linear size.
- **Velocity Aberration**: Transverse motion of the Moon in its orbit together with Earth rotation impose a roughly 4–6 μrad angular deviation on the returning light, displacing the return beam with respect to the ground station. If the CCR is too large, the diffractive spread of the return beam is smaller than the velocity offset, resulting in little or no light at the ground station.
- **Spoiling**: Deliberately spoiling the angles of one or more of the reflecting surfaces can effectively compensate for velocity aberration, at some cost to the peak cross section.
- **Thermal Isolation**: Thermal gradients within the CCR will negatively impact its performance, via distortion and refractive index variation. Solar absorption on the surfaces and in the bulk material (in the case of solid CCRs), radiation from the pocket in which the CCR is nested, and conduction to the mounting structure—which must be robust enough to withstand launch accelerations—must all be considered and minimized.

Solid Corner Cube Design (2.1): A single 100 mm CCR will return half the signal of the smaller Apollo arrays of 100 38 mm CCRs. We will investigate the use of five such 100 mm CCRs—using the same Hereaus Suprasil material still functioning in the Apollo arrays—individually implanted at separations of $\sim$ 10 m. This approach has the advantage that it is the extrapolation of a proven technological approach that has successfully operated on the Moon for forty years. However, there are several challenges that need to be addressed.

A larger CCR is more sensitive to thermal distortion than the smaller CCRs employed in the Apollo arrays. Relevant to solid CCRs are solar absorption, radiation to the housing, mount conductance, and TIR breakthrough—where at large incident angles the sunlight can pass into the pocket causing a high heat load. Low emissivity, nested cans of polished gold within the pocket, carefully designed structural mounts, and baffling shades may be used to mitigate these effects. Initial simulations of the solar absorption, radiative coupling, and conduction to the mount are encouraging for the solid cube design. If these tests indicate that solar absorption within the CCR remains a challenge, a coating to reflect incoming infrared radiation can be placed on the front face. Dielectric charging and other lifetime issues for such a coating would then need to be addressed.

Hollow Corner Cube Design (2.2): An option being investigated at GSFC is to replace solid glass cubes with hollow cubes that weigh much less than their solid counterparts. For example, 300 unspoiled 5 cm beryllium hollow cubes would have a total mass less than that of the Apollo 15 array but would have ~ 3 times higher optical cross section.

Thermal distortions are less, especially in hollow cubes made of beryllium, so the cubes can be made larger without sacrificing optical performance. Hollow cubes (built by PLX) have been flown on the Japanese ADEOS satellite and on the Air Force Relay Mirror Experiment, but are generally not used on satellites for laser ranging. This is due in part to the lack of optical performance test data on these cubes under expected thermal conditions, but also because of early investigations showing that hollow cubes were unstable at high temperatures. Advances in adhesives and other techniques for bonding hollow cubes make it worthwhile to reinvestigate them. ProSystems developed and tested adhesive methods for Goddard capable of surviving thermal cycles from 20 °C to 150 °C.

Cube Testing: An environmental test chamber at GSFC will allow some testing of the thermal performance of the CCRs. But for full characterization, we will create a simulated lunar environment using the unique Space Climatic Facility (SCF)—a thermal vacuum/optical/infrared testing facility at INFN/LNF in Frascati, Italy, near Rome. The infrared-transmissive window on this test chamber permits measurement of the temperatures of the elements of the CCR array under simulated thermal loading from the Sun, Earth, and Moon. In addition, optical performance can be monitored as the ultimate test of the cube performance. There are no ITAR restrictions on the proposed activity.

Years 1-2: GSFC is currently working with the group at INFN/LNF to test the thermal and optical performance the PLX hollow cubes designed to fly on GPS III. At the University of Maryland, development is underway for solid cubes, with a test at the SCF scheduled for September 2008 using the large cube pictured in Figure 10. We will use these results to develop the mechanical, optical, and thermal design of lunar reflectors that takes into account cube mounting, baffling, and the method for orientation. For each design, a prototype CCR will be procured and mounted for testing at GSFC or the SCF. The data will be used to verify that issues of solar absorption, radiation from the housing, conductance to the mount, and TIR breakthrough (in the case of the solid cubes) are all mitigated successfully. Simulations using Thermal Desktop will allow for useful comparison between theory and experiment, and to predict performance in the actual lunar environment.

Years 3-4: Having established performance parameters for solid and hollow designs, we will converge on an optimal strategy, then obtain a final prototype and test its performance at the SCF—the results of which will inform a final, converged design. It should be emphasized that a major strength of this proposal is the merger of groups currently pursuing different CCR approaches under the Lunar Suitcase Science Opportunity program, which will result in the LUNAR team's ability to chose the most robust CCR design for future lunar missions.

Work Package #3—Transponder Design: An asynchronous transponder consists of a laser transmitter, receiver, and clock at both the ground station and the spacecraft. Each system pulses its laser independently (asynchronously) and records both its pulse times and arrival times from the other terminal. Information from both the ground and the spacecraft systems are sent either via RF telemetry or on the laser beam itself to a ground processing computer where the ranging information and relative clock offsets are determined. Due to the "regeneration" of the signal after a one-way propagation, laser transponders have a $1/r^2$ link advantage over the $1/r^4$ of passive systems.

To illustrate this, a passive link from a 3.5 m telescope to the Apollo 15 reflector requires about 100 mJ of laser pulse energy concentrated to a 5 μrad outgoing divergence in order to register a single photon. To achieve the same single-photon performance, a 50 mm diameter receiver of an active transponder on the Moon would need only 0.1 μJ of energy sent from Earth in a more forgiving 20 μrad outgoing divergence. Likewise, a 1 mJ pulse from the Moon spanning the entire 2° face of the Earth would produce a single photon detection in a 1 m telescope on Earth.

The robust link margin of a transponder will enable the use of much smaller ground stations, which would provide for more complete time and geometric coverage by using the $\sim$ 35 currently active SLR stations worldwide, averaging over local conditions imposed by atmosphere and crustal loading phenomena. A lunar transponder will also pave the way for interplanetary laser ranging.

Years 1-2: We propose to investigate several laser transponder design options. We will begin by looking at adapting existing transponder architectures to a lunar instrument. These include the Next Generation Satellite Laser Ranging system, the GSFC laser communications transceiver system, the Mars Laser Communication Demonstration, and the Mars Laser Ranging Transponder.

Years 3-4: Having established the overall architecture and parameters to meet the optical requirements, we will investigate the thermal design, anchoring to the lunar surface, dust mitigation, and issues concerning low power and nighttime operation.

Work Package #4—Lunar Placement

Array Layout (4.1): Apart from the design of the cubes themselves, options for their distribution within an array also need to be investigated. A sparsely distributed array of retroreflectors has the potential to significantly reduce range error while maintaining a high return rate. Precision placement is unimportant, as long as the positions are stable—though this general scheme has not yet been adequately explored. Concerning the distribution of arrays on the Moon, the best science will result from a widespread distribution on the near side, with stations near the limb offering a key advantage in determining lunar orientation—and thus interior physics.

Lunar Emplacement and Environment (4.2): To achieve 10 μm ranging performance, we must anchor the CCRs to a thermally stable mass. During the day/night lunar cycle, the regolith will rise and fall by almost 500 μm. Yet, it is estimated that the thermal variation 1 m below the surface is less than 0.1°C throughout the month. Drilling into the regolith with an invar drill bit that can then double as a support rod for the CCR is an attractive option. An alternative approach worth exploring is thermal shielding of the region around the CCR to $\sim$ 1 m radius with multi-layer insulation to keep the immediate area thermally stable.

Dust is also an important consideration with regard to the lunar environment. Not only is dust likely electrostatically transported close to the surface (Stubbs *et al.*, 2006), but meteoric impacts send high-velocity dust on ballistic trajectories around the lunar surface. The lunar dust is sharp and abrasive, so that high-velocity particles can slowly sandblast essential optical surfaces. Recent analysis by the new APOLLO station indicates that the Apollo reflector response is at least ten times worse than it should be, and than it was seen to be in the earliest days of LLR activity. The Lunokhod array appears to be in even worse shape, based on recent experience from APOLLO. Besides obstructing and scattering light, dust on the surfaces will change the thermal behavior.

A simple shield limiting the solid angle visible to each reflector may cut down the magnitude of the problem. But these could become collectors of dust for the observed east-west electrostatic dust motions associated with the crossing of the day/night terminator. Appropriately baffled designs can shed collected dust without depositing the catch onto the critical optical surfaces. The baffles may also be effective in limiting thermal influences from the sun, except near full Moon.

Year 1: We will adapt a laser altimeter simulation code, developed at GSFC for the Mars Laser Altimeter, to simulate the returns from a distributed array of lunar retroreflectors. We will use this code to optimize the array design, predict the ranging performance and verify a number of new data analysis techniques necessary to analyze data from a distributed array.

Year 2: We will investigate issues related to array deployment, such as mass, ease of deployment, range signature as a function of lunar libration, and thermal stability. We will also seek to understand the potential threat of dust and begin devising ways to mitigate its importance.

Years 3-4: We will develop anchoring plans to drill through the regolith—using drills of the type used for the Apollo heat flow experiments—to approximately 1 m depth, where monthly thermal variations are minimal. We will also study the thermal blanket approach. We will finalize a dust/shading baffle compatible with the final CCR design for testing in year 4.

LLR Team Heritage: The LLR contingent of the LUNAR team has a uniquely appropriate heritage. Currie was involved in the design and thermal analysis of the original Apollo corner cube arrays, and directed the McDonald Observatory LLR station in the 1970's. He also has been an instrumental contributor to construction of the SCF in Frascati, which we plan to use for testing corner cube prototypes. Currie was selected for the Lunar Suitcase Science Opportunity (LSSO) study to develop a concept for next-generation solid CCRs for the Moon. Merkowitz was also selected for an LSSO study to advance the design of both CCRs and transponders for the Moon. Also participating from GSFC are Jan McGarry and Thomas Zagwodzki, who developed the next-generation satellite laser ranging station concept for GSFC, and are co-investigators in the GSFC LSSO study. Murphy is the PI of the APOLLO project, which recently pushed LLR into the one-millimeter regime. Murphy is also PI on a mission concept study for placing a transponder on Mars—highly relevant to the present study. Additionally, Murphy is a collaborator on a recent NASA proposal (led by Bob Reasenberg and Irwin Shapiro) to modernize the PEP analysis package to handle millimeter-quality LLR data, dovetailing perfectly with the needs of the LUNAR team. Nordtvedt is especially tightly connected to LLR in that the signal betraying violation of the strong equivalence principle bears his name (Nordtvedt, 1968).

3.4 Key Project: Radio Heliophysics from the Moon

Lead Scientists: J. Kasper (SAO), R. MacDowall (GSFC)

Fundamental understanding of particle acceleration within the heliosphere could result from a simple low-frequency radio array on the near side of the Moon. The Radio Observatory for Lunar Sortie Science (ROLSS) is an experiment that could be deployed by astronauts during a sortie landing. ROLSS would image emission produced by accelerated electrons in the solar corona and inner heliosphere, provide warning at the Moon of radiation events, conduct pathfinding astrophysical imaging of the sky, and serve as a pathfinder for the Cosmology LRA. The investigations proposed here for the Radio Heliophysics Key Project is highly synergistic with the Cosmology LRA Key Project described in Section 3.2. The Cosmology and Heliophysics teams have been collaborating for several years on a common design for ROLSS and will continue to work closely together.

3.4.1 Key Heliophysics Radio Science

High energy particle acceleration occurs in diverse astrophysical environments including the Sun and other stars, supernovae, black holes, and quasars. A fundamental problem is understanding the mechanisms and sites of this acceleration, in particular the roles of shock waves and magnetic reconnection. Within the inner heliosphere, an interval of $1 - 10$ solar radii (R_s) from the Sun, solar flares and coronal mass ejections (CMEs) are efficient particle accelerators. Low frequency observations are an excellent remote diagnostic because electrons accelerated by these structures can produce intense radio bursts. The intensity of these bursts make them easy to detect, but they also provide information about the acceleration regions. For example, the radio burst mechanisms discussed here involve emission at the local plasma frequency, $f_p \approx 9n_e^{1/2}$ kHz, or its harmonics, where n_e is the electron density in cm^{-3}. With a model for n_e, f_p can be converted into a height above the corona, and changing f_p can be converted into radial speed.

Solar radio bursts are one of the primary remote signatures of electron acceleration in the inner heliosphere and our focus is on two emission processes, referred to as Type-II and Type-III radio bursts. Type II bursts originate from suprathermal electrons (E>100 eV) produced at shocks. These shocks are generally produced by CMEs as they expand into the heliosphere with Mach numbers greater than unity. Emission from a Type-II burst drops slowly in frequency as the shock moves away from the Sun into lower density regions at speeds of $400 - 2000$ km s^{-1}. Type III bursts are generated by fast ($2 - 20$ keV) electrons from magnetic reconnection. As the fast electrons escape at a significant fraction of the speed of light into the heliosphere along magnetic field lines, they produce emission that rapidly drops in frequency.

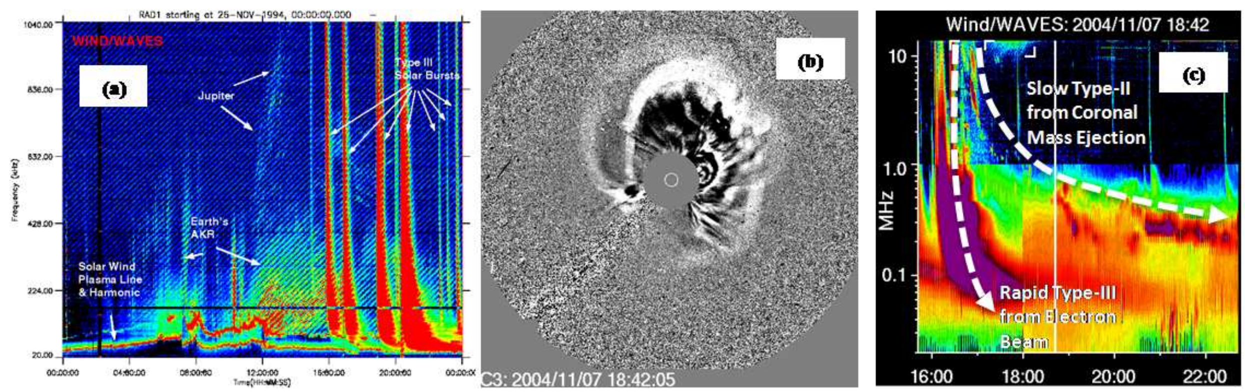


Figure 11: A survey of the low-frequency radio heliosphere. (a) A 24-hour dynamic spectrum covering $0.02-1$ MHz as observed by Wind/WAVES. (b) The difference between two images of the solar corona shows a bright shell as a strong CME drives a shock in the corona (circle in image center indicates solar diameter). (c) Another spectrum, this time covering $1-14$ MHz in a 5-hour interval including the CME in the middle image. See text for details.

