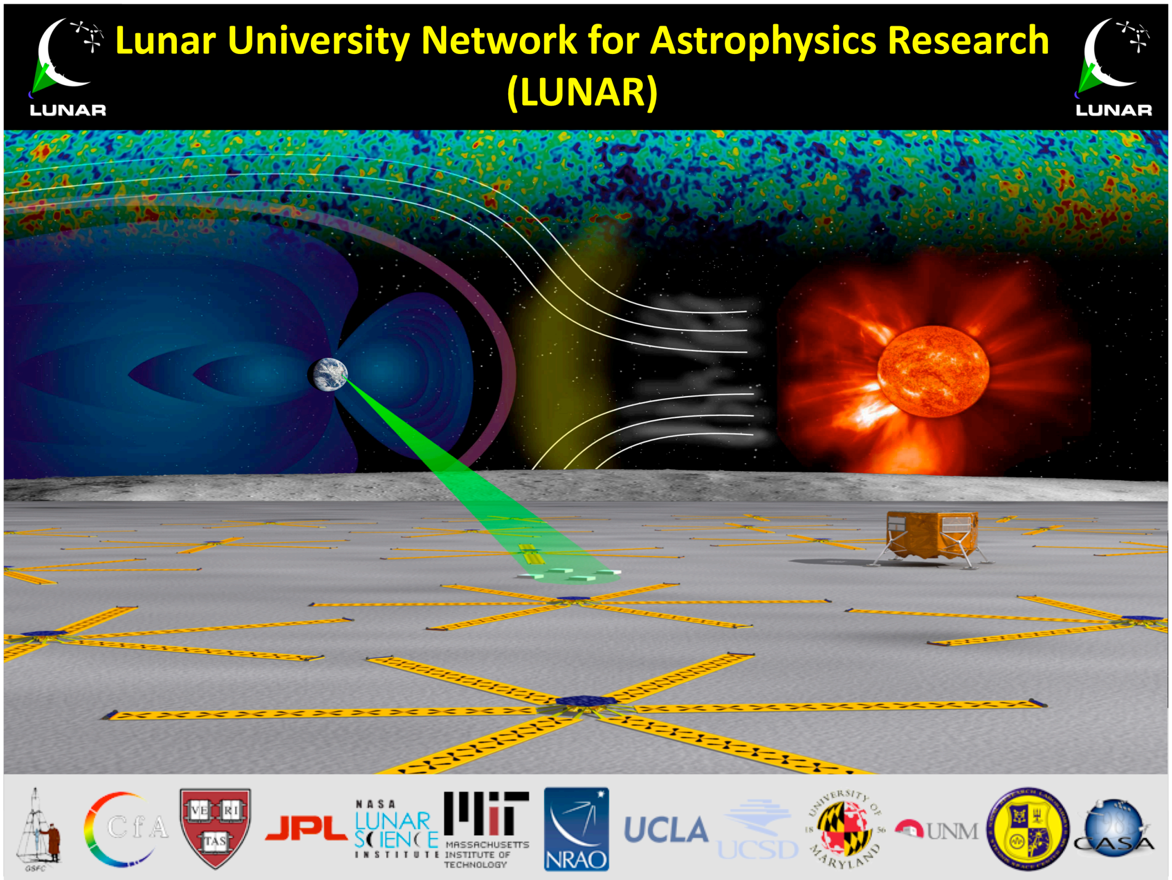

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Executive Summary

The **Lunar University Network for Astrophysics Research (LUNAR)**, a consortium of top research institutions led by the University of Colorado is performing research, education and outreach, and community development to advance *Astrophysics From the Moon*. 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 is pioneering 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.

Key Project - Low Frequency Cosmology and Astrophysics: The most abundant element in the Universe is hydrogen, and it is the raw material from which stars form. After the Big Bang, there was a short interval known as the Dark Ages, perhaps a few hundred million years long, before the formation of the first stars, in which hydrogen was spread relatively uniformly throughout the Universe. Probing the evolution of the Universe during the Dark Ages and as the first stars form is uniquely possible by a low radio frequency telescope on the far side of the Moon. The Low-frequency Cosmology & Astrophysics Key Project of the LUNAR team has the goal of advancing the science and technology required to track the evolution of the Universe and enabling the use of the Moon as a platform for conducting science. Over the past year, work within the Low-frequency Cosmology and Astrophysics Key Project has begun to refine predictions of the strength the hydrogen signal from the Dark Ages. Further, the proposed Lunar Radio Array telescope will be extremely powerful, and the team has explored secondary observations, such as searching for extra-solar planets, that might be possible. The team has also started to design, model, and construct antenna concepts that might be used for a lunar radio telescope. The modeling and testing has included computer modeling, conducting experiments to simulate the harsh conditions with which antennas will experience on the Moon, and testing how well the antennas can receive the intended hydrogen signal.

Theoretical Tools: Work in Year 1 included simulating the signals that potentially will be observed by the Lunar Radio Array to assessing the (astrophysical) foregrounds with which the analysis of the signals will have to contend to expanding upon the potential secondary science observations that might be undertaken by the Lunar Radio Array. As a part of our simulations we began to build a fast, portable code to generate hydrogen maps of the high-redshift early universe, useful even with limited computing capacity. This is ideal for generating a wide range of predictions about low frequency radio signal that we seek. For the first time, this code includes all the relevant thermal processes; **Figure ES 1.**

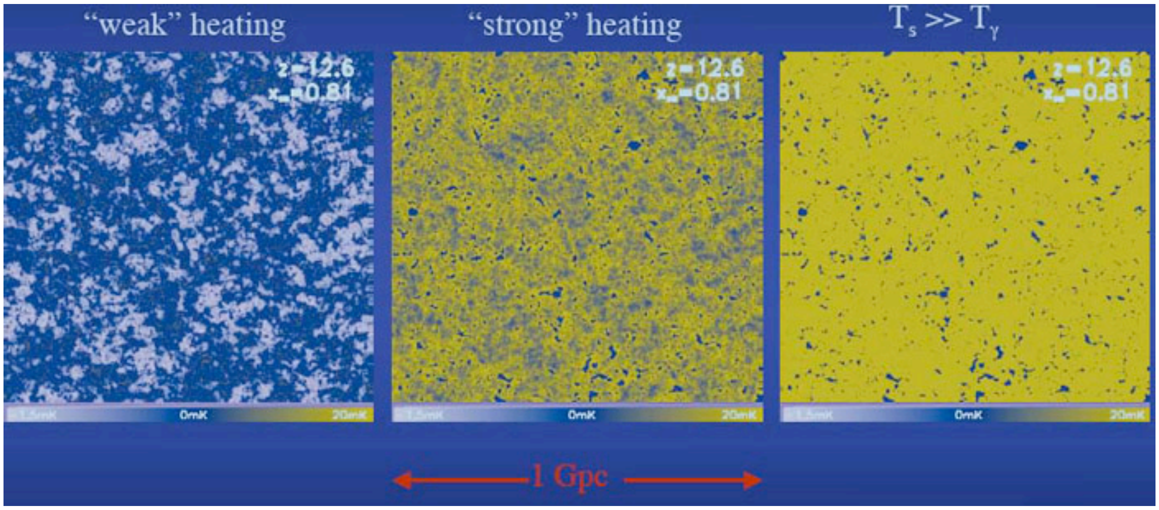


Figure ES 1: Low Frequency

Three simulated 21-cm maps of the high-redshift Universe. The three panels show the same slice of the Universe, assuming three different heating scenarios (weak, strong, and extremely strong, from left to right) in the "pre-reionization" era accessible to the Lunar Radio Array. The color scale shows the brightness temperature of the intergalactic medium, relative to the cosmic microwave background; negative values correspond to absorption, and positive values to emission. From work by **Furlanetto** et al.

Furthermore we completed a computer code that provides a comprehensive description of the full evolution of the radio signal throughout the entire cosmic history between ten million years after the Big Bang and the present time. This code allows us to explore the important scientific advantages of a lunar observatory over ground-based radio arrays. Another simulation that is helping to constrain our knowledge of foreground signals is modeling the early epoch of X-ray preheating near the end of the Dark Ages by inserting X-ray sources in the cosmological simulations that will heat and ionize regions around a population of early quasars. This is a first stage to a full modeling of reionization, which will include stellar/galactic sources of ultraviolet photons, in addition to the X-rays generated at quasars.