For the inner heliosphere the key frequencies are $<$ 10 MHz. Observations in this range must be conducted from space because the ionosphere is opaque in this range. Fig. 11 illustrates the active low-frequency radio environment in space, as seen by the WAVES instrument on the Wind spacecraft (Bougeret *et al.*, 1995). Fig. 11*(a)* is a 24-hour dynamic spectrum covering $0.02 - 1$ MHz. Highlighted features include oscillations at the plasma frequency of the solar wind, Auroral Kilometric Radiation (AKR) from the Earth, Jovian emission, and intense Type-III radio bursts. Fig. 11(b) is the difference between two images of the corona showing a strong CME driving a shock. Fig. 11(c) is another spectrum, this time covering $1 - 14$ MHz in a 5-hour interval including the CME in the middle image. The spectrum includes both Type-III bursts at the start of the event and a Type-II burst as the CME propagates. We have identified three key scientific questions and the measurement requirements for a small lunar radio array to address them:

#1—Acceleration at Shocks: Observations of CMEs near Earth suggest electron acceleration generally occurs where the shock normal is perpendicular to the magnetic field, (Bale *et al.*, 1999), similar to acceleration at planetary bow shocks and other astrophysical sites. This geometry may be unusual in the corona, where the magnetic field is largely radial, as shown schematically in Fig. 12(a). However, geometric arguments suggest that the shock at the front of a CME generally have a quasi-parallel geometry (Q–∥). Acceleration along the flanks of the CME, where the magnetic field-shock normal is quasi-perpendicular (Q–⊥) would seem to be a more likely location for the electron acceleration and Type II emission. The array needs 2° resolution to localize the acceleration site(s) and geometry (Q–∥ vs Q–⊥) around CMEs.

#2—Electron and Ion Acceleration: Observations at $2 - 15$ MHz made with the Wind spacecraft showed that complex Type III-L bursts are highly correlated with CMEs and intense (proton) solar energetic particle (SEP) events observed at 1 AU (Cane *et al.*, 2002; MacDowall *et al.*, 2003). While the association between Type III-L bursts, proton SEP events, and CMEs is now secure, the electron acceleration mechanism remains poorly understood. Two competing sites for the acceleration have been suggested: at shocks in front of a CME or in reconnection regions behind a CME Fig. 12(b). For typical limb CMEs, the angular separation of the leading edge of the shock and the hypothesized reconnection region behind the CME is approximately 1.5° when the CME is $3 - 4R_s$ from the Sun.

#3—CME Interactions and Solar Energetic Particle (SEP) Intensity: Unusually intense radio emission can occur when successive CMEs leave the Sun within 24 hours, as if CME interaction can produce enhanced particle acceleration (Gopalswamy *et al.*, 2001, 2002). Statistically associated with intense SEP events (Gopalswamy *et al.*, 2004), this enhanced emission could result from more efficient acceleration due to changes in field topology, enhanced turbulence, or the direct interaction of the CMEs. The lack of radio imaging makes it difficult to determine the nature of the interaction. Images with degree resolution would be sufficient to localize Type II locations and permit identification of the causal mechanism as well as the relation to intense SEPs.

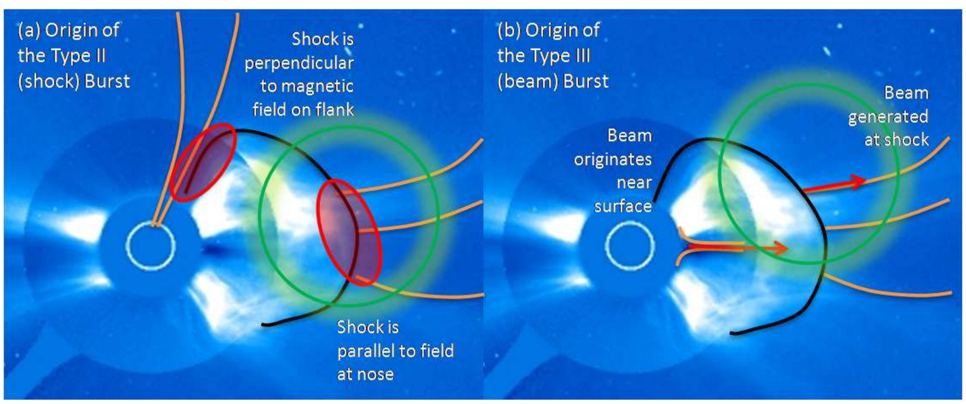


Figure 12: (a) Possible source regions of Type-II bursts created by electrons accelerated near shock surfaces. (b) Possible source regions of Type-III bursts due to electron beams escaping along magnetic field lines into the heliosphere. In both images are of a CME observed by SOHO and superposed lines indicate notional magnetic field lines (orange), shock waves (black), acceleration sites (red), and ROLSS angular resolution at 10 MHz (green).

3.4.2 A Radio Observatory for Lunar Sortie Science (ROLSS)

The Radio Observatory for Lunar Sortie Science (ROLSS) is a concept for a low-frequency array that would be deployed during the first lunar sorties. ROLSS is designed to conduct radio imaging observations of the Sun to address the particle acceleration questions discussed in Sec. 3.4.1. The concept of low-frequency radio imaging from space is not new, but has generally been based on a constellation of free-flying spacecraft, each with an antenna (Jones *et al.*, 2000; MacDowall *et al.*, 2005). Building an array on the Moon has three advantages over the spacecraft. First, with

ROLSS will be a powerful probe of particle acceleration from the Sun, an important issue in solar physics and in safeguarding astronauts on the Moon.

the lunar surface as a structural support, the antennas can be lighter. Second, fuel is not spent to maintain the array configuration. Finally, the Moon blocks half the sky, simplifying the imaging. ROLSS uses three arms arranged in a Y configuration, much like the Very Large Array (VLA). Instead of VLA dishes, ROLSS would use simple electrically-short dipole antennas. Each arm is a thin, 500-m long polyimide film (PF) with metal circuit traces for the antennas and to bring the signals back to a central station (CS). The CS would house signal processing, solar panels, batteries and heaters, and an Earth-directed antenna. Fig. 13 compares ROLSS with the Apollo 17 lunar surface experiment package (ALSEP). Fig. 13(a) shows how individual experiments were placed up to 90 meters from the CS. In Fig. 13(b) a single experiment is shown connected to the CS in the distance using a narrow PF that is similar to our concept for ROLSS. Finally, Fig. 13(c) shows a concept of ROLSS with one arm reaching past the observer, the CS in the distance, and emission from the Sun and Earth visible above.

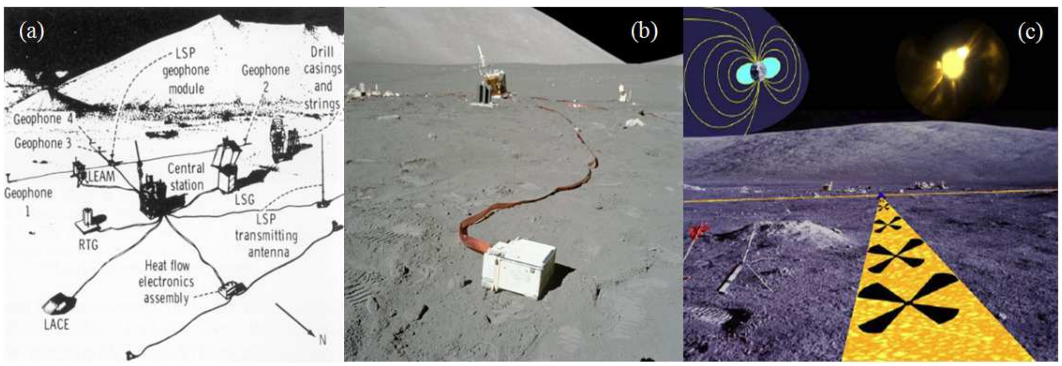


Figure 13: (*a*) Sketch of ALSEP with experiments deployed up to 90 meters from a Central Station (Figure 2-3 of Apollo 17 Preliminary Science Report). (*b*) Photograph of ALSEP with experiments deployed taken by Jack Schmitt at the end of EVA-3 showing the Lunar Mass Spectrometer experiment in the foreground connected to the Central Station with a thin Kapton signal cable (Photo AS17-134-20499). (*c*) Artist concept of ROLSS, showing antennas on Kapton sheets rolled out from a central electronics module similar to ALSEP.

3.4.3 Secondary Applications of ROLSS

In addition to the key science, ROLSS would also enable low-risk astrophysics and technology pathfinding. ROLSS would measure the continuum flux density from strongest sources, e.g., Cas A and M87. The degree to which their long-wavelength spectra flatten will constrain their low-energy electron populations. Radio waves do not propagate through a plasma if their frequency is lower than the plasma frequency. ROLSS array will use solar bursts to characterize the daytime lunar ionosphere by looking for absorption at the lowest frequencies. Finally, ROLSS would serve to demonstrate the technologies proposed for larger, far-side radio arrays.

3.4.4 Technical Approach / Methodology

This Key Project will be lead by Dr. Kasper (SAO). The team will consist of Dr. Kasper and a postdoc at SAO, Dr. MacDowall (GSFC), Dr. Bastian (NRAO), and Prof. Bale (Berkeley). Bale is a Co-I on a separate NLSI proposal to understand the heliophysics environment (plasma, dust, fields) of the Moon. In addition to his involvement below, Bale would provide information about the lunar environment. Kasper is a collaborator on that proposal, and would communicate the development of ROLSS.

The technical approach for the radio heliophysics component of this proposal has been divided into four work packages - science investigation of the lunar radio environment, telescope science requirements and performance, telescope system design and deployment, and technology challenges and solutions. There is a great deal of overlap between the science and technology development required for the ROLSS and LRA concepts. The assignment of tasks was coordinated between the two teams to take advantage of the strengths of each group and to minimize duplication of effort while fostering interaction between the teams.

Work Package #1—Science Investigation of the Lunar Radio Environment: A sufficiently sensitive radio observatory could detect (1) solar radio bursts (2) terrestrial sources, (3) emission from Jupiter and Saturn, and possibly other solar system sources, (4) stellar radio bursts, and (5) emission from numerous galactic and extra-galactic sources. The solar and terrestrial emission represent major sources of interference to the detection of weak astrophysical signals, and it is an open question how far below the horizon the Sun and the Earth would have to be for their signals to be blocked. The objective of this work package is to understand the lunar radio environment using public spacecraft data from the National Space Science Data Center. We will focus on the frequency range most unexplored from the ground, below 14 MHz. The radio data will come from the Wind, STEREO, and RAE-2 spacecraft. Wind has engaged in numerous lunar flybys, as shown in Fig. 14(a). The STEREO spacecraft orbit the Sun at a distance of approximately 1 AU. RAE-2 was launched in 1973 into an elliptical orbit around the Moon. Kasper and MacDowall will gather the WAVES data. Bale has obtained the 9-track RAE-2 data from the NSSDC and written DVDs.

Year 1 – Terrestrial RFI: We will examine RFI using data collected by Wind over a series of lunar flybys. Fig. 14(b) shows frequency contamination by RFI, with the sources changing as Earth rotates. A statistical understanding of the time and frequency variation of RFI as a function of position in terrestrial longitude, latitude, and hour angle will provide important constraints on lunar-based radio observatory parameters. We will also evaluate the intensity of the RFI with distance, to quantify the benefit of being at the Moon relative to other orbits.

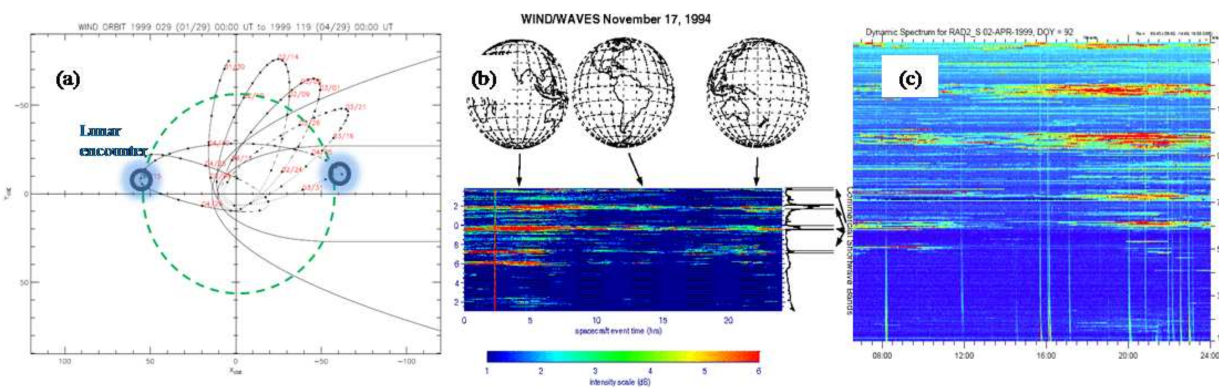


Figure 14: Characterizing the terrestrial and solar contributions to the lunar radio environment. (a) Wind orbits permit exploration of terrestrial RFI with distance from Earth up to and beyond the Moon. (b) Shortwave radio can be seen and varies as a function of visible continents and time of day. (c) This example includes both terrestrial short wave and solar type III bursts.

Year 2 – Solar Background: We will develop a statistical analysis of the background level due to solar radio emissions as a function of frequency and solar cycle. This study will be used to guide plans for radio heliophysics observation from the Moon, as well as determination of interference for astrophysical observations.

Study 3 – Farside Protection: We will use the RAE-2 data to evaluate leakage of terrestrial RFI inside the lunar umbra. We will identify the extent of the leakage and determine if it is described by a geometric model or if solar wind conditions modulate the leakage. The extent of the leakage is of critical importance to concepts for placing radio observatories just behind the lunar limb.

Study 4 – Non-solar Transients: We will search for evidence of low frequency radio transients that are not of solar or planetary origin. If detected, these transients would be a significant scientific target for a lunar array. We will use the two STEREO spacecraft, which are in solar orbits lagging and leading Earth at about 1 AU from the Sun. At the time of this proposal, the spacecraft are about 40° apart around the Sun, leading to a light travel time of about 10 minutes that is much larger than the 16-second time resolution of the data. We will use the arrival delay to search for bursts that do not appear to be of solar or planetary origin.

Work Package #2—Science and Performance Requirements: The objective of this task is to refine the science and performance requirements of ROLSS to optimize the design of the array. All members of the team will contribute to this task. In particular, the postdoc and Dr. Kasper will make use of software developed at MIT and SAO to model the response of low frequency radio arrays to simulate ROLSS observations. The software is written for generic but Earth-based arrays, so the code will be modified slightly to include the rotation rate and orientation of the lunar surface. The output of these simulations will be used to demonstrate the capability of ROLSS to distinguish between burst source locations and to identify the optimum layout of the antennas.

Work Package #3—ROLSS System Design and Deployment:

The objective of this task is to examine the antenna deployment challenge that is unique to an experiment such as ROLSS. This effort will be supported by the science team and by engineers at SAO and GSFC.

Year 1 – We will examine the ROLSS design at a high level to determine if there are additional methods for reducing mass or complexity. This work will include procurement and testing of polyimide film (PF) and investigation of structural and strength requirements of the PF.

Year 2 – We will develop a more detailed thermal model of ROLSS and determine the mechanical stress on the antennas and the heating requirements of the components. We will experiment with folding up and unfurling the PF, both in the laboratory and in a more strenuous environment, such as a parking lot or rough, gravel surface.

Year 3 – We will construct a prototype mechanical device that an astronaut might use to deploy one of the ROLSS arms and test it. We will identify any problems with the deployment process and if time permits improve the mechanical design.

Year 4 – We will investigate an automated deployment process, such as a motorized roll, which would be supervised by an astronaut but potentially less labor intensive.

Work Package #4—Identify Technology Challenges and Solutions: The design risk associated with lunar surface operations can be substantially reduced by Ultra Low Power/Ultra Low Temperature (ULP/ULT) electronics. In this task we will support development of ULP/ULT for lunar applications. ULP/ULT examples include spacecraft components developed by the Center for Advanced Microelectronics and Biomolecular Research (CAMBR), University of Idaho, in partnership with NASA. Currently in development, CAMBE has a ULP correlator with $> 38,000$ correlators on a chip, running at $100 - 200$ MHz for $1 - 2$ bit correlation, requiring only ~ 2 W. This correlator is of significant interest to radio interferometry on the Moon.

Year 1 – We will inventory available ULP/ULT components with particular attention to the needs of radio astronomy from the Moon. Collaborator Pen-Shu Yeh, the technology lead for ULP/ULT electronics at NASA/GSFC, will provide guidance in this activity. We will work together with other nodes of the NLSI to identify lunar-oriented priorities for future ULP/ULT development.

Years 2–4 – We will refine the priority list for ULP/ULT development. We will contact and work with the potential providers of ULP/ULT hardware to identify development paths to production for the priority components. The $25k/year dedicated to this work activity is intended to be seed money to be used by LUNAR in the most effective manner to advance ULP/ULT development. Possible uses are funding focused research related to a specific component such as a ULP/ULT analog-digital converter.

3.5 Key Project: Assessment of Other Astrophysics Enabled by a Return to the Moon

Lead scientists: E. Hallman and J. Burns (Colorado)

The NRC and NAC have identified a few high-priority endeavors that are uniquely enabled by the lunar surface. There are a number of other concepts which have been discussed that may warrant further study. It is our intention to assess all relevant concepts for lunar astrophysics on behalf of the NLSI. To perform this assessment, we propose to operate a small grants program ($100,000/yr) as part of our NLSI astrophysics node. The purpose is to provide study grants to proposers interested in evaluating creative new ideas for utilizing the lunar surface for physics and astrophysics.

LUNAR will coordinate external peer review of these proposals in order to critically evaluate their scientific potential and uniqueness to the lunar surface. This review process is the first key step to determine if these ideas should receive further attention as projects for lunar astrophysics. The next step will be presentations by proposers at yearly science conferences described in the technical management section.

3.5.1 Example Science Projects

Here we provide examples of projects which have been proposed in the past for lunar observatories. We do not advocate these projects individually, but show them as examples of the types of projects that may be worthy of additional study via our LUNAR grants program.

Astronomy with Liquid Mirror Telescopes: The use of rotating liquid mirrors for astronomical observations has been suggested by several investigators (Borra *et al.*, 2007; Angel *et al.*, 2008). Liquid mirror telescopes have lower cost to build and operate than do conventional rigid mirrors. This unique design could allow a large diameter (20-100m) optical telescope to be constructed on the Moon. Telescopes of this type are not suited to free space implementation due to the microgravity conditions.

Lunar Surface Cosmic-Ray and Neutrino Detectors: The Moon has been suggested as a potential site for particle astrophysics experiments. With the lack of a thick atmosphere on the Moon, these instruments do not suffer from high backgrounds generated in cosmic-ray air showers. The Moon is a unique site in that CRs induce a far lower neutrino background in the lunar regolith than are generated in the terrestrial atmosphere (Miller & Cohen, 2006; Learned, 1990). Additionally, the lunar surface may be ideal for detecting heavy nuclei as cosmic rays (Salamon *et al.*, 1990).

Optical & IR/Submillimeter Interferometry: The lunar surface has been suggested as a potential site for a long baseline (km-scale) optical or IR/Submillimeter interferometer (e.g., Shao, 1990; Colavita *et al.*, 1991; Burns *et al.*, 1992). Long-baseline interferometers may be well suited to a solid surface, and passive cooling of instrumentation could be effective in shadowed lunar craters. The astrophysical observations enabled by such an array include exoplanet detection and imaging, and microarcsecond astrometry measurements, as well as studies of the central engine of active galactic nuclei. However, trade studies between L2 and the lunar surface are required to assess the viability of these locations.

Large Aperture Telescopes and the Constellation Infrastructure: There are, in addition, a number of attractive options for using the capabilities being developed for returning humans to the Moon (Ares V) to carry large payloads (e.g., large aperture telescopes) to the lunar surface as well as to L2. The NAC (Schmitt, 2007) has recommended "trade studies should be conducted (including independent cost analysis) to investigate ways in which the exploration architecture can be enabling for astrophysics science through human and robotic operations". For this reason, it may be valuable for NLSI to support limited studies of in-space deployment/servicing options that would be useful to the science communities and NASA's Constellation office.

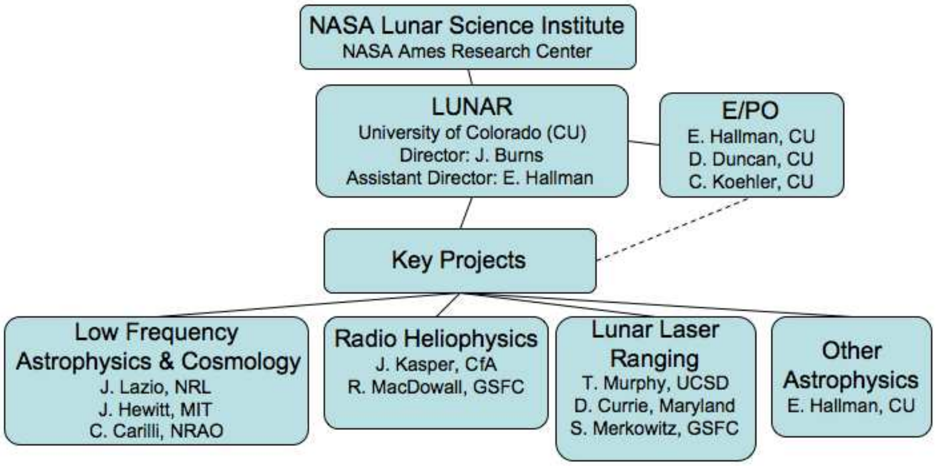


Figure 15: Organization chart for LUNAR. Only the lead Co-investigators for each Key Project are shown.

Management of LUNAR Grants Program: The grants program will consist of a yearly call for proposals, from which ≈5 grants per year will be selected. These grants will be funded at the ≈$20K/yr level. For each grants cycle, we will invite 6 expert reviewers to serve as panelists at U. Colorado. The criteria for selection will include scientific merit and unique applicability to the lunar surface and/or the Constellation infrastructure. We will require grantees to present their results at a yearly LUNAR science symposium. All papers from the Symposium will be published as a proceedings. Also, we will ask the prior year's review panel, as well as members of our NLSI node to evaluate the potential of each grantee's project. Attached to each project's scientific results will be reviewer evaluations of the progress and prospects for each concept. At the end of the grant period for LUNAR, we will have assembled worthy *Astrophysics From the Moon* concepts, along with expert critical evaluations.

3.6 Overall Management Plan for LUNAR

All research supported through the NLSI LUNAR will be coordinated and managed via U. Colorado. The P.I. functions as director of LUNAR and will serve on the NLSI Executive Council. Each Key Project will be managed by Lead Scientist Co-Is, using research facilities provided by the institutions associated with each Key Project team. Burns, Hallman, and the Lead Scientists will comprise a steering committee for LUNAR. See organization chart in Fig. 15. E/PO activities will be managed by Assistant Director Hallman in coordination with the P.I. A Gantt chart with timelines and deliverables for each Key Project is presented in Section 10.

Resources will be managed through U. Colorado and funds will be allocated for use by each Co-I. U. Colorado will maintain financial oversight of each account. The necessary financial reports will be generated in Colorado's Sponsored Projects Accounting office. The P.I. will have final authority on allocation of resources, implementation of the program, and oversight of research and other activities, and responsibility for financial management and reporting to the NLSI and to NASA.

LUNAR will: (1) form Key Project working groups composed of Co-Is, collaborators, postdocs, and students, meeting on a regular basis; (2) Have monthly telecons of the Steering Committee to discuss financial and programmatic issues; (3) Conduct technology-themed meetings to review progress, challenges, and synergies between the Key Projects and with scientific leaders of other NLSI nodes; (4) Host a yearly science symposium composed of LUNAR research teams, along with members of the astrophysical, lunar science, and lunar exploration communities; (5) Schedule monthly LUNAR colloquia rotated among the partner institutions on science of/on/from the Moon.

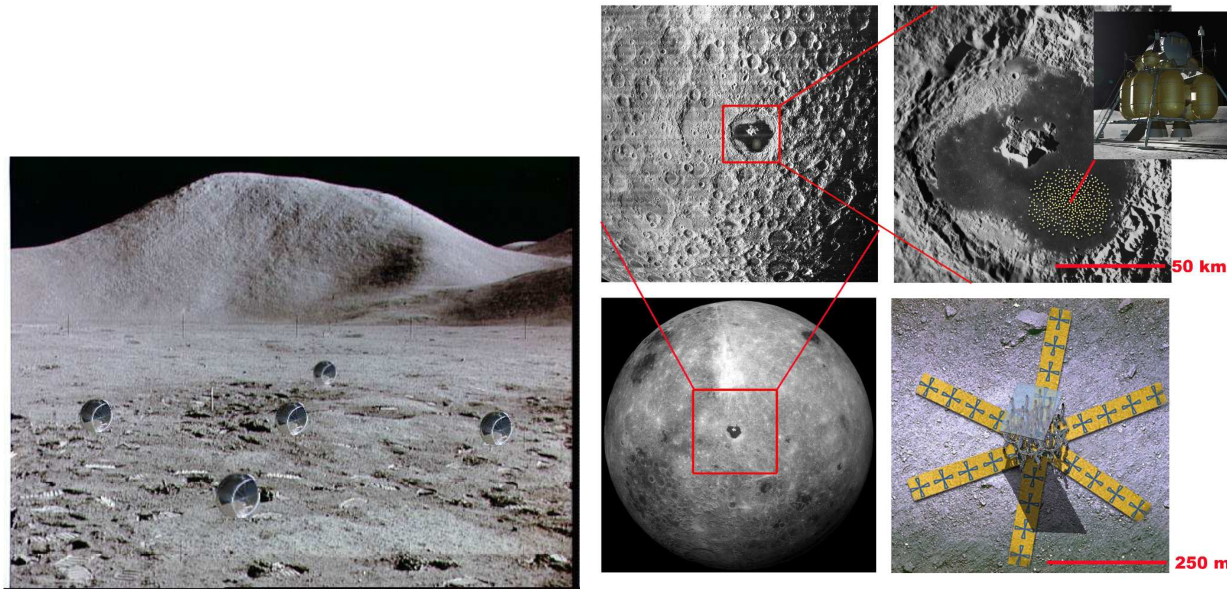


Figure 16: *Left:* Depiction of next-generation lunar reflectors, minus housings and bafles. A sparse array allows resolution of individual reflectors, permitting advances in ground technology to realize 10 μm range precision. *Right:* Dark Ages Lunar Interferometer (DALI). Electrically-short dipoles are grouped into "stations" and deployed via rovers over an area ~50 km in diameter. There will be ~1000 stations, each containing ~100 dipoles.

4 Relevance

It has long been recognized that the Moon is an important platform from which to conduct certain classes of astrophysical observations of the Sun, the heliosphere, and the larger cosmos as well as fundamental measurements of gravitation (e.g., Burns *et al.*, 1990). The prescient Arthur C. Clarke first wrote about the value of Moon as a site for astronomical observatories, acknowledging that special telescopes would be required for the lunar surface conditions (Clarke & Smith, 1954).

In 1965, an NRC Working Group on Optical Astronomy led by Lyman Spitzer recommended two or more 40-in aperture telescopes be placed on the Moon as part of the Apollo Extension Systems Program, which could lead to the development of an optical interferometer (Working Group on Optical Astronomy, 1966). Also in 1965, Nancy Roman chaired a NASA Astronomy Study Group that recognized the unique, radio-quiet of the lunar farside (Alexander & Kaiser, 1976b) and recommended a feasibility study of radio astronomical observations at frequencies between 50 kHz and 10 MHz.

An enduring legacy of Apollo is the laser lunar ranging package. In the 1960's, it was perceived that laser ranging to the Moon could probe fundamental physics by testing alternate theories to Einstein's General Relativity (see e.g., Bender *et al.*, 1973). Thus, the Apollo missions made the placement of laser reflectors on the lunar surface a high priority. Three reflectors were successfully positioned on the Moon by the crews of Apollo 11, 14, and 15, and are still used routinely today (see Figure 1) - making these the only functional pieces of equipment from the original ALSEP (Apollo Lunar Surface Experiment Package). Lunar Laser Ranging was an early example of the benefits of joint human and scientific explorations from the Moon.

Post-Apollo planning for lunar-based telescopes began at a NASA symposium on *Lunar Bases and Space Activities of the 21st Century* (Mendell, 1985). Proposed telescopes included a low frequency array for the lunar surface with dimensions of 15 × 30 km and operating at $\lambda = 30 - 300$ m ($\nu = 1 - 10$ MHz) (Douglas & Smith, 1985), a 20-km baseline optical interferometer (Burke, 1985), a

VLBI station on the Moon (Burns, 1985), a γ-ray telescope (Haymes, 1985), a cosmic ray detector (Adams & Shapiro, 1985), and lunar-based neutrino instruments (Cherry & Lande, 1985). NASA subsequently funded workshops dedicated specifically to astronomical telescopes on the Moon, many organized by P.I. Burns. These included a conference in Houston in 1986 entitled *Future Astronomical Observatories on the Moon* (Burns & Mendell, 1988). This was followed by workshops on *A Lunar Farside Very Low Frequency Array* (Burns *et al.*, 1989) and on *A Lunar Optical-Ultraviolet-Infrared Synthesis Array* (Burns *et al.*, 1992). NASA's sponsorship of these studies demonstrated an early relevance to NASA's science mission and to the potential synergy between exploration and telescopic observations from the Moon.

The 1991 NRC Decadal Survey led by John Bahcall (Astronomy and Astrophysics Survey Committee, 1991) devoted an entire chapter to "Astronomy from the Moon". The report stated "the committee is convinced that the Moon is potentially an excellent site for certain astronomical observatories that are capable of making fundamental discoveries." The report recommended that "NASA should develop the technology necessary for constructing large telescopes and should investigate which of these facilities are best placed in Earth orbit and which are best placed on the Moon." It went on to advise that "NASA, along with other governmental and international agencies, should strive to have the farside of the Moon declared a radio-quiet zone." These recommendations remain valid today.