Array Concept & Algorithm Development: Work in Year 1 further solidified the requirements for the Lunar Radio Array. One such advance was developing the scientific requirements for the Lunar Radio Array with a specific focus on developing the array design. The robustness of the array design to failures of individual elements within a single station was explored. Aside from the designing of hardware, we worked on issues relating to low frequency measurements of the hydrogen radio signal from the epoch when the first stars/galaxies form. This work involved simulations of dynamic range limitations and calibration requirements for future low frequency arrays.

Technology Development (Science Antenna): The Lunar Radio Array will require a large number of science antennas, so that high sensitivity per unit mass is a key requirement. Two antenna concepts are being explored:

- A helical antenna for use in the Self-Tending Array Node and Communication Element (STANCE); and

- A polyimide film-based dipole antenna. **Figure ES 2**.

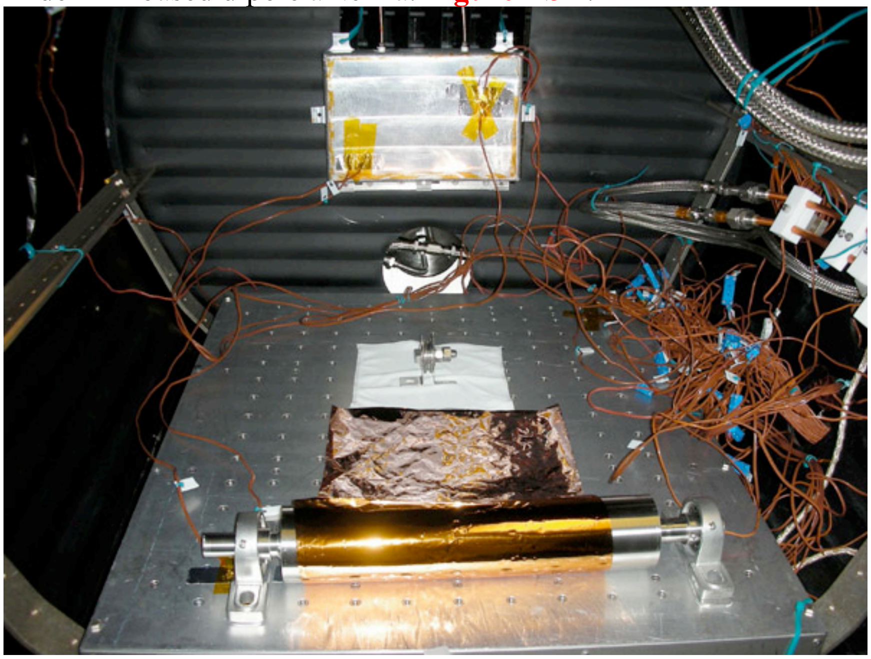


Figure ES 2: Testing of polyimide film in a vacuum chamber at the University of Colorado

Work in Year 1 focused on the electromagnetic performance of both concepts as well as developing the capability to conduct environmental testing of polyimide film in lunar-like conditions. We have focused on the development of the helical antenna in the Self-Tending Array Node and Communication Element (STANCE) concept. Over the past year, the work has been focused on improving the electromagnetic performance of the helix along with developing a system for accurately measuring the beam pattern of the antenna *in situ*.

There has also been significant development of the infrastructure to conduct simulated lunar environmental testing of polyimide film, which may serve as the backbone for Lunar Radio Array antennas. The array will be rolled up during transport to the Moon, much like a carpet, and then unrolled by astronauts or robots once there. The radio antenna will be exposed to the harsh environment for many months. We are recreating these conditions in a laboratory vacuum chamber in order to ascertain whether the polyimide film exhibits any changes, such as in tensile strength or electrical conductivity.

There has also been development work on self-deploying antennas, which require minimum structure to save mass, as well as pack tightly to allow thousands to be carried in one payload. A helical antenna can be compressed to a small volume, but, to regain its original height, additional supporting structures must be included, easily doubling the mass and volume. The use of memory shape metals can greatly reduce or even eliminate the need for support, as they have sufficient elasticity to spring back to tall heights in the low lunar gravity.

Key Project - Radio Heliophysics: The high temperature solar corona produces the supersonic solar wind that creates a magnetic bubble around our solar system called the heliosphere. Over the course of the eleven-year cycle of solar activity the heliosphere changes.

These changes include violent solar flares and coronal mass ejections, which can create high-energy radiation and magnetic disturbances that, can effect communications, navigation, and human safety. The goal of the Heliophysics Key Science Project is to conduct low-frequency radio science of the heliosphere from the surface of the moon in order to determine how the Sun accelerates particles to high energy. Our work is divided between investigations of radio emission from space, designing a solar imaging radio array, and developing new technology to make radio astronomy on the lunar surface possible.

In the first year of this project, our investigations of radio emission included characterization of the lunar radio frequency interference (RFI) environment and a search for low frequency radio transients using existing observations in deep space and near the Moon. For the low frequency radio array, computer simulations of the array were undertaken. Similar radio observations at much higher frequencies using data the Murchison Widefield array in Western Australia were also examined. Our technology development included studies of automated systems for deploying antennas, work on low power electronics, and development of radio receiver technology. Low frequency radio observations are an excellent diagnostic of electron acceleration because the emission process encodes information about the source region.

As the first component of our analysis of the lunar RFI background, we analyzed Wind Waves RAD2 radio data (frequency range 1-14 MHz), acquired from November 1994 through the present, to measure the intensity level of radio bursts and terrestrial emissions observed by the Wind spacecraft along its complex trajectory that includes passes very close to the Moon. While these data demonstrate that successful radio observations of cosmological sources from an observatory anywhere near Earth will be best accomplished on the far-side of the Moon, they also indicate what might be accomplished from the near side. Solar radio bursts are another potential source of interference for the lunar radio observatory; the most intense of the solar radio emissions in this band is the type III burst, but covering less area in frequency-time space.

Using data and telemetry of the Stereo A & B spacecraft we have begun our search for transient emissions employing two strategies: a blind search and a search given known times of astrophysical explosions. The blind search method consists of looking for intervals where statistically significant increases in the emission power are seen within the light travel time between the two spacecraft at similar frequencies. In addition to our blind search, we have also begun a search for transient emission associated with Gamma Ray Bursts (GRBs). We have downloaded and updated on an occasional basis the SWIFT GRB catalog. We are currently examining every GRB, but we will focus our efforts on nearby GRBs at high galactic latitudes (less likely to experience scattering from electrons in our own galaxy).

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.

The Lunar Laser Ranging team of the LUNAR group has been addressing the design, fabrication and emplacement of the next generation of retroreflectors for the moon. These can improve the accuracy and thus the science by a factor of more than 100. To this end, different retroreflector designs have been developed and their performance in the lunar environment simulated in various computer programs. The best designs have been implemented in hardware and tested in thermal vacuum chambers to evaluate their performance in the harsh environment on the lunar surface. In addition, the method of deployment on the lunar surface is critical for maintaining the accuracy. Various methods of deployment have been devised. Some of these have been tested in the laboratory and recently in NASA organized field tests in areas on earth that have been deemed similar to the lunar soil (Mauna Kea volcano in Hawaii). The ground station requirements are being explored by LLR to the LRO satellite. We are also investigating the accuracy of the software programs to the analysis of the data and are working to improve this in the areas of weakness.

A surprising result of the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) is that the reflector arrays show a clear signature of degradation that is exacerbated at full moon--likely due to enhanced thermal gradients imposed by dust or abrasion. The full-moon signal reduction is roughly a factor of ten, on top of a suspected factor-of-ten reduction at all lunar phases. This discovery comes at a crucial time in the design phase of next-generation corner cubes.

Much effort during the first year of LUNAR was spent refining the science case for new lunar laser ranging capabilities. The possibility of testing modified general relativity using lunar laser ranging was explored. In conjunction with testing GR, the laser clean room at the 1.2m Telescope Tracking Facility at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt Maryland was converted to support the capture and analysis of cube corner far field diffraction patterns (FFDP). This laboratory with remote access to the telescope Coude' room originally housed high power short pulse lasers for satellite laser ranging (SLR) operations.

Key Project - Assessment of Other Astrophysics Enabled by a Return to the Moon: Additional potential concepts for lunar-based astrophysics were assessed, via a small grants program. LUNAR solicited the astrophysics community for new ideas for lunar-based telescopes in the Fall of 2009. This call requested the following types of proposals:

- Theory: Theoretical studies as relate to possible astrophysical observations enabled by a return to the moon.
- Instrumentation: Studies to develop instruments which could be used for lunar astrophysical observatories.
- Concept Studies: development of concepts for astrophysical observatories.

Proposals were peer reviewed for potential yearlong subcontracts. Three projects were selected for funding:

1. Scalable Superconductor Bearing System for Lunar Telescopes and Instruments: Design and Proof of Concept (PI: Peter C. Chen, Lightweight Telescopes, Inc.)
2. Material Development and Characterization for Instruments, Support Structures, and Large Aperture Astrophysical Observatories on the Moon (PI: Michael E. Van Steenberg, NASA Goddard Space Flight Center)
3. Lunar Occultation Observer (LOCO) (PI: Richard S. Miller, University of Alabama, Huntsville)

The LUNAR team is also now coordinating the yearly science symposium as specified in our original proposal. This will include the 3 funded research teams, who will report on their progress at this symposium. The symposium is tentatively being scheduled for the early fall in Boulder, Colorado.

Education and Public Outreach (EPO): As part of LUNAR EPO, we have begun to produce two planetarium programs, both in English and Spanish. The first, is a program designed for adults and will reprise the history of the Apollo explorations of the moon and then focus on the science to be done by NLSI teams. The second, "Max Goes to the Moon," is designed for kindergarten through fifth grade students. The plot of the show is based on the award-winning book, "Max goes to the Moon". Max, a real dog belonging to author and scriptwriter Jeff Bennett, helps make tangible to children the story line of preparations needed for going to the Moon. A nice touch is the idea that Max's first lunar paw print will be preserved just like Armstrong's first lunar footprint. Fiske Planetarium staff has interviewed and selected narrators for each of these programs.

In addition to the planetarium shows our E/PO plan includes developing and implementing teacher workshops for K-12 teachers. We are in the beginning stages of developing the workshops and plan to host our first workshop at the ASP (Astronomical Society of the Pacific) during the first week of August 2010 at the University of Colorado Boulder. We have also hosted public events and lectures that highlight and enhance the general public's awareness of lunar science. One such event was associated with the LCROSS impact. We held a "Lunar Bagel Breakfast" where more than 400 people filled the U. Colorado Fiske Planetarium Theater and lobby, and where we broadcast NASA select TV **Figure ES 3.**

Figure ES 4: LCROSS Event at Fiske Planetarium

Low-Frequency Cosmology & Astrophysics – (LFCA)

As originally proposed, the LFCA key project had three work packages: theoretical tools, array concept & algorithm development, and technology development. A combination of the reduced budget and guidance from NASA HQ led to the anticipated work being different than what was proposed originally. First, for technology development, no rover development work will be executed, per NASA HQ direction. Second, the reduced budget had the implication that the focus of work in Year 1 was theoretical tools and science antenna technology development, with array concept & algorithm development being conducted on a "best-effort" basis.

Theoretical Tools

Work in Year 1 included the full range of activities, from simulating the signals that potentially will be observed by the Lunar Radio Array to assessing the (astrophysical) foregrounds with which the analysis of the signals will have to contend to expanding upon the potential secondary science observations that might be undertaken by the Lunar Radio Array. Specific activities by various LUNAR team members are the following.

- **Furlanetto**'s theory program advanced along several fronts during the first funding year. First, Furlanetto & **Johnson Stoever** completed a detailed look at the fate of fast electrons in the high-redshift intergalactic medium. These are crucial to understanding the 21-cm signal that we hope to see with the Lunar Radio Array, and this study significantly updated past calculations with new processes and cross sections. Second, **Holzbauer** & Furlanetto began a fresh look at the fluctuations induced in this background by the soft-ultraviolet photons from the first sources of light, using a brand new formalism for the purpose. The paper should be submitted within six months. Third, **Mesinger** & Furlanetto began to build a fast, portable code to generate 21-cm maps of the high-redshift universe, useful even with limited computing capacity. This is ideal for generating a wide range of predictions about the 21-cm signal we seek. For the first time, this code includes all the relevant thermal processes; **Figure LF 1** shows example maps resulting from this analysis and illustrates the importance of properly tracking heating to the 21-cm signal. Finally, Furlanetto acquired a new computer cluster that will be used to generate more detailed models in the future.

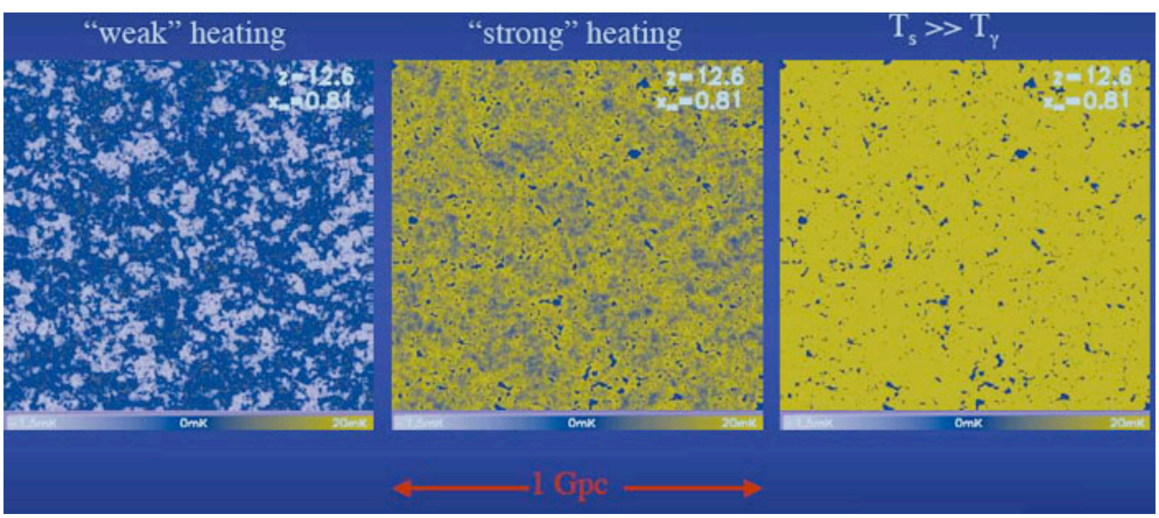


Figure LF 1:

Three simulated 21-cm maps of the high-redshift Universe. The three panels show the same slice of the Universe, assuming three different heating scenarios (weak, strong, and extremely strong, from left to right) in the "pre-reionization" era accessible to the Lunar Radio Array. The color scale shows the brightness temperature of the intergalactic medium, relative to the cosmic microwave background; negative values correspond to absorption, and positive values to emission. From work by **Furlanetto** et al.

- **Mirocha**, under the supervision of **Burns** and **Hallman** and in collaboration with **Furlanetto**, has generated models of the high redshift AGN population consistent with the unresolved X-ray background for use in numerical hydro/N-body radiative transport simulations. These simulations will model the early epoch of X-ray preheating prior to reionization by inserting X-ray sources in the cosmological simulations that will heat and ionize regions around the AGN population. This is a first stage to a full modeling of reionization, which will include stellar/galactic sources of UV photons, in addition to the X-rays generated at AGN.

  Future work will include building models for a variety of X-ray AGN populations at high redshift, as this population is nearly unconstrained by observations. This grid of models will encompass the parameter space from small numbers of very rare but luminous AGN to larger numbers of more distributed, but less luminous AGN under the constraint that the total X-ray flux from our source population not exceeds the remaining portion of the unresolved X-ray background. Once these different source models have been incorporated into the simulation, the redshifted 21-cm signal from neutral hydrogen in the simulation volume will be examined. In this way predications can be made for the global sky signal and the angular power spectrum for low frequency radio observations of the cosmic Dark Ages. Mirocha has also developed the tools necessary to synthetically observe the 21-cm signal from the simulations, and additional tools for analysis of the simulation data.