More recently, the NRC report on *The Scientific Context for the Exploration of the Moon* (Committee on the Scientific Context for Exploration of the Moon, 2007) devoted an entire chapter to "Observations and Science Potentially Enabled by the Vision for Space Exploration." They described the benefits and scientific opportunities for astrophysics, gravitational physics, cosmic-ray physics, and heliophysics - all of which are components of the LUNAR research program.

LUNAR gathers together many of the top researchers in astrophysics, gravitational physics, and heliophysics under one umbrella that, in turn, brings a major portion of the physical sciences *from the Moon* into the NLSI.

The NAC recommendations from its *Workshop on Science Associated with the Lunar Exploration Architecture* (Schmitt, 2007) also point out ways in which the LUNAR research components will support future lunar space missions and technology development related to these missions. Among the NAC's cross-cutting recommendations are:

- **Options for large-area lunar-surface emplacement.** "There should be an assessment of the mobility or emplacement capabilities needed to deploy high-priority science experiments such as dipole antennae, retroreflector/transponders, and geophysical instruments or packages across broad areas of the far and near sides of the Moon as well as globally in the case of a variety of geophysical instruments. For example, a farside facility designed to conduct radio astronomy requires a significant amount of collecting area on the lunar farside (tens of km^2). Tests of theories of gravity require widely dispersed laser retroreflectors, transponders, or both on the near side of the Moon."
- **Far-side meter-wavelength radio environment.** "Appropriate steps should be taken throughout architecture planning to ensure that a radio-quiet environment can be maintained on the lunar farside at a site suitable for deployment of a low frequency, meter wavelength ($\sim$10-250 MHz) radio observatory and that the architecture would enable eventual deployment of such a facility. The principal advantage offered by the Moon as an observatory platform for Astrophysics is the radio-quiet environment of the lunar farside and the potential to emplace a low frequency (meter-wave) radio telescope. Because of shielding from terrestrial (continuous) and solar (half time) radio emissions and lack of a lunar ionosphere [that would affect low frequency observations], a

far-side observatory offers the potential for extremely sensitive probes of cosmic evolution of the Universe. If 21-cm radiation from hydrogen, emitted early during the formation of structure in the universe, can be detected, this redshifted signal would provide a unique and sensitive probe of cosmic evolution."

We now describe the relevance of each LUNAR Key Project to NASA's mission and to recent SMD strategy documents.

Relevance of Low Frequency Cosmology and Astrophysics: In characterizing the formation of the first structures in the Universe and using the intergalactic medium as a cosmological probe, the Lunar Radio Array (LRA) and the work described herein to advance the concept responds to NASA Strategic Goal 3D, "Discover the Origin, Structure, Evolution, and Destiny of the Universe . . ."; and key problems identified in the NRC Decadal Survey report *Astronomy and Astrophysics in the New Millennium* including, "Study the dawn of the modern Universe, when the first stars and galaxies formed."

The LRA is recognized as a promising future lunar science mission, and, indeed, a lunar-based telescope such as the LRA is potentially the only means of acquiring the data necessary to probe into the Dark Ages. 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 farside" as one of the two most promising aspects of lunar-based astrophysical observations (the other being Lunar Laser Ranging, another LUNAR Key Project).

The technology development proposed, particularly toward capable, autonomous rovers, is not only clearly related to potential future lunar missions, it will leverage previous NASA planetary rover developments (e.g., from various Mars missions) and provide benefits for synergistic human-robotic exploration. Examples of other science packages that rovers could deploy include lunar laser retroreflectors and lunar seismometers. Further, the Apollo missions made use of rovers, and plans exist for a next-generation, crewed rover. While a crewed rover has design constraints not faced by an autonomous, robotic rover, there may still be synergies between the developments of the two kinds of rovers.

This component of the NLSI node will help motivate and train the next generation of lunar researchers. The proposed funding includes support for students and post-doctoral researchers, who will be involved with all three work packages of this component of the NLSI node. Further, team members have a long history of involving students and post-doctoral researchers in related projects. Undergraduate students, graduate students, and post-doctoral researchers have all been involved in the development of the LWA, MWA, and PAPER projects, which serve as part of the foundation for the proposed work. Also, undergraduate students, graduate students, and post-doctoral researchers have all been involved in the ROLSS and DALI-LARC concept studies. In addition to the direct involvement in the proposed scientific and technical development work, there will be coordination of the rover development work with the E/PO component of this node.

In a broader context, the proposed work leverages a long history of development of ground-based radio astronomy, supported largely by the National Science Foundation (NSF), but also by the Department of Defense (DoD). The development of both low-mass antennas and capable, autonomous rovers may have synergies with various remote sensing needs or other DoD programs (e.g., DARPA's work on autonomous, unmanned vehicles).

Finally, the proposed technology development portion of this NLSI node addresses key risks identified in the Dark Ages Lunar Interferometer (DALI) concept in the Astrophysics Strategic

Mission Concept Studies (ASMCS) program. Among the technological "tall poles" noted was that the "system mass and antenna deployment strategy are highly dependent on the development" of the antenna and "designing a rover that can 'walk' over an unknown landscape and [deploy antennas]."

Relevance of Lunar Laser Ranging: Lunar Laser Ranging (LLR) is the only remaining functional component of the Apollo Lunar Surface Experiment Package. LLR has provided the most stringent limits on testing the fundamental nature of gravity since the program began in 1969. The activity proposed here will keep LLR on the cutting edge of probing the basic nature of spacetime.

Along with low frequency radio observatories, LLR is recognized as one of the two most promising elements of future astrophysics possibilities from the Moon, as identified by the community workshop "Astrophysics Enabled by the Return to the Moon."

NASA's Astrophysics Roadmap from 2006 asserts on page 20 that:

> NASA should continue to subject gravity and its underpinnings to tests of extreme precision in its solar system missions. A departure from Einstein's theory would shed light on the dark energy problem, and could also be of key importance in interpreting results from gravitational-wave observatories. With the right instruments on NASA spacecraft, the solar system becomes a laboratory for seeking the effects of new physics: dark matter, dark energy, and perhaps even new dimensions of space.

NASA's strategic science plan for the Science Mission Directorate covering 2007–2016 lists astrophysics as one of four major science themes. Within this, Table 7.1 on page 142 has as the first of the four major questions for astrophysics: *What are the Origin, Evolution, and Fate of the Universe?*, under which the first two mandates are:

- Test the validity of Einstein's general theory of relativity;
- Investigate the nature of spacetime through tests of fundamental symmetries.

Additionally, page 148 notes that:

> ...laser-ranging equipment on interplanetary probes may provide precision tests of relativity in the solar system.

The National Research Council report titled *The Scientific Context for Exploration of the Moon* notes in a box on page 66 the role that lunar laser ranging has played not only in testing fundamental gravity, but also in providing information on the lunar interior. By judging the Moon's reaction to gravitational torques, one is able to construct an accurate multi-pole decomposition of the Moon's gravity field, and thus mass distribution. It is also possible to see the presence of a liquid core, and observe friction at the core-mantle boundary—addressing goal 2 in Table 3.1 of the NRC report, *The Scientific Context for Exploration of the Moon*. Additionally, LLR provides information on Earth orientation, relating to issues of geophysics and climate change.

Many issues associated with the design and deployment of next-generation LLR reflectors or transponders are relevant to other facets of lunar exploration. The connection to surface rovers has already been noted. The reflector design will carefully assess the threat of dust obscuration, and seek ways to mitigate its influence—a common threat to many future lunar emplacements, both optical and mechanical in nature. Techniques for anchoring reflectors into the regolith may also find synergy with other applications in which surface drilling is required.

A laser transponder on the Moon will not only result in a large leap in range accuracy to the Moon, but will also pave the way for precision range measurements to planets such as Mars—currently limited to roughly 1 m range accuracy via radio techniques—and thus extend our capability for testing general relativity. The Moon-Mars Science Linkages Science Steering Group identified the need for communication and ranging instrument development in the context of similar lunar science for future Mars missions (Shearer, 2004). These versatile devices may not only serve fundamental physics interests, but also navigation and optical communications applications. Even one LLR transponder would open the technique to small-aperture satellite laser ranging stations around the world, many of which are NASA-supported.

Relevance of Radio Heliophysics: The connection between solar explosions, magnetic fields, and particle acceleration (traced by radio emission) ties directly to NASA Strategic Goal 3B ("Understand the Sun and Its Effects on the Earth and the Solar System") and the NRC report "The Sun to the Earth and Beyond: A Decadal Research Strategy in Solar and Space Physics" (Lanzerotti et al. 2002). This later report identifies "the initiation and evolution of CMEs," "the role of magnetic reconnection," "the spatial and temporal evolution of [solar energetic particle] sources," and "basic SEP acceleration and transport processes" as key questions.

Our key heliophysics science goals are to use radio emission to study particle acceleration, addressing NASA Strategic Goal 3B ("Understanding the Sun and Its Effects on Earth and the Solar System"), and the lunar ionosphere, addressing NASA Strategic Goal 6 (Establish a Lunar Return Program...), by searching for cutoffs of broadband solar bursts.

ROLSS science cuts across all three components of the heliophysics research focus areas, as identified in the 2006 NASA Heliophysics Roadmap Report. Determining the relationship between particle acceleration and coronal mass ejections and coronal magnetic fields addresses RFA F, "Fundamental Physics". Tracking these CMEs into the heliosphere will allow us to better understand the effects of CMEs on Earth, responsive to RFA H, "Understand our Home". Finally the ROLSS observations are directly applicable to RFA J, "Safeguarding the Journey", since they will permit a local understanding of developing radiation events from the Moon that would be useful as a warning to astronauts.

ROLSS is also called out in the NASA report on "Heliophysics at and of the Moon."

Relevance of Assessment of Other Astrophysics Key Project: Our assessment program for other potential astrophysical instruments on the Moon is highly relevant to NASA and to the NLSI in terms of the lunar missions. Assessing and ranking the concepts for astrophysics from the Moon provides a roadmap for future lunar missions, which will guide the planning for lunar surface observatories. In addition, each of these concepts will likely require certain infrastructure on the lunar surface, and the technology and instrument development for these projects will be valuable for future lunar missions. It is also clear that these projects will lay the groundwork for acquiring and interpreting data from the Moon, and thus should be labeled fundamental research.

Providing these study grants will allow awardees to support the research of graduate and undergraduate students working on lunar science. In addition many of the proposers will likely be scientists in their early professional years, who may be encouraged to spend a long career working on astrophysics from the Moon. As our grants are relatively small, it is also likely that our funds will supplement the funding of other grant agencies, including the NSF, with synergistic overlap of projects.

References

Adams, Jr., J. H., & Shapiro, M. M. 1985. Irradiation of the moon by galactic cosmic rays and other particles. *Pages 315–327 of:* Mendell, W. W. (ed), *Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, TX.*

Adelberger, EG, Heckel, BR, & Nelson, AE. 2003. Tests of the gravitational inverse-square law. *ANNUAL REVIEW OF NUCLEAR AND PARTICLE SCIENCE*, **53**, 77–121.

Ahn, K., Shapiro, P. R., Iliev, I. T., Mellema, G., & Pen, U.-L. 2008. The Inhomogeneous Background of Hydrogen-Molecule Dissociating Radiation during Cosmic Reionization. *ApJ*, **submitted**(July).

Alexander, J. K., & Kaiser, M. L. 1976a. Terrestrial kilometric radiation. I - Spatial structure studies. *J. Geophys. Res.*, **81**(Dec.), 5948–5956.

Alexander, J. K., & Kaiser, M. L. 1976b. Terrestrial kilometric radiation. I - Spatial structure studies. *JGR*, **81**(Dec.), 5948–5956.

Angel, R., Worden, S. P., Borra, E. F., Eisenstein, D. J., Foing, B., Hickson, P., Josset, J.-L., Ma, K. B., Seddiki, O., Sivanandam, S., Thibault, S., & Susante, P. v. 2008. A Cryogenic Liquid-Mirror Telescope on the Moon to Study the Early Universe. *ApJ*, **680**(June), 1582–1594.

Astronomy and Astrophysics Survey Committee. 1991. *Pages 1–202 of: The Decade of Discovery in Astronomy and Astrophysics, National Academies Press, Washington, DC.*

Bailey, Quentin G., & Kostelecky, V. Alan. 2006. Signals for Lorentz violation in post-Newtonian gravity. *PHYSICAL REVIEW D*, **74**(4).

Bale, S. D., Reiner, M. J., Bougeret, J.-L., Kaiser, M. L., Krucker, S., Larson, D. E., & Lin, R. P. 1999. The source region of an interplanetary type II radio burst. *Geophys. Res. Lett.*, **26**(June), 1573–1576.

Barkana, R., & Loeb, A. 2005. Detecting the Earliest Galaxies through Two New Sources of 21 Centimeter Fluctuations. *ApJ*, **626**(June), 1–11.

Bekenstein, JD. 2004. Relativistic gravitation theory for the modified Newtonian dynamics paradigm. *PHYSICAL REVIEW D*, **70**(8).

Bender, P. L., Currie, D. G., Dicke, R. H., Eckhardt, D. H., Faller, J. E., Kaula, W. M., Mulholland, J. D., Plotkin, H. H., Poultney, S. K., Silverberg, E. C., Wilkinson, D. T., Williams, J. G., & Alley, C. O. 1973. The Lunar Laser Ranging Experiment. *Science*, **182**(Oct.), 229–238.

Bond, J. R., & Myers, S. T. 1996. The Peak-Patch Picture of Cosmic Catalogs. III. Application to Clusters. *ApJS*, **103**(Mar.), 63–+.

Boone, F. 2002. Interferometric array design: Distributions of Fourier samples for imaging. *A&A*, **386**(May), 1160–1171.

Borra, E. F., Seddiki, O., Angel, R., Eisenstein, D., Hickson, P., Seddon, K. R., & Worden, S. P. 2007. Deposition of metal films on an ionic liquid as a basis for a lunar telescope. *Nature*, **447**(June), 979–981.

Bougeret, J.-L., Kaiser, M. L., Kellogg, P. J., Manning, R., Goetz, K., Monson, S. J., Monge, N., Friel, L., Meetre, C. A., Perche, C., Sitruk, L., & Hoang, S. 1995. Waves: The Radio and Plasma Wave Investigation on the Wind Spacecraft. *Space Science Reviews*, **71**(Feb.), 231–263.

Bowman, J. D., Morales, M. F., & Hewitt, J. N. 2006. The Sensitivity of First-Generation Epoch of Reionization Observatories and Their Potential for Differentiating Theoretical Power Spectra. *ApJ*, **638**(Feb.), 20–26.