- **Loeb**, **Pritchard**, **Visbal**, and **Bittner** completed a computer code that provides a comprehensive description of the full redshift evolution of the 21-cm signal throughout the entire cosmic history between ten million years after the Big Bang and the present time (corresponding to the redshift interval between 0–100). This code allows us to explore the important scientific advantages of a lunar observatory over ground-based radio arrays. Our code includes contributions to the 21-cm signal from fluctuations in the gas density, temperature and neutral fraction, as well as the Lyman-alpha flux, and allows for a post-reionization signal from damped Lyman-alpha systems. Our comprehensive analysis provides a useful foundation for optimizing the design of future arrays whose goal is to separate the particle physics from the astrophysics. In addition, they also explored, in a separate paper, the constraints on the reionization history that are provided by current observations of the Lyman-alpha forest and the microwave background. These constraints led them to the conclusion that the 21-cm signal-to-noise ratio peaks at a redshift $z \sim 10$ and will be detectable by future experiments.

- **Harker** arrived at Colorado in mid-October of 2009. Much of his effort so far has focused on finishing a paper on power spectrum extraction for the LOFAR Epoch of Reionization experiment that has applications for the Lunar Radio Array. The emphasis has been on the effect of foreground subtraction on the quality of the extraction, a topic that will become even more important for the Lunar Radio Array to study the cosmic Dark Ages, since the foregrounds become yet larger at lower frequencies. This work was in collaboration with the LOFAR-EoR team. Harker has begun extending this work with a more quantitative estimate of parameter errors, a more complete characterization of the instrument, and alternative methods of power spectrum estimation (for example, cross-correlation).

- **Harker** has also begun collaborating with **Bowman** at Caltech, visiting him there on 2009 November 17–18. They discussed ways in which Harker could contribute to the EDGES project to detect the signature of reionization with an all-sky, single-dipole measurement. A document detailing what was discussed, including the future development of EDGES and its relevance to a single-dipole experiment in lunar orbit was circulated to the LUNAR team. Parameter estimation and foreground subtraction, and investigation of the possible use of the Moon as a calibration source or a "knife-edge" to assist in producing a sky model, were identified as areas on which Harker could particularly focus. Pritchard has allowed us the use of his global 21-cm modeling code, which will help in parameter estimation.
- A paper on H_2CO in a gravitational lens has just been published, showing that formaldehyde absorbs CMB photons and thus can be used as a mass-limited redshift-independent tracer of star formation. There are three more papers in progress on this (**Darling** & **Zeiger**; Zeiger & Darling; **Mangum** et al.).
- **Stocke**, **Yan**, & **Darling** are finding some success with a new method to identify gas-rich radio-loud sightlines, leading potentially to the detection of molecular absorption lines that can be used to test the cosmic evolution of fundamental physical constants (a nice dovetail with the lunar laser ranging work). **Darling** & **Macdonald** are writing up the first wide-field "blind" survey for H I 21-cm absorption at $z < 0.07$. Darling & **Grasha** are doing a large-scale pointed, but redshift-blind, H I survey out to $z \sim 3$, which may test the claim that DLAs "go molecular" for high column densities. These two blind surveys will produce limits on $W_{\rm H\,I}$.
- **Darling** is also working with two groups to measure magnetic fields in DLAs either via Zeeman splitting or via "rotation synthesis."
- **Darling** & **Willett** have been searching for redshifted OH lines with some limited success. On February 1, they will be proposing a large survey using a new sample in the COSMOS survey. The ultimate goal is to directly detect magnetic fields via Zeeman splitting at $z \sim 1$, and one of the new detections has already shown strong splitting and high B fields. This survey will also allow them to study the star formation history of the strongest starbursts, merging history of galaxies, and growth of black holes.
- **Lane Peters**, **Lazio**, Darling, and colleagues have prepared a paper examining the state of research on radio recombination lines below a few hundred MHz. These lines are potentially important because they could form a *spectral* foreground to the cosmological 21-cm signal, itself a spectral signature, in contrast to the many other foregrounds that are continua. Submission is expected within the next few months.
- **Lazio**, in conjunction with high school students at Thomas Jefferson High School for Science & Technology, conducted a blind search for magnetospheric emissions from extrasolar planets in the solar neighborhood. These would be the equivalent of the Jovian decametric radiation and could be a potential secondary science goal for the Lunar Radio Array.

- **Lazio**, in conjunction with NRL colleagues, has prepared a paper on the use of the Long Wavelength Demonstrator Array (LWDA) for searching for radio transients. There are numerous classes of radio transients known within the anticipated frequency range for the Lunar Radio Array, and this paper illustrates a potential secondary science goal for the LRA.

Array Concept & Algorithm Development

Work in Year 1 was necessarily limited, but advances were made in solidifying the requirements for the Lunar Radio Array.

- **Taylor**, **Rodriguez**, and **Kogan** worked to develop the scientific requirements for the Lunar Radio Array with a specific focus on developing the array design. Starting with a design optimized to minimize sidelobe levels, they explored the robustness of the array design to failures of individual elements within a single station. Understanding how a station responds to failures is critical as it is likely that visits to repair stations may be infrequent, or even nonexistent. They applied an array configuration optimization algorithm, developed by Kogan, which has been used in the configuration studies of various ground-based radio arrays. This algorithm seeks to minimize the array's side lobes. They considered several scenarios for failure including random and systemic failures and found that while the degradation from random failures is fairly slow, systemic failures of large groups of elements in the same part of the array are much more serious (**Figure LF 2**).

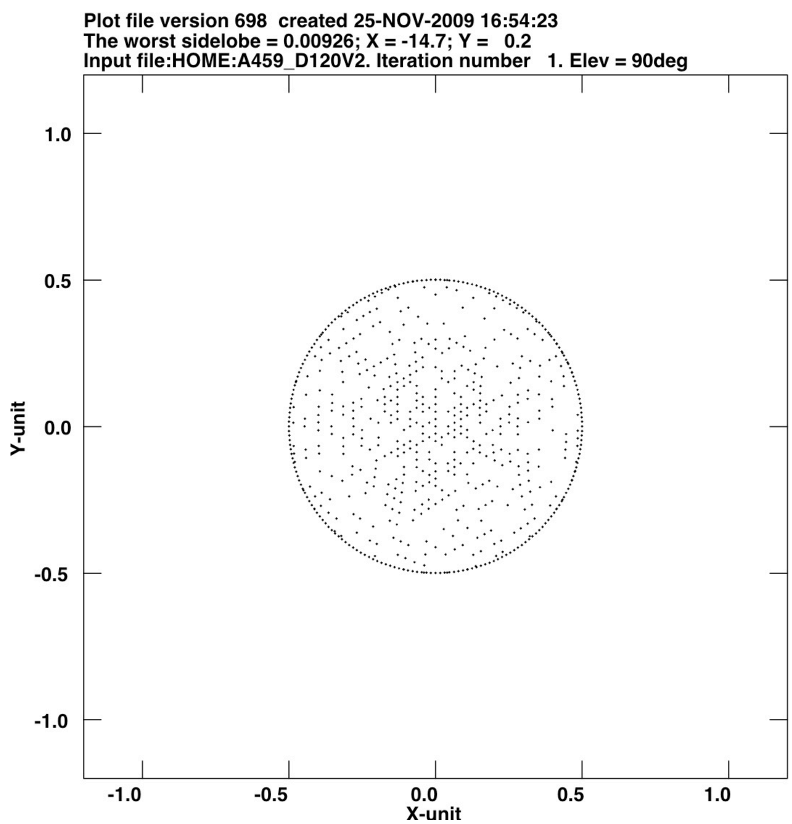


Figure LF 2:

Optimized hexagonal station configuration after the random failure of 50% of the elements. While there is a 50% loss in sensitivity, the maximum sidelobe level only increases by 8 dB. From work by **Taylor** et al.

- **Carilli** and **Datta** worked on issues relating to low frequency measurements of the H I 21-cm signal from cosmic reionization. This work involved simulations of dynamic range limitations and calibration requirements for future low frequency arrays. While not funded by LUNAR, the work is relevant to the design of the low frequency array on the Moon, and they plan to expand the work further in this direction in the near future.

Technology Development (Science Antenna)

The Lunar Radio Array will require a large number of science antennas, so that high sensitivity per unit mass is a key requirement. Two antenna concepts are being explored, both of which build upon work done under the Lunar Radio Array concept study in the Astrophysics Strategic Mission Concept Studies (ASMCS) program.

- A helical antenna for use in the Self-Tending Array Node and Communication Element (STANCE); and
- A polyimide film-based dipole antenna.

Work in Year 1 focused on the electromagnetic performance of both concepts as well as developing the capability to conduct environmental testing of polyimide film in lunar-like conditions.

- **Bradley**, **Czekala**, **Klima**, and **Boyd** have focused on the development of the helical antenna in the Self-Tending Array Node and Communication Element (STANCE) concept, a concept first introduced under NASA Award NNX08AM30G. Over the past year, the work has been focused on improving the electromagnetic performance of the helix along with developing a system for accurately measuring the beam pattern of the antenna *in situ*.

  A tapered helical antenna was designed with the aid of CST Microwave Studio simulation software. The taper has greatly improved the impedance match while only slightly reducing the antenna's gain. In addition, the cavity-type grounding structure used in the original design was replaced by a hexagonal ground plane that folds flat to reduce its size (leading to an increase in packing density) during transport to the Moon. This foldout feature also reduces the complexity of the self-deployment mechanism. **Figure LF 3** shows a model of the design for operation at 137.5 MHz. This ten-turn helix has a base diameter of about 78 cm, is 5.2 m tall, and tapers approximately 1.0 cm per turn. A prototype of this antenna along with a three-helix phased array will be fabricated and evaluated over the coming year.

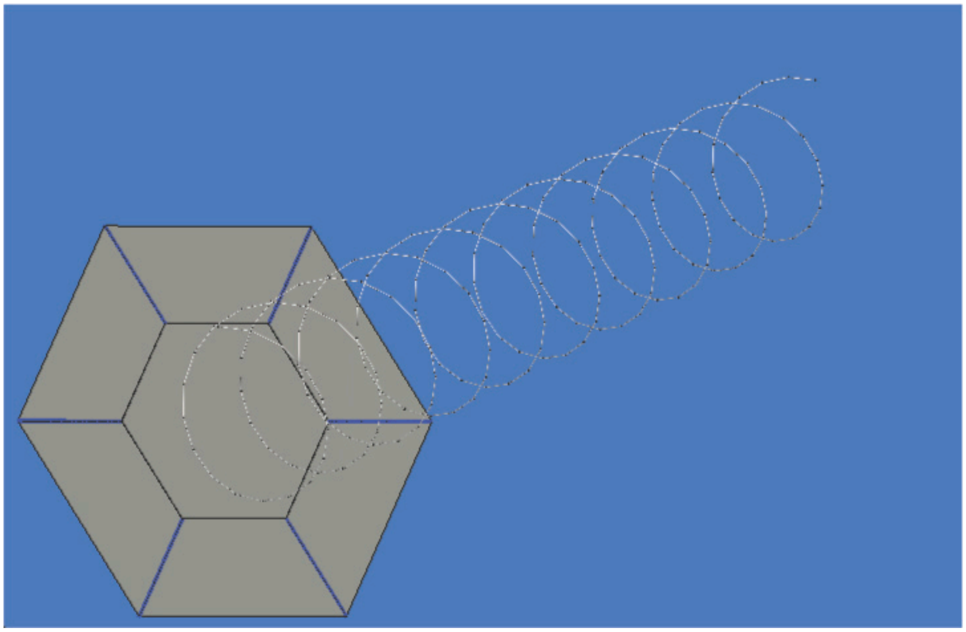


Figure LF 3

Drawing of the tapered helical antenna, from work by **Bradley** et al.

We continue to develop a system to measure the beam pattern of a deployed antenna using ORBCOMM satellite downlink signals. Some effort was directed toward developing a parameterized dynamical model of the satellites that takes into account spin, wobble, and precession so that such effects could be removed to normalize the downlink power. However, it became clear that significant variability among the satellites and the non-stationary nature of the dynamics would reduce the accuracy of the beam pattern measurements based on this approach. The decision was made to employ a ratio method to compare the performance of the helix to a well-modeled reference antenna. CST Microwave Studio was used to develop and characterize a simple, yet rugged, cross dipole antenna for this purpose. Such an antenna was fabricated and deployed at our Beaver Creek field station (**Figure LF 4**).

Figure LF 4

Photograph of a reference dipole over the ground plane, from work by **Bradley** et al.

A second reference antenna, identical to the first, was fabricated and deployed 30 m south of the original. Satellite downlink power was measured from both antennas, simultaneously (single polarization) during each pass to calibrate the system and evaluate the local electromagnetic scattering environment. **Figure LF 5** shows a false color plot of this power ratio for one day's worth of data, as a function of azimuth and elevation. While the nearby Beaver Creek site is useful for system development, the blue and green regions of the plot clearly indicate the presence of strong scattering from local power lines. This scattering will make it difficult to calibrate the system to the level necessary for high dynamic range beam pattern measurements. A more open environment, such as that presented by our field station at the NRAO in Green Bank, WV, will be required. Plans are in place to move our system to this site in the near future.

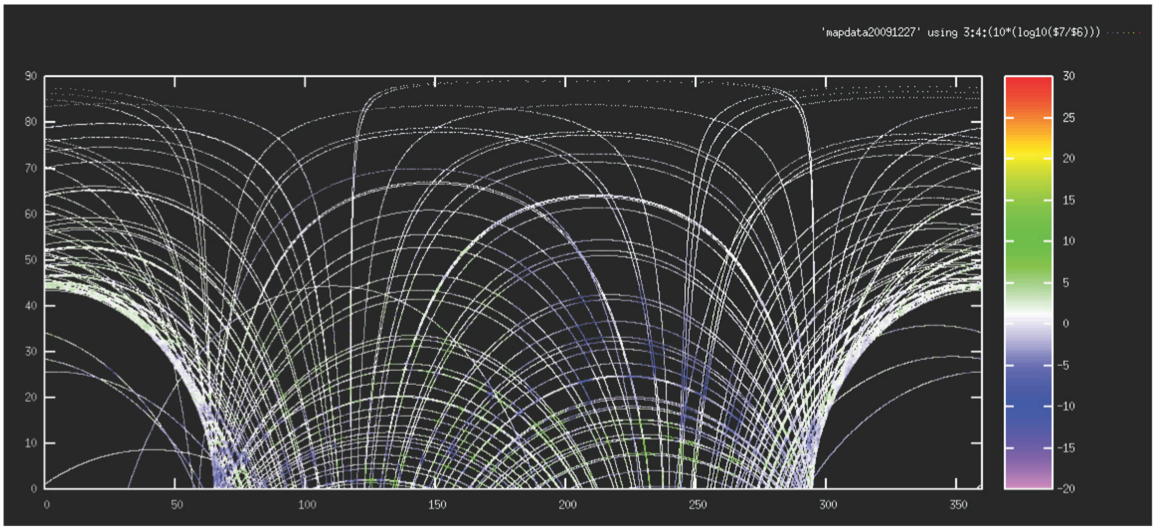


Figure LF 5

Plot of dipole power ratio in dB as a function of azimuth and elevation, from work by **Bradley** et al.

- **Stewart**, in consultation with **Jones** and **Weiler**, is conducting gain and impedance calculations for thin film antennas on the Moon (**Figures LF 6** and **LF 7**) using realistic values for the electromagnetic properties of the lunar regolith. The work is being done for the full range of antenna sizes that are relevant, from antennas for heliophysics work (ROLSS) to those for cosmology (LRA). This determines the requirements for transmission line designs and is necessary to understand how much power is delivered into the receiver, which in turn affects the entire electronics package.

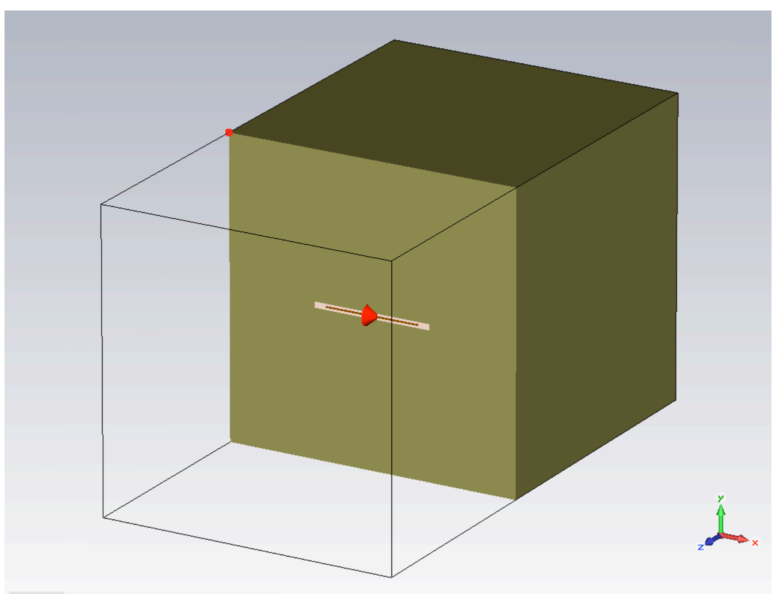


Figure LF 6

The model used to simulate the performance of thin-film dipoles. The antenna (Cu on polyimide) is placed directly on the lunar soil. From work by **Stewart** et al.