Bowman, J. D., Rogers, A. E. E., & Hewitt, J. N. 2008. Toward Empirical Constraints on the Global Redshifted 21 cm Brightness Temperature During the Epoch of Reionization. *ApJ*, **676**(Mar.), 1–9.

Burke, B. F. 1985. Astronomical interferometry on the moon. *Pages 281–291 of:* Mendell, W. W. (ed), *Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, TX*.

Burns, J. O. 1985. A moon-earth radio interferometer. *Pages 293–300 of:* Mendell, W. W. (ed), *Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, TX*.

Burns, J. O., & Mendell, W. W. 1988 (Mar.). Future Astronomical Observatories on the Moon. *In:* Burns, J. O., & Mendell, W. W. (eds), *Workshop held in Houston, TX, 10 Jan. 1986; sponsored by NASA, Johnson Space Flight Center, Houston, TX and American Astronomical Society, Washington, DC*.

Burns, J. O., Duric, N., Johnson, S., & Taylor, G. J. 1989. A lunar far-side very low frequency array. *NASA STI/Recon Technical Report N*, **90**(Nov.), 10805.

Burns, J. O., Duric, N., Taylor, G. J., & Johnson, S. W. 1990. Observatories on the moon. *Scientific American*, **262**(Mar.), 42–49.

Burns, J. O., Johnson, S. W., & Duric, N. 1992 (Nov.). *A Lunar Optical-Ultraviolet-Infrared Synthesis Array (LOUISA), NASA*. Tech. rept.

Cane, H. V., Erickson, W. C., & Prestage, N. P. 2002. Solar flares, type III radio bursts, coronal mass ejections, and energetic particles. *Journal of Geophysical Research (Space Physics)*, **107**(Oct.), 1315.

Cherry, M., & Lande, K. 1985. A lunar neutrino detector. *Pages 335–343 of:* Mendell, W. W. (ed), *Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, TX*.

Chippendale, A. P., Subrahmanyan, E., & Ekers, R. 2005. *Cosmological Reionization Experiment (CoRE)*. unpublished.

Clarke, A. C., & Smith, R. A. 1954. *Pages 1–112 of: The Exploration of the Moon, Harper and Brothers*.

Cohen, A. S., Lane, W. M., Cotton, W. D., Kassim, N. E., Lazio, T. J. W., Perley, R. A., Condon, J. J., & Erickson, W. C. 2007. The VLA Low-Frequency Sky Survey. *AJ*, **134**(Sept.), 1245–1262.

Colavita, M. M., Shao, M., Hines, B. E., Levine, B. M., & Gershman, R. 1991 (Sept.). Optical system design for a Lunar Optical Interferometer. *Pages 168–181 of:* Bely, P. Y., & Breckinridge, J. B. (eds), *Space astronomical telescopes and instruments; Proceedings of the Meeting, Orlando, FL, Apr. 1-4, 1991 (A92-45151 19-89). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 168-181.* Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference, vol. 1494.

Colless, M., Dalton, G., Maddox, S., Sutherland, W., Norberg, P., Cole, S., Bland-Hawthorn, J., Bridges, T., Cannon, R., Collins, C., Couch, W., Cross, N., Deeley, K., De Propris, R., Driver, S. P., Efstathiou, G., Ellis, R. S., Frenk, C. S., Glazebrook, K., Jackson, C., Lahav, O., Lewis, I., Lumsden, S., Madgwick, D., Peacock, J. A., Peterson, B. A., Price, I., Seaborne, M., & Taylor, K. 2001. The 2dF Galaxy Redshift Survey: spectra and redshifts. *MNRAS*, **328**(Dec.), 1039–1063.

Committee on the Scientific Context for Exploration of the Moon. 2007. *Pages 1–120 of: The Scientific Context for Exploration of the Moon, National Academies Press, Washington, DC.*

de Oliveira-Costa, A., Tegmark, M., Gaensler, B. M., Jonas, J., Landecker, T. L., & Reich, P. 2008. A model of diffuse Galactic radio emission from 10 MHz to 100 GHz. *MNRAS*, **388**(July), 247–260.

Deffayet, C, Dvali, G, & Gabadadze, G. 2002. Accelerated universe from gravity leaking to extra dimensions. *PHYSICAL REVIEW D*, **65**(4).

Dickey, JO, Bender, PL, Faller, JE, Newhall, XX, Ricklefs, RL, Ries, JG, Shelus, PJ, Veillet, C, Whipple, AL, Wiant, JR, Williams, JG, & Yoder, CF. 1994. Lunar Laser Ranging - A Continuing Legacy of the Apollo Program. *SCIENCE*, **265**(5171), 482–490.

Douglas, J. N., & Smith, H. J. 1985. A very low frequency radio astronomy observatory on the moon. *Pages 301–306 of:* Mendell, W. W. (ed), *Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, TX.*

Dvali, G, Gruzinov, A, & Zaldarriaga, M. 2003. The accelerated universe and the Moon. *PHYSICAL REVIEW D*, **68**(2).

Eisenstein, D. J., Zehavi, I., Hogg, D. W., Scoccimarro, R., Blanton, M. R., Nichol, R. C., Scranton, R., Seo, H.-J., Tegmark, M., Zheng, Z., Anderson, S. F., Annis, J., Bahcall, N., Brinkmann, J., Burles, S., Castander, F. J., Connolly, A., Csabai, I., Doi, M., Fukugita, M., Frieman, J. A., Glazebrook, K., Gunn, J. E., Hendry, J. S., Hennessy, G., Ivezić, Z., Kent, S., Knapp, G. R., Lin, H., Loh, Y.-S., Lupton, R. H., Margon, B., McKay, T. A., Meiksin, A., Munn, J. A., Pope, A., Richmond, M. W., Schlegel, D., Schneider, D. P., Shimasaku, K., Stoughton, C., Strauss, M. A., SubbaRao, M., Szalay, A. S., Szapudi, I., Tucker, D. L., Yanny, B., & York, D. G. 2005. Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies. *ApJ*, **633**(Nov.), 560–574.

Farrell, W. M., Desch, M. D., & Zarka, P. 1999. On the possibility of coherent cyclotron emission from extrasolar planets. *J. Geophys. Res.*, **104**(June), 14025–14032.

Furlanetto, S. R., Oh, S. P., & Briggs, F. H. 2006a. Cosmology at low frequencies: The 21 cm transition and the high-redshift Universe. *Phys. Reports*, **433**(Oct.), 181–301.

Furlanetto, S. R., Oh, S. P., & Pierpaoli, E. 2006b. Effects of dark matter decay and annihilation on the high-redshift 21cm background. *Phys. Rev. D*, **74**(10), 103502–+.

Gleser, L., Nusser, A., & Benson, A. J. 2008. De-contamination of cosmological 21-cm maps. *MNRAS*, **in press**.

Gopalswamy, N., Yashiro, S., Kaiser, M. L., Howard, R. A., & Bougeret, J.-L. 2001. Radio Signatures of Coronal Mass Ejection Interaction: Coronal Mass Ejection Cannibalism? *ApJL*, **548**(Feb.), L91–L94.

Gopalswamy, N., Yashiro, S., Kaiser, M. L., Howard, R. A., & Bougeret, J.-L. 2002. Interplanetary radio emission due to interaction between two coronal mass ejections. *Geophys. Res. Lett.*, **29**(8), 080000–1.

Gopalswamy, N., Yashiro, S., Krucker, S., Stenborg, G., & Howard, R. A. 2004. Intensity variation of large solar energetic particle events associated with coronal mass ejections. *Journal of Geophysical Research (Space Physics)*, **109**(18), 12105.

Griessmeier, J.-M., Stadelmann, A., Motschmann, U., Belisheva, N. K., Lammer, H., & Biernat, H. K. 2005. Cosmic Ray Impact on Extrasolar Earth-Like Planets in Close-in Habitable Zones. *Astrobiology*, **5**(Oct.), 587–603.

Haymes, R. C. 1985. Lunar based gamma ray astronomy. *Pages 307–314 of:* Mendell, W. W. (ed), *Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, TX*.

Jones, D. L., Allen, R. J., Basart, J. P., Bastian, T., Blume, W. H., Bougeret, J.-L., Dennison, B. K., Desch, M. D., Dwarakanath, K. S., Erickson, W. C., Farrell, W., Finley, D. G., Gopalswamy, N., Howard, R. E., Kaiser, M. L., Kassim, N. E., Kuiper, T. B. H., MacDowall, R. J., Mahoney, M. J., Perley, R. A., Preston, R. A., Reiner, M. J., Rodriguez, P., Stone, R. G., Unwin, S. C., Weiler, K. W., Woan, G., & Woo, R. 2000. The ALFA Medium Explorer Mission. *Advances in Space Research*, **26**, 743–746.

Khan, A, Mosegaard, K, Williams, JG, & Lognonne, P. 2004. Does the Moon possess a molten core? Probing the deep lunar interior using results from LLR and Lunar Prospector. *JOURNAL OF GEOPHYSICAL RESEARCH-PLANETS*, **109**(E9).

Khatri, R., & Wandelt, B. D. 2008. Cosmic (Super)String Constraints from 21cm Radiation. *Physical Review Letters*, **100**(9), 091302–+.

Kogan, L., & Cohen, A. 2005. *Optimization of the LWA Antenna Station Configuration Minimizing Side Lobes*. Tech. rept. LWA Memorandum 21. http://www.ece.vt.edu/swe/lwa/memo/memo0021.pdf.

Komatsu, E., Dunkley, J., Nolta, M. R., Bennett, C. L., Gold, B., Hinshaw, G., Jarosik, N., Larson, D., Limon, M., Page, L., Spergel, D. N., Halpern, M., Hill, R. S., Kogut, A., Meyer, S. S., Tucker, G. S., Weiland, J. L., Wollack, E., & Wright, E. L. 2008. Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation. *ArXiv e-prints*, **803**(Mar.).

Lazio, T. J. W., Cohen, A. S., Kassim, N. E., Perley, R. A., Erickson, W. C., Carilli, C. L., & Crane, P. C. 2006. Cygnus A: A Long-Wavelength Resolution of the Hot Spots. *ApJ*, **642**(May), L33–L36.

Learned, J. G. 1990. Lunar neutrino physics. *Pages 119–127 of:* Potter, A. E., & Wilson, T. L. (eds), *Physics and Astrophysics from a Lunar Base*. American Institute of Physics Conference Series, vol. 202.

Lidz, A., Zahn, O., McQuinn, M., Zaldarriaga, M., Dutta, S., & Hernquist, L. 2007. Higher Order Contributions to the 21 cm Power Spectrum. *ApJ*, **659**(Apr.), 865–876.

Liu, A., Tegmark, M., & Zaldarriaga, M. 2008. Will point sources spoil 21 cm tomography? *ArXiv e-prints*, **807**(July).

Loeb, A., & Zaldarriaga, M. 2004. Measuring the Small-Scale Power Spectrum of Cosmic Density Fluctuations through 21cm Tomography Prior to the Epoch of Structure Formation. *Physical Review Letters*, **92**(21), 211301–+.

Lue, A, & Starkman, G. 2003. Gravitational leakage into extra dimensions: Probing dark energy using local gravity. *PHYSICAL REVIEW D*, **67**(6).

MacDowall, R. J., Lara, A., Manoharan, P. K., Nitta, N. V., Rosas, A. M., & Bougeret, J. L. 2003. Long-duration hectometric type III radio bursts and their association with solar energetic particle (SEP) events. *Geophys. Res. Lett.*, **30**(12), 120000–1.

MacDowall, R. J., Bale, S. D., Demaio, L., Gopalswamy, N., Jones, D. L., Kaiser, M. L., Kasper, J. C., Reiner, M. J., & Weiler, K. W. 2005 (Jan.). Solar Imaging Radio Array (SIRA): a multispacecraft mission. *Pages 284–292 of:* Komar, G. J., Wang, J., & Kimura, T. (eds), *Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing. Edited by Komar, George J.; Wang, Jinxue; Kimura, Toshiyoshi. Proceedings of the SPIE, Volume 5659, pp. 284-292 (2005)*. Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference, vol. 5659.

Mack, K. J., & Wesley, D. H. 2008. Primordial black holes in the Dark Ages: Observational prospects for future 21cm surveys. *ArXiv e-prints*, **805**(May).

Meiksin, A., & White, M. 2004. The effects of ultraviolet background correlations on Lyα forest flux statistics. *MNRAS*, **350**(May), 1107–1126.

Mendell, W. W. 1985. Lunar Bases and Space Activities of the 21st Century. *In:* Mendell, W. W. (ed), *Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, TX*.

Mesinger, A., & Dijkstra, M. 2008. UV Radiative Feedback During the Advanced Stages of Reionization. *ArXiv e-prints*, **806**(June).

Mesinger, A., & Furlanetto, S. 2007. Efficient Simulations of Early Structure Formation and Reionization. *ApJ*, **669**(Nov.), 663–675.

Miller, R. S., & Cohen, T. 2006. Cosmic-ray induced neutrino fluxes at the Moon: A semi-analytic approach. *Astroparticle Physics*, **25**(July), 368–374.

Murphy, T. W., Adelberger, E. G., Battat, J. B. R., Carey, L. N., Hoyle, C. D., Leblanc, P., Michelsen, E. L., Nordtvedt, K., Orin, A. E., Strasburg, J. D., Stubbs, C. W., Swanson, H. E., & Williams, E. 2008. The Apache Point Observatory Lunar Laser-ranging Operation: Instrument Description and First Detections. *PASP*, **120**(Jan.), 20–37.

Murphy, Jr., T. W., Nordtvedt, K., & Turyshev, S. G. 2007. Gravitomagnetic influence on gyroscopes and on the lunar orbit. *PHYSICAL REVIEW LETTERS*, **98**(7).

Murphy, Jr., T. W., Adelberger, E. G., Battat, J. B. R., Carey, L. N., Hoyle, C. D., LeBlanc, P., Michelsen, E. L., Nordtvedt, K., Orin, A. E., Strasburg, J. D., Stubbs, C. W., Swanson, H. E., & Williams, E. 2008. The apache point observatory lunar laser-ranging operation: Instrument description and first detections. *PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC*, **120**(863), 20–37.

Nordtvedt, K. 1968. Equivalence Principle for Massive Bodies 1: Phenomenology. *PHYSICAL REVIEW*, **169**(5), 1014.

Perlmutter, S., Aldering, G., della Valle, M., Deustua, S., Ellis, R. S., Fabbro, S., Fruchter, A., Goldhaber, G., Groom, D. E., Hook, I. M., Kim, A. G., Kim, M. Y., Knop, R. A., Lidman, C., McMahon, R. G., Nugent, P., Pain, R., Panagia, N., Pennypacker, C. R., Ruiz-Lapuente, P., Schaefer, B., & Walton, N. 1998. Discovery of a supernova explosion at half the age of the universe. *Nature*, **391**(Jan.), 51–+.

Pritchard, J. R., & Furlanetto, S. R. 2007. 21-cm fluctuations from inhomogeneous X-ray heating before reionization. *MNRAS*, **376**(Apr.), 1680–1694.

Pritchard, J. R., & Loeb, A. 2008. Evolution of the 21 cm signal throughout cosmic history. *ArXiv e-prints*, **802**(Feb.).

Riess, A. G., Filippenko, A. V., Challis, P., Clocchiatti, A., Diercks, A., Garnavich, P. M., Gilliland, R. L., Hogan, C. J., Jha, S., Kirshner, R. P., Leibundgut, B., Phillips, M. M., Reiss, D., Schmidt, B. P., Schommer, R. A., Smith, R. C., Spyromilio, J., Stubbs, C., Suntzeff, N. B., & Tonry, J. 1998. Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant. *AJ*, **116**(Sept.), 1009–1038.

Salamon, M. H., Price, P. B., & Tarle, G. 1990. LBHNC - A lunar-based heavy nucleus detector. *Pages 622–626 of:* Mumma, M. J., & Smith, H. J. (eds), *Astrophysics from the Moon*. American Institute of Physics Conference Series, vol. 207.

Schmitt, H. H. 2007 (Nov.). Recommendations from the Workshop on Science Associated with the Lunar Exploration Architecture. *Pages 1–282 of:* Joliff, B. (ed), *http://www.hq.nasa.gov/office/oer/nac/ recommendations/Recommend-5-07.pdf*.

Shao, M. 1990. Lunar optical interferometer. *Pages 486–494 of:* Mumma, M. J., & Smith, H. J. (eds), *Astrophysics from the Moon*. American Institute of Physics Conference Series, vol. 207.

Shearer, C. et al. 2004 (October). *Findings of the Moon Mars Science Linkage Science Steering Group*. Unpublished white paper from the Mars Exploration Program Analysis Group (MEPAG).

Stubbs, TJ, Vondrak, RR, & Farrell, WM. 2006. A dynamic fountain model for lunar dust. *MOON AND NEAR-EARTH OBJECTS*, **37**(1), 59–66.

Tegmark, M., & Zaldarriaga, M. 2008. The Fast Fourier Transform Telescope. *ArXiv e-prints*, **805**(May).

Thompson, A. R., Moran, J. M., & Swenson, G. W. 1986. *Interferometry and synthesis in radio astronomy*. New York, Wiley-Interscience, 1986, 554 p.

Valdés, M., Ferrara, A., Mapelli, M., & Ripamonti, E. 2007. Constraining dark matter through 21-cm observations. *MNRAS*, **377**(May), 245–252.

Will, C. M. 1981. *Theory and Experiment in Gravitational Physics*. Cambridge University Press.

Will, CM, & Nordtvedt, K. 1972. Conservation Laws and Preferred Frames in Relativistic Gravity 1: Preferred-Frame Theories and an Extended PPN Formalism. *ASTROPHYSICAL JOURNAL*, **177**(3), 757.

Williams, JG, Newhall, XX, & Dickey, JO. 1996. Relativity parameters determined from lunar laser ranging. *PHYSICAL REVIEW D*, **53**(12), 6730–6739.

Williams, JG, Turyshev, SG, & Boggs, DH. 2004. Progress in lunar laser ranging tests of relativistic gravity. *PHYSICAL REVIEW LETTERS*, **93**(26).

Working Group on Optical Astronomy. 1966. In Part 2 of Space Research: Directions for the Future, Woods Hole, MA. *Space Science Board, National Academy of Sciences, Washington, DC.*

5 Plan to Support Other Institute Objectives

Members of the LUNAR Consortium have a long history of working to strengthen the lunar science and exploration communities within an interdisciplinary framework that is illustrative of our strong commitment to the goals of the NLSI. The P.I. has a 25 year collaborative partnership with leaders of the lunar science and exploration communities (see CV). He has served as a bridge between astrophysicists, physicists, lunar geologists, and engineers. Burns began working with Wendell Mendell, Jeff Taylor, Paul Spudis, and Stewart Johnson on research and on a series of workshops that explored concepts for lunar-based telescopes interfaced with outposts on the Moon beginning in the mid-1980's.

Similar commitments to the objectives of NLSI have been exhibited by other members of the LUNAR Consortium. Co-I Currie was a member of the original Apollo Lunar Ranging research team (Bender *et al.*, 1973) and has led a Lunar Science Sortie Opportunities (LSSO) study of a new generation retroreflector array for the Moon. Co-I Merkowitz has led another LSSO concept study of enhanced precision reflector arrays and asynchronous transponders for lunar laser ranging.

Co-I Lazio was funded by the LSSO program to design a technology prototype of a low frequency interferometer for the lunar surface. Lazio and Co-I Jackie Hewitt led successful proposals for funding by NASA Astrophysics for Strategic Mission Concept Studies of a farside low frequency array for Dark Ages cosmology. Presentations about the Lunar Low Frequency telescope have been made at NASA workshops and NRC panel meetings.

All these workshops and projects have involved education and public outreach, training the next generation of students and postdocs, publications, seminars, and extensive use of institutional facilities - all representative of the objectives of the NLSI. Our group of LUNAR investigators is built largely of researchers who excel both at the science and in providing programmatic and intellectual leadership to the community. The LUNAR institutions have all committed to develop lunar science and exploration as a research endeavor and as a program. As detailed below, this commitment includes funding graduate students and academic year release time for investigators, as well as funds for equipment and administrative support. We now detail our new efforts for LUNAR to support the broader objectives of the NASA Lunar Science Institute.

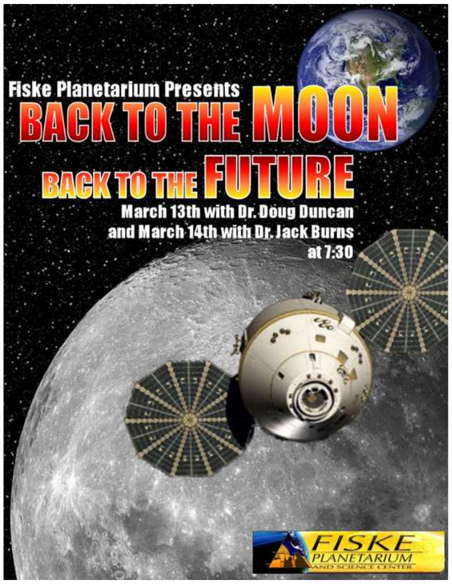
5.1 Education and Public Outreach

Leads for E/PO: E. Hallman and D. Duncan (Colorado)

The LUNAR E/PO effort will consist of four projects: new planetarium programs, new visualizations of the Moon using Science on a Sphere, teacher workshops, and coordination with the International Year of Astronomy. The requested funding (see budget details in Section 10) for the E/PO program is <2% of the entire budget for LUNAR. However, U. Colorado is providing a one-to-one cost-match, thus doubling the resources invested into this important aspect of our LUNAR effort. E/PO lead Dr. Duncan requests 0.5 month/yr salary (cost-matched by Colorado) and Fiske Educator Dr. Trab-Metlay requests 1 month/yr salary to organize funding for the teacher workshops. Our E/PO budget also has funding for a Planetarium show producer (25% time for 3 yrs), an audio/video technician (1.5 months/yr), and 600 hrs of student assistants. Funding is requested to perform summative and formative evaluations of all the E/PO programs. Dr. Duncan will serve as the LUNAR representative to the NLSI E/PO Working Group.

Planetarium Programs

At the heart of E/PO for our LUNAR proposal will be two planetarium programs, one for adults, and one for children, and a presentation for use with "Science on a Sphere," the new NOAA display designed to show planetary data that is being installed in many American museums. The adult



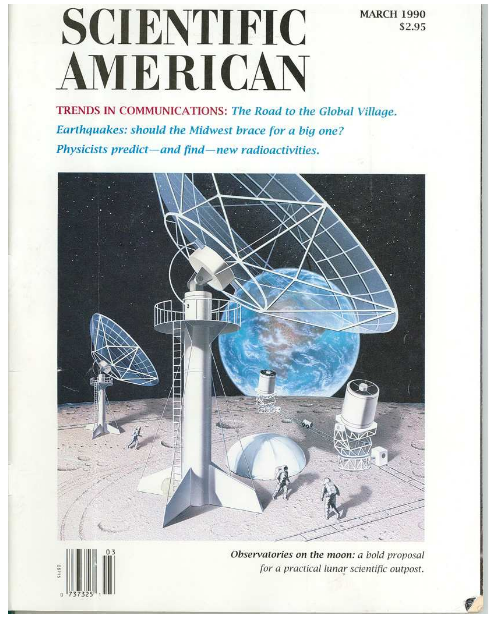


Figure 17: *Left:* Poster for Fiske Planetarium program on NASA's return to the Moon at the University of Colorado. *Right:* Cover of *Scientific American* that featured article by PI Burns on earlier concepts for telescopes on the Moon.

program, "Back to the Moon, Back to the Future", will be based on live planetarium presentations given by PI Jack Burns and EPO Co-I Doug Duncan to audiences at the University of Colorado's Fiske Planetarium. The children's program, "Max Goes to the Moon," will be based on the award-wining book of the same name written by Boulder author Dr. Jeff Bennett.

"Back to the Moon, Back to the Future" is currently a program presented live at the University of Colorado's Fiske Planetarium by LUNAR P.I. Burns. The program reminds audiences of NASA's past accomplishments exploring the Moon, then goes on to describe the science that can be done nowadays. Highlighting key discoveries from the Moon rocks, such as the evidence that the origin of the Moon involved a major impact with the Earth, has proven interesting to audiences and given them more appreciation of the science resulting from the original lunar explorations. The program then describes in some detail what can be done on the Moon today, especially the unique advantages of the lunar far side for radio telescopes. Cosmology is a very popular topic with planetarium audiences and the science of the "dark ages" and early formation of structure in the universe is something that we present in a way that resonates with audiences. We are confident that this successful live local program can be developed into a form suitable for national distribution that will be popular and informative. The script is mostly developed; excellent lunar photographs are in hand; additional artwork, (recorded) professional narration, and music would be added.

The children's book "Max Goes to the Moon" is based on the imaginary adventures of author Jeff Bennett's Rotweiler Max as he prepares for and then experiences a trip to the Moon, along with several children. Max's adventures emphasize the real-life needs of a trip to the Moon and what Max will need to go there, such as food, water, air, and suitable shelter. It poses the question, "What will Max discover when he gets to the Moon?" "Max goes to the Moon" won Colorado Children's Book of the Year award in 2005. Bennett is also author of the leading middle-school mathematics text in the US and the lead author of *The Cosmic Perspective*, the most widely used astronomy text. He is very enthusiastic about writing the script for a nationally-distributed planetarium program and for helping us prepare age-appropriate, standards-based materials about lunar science for classroom use.

The two planetarium shows will be designed to *Educate and Engage* both K-14 students and the general public, supporting the mission of the Lunar Science Institute and the measurable outcomes called for by the *NASA Education Strategic Coordination Framework: A Portfolio Approach*. Co-I Duncan has extensive experience of using formative evaluation and assessment to improve the success of education programs and document the outcomes.

In the past several years Fiske Planetarium has been chosen to develop programs for a number of NASA missions including the Deep Impact comet mission, the TRACE solar mission, and the Hubble Space Telescope. Formative evaluation and review by a committee of scientists and educators are always used to make sure that programs meet their design goals. The University of Colorado has several well-known assessment and evaluation groups that we draw on to evaluate programs we produce, both during development (formative evaluation) and when the program is done (summative assessment). Fiske has developed a good dissemination mechanism through the International Planetarium Society. We know from email responses that our planetarium programs are in use throughout the US and also in Spain, Belgium, Italy, and Sri Lanka.

Science on a Sphere - an exciting new way to show LUNAR science!

Science on a Sphere ("SOS") was invented at NOAA to show images from all the Earth's weather satellites at once. It has the unique capability to illustrate dynamic video images of a planet surface and atmosphere, on a 6 foot diameter sphere, seen as if you are floating in space and looking down on the planet or Moon. The effect is very dramatic. Although SOS was only invented a few years ago, there are now 20 SOS installations at museums throughout the United States. We will develop a complete Moon map based on current high resolution images, and offer it to all the SOS museums at no cost to them. As one of the members of the SOS consortium, Fiske Planetarium shares programs with these other museums, making it easy to disseminate to a large national audience. This is a way to place our interesting NASA-supported science on the clever new NOAA-invented Science on a Sphere. Our imagery would have superimposed on it the locations of expected future NASA lunar missions, including our proposed lunar laser ranging stations and the radio telescope on the lunar farside. We would distribute it with short explanations of each of these missions. SOS is an important new venue to add to NASA's "Education Portfolio."

Teacher Workshops and Local Partnerships

Colorado Project Astro-Geo (CPAG), a node of the national Astronomical Society of the Pacific Project ASTRO, will be used to run workshops for teachers from urban and rural Colorado school districts. Funding is included in our budget to pay for rural schools to participate and to visit Fiske. Teacher workshops will be designed to increase teachers' understanding of lunar science and prepare their students to appreciate the planetarium program we produce. Teacher workshops designed at Fiske Planetarium are always linked to the appropriate national science standards.

CPAG was created in 2005 by a joint coalition of several partners, initiated by the Space Science Institute in their role as NASA broker. It facilitates relationships between educators and scientists dedicated to improving space science and Earth science education for grade 6-12 students. Specifically, CPAG partners scientists and engineers with teachers for a minimum of four sessions per academic year, in which the scientists visit for in-class or after-school activities focused on space and Earth science. The primary goals are to expose students to inquiry-based activities that expand their understanding of scientific material and the scientific process, and to acquaint them with scientists who serve as role models. Successfully piloted throughout the Boulder-Denver area in the 2005-2006 academic year, CPAG continues to build active partnerships between volunteer scientists/engineers and Colorado teachers.

The design of our workshops will leverage Colorado's considerable space science talent pool. Many space and planetary scientists are based in Boulder and we often draw on them as we create educational programs. The activities we develop will also draw strongly on the current research and knowledge of the science team participating in the parent research project.

Teacher workshops and curriculum development will be organized by Dr. Suzanne Traub-Metlay of Fiske Planetarium. Dr. Traub-Metlay has a Ph.D. in planetary sciences and has developed and run many workshops. First, we will adapt and develop curriculum, aligned with state and national educational standards, that focuses on observations of the Moon, the Moon's physical nature in the context of understanding the solar system, and science that can be done from the Moon. The result will be a series of hands-on classroom activities. New lessons will be developed to specifically relate classroom activities to the topics of the parent research grant. We then will host a workshop for CPAG participants and Colorado teachers. Scientists/engineers will be recruited from local planetary scientists and established CPAG partners and industry contacts (Ball Aerospace, IBM, etc.). Students will participate by doing the activities in their classroom and then visiting Fiske to see the planetarium program. Watching a dynamic visual planetarium presentation will emphasize and enhance the classroom material that the students have been exposed to as a part of CPAG visits and help students tie concepts together.

Each teacher who participates in a LUNAR workshop will be provided with one "activity kit" used during the workshop that they can take back to their classrooms. Teachers will use workshop time to begin planning their classroom activities and will have the chance to consult with our educators and CPAG scientist at that time.