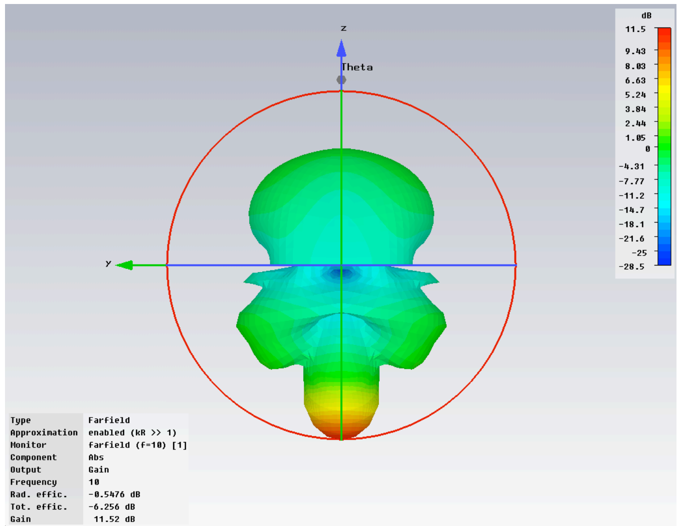


Figure LF 7

The gain of a 16 m long thin-film dipole calculated at 10 MHz using values of the dielectric constant and loss tangent for average lunar soil (Lunar Sourcebook). From work by **Stewart** et al.

- **Stewart**, **MacDowall** *(Radio Heliophysics)*, **Lazio**, and Weiler have also explored the extent to which NASA/GSFC resources are available, at no cost to the LUNAR team, for conducting simulations of the properties of transmission lines on the polyimide film. Implementing the transmission lines on the polyimide film is desirable from the standpoint of minimizing the additional infrastructure for signal transport, but there are significant issues related to the electromagnetic coupling between the antennas and transmission lines that need to be quantified.
- **Burns**, **Kruger**, **Alfaro**, **Lettang**, and **Kaiser** have been developing the infrastructure to conduct simulated lunar environmental testing of polyimide film, which has been both widely used and well studied in the space sciences. It has been employed on many space vehicles and on planetary surfaces (e.g., Mars rovers), and exhibits excellent performance under extreme conditions. However, the LUNAR Program is attempting to use the film in the design of a revolutionary radio antenna array. The radio antenna would consist of a polyimide film base on which metallic dipoles will be deposited. The array will be rolled up during transport to the Moon, much like a carpet, and then unrolled by astronauts or robots once there. The radio antenna will be exposed to the harsh environment for many months. They seek to recreate these conditions in the laboratory in order to ascertain whether the polyimide film exhibits any changes, such as in tensile strength or electrical conductivity. Initial testing previously done by a team led by Burns suggests there is little resultant change. They are now proceeding with more detailed and controlled experiments to ensure that

polyimide film is a viable material. While the entire test will be completed under vacuum, the specific variables that will be adjusted are temperature (varying from −150˚C to 100˚C) and UV light exposure (similar to the solar intensity at the Moon). They will closely monitor and document film temperature and electrical conductivity during the test and conclude with stress/strain measurements.

Laboratory testing is planned to begin in 2010 February. The test will last for approximately one month. The chamber will cycle from one temperature extreme to another every 24 hours, i.e., two days will simulate one month in real time. In this process, the UV lamp will be turned on during the hot cycle and off during the cold cycle. The film will begin rolled around a rod to simulate its shape of transport (**Figure LF 8**). It will then be unrolled remotely during the test to model its deployment once on the Moon. A shaft, connected to the film by copper wire, will rotate when activated by a stage motor, winding the wire around it. The direction of the wire will be redirected at a 90˚ angle to pull the polyimide film horizontally along the table.

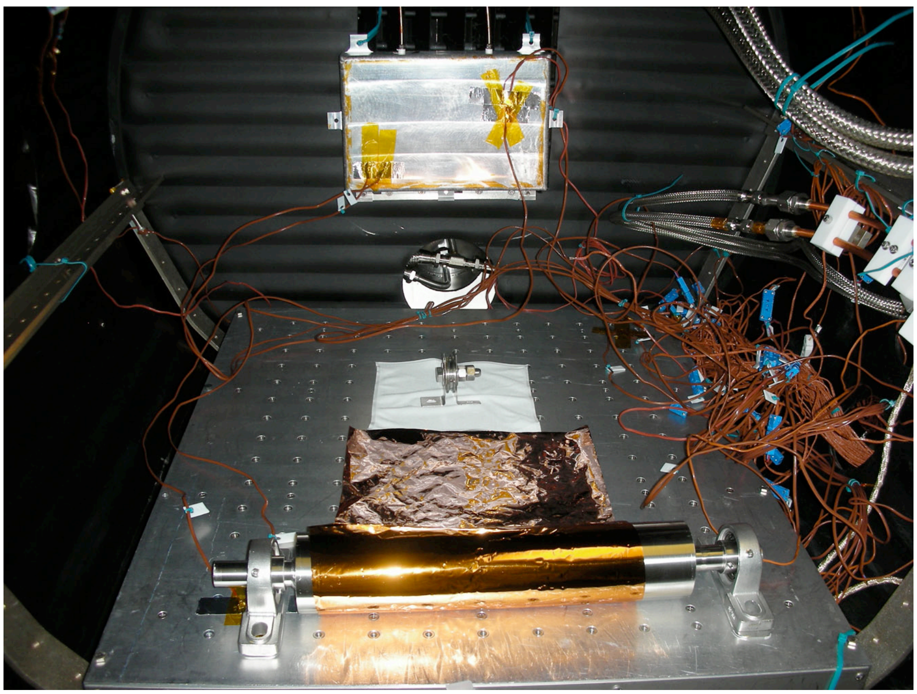


Figure LF 8

The interior of a vacuum chamber at the University of Colorado showing the rolled polyimide film and deployment mechanism. From work by **Burns** et al.

Beginning in the summer of 2009, our team designed the experiment, prepared the vacuum chamber for testing, and assembled and constructed the components to unroll the film. We have also conducted a variety of research projects to understand what metals are safe for a vacuum, how we can remotely monitor conductivity and temperature, and which UV lamps fit our requirements for mimicking solar intensity.

From this experience, the students have gained many new skills and knowledge. They have learned to create management tools such as Work Breakdown Structures, managed budgets, tracked our timeline and expenses, and developed experimental protocols (**Figure LF 9**). Along the way they have discovered that an experiment that should be simple in theory can be much more challenging and time consuming than initially expected. This opportunity has also allowed the team to develop a network of resources, such as faculty expertise, companies, and the key websites, to aid in this and future projects.

Figure LF 9

Readying the University of Colorado's vacuum chamber for the polyimide film environmental tests. Leading the preparations are **Kruger** and **Alfaro**, both students at the University of Colorado. From work by **Burns** et al.

- **Villasenor**, **Hewitt**, **Miller**, **Fitzgerald**, and **Beck** conducted initial development work on self-deploying antennas, which require minimum structure to save mass, as well as pack tightly to allow thousands to be carried in one payload. A helical antenna can be compressed to a small volume, but, to regain its original height, additional supporting structures must be included, easily doubling the mass and volume. The use of memory shape metals can greatly reduce or even eliminate the need for support, as they have sufficient elasticity to spring back to tall heights in the low lunar gravity. The current investigation looks into the different types of memory metals, and the fabrication steps needed to eventually create the 90 and 45 MHz antennas envisioned for lunar arrays. Specifically, the memory setting procedure requires heating the wire to temperatures above 900° F while set in its final form. For trial purposes, we have obtained various nitinol samples, with the intermediate step of fabricating a 137 MHz antenna that can be tested for its mechanical (compared with the spring equations) and electrical (antenna) properties. The initial run will be carried out in a vacuum furnace at MIT.