This *Educator Professional Development* supports another of the desired outcomes of the NASA Education Framework.

Taking advantage of the International Year of Astronomy

We intend to encourage live observation of the Moon by those who see the planetarium programs. Observations will make use of the low cost 40-magnification telescope being developed for the International Year of Astronomy (IYA). The IYA project aims to produce one million telescopes at a cost of only $10 each. This can leverage the impact of our NASA EPO due to the low cost. Live observations could also be done with binoculars. Several IYA telescopes will be provided to teachers who participate in our workshops. Planetariums that run the public programs will be encouraged to sell IYA telescopes to the general public. We will develop two sets of activities. One set will be linked to national science standards, designed for elementary and middle school use. A second set of activities will be for the public, emphasizing observation of the Moon, using naked eyes, binoculars, and the IYA 40x telescope.

Evaluation and Assessment

Co-I Duncan is a strong proponent of good formative and summative evaluation. He served on STACE (Space Telescope Advisory Committee on Education) that oversaw the founding of the Hubble Space Telescope Education and Public Outreach office and recommended that they hire their first evaluator. The presentation of Hubble science to the public is one of the most successful efforts of its type. Fiske Planetarium is on an academic campus that encompasses both informal and formal science education. Led by Nobel Laureate Carl Wieman, Colorado has established a new Science Education Center with multiple ongoing research projects to discover and encourage the best science teaching methods. We take advantage of this resource and what we learn informs what we produce for NASA. We also are able to hire an experienced evaluator from some of these projects to work on Fiske projects.

LUNAR E/PO will immediately form an Advisory Board to help the Project Team identify the most important issues to teach in the context of the planetarium shows. A number of LUNAR scientists will be involved. User surveys will be a key tool in our assessment of effective learning and communication with various audiences.

Some of the most important work of our (experienced) evaluator will be done at the first meetings of the project team when she helps the team formulate their goals in clear and measurable ways. Project team educators will contribute what is age-appropriate for our different target audiences. The evaluator and project manager make sure that everyone has the same clear goals when development starts. This kind of beginning is critical for a successful project, in our experience.

The evaluation will include front-end, formative, and summative analyses. A front-end evaluation will be conducted before development is done to determine what audiences already know (or think they know) about NASA and the Moon. This will help us produce effectively-targeted programs. As we develop the shows we will pilot them and review comments from test audiences and use the results to improve the programs.

A procedure we have used before and would use on this project is to have the professional evaluator train some of our docents to gather and tabulate data. The professional evaluator does the most critical work, such as meeting with the project team, and preparing reports, but her hours are more limited than if she did all the work. This saves money and is educational for our docents, many of whom are future teachers.

Some evaluation will be in the affective domain. We want to know, "Do audiences think we should go back to the Moon? Do the planetarium programs increase their enthusiasm?"

The evaluator will consult with the project team to design and run a series of focus groups to assess the effectiveness of the Spanish language recorded and live presentations. Representative Spanish-speaking students and visitors will be given the presentations and gathered together afterwards to discuss their experience. Data from these sessions will be translated by the project team and provided to the evaluator for analysis.

The evaluator will conduct a summative evaluation which we will make available.

5.2 Other LUNAR Contributions to the Objectives of NLSI

Training

Lead scientists: C. Koehler, E. Hallman, J. Burns (Colorado)

The University of Colorado (CU) has a long and successful history of training undergraduate and graduate students as well as postdoctoral fellows in the space sciences and engineering. CU has educated 17 astronauts (beginning with Mercury astronaut Scott Carpenter) over the past 50 years. The university prides itself in a broad, interdisciplinary curriculum that includes top-ranked programs in aerospace engineering, astrophysics and planetary science, physics, geology, and atmospheric science all of which participate in training space scientists and engineers at the undergraduate and graduate levels.

We will involve undergraduate students, graduate students, and postdoctoral fellows in the research and E/PO program described in the previous sections. For example, over the past 2 years, 3 Colorado undergraduate astrophysics majors have been involved in the design and fabrication of a vacuum chamber that was used to thermal cycle and UV-expose polyimide film as a potential backbone for the low frequency lunar array. We propose to involve 3 additional undergraduates and a graduate student (funded by CU) in more advanced antenna testing as described in Section 3.2.

NASA astronaut Dr. John Grunsfeld (HST SM-4 servicing mission) will collaborate with us on these student classes and projects, bringing a wealth of experience on deployment of complex instruments in challenging space environments.

Curricula in Space/Lunar Science at Colorado: The University of Colorado has recently developed undergraduate courses involving space and lunar science, the space program, and space public policy. P.I. Burns has revamped *Astronomy 4800 - Space Science: Practice & Policy* to focus on the history of international space efforts and NASA's Vision for Space Exploration. Astr 4800

Figure 18: Pictures from Burns' senior-level undergraduate course on *Space Science: Practice & Policy* at the University of Colorado. (*Left*) Apollo 17 astronaut, former U.S. Senator, and NAC Chairman, Dr. Harrison Schmitt spent two days at Colorado meeting with students and faculty to discuss science and engineering challenges in returning to the Moon. (*Right*) Congressman Mark Udall, Chairman of the House Subcommittee on Space & Aeronautics, visited the class to discuss Congress' role in appropriations for NASA and his views of the Vision for Space Exploration. Here he greets the student who role-played the Congressman in a class project involving a mock House Science Committee hearing on the NASA budget.

is a popular, advanced General Education class that enrolls a diverse population of astrophysics and physics majors, aerospace engineering students, as well as students from a broad cross section of majors including psychology, drama, philosophy, etc. (25-30 students per semester). It is a wonderful interdisciplinary opportunity to educate students as citizens and as possible aerospace professionals on issues such as the Apollo program, the new Constellation infrastructure, and science of/on/from the Moon, Mars, and the larger cosmos. Burns involves guest lecturers including NASA Administrator Mike Griffin, NAC Chair Jack Schmitt, former NASA Administrator Dick Truly, NASA astronaut John Grunsfeld, Dr. Wendell Mendell, and many others in this class each year. As part of this LUNAR proposal, we plan to expand the lunar science aspect of this class and to involve the CU-funded graduate student TA in further development of the class (including development of the new Planetarium shows).

A second undergraduate course entitled *Astr 2500 - Gateway to Space* will be taught by Co-I Koehler (Colorado Space Grant Consortium). This class introduces the basics of atmospheric and space sciences, space exploration, spacecraft design, rocketry, and orbits. Students design, build, and launch a miniature satellite on a high altitude balloon. This class explores the current research in space through lectures from industry.

Burns, Co-I Hallman, and graduate TAs will expand and revise a third undergraduate class at U. Colorado entitled *ASTR 2020 - Introduction to Space Astronomy*. This freshman/sophomore class currently discusses reasons for making astronomical observations from space, scientific goals, practical requirements for placing instruments in space, politics of starting new programs, and selected missions. We will refocus a significant portion of this class on lunar-based science and conduct class projects associated with astronomy, physics, and geological sciences to be conducted on the Moon. We propose to grow this class to 75-100 students per semester.

A Student Hands-on Training Project to Design Deployment of Dipole Antennas: LUNAR, in partnership with the Colorado Space Grant Consortium (COSGC) plans to implement a new hands-on student project centered around the science goals and objectives of the LUNAR project. COSGC is a leader both in Colorado and across the nation in creating student, hands-on research projects that are closely aligned with NASA's science and engineering goals. COSGC is part of the National Space Grant program funded by NASA's Higher Education division. Since its creation in 1989, COSGC has led the way in engaging college students in real world, hands-on engineering projects that not only provide the student with meaningful engineering and science experiences but prepares them to enter science and engineering companies and research institutions with skills not typically found with new hires. The hands-on projects at COSGC range from high altitude balloon satellites and sounding rockets to low Earth orbiting satellites. Each project is managed and staffed with graduate and undergraduate students from all majors. The COSGC staff advises student teams but the students manage the design, build, test, fly, and operations phases of the project. COSGC has had numerous student hands-on programs that have teamed students with scientists and engineers from the Jet Propulsion Laboratory, Ames Research Center, Goddard Space Flight Center, Kennedy Space Flight Center and aerospace companies like Lockheed Martin, Boeing, and Ball Aerospace. COSGC is always looking for ways to add new and challenging projects and mentors to the program. The LUNAR project will allow COSGC to enter a new realm of projects not previously available to students. Co-I Koehler is director of COSGC.

The proposed LUNAR project will enable students to help faculty involved in LUNAR to demonstrate key engineering concepts needed for the overall LUNAR science goals. COSGC will work with LUNAR scientists on the design and fabrication of a mechanism to deploy dipoles (or polyimide film imprinted with dipoles) with astronaut assistance and via a robotic rover. In particular, students will focus on designing a computer-controlled, motor-driven deployment spool mechanism that includes direct sensing of the rate of motion over the lunar surface (not necessarily given by the rover wheel/limb motion) and unrolls the polyimide film so that it will fall vertically onto the surface with no residual tension. This will be a valuable contribution to the entire lunar array concept. JPL, coordinated by Co-I D. Jones, has agreed to mentor students on this multiyear program. JPL engineers that are currently working on the Mars rover programs at JPL have been identified to work on this effort. These engineers also are former COSGC students and have worked with students on past COSGC projects to successfully demonstrate technologies and ideas suggested by JPL on high altitude balloons and ground deployments.

Students will be recruited in the middle of the academic spring semester and work would begin during the summer period. A team of three to four students will work with COSGC staff and faculty involved with LUNAR project along with JPL engineers to the finalize the requirements for the rover. Students would follow typical NASA project development process with design reviews and requirements definition with project mentors. Telecons with students and JPL engineers would be held on a regular basis and all mentors would review student design work and documentation. Engineers from JPL are expected to attend two to three day long design intensive sessions with students in Colorado. Students would develop designs and test concepts on a small scale and eventually hardware demonstrations would be performed.

Through the LUNAR project, funds will provide paid summer positions to COSGC students working on the project. Funds will also support a portion of the COSGC staff time mentoring the students. Other mentoring support will be provided by LUNAR faculty (such as co-I Hallman) and students.

For projects, continuing beyond the summer program, it is expected that funds needed to keep a small subset of the students on staff during the fall and spring would come from other LUNAR sources. COSGC would recruit all students needed for the hands-on projects and assist in all phases of the project.

COSGC has been successful with projects like this for many years. The COSGC program entitled DemoSat has been demonstrating 1.5 kg payload concepts suggested by NASA engineers and scientists at JPL, Ames, and KSC since 2002 with student teams from all over the state of Colorado. These demonstrations have included fully autonomous rovers, imaging systems, and weather monitoring packages designed to work on the surface of Mars. COSGC is confident that similar successes will be accomplished with the LUNAR project.

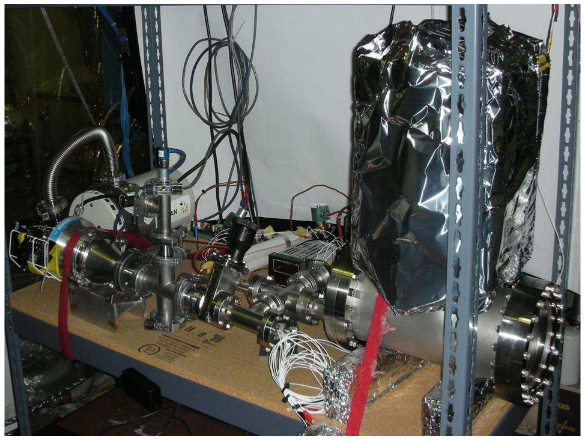


Figure 19: Vacuum, thermal cycling, and UV-exposure test chamber for polyimide foil built by Burns and undergraduate students at Colorado. This foil is a possible backbone for roll-out dipole antennas (ROLSS) on the Moon.

Professional Community Development

LUNAR will undertake a vigorous program of activities to strengthen the profession of lunar science. First, we will conduct multidisciplinary technology-themed meetings and workshops to explore some of the "tall pole" issues, such as power and mass of our instruments that are common across all the NLSI nodes. A broad cross-section of NLSI will be invited to participate. Publications on technology solutions will be developed and submitted to peer review journals. Second, we will hold a yearly science symposium dedicated to the four Key Projects described in Section 3 and our E/PO program. We will invite all members of the research and E/PO teams along with members of the astronomical, lunar science, and lunar exploration communities. One session at each yearly symposium will be devoted to cross-cutting issues that affect all the science goals for astrophysics, geoscience, dust, lunar atmosphere, etc. A conference proceedings will be published each year. Third, we will have a robust colloquium series at each of the partner institutions devoted to lunar-based science. We will coordinate our schedule such that each month, at least one colloquium featuring a prominent speaker from the lunar science community will speak at one of the LUNAR institutions. Our goal is strengthen the lunar science community through the broad involvement of faculty, students, researchers, and educators in colloquia at LUNAR institutions from coast to coast.

Information Technology

Lead Scientist for IT: E. Hallman (Colorado)

LUNAR investigators will participate in activities designed to take advantage of the "virtual institute" aspect of NLSI. We will take part in videoseminars, videoconferencing, and development activities led by the NLSI of new approaches for file sharing and exchange. For example, we will make the technology workshops, the yearly science symposium, and the monthly colloquia available via webcast to all members of the NLSI. We will also use teleconferencing and videoconferencing extensively in regular monthly meetings of the LUNAR leadership team as well as meetings to exchange ideas between Key Project members. We will establish websites for each of the Key Projects and, where appropriate, publicly-available archives of data and numerical simulations. These websites will comply with all NASA accessibility guidelines. Assistant Director Hallman will represent LUNAR on the NLSI IT Working Group.

Bilingual Program Development and Assessment

The Fiske Planetarium at Colorado is one of the few planetariums in the US that consistently produces bilingual programs. Planetarium programs we produced in the past three years are available in both English and Spanish, as well as in music-only versions that have been translated into other languages. As NASA has repeatedly emphasized (such as in the Chicago workforce development meeting that Fiske staff attended) a high and increasing percentage of K-12 children are from Hispanic backgrounds, but the percentage of Hispanic children who choose careers in science and engineering is low. This is a potential workforce problem for NASA and for US industry. We view the production of bilingual programs as a way of interesting in space science and engineering bilingual children who may not be fluent in scientific English. Both planetarium programs we propose here will be produced in English and Spanish.

Fiske has a bilingual docent program in which students who will be future teachers, museum personnel, or scientists are hired to explain our lobby scientific exhibits and to take an inflatable, portable planetarium to local schools. They present programs in English and Spanish. One of our goals in the docent program is to encourage and mentor future science and math teachers who are bilingual. These docents are available to help test the programs we propose to develop. This program supports the outcome called for in the NASA Education Framework: *Provide opportunities to improve the competency and qualifications of STEM informal educators, enabling them to effectively and accurately communicate information about NASA activities and access NASA data for programs and exhibits.*

Collaboration with Commercial Space Industry

LUNAR has forged a collaboration with the Lockheed-Martin Corporation (LMC) Space Systems Division, Orion CEV project, in Littleton, CO and Ball Aerospace in Boulder, CO to participate in our training and E/PO activities (see commitment letters in Section 9). In particular, LMC and Ball will (1) assist LUNAR and the University of Colorado in development of our Planetarium shows which will feature the Orion crew capsule and the Constellation infrastructure. (2) LMC and Ball scientists and engineers will provide guest-lectures within the Colorado space/lunar science curriculum, assist with class project development, and provide tours of the Orion design/fabrication facilities. (3) LMC and Ball personnel will provide mentorship to students involved in LUNAR engineering projects associated with our research and will work toward providing internships for the most promising students.