Later fabrication attempts will be made through ohmic heating of the wire, by passing large currents in an open-air structure. This second method allows construction of helices several meters long without requiring large vacuum chambers

Radio Heliophysics Key Science Project

Heliophysics Key Project Year One Goals were divided between (1) Studies of fundamental low frequency radio science, (2) Heliophysics radio array development, and (3) Technology pathfinder development. Tasks for (1) included characterization of the lunar RFI environment and a search for low frequency radio transients using existing observations in deep space and near the moon along with community interactions to support development of a heliophysics radio array. For (2) our work included refinement of the science and performance requirements for the low frequency radio array, development of a simulation framework for modeling observations with a low frequency array on the moon, analysis of similar radio observations using data from a prototype of the Murchison Widefield array in Western Australia, and participation in antenna design studies. For (3) our work included studies of automated systems for deploying antennas, systems level studies of the array concept, studies of antenna coupling to polyimide films, work on low power electronics, and development of radio receiver technology. The following subsections describe our progress on these goals and tasks in the first year.

Lunar RFI Background

As the first component of our analysis of the lunar RFI background, we analyzed Wind Waves RAD2 radio data (frequency range 1-14 MHz), acquired from November 1994 through the present, to measure the intensity level of radio bursts and terrestrial emissions observed by Wind along its complex trajectory that includes passes very close to the Moon. While these data demonstrate that successful radio observations of cosmological sources from an observatory anywhere near Earth will be best accomplished on the far-side of the Moon, they also indicate what might be accomplished from the near side. As shown by Figure 1, with RAD2 data taken during a close perigee pass (12,000 km) on Dec 1, 1994, terrestrial radio transmitters fill the band between 1 and 14 MHz, although some frequencies are less impacted than others. This interference represents a severe problem for near-side lunar radio arrays. Solar radio bursts are another potential source of interference for the lunar radio observatory; the most intense of the solar radio emissions in this band, the type III burst, appearing as a short duration vertical "stripe," of comparable intensity to the terrestrial transmission, but covering less area in frequency-time space. Given that the bursts are of short duration in this band, typically a few minutes at 10 MHz, they impact lunar radio observations of non-solar sources less than do terrestrial transmissions. Furthermore, they are almost non-existent during solar minimum, so that a far-side lunar radio observatory making measurements from the day side of the moon during solar minimum would probably see the thermal sun and corona as a background source, with intensities many orders of magnitude less than the non-thermal solar radio bursts.

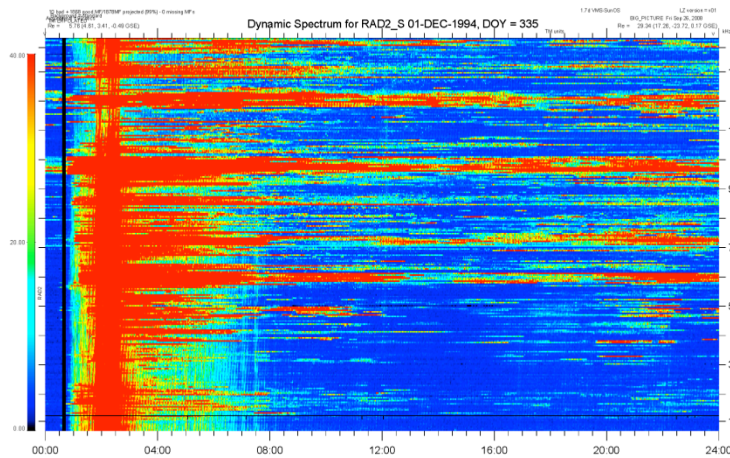


Figure RH 1

Close perigee pass (12,000 km) early in Wind mission (Dec 1, 1994), shows “worst case” interference at 0200 UT; no frequency channel is unaffected by the terrestrial transmitter noise. Data from Wind Waves RAD2 receiver cover 24 hours of observation in the band from 1 – 14 MHz

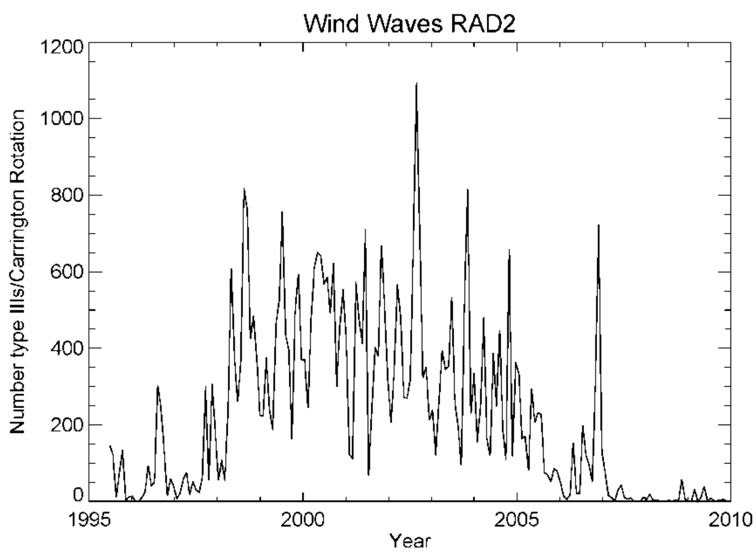


Figure RH 2

The number of type III solar radio bursts per Carrington Rotation is indicative of solar activity throughout the solar cycle. Note recent lack of activity during solar minimum.

Search for Low Frequency Transients

The two main motivations for low frequency radio arrays on the lunar surface currently identified by the LUNAR team are understanding electron acceleration by imaging solar radio bursts and exploring early structure formation in the universe through redshifted 21-cm emission. A potentially significant additional motivation would be the detection of astrophysical low frequency radio transients. These transients could be used to identify and classify new astrophysical objects, to characterize the environments and processes in known objects, and for probing the structure of intergalactic and intergalactic space. As part of our scientific activities for LUNAR we are using a new dataset to explore the possibility for such transient emission by looking for evidence of radio bursts associated with gamma-ray bursts and the galactic center. These data are taken from the WAVES low frequency radio instruments on the twin STEREO spacecraft.

Launched in October 2006, the STEREO spacecraft are in heliocentric orbits at about 1 AU, with one spacecraft leading Earth (STEREO-A) and the other trailing Earth (STEREO-B. For three months after launch, the two spacecraft were in highly elliptical orbits extending from very close to Earth to just beyond the Moon's orbit. About two months after launch they encountered the Moon, at which time one of them was close enough to use the Moon's gravity to redirect it to a position "behind" Earth. Approximately one month later, the second observatory encountered the Moon again and was redirected to its orbit "ahead" of Earth. Since the final encounters with the Moon, the STEREO spacecraft each drift away from the Earth at a rate of about 20 degrees of longitude a year. The spacecraft are currently (as of February 2010) 135 degrees apart around the Sun. At these separations, light takes about 15 minutes to travel between the spacecraft. With that time delay, we can use the WAVES instrument to solve for the angle of propagation of a burst coming from an unknown source and compare that angle with known source locations. We will use this technique to search for unknown low frequency radio transients. We now describe our progress in the first year.

The WAVES instruments consist of three mutually orthogonal monopole stacer antenna elements, each 6 meters in length. The antenna design was optimized for response in the 16MHz - 30kHz frequency range and has a high signal-to-noise ratio for expected solar type II, type III, and other solar and interplanetary radio emissions. Our focus is on the High Frequency Receiver (HFR), which operates from 0.125-16.075 MHz. In this band, two spectra from two antenna pairs (a total of 4 spectra) are obtained, giving the power and phase for each of 16 frequencies. A full measurement sweep consists of 16 sets of 8 12-bit samples with a nominal sweep rate of once every 16 seconds. Since the light travel time between the spacecraft is now close to fifteen minutes, we can solve for an angle of arrival of a signal observed by both spacecraft with a good deal of precision given this 16-second resolution at scanning through the frequency range. In the beginning of the year we met with the STEREO WAVES team and obtained 42GB of calibrated HFR observations at the highest time resolution. Our work since receiving these data has consisted of developing methods to characterize and manipulate the data and of techniques for solving the predicted time delay for a signal as a function of source location, spacecraft location, and absolute time.