Facilities

The Center for Astrophysics & Space Astronomy (CASA) at the University of Colorado has advanced laboratory facilities for the construction and testing of space-rated hardware. Major components of FUSE, the Cosmic Origins Spectrograph for HST, along with dozens of rocket experiments (both X-ray and far-UV) have been constructed at CASA. More details on CASA laboratory facilities are given in Section 6.

As shown in Figure 19, Burns has used these CASA facilities to construct a vacuum chamber that has thermally cycled and UV-exposed polyimide film to conditions similar to those expected on the Moon. Three Colorado undergraduate students were involved in the construction and operation of the vacuum chamber testing. The ROLSS low frequency array described in Section 3.4 would potentially use conducting dipoles deposited onto polyimide film as a creative solution for a light-weight, easy-to-deploy interferometer during an early return to the Moon. After thermal-cycling equivalent to a year on the Moon, we found no change the material or electronical properties of the polyimide film. The antenna testing at CASA was funded by a NASA LSSO grant (via subcontract from NRL). These CASA laboratory facilities will be made available to the LUNAR consortium for the antenna development and testing described in Section 3.

Institutional Commitments

The partner institutions are investing their own resources into our LUNAR research and E/PO

Table 4: Institutional Commitments of Resources

Institution	**Nature of Commitment over 4 years**	**4-yr Total Value**
University of Colorado	graduate TA/RA ($250,000); Burns academic year release time ($130,000); equipment & administrative support ($80,000); personnel for planetarium shows ($96,000)	$556,00
Naval Research Laboratory	Proposed Postdoctoral Fellow ($520,000)	$520,000 (pending approval)
National Radio Astronomy Observatory	salaries for Carilli ($57,200), Ulvestad ($33,600), Bastian ($24,000), software engineer ($8,400), Bradley ($23,200)	$156,400
NASA GSFC	polyimide film ($17,000); GS15 scientist ($96,500)	$113,500 (pending approval)

program, allowing us to leverage the NASA funding to support a broader and larger program. In particular, the University of Colorado is pledging over $550,000 in cost-match for administrative support, equipment, academic year release time for the P.I., personnel for the E/PO planetarium shows, and a fully funded graduate student. Each institution pledges office and laboratory space, as required, to house personnel working on LUNAR.

NRL has proposed a postdoctoral fellowship as institutional commitment. It is the intention of NRL to solicit for a postdoctoral research associate via the National Research Council's Postdoctoral Research Associateship program. If a suitable candidate can be found, NRL will host an NRC Postdoctoral Research Associate, which would provide an additional benefit of approximately $130k per year. This is pending approval by the NRC.

NRAO has demonstrated a serious commitment to LUNAR by cost-sharing on salaries for 3 scientists and a partial salary for a software engineer.

GSFC provides a form of cost-sharing in the framework of internal research and development funding, for which a successful, internally-reviewed proposal is necessary. In FY08 (beginning Oct. 2007), Nat Gopalswamy and Robert MacDowall were recipients of internal research funding for lunar radio development activities of 0.5 FTEs, which, if evaluated at the level of a GS15 scientist, corresponds to salary, benefits, and overhead of $96,500. For FY09, they have requested 0.45 FTEs and $17,000 for purchasing samples of polyimide for antenna testing and payment of contractor staff in the materials branch. Evaluating the FTEs at the level of a GS15 scientist, the total amount corresponds to $113,500 (pending approval). These funds would be used primarily to test various antenna materials of various thicknesses to determine the best candidate for the lunar thin-foil antenna development. In subsequent years, FY10-12, we anticipate submitting similar proposals for GSFC internal funding.

Details of the institutional commitments for the partners are provided in Table 4. This table shows the fully burdened salaries including fringe benefits and institutional F&A (overhead). **The total commitment of resources in support of this proposal is potentially over $1 million over four years.**

6 Facilities and Equipment

University of Colorado

University of Colorado Center for Astrophysics and Space Astronomy's Astrophysics Research Laboratory: The Astrophysics Research Laboratory (ARL) is located in the University of Colorado's Research Park on the East Campus, about a mile from the center of the main campus. It is a single story building situated in the wetlands of Boulder Creek and has free and plentiful parking for its users. With a total of about 35,000 square feet it includes laboratories dedicated to space astronomy and offices for the scientists, engineers and students who work on the projects.

The building was constructed in 1985, and renovated for astronomy in 1995 when CASA moved in. In August 2004, CASA completed a new office wing to ARL designed to support the additional needs for data analysis when the Cosmic Origins Spectrograph is installed on the Hubble Space Telescope. The building is wired for high speed communications and computing. CASA's staff provides support for computer needs in both the laboratories and the offices.

Features of ARL include:

- Six private laboratories that can be isolated from traffic and darkened as needed by the experimenters.
- An 8000 square foot high bay that allows for long baseline optical work and which houses some of the large common usage vacuum facilities.
- A class 1000 Clean Room
- A dedicated room for Bonded Storage
- A dedicated room for Bonding and Cleaning
- A Machine Shop
- A large vacuum tank that opens into the clean room for calibration and testing of flight quality components and systems.
- A facility for vacuum bakeout, cleanliness assessment and thermal cycling.
- A 20 foot long 30" diameter vacuum facility with Newtonian telescope for calibration and testing of x-ray and ultraviolet experiments in less rigorous contamination environment.
- A vacuum facility for calibration of optics and detectors. Fed by both x-ray and UV monochromators, the facility has a six axis goniometer, resident detectors and calibration transfer standards.

ARL, although less than ten years old, already has an extensive history in support of astronomical instrumentation. It has been used in support of:

- The spectrograph for the Far Ultraviolet Spectroscopic Explorer (FUSE).
- The optics for the HST Cosmic Origins Spectrograph (COS).
- Numerous sounding rocket experiments in the ultraviolet, extreme ultraviolet and soft x-rays
- SOFIA, NASAs infrared stratospheric facility
- Bolocam, a deep infrared ground based project

- X-ray Interferometry for MAXIM and the Black Hole Imager
- NICFPS, a focal plane package for APO.

Colorado Space Grant Consortium (COSGC): Students will have access to COSGC laboratory facilities which include a 10,000 class cleanroom and assembly lab as well as facilities used by the LUNAR project. It is expected that the LUNAR facilities (i.e. ARL) will be the primary location for all student activity due to space constraints at COSGC but more importantly so the students are in close proximity to the LUNAR faculty.

Fiske Planetarium: Fiske is the largest university planetarium between Los Angeles and Chicago, and the most active academic planetarium in the US. It serves over 30,000 people each year. More than 3000 are CU students, who study more detailed programs that usually use wireless response systems ("clickers") to fully engage students and enhance learning. The majority of the rest are K-12 students from the Boulder-Denver area.

Fiske staff have developed nationally-distributed planetarium programs for the Deep Impact, TIMED, and Hubble Telescope missions that have been nationally distributed. Staff members also conduct nearly 100 outreach visits each year, using a portable planetarium, mid-Infrared camera, and meteorite specimens.

A number of Fiske staff and docents speak scientific Spanish, and programs are routinely made available bilingually.

In 2007, Fiske was one of 3 museums in the US chosen to implement "Science on a Sphere," invented by NOAA. Science on a Sphere is a remarkable room-sized, global display system that uses computers and video projectors to display planetary data onto a six foot diameter sphere, analogous to a giant animated globe. The true 3-dimensional nature of the "screen" an actual globe makes the display incredibly lifelike. Museum visitors feel as if they are in space, like astronauts, looking down at Earth or another planet. Because of its spherical nature, this new display system is ideally suited for showing many NASA data sets.

Fiske programs are all targeted carefully for the intended audience and tied to appropriate National Science Standards when that audience is K-12 students. A process of formative evaluation is used to make sure that programs work in the way they were intended. The University of Colorado is very strong in science education research and evaluation. We cooperate closely with the science education group founded by physics Nobel Laureate Carl Wieman.

Naval Research Laboratory

The NRL has a long standing commitment (>$20M investment over the past 20 years) to low frequency radio astronomy research and instrumental development. NRL personnel have also been active in supporting planning and development of the LOw Frequency ARray (LOFAR), particularly as members of the LOFAR consortium from 1999 to 2003 and currently as an active member with the Southwest Consortium for designing and building the Long Wavelength Array (LWA) is New Mexico. Additionally, Dr. Lazio is the Project Scientist for the Square Kilometer Array (SKA) project to design and build the next generation array radio telescope, which is expected to require many aspects of the technology necessary for building lunar radio arrays (LRAs). Thus, in addition to the funding requested, NRL expects to provide, at no cost to the NLSI project, the expertise of Dr. Namir Kassim (past International Project Scientist for LOFAR and current Project Scientist for the LWA; 0.1MY = $23.6K), the array layout capability of Dr. Aaron Cohen (0.15MY = $25.4K), the computer low frequency antenna design capability of Dr. Kenneth Stewart (0.05MY = $10.7K), the HF/VHF electrical engineering capability of Mr. Brian Hicks (0.05MY = $10.7K), and additional NRL funded effort by the two Co-Is Dr. T. Joseph W. Lazio (0.15MY = $32.1K) and Dr. Kurt Weiler (0.1MY = $26.6K). These costs total $105.5K/yr.

National Radio Astronomy Observatory

The NRAO operates a complementary suite of powerful telescopes for exploring the Universe:

- Robert C. Byrd Green Bank Telescope (GBT), the world's most sensitive single-dish radio telescope.
- Very Large Array (VLA), an array of 27 radio telescopes that is among the most productive research tools in astronomy.
- Very Long Baseline Array (VLBA), an array of 10 radio telescopes and the highest resolution astronomical telescope.

The NRAO is also building two new major facilities that will significantly enhance astronomers' research capabilities and open new scientific frontiers:

- Atacama Large Millimeter/submillimeter Array (ALMA), a partnership with Europe, Japan, and Chile that will be available to the U.S. and Canadian astronomical communities through the North American ALMA Science Center (NAASC).
- Expanded Very Large Array (EVLA), a partnership with Canada and Mexico, and a major step towards the international Square Kilometre Array (SKA), a next-generation, centimeter-wavelength telescope.

Detection of the radio waves emitted by astronomical objects demands technology and signal processing that push the state-of-the-art. The scientists and engineers at the NRAO Technology Center (NTC) perform much of the innovative research and development that yields the required instrumentation and processing advances.

University of California, Los Angeles

Furlanetto is a member of the UCLA Department of Physics and Astronomy, which will provide office space, journal access, computing, and library resources for Furlanetto and the graduate student. The major computational analysis will be performed on a 32 GB, 8-core desktop run by the PI as well as the Hoffman2 Campus/Shared Cluster, a campus-wide Beowulf cluster open to faculty who contribute to its construction; any faculty member who contributes nodes will have access to those nodes at all times and any other unused nodes when desired. The cluster now has 400 nodes (of which two-thirds are contributed by faculty research groups) and is ultimately scalable to 1600 nodes. We have requested funds to purchase 6 nodes for this system (see the Budget Justification for details); these nodes will always be available to us, and spare capacity from other nodes is also available occasionally. The university infrastructure, system, and software support (provided by UCLA's Academic Technology Services), in addition to occasional access to a much larger cluster, will allow us to leverage the investment for a much more powerful computing return.

Harvard University

The Harvard-Smithsonian Center for Astrophysics (CfA) is a joint facility of Harvard University and the Smithsonian Institution. The CfA combines the resources, staff, and research facilities of the Harvard College Observatory (HCO) and the Smithsonian Astrophysical Observatory (SAO). The computational facilities of the Institute for Theory and Computation (ITC) at Harvard are available for high performance computing.

The project staff will have use of SUN or similar computers; IBM PCs and laptops or similar; Macintosh desktops and PowerBooks or similar; word processing, spreadsheet and graphic software; HP 9000dn laser printer or similar; scanner; fax machine; copier; Beowulf cluster of 150 dual processor nodes or similar.

The project will have the use of the CfA's local area network and the CfA electronic mail gateway to the Internet. Monthly space and local telephone line charges are provided by HCO to the project. Adequate office space is available to carry out the proposed research.

As needed, project staff has the use of all the Harvard University libraries, including the CfA's on-site Wolbach astronomical library.

These facilities will serve Prof. Abraham Loeb, his graduate student, Eli Visbal, and the Hubble postdoctoral fellow, Dr. Jonathan Pritchard, who all reside within the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics

Jet Propulsion Laboratory

All facilities needed for this task (engineering software tools, generic rover testbeds, general computing resources, network connections, and office infrastructure support) are already available at JPL.

University of New Mexico

The University of New Mexico is the lead institution for the Long Wavelength Array (LWA). The LWA will be a premier U.S. facility for exploring the low-frequency radio spectrum over the next 15 to 20 years, and will provide fundamental advances in knowledge, particularly in the areas of astrophysics and ionospheric physics. This facility will also be important for educating U.S. students and for creating an expert academic user community that can achieve future scientific advances in important areas of ionospheric and astrophysical research, and can stage a Lunar Radio Array on the Moon. In the process of designing and constructing the LWA, we have developed significant capability in long wavelength techniques at UNM. We have developed equipment for characterizing sites, including devices for RFI surveys, soil analysis, environmental monitoring, data communication, etc.. We have considerable expertise in designing, building and deploying dipole arrays. We have laboratory space for building and testing of RF equipment. We also have access to sites where our LWA stations will be deployed in the near future. Some of these are in remote parts of New Mexico and are among the most quiet radio environments in the U.S.

Princeton University

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From: David Spergel <dns@astro.princeton.edu>
To: Andrei Mesinger <mesinger@astro.columbia.edu>
Cc: Joseph.Lazio@nrl.navy.mil
Subject: Re: NLSI proposal
Date: Mon, 18 Aug 2008 11:02:07 -0400

Dear Dr. Lazio,

I confirm that Andrei Mesinger is appointed as a Hubble Fellow at the
Department of Astrophysics at Princeton University, starting Sept.
1st, 2008.  As such he will have an office, an 8 core, 3.2 GHz 32GB
Mac Pro personal computer for running simulations, as well as access
to multiple computer clusters at Princeton University's Tigress High
Performance Computing Center.  The Tigress facility are described at
tigress.princeton.edu
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7 Curriculum Vitae

Appended at end of document.

8 Current and Pending Suport

Appended at end of document.

9 Statements of Commitment from Proposing Institutions and Personnel

Appended at end of document.

10 Budget Summary and Details

10.1 Schedule for LUNAR Key Projects

10.2 Budget Narratives and Budgets

Appended at end of document.