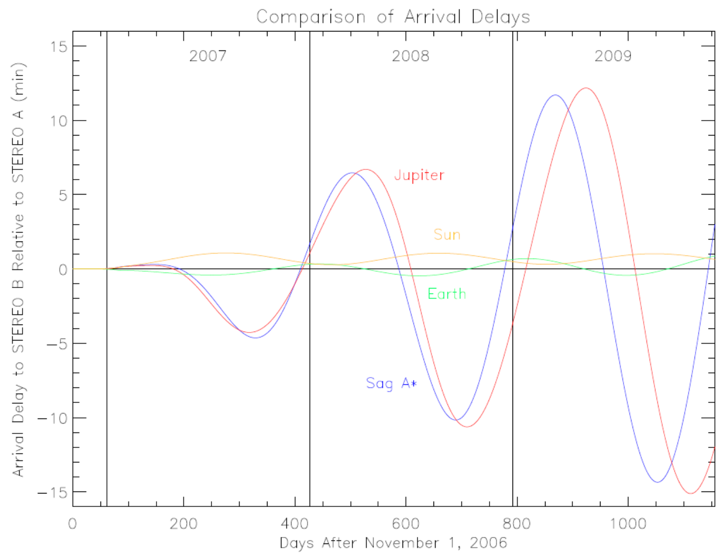


Figure RH 3

The delay in arrival time of a wave front reaching STEREO B after it is detected at STEREO A as a function of time since launch of the spacecraft for four candidate emission sources (Earth, Sun, Jupiter, and Sag A*).

We combined NSSDC orbital trajectory data with IDL coordinate manipulation software to generate plots of the relative delays between the spacecraft for signals from a variety of sources, including the Sun, the Earth, Jupiter, and Sag A*, the black hole at the center of the galaxy. We use Sag A* as a proxy for the center of the galaxy, the motivation being that the dense galactic center may be the most probable region for previously unidentified radio transients. We have learned several things from this analysis. First, It was only after several hundred days that the spacecraft has sufficient separation for the timing analysis to work. Second, since the two spacecraft are moving away from the Sun-Earth line at approximately the same rate, they tend to both produce signals with near-zero time delay. This means that other sources, such as Jupiter or Sag A*, have seasons where they are well separated from terrestrial and solar emissions. We also discovered that for the first two years of the mission Jupiter (a known low frequency source) and Sag A* were coincidently close to each other on the sky. Clearly the most recent data are the best suited for searching for galactic transients that are distinct from Jovian emission.

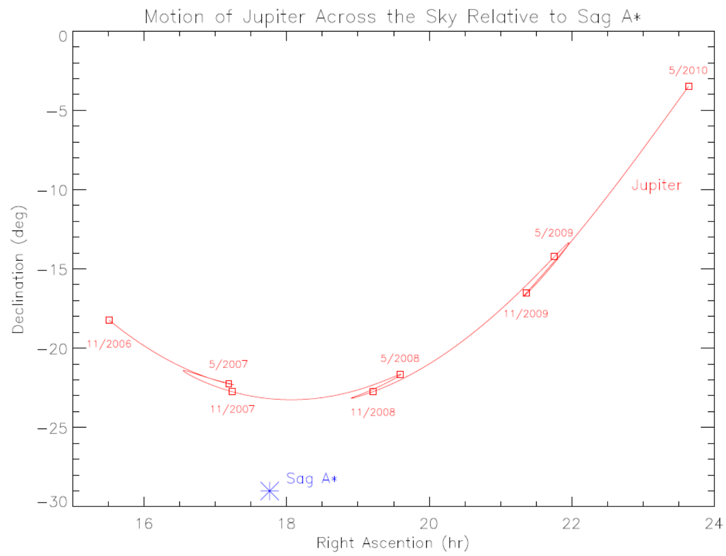


Figure RH 4

The apparent motion of Jupiter across the sky as a function of time (as viewed from Earth) relative to Sag A*, showing that early in the mission the two sources were nearby, but that the separation has grown tens of degrees for the recent observations.

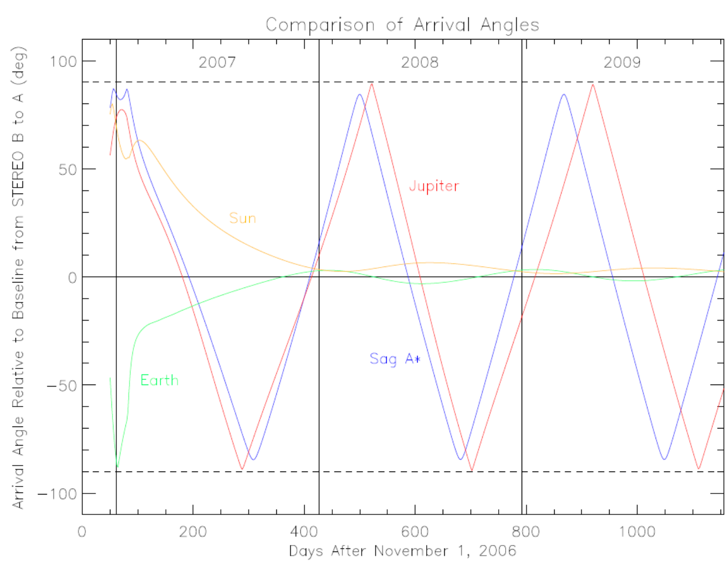


Figure RH 5

The apparent angle of arrival of signals from candidate sources in the sky including Earth, the Sun, Jupiter, and Sag A*, the black hole at the center of our galaxy.

We have begun our search for transient emission employing two strategies: a blind search and a search given known times of astrophysical explosions. The blind search method consists of looking for intervals where statistically significant increases in the emission power are seen within the light travel time between the two spacecraft at similar frequencies. We are still in the process of improving this code to make it more sensitive, but we have been able to detect solar radio bursts and are using them as practice to refine the code. Figure 6 is an illustration of a Type-III burst seen by both spacecraft, but arriving at STEREO A a few minutes before STEREO B. This delay is consistent with the geometry of the Sun and the two spacecraft at the time of the event, and we are developing code to calculate the precise arrival delay.

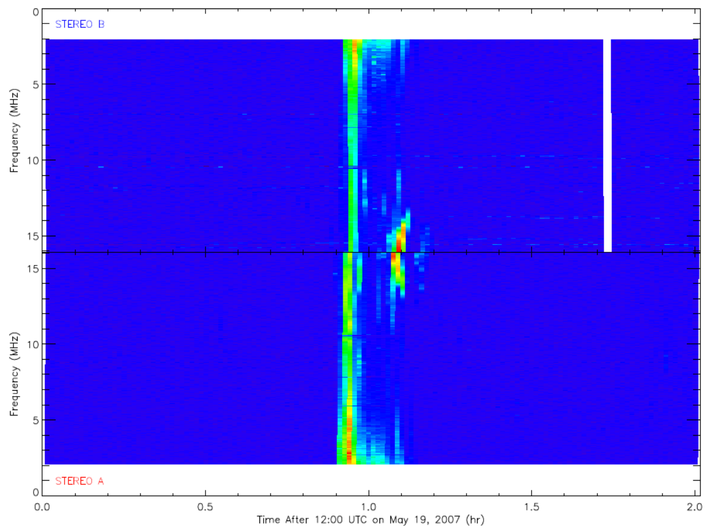


Figure RH 6

Example of a Type-III solar radio burst observed by both spacecraft. Note that the emission is observed to arrive at STEREO A several minutes before STEREO B, consistent with the predicted delay above.

In addition to our blind search, we have also begun a search for transient emission associated with Gamma Ray Bursts (GRBs). We have downloaded and update on an occasional basis the SWIFT GRB catalog. We are currently examining every GRB, but we will focus our efforts on low redshift GRBs at high galactic latitudes (less likely to experience scattering from electrons in our own galaxy). An example of our GRB analysis is sown in Figure 6. In this case there is a transient about an hour after the GRB. If this was indeed a signal from the GRB that experienced dispersion delay, we would expect the signal delay to increase quadratically with decreasing frequency and it does not. We would also expect it to be seen at B about 7 minutes after it was seen at A and instead the reverse is true. It is likely therefore that this event is actually emission from Jupiter occurring right after a GRB. We will continue to analyze events such as these.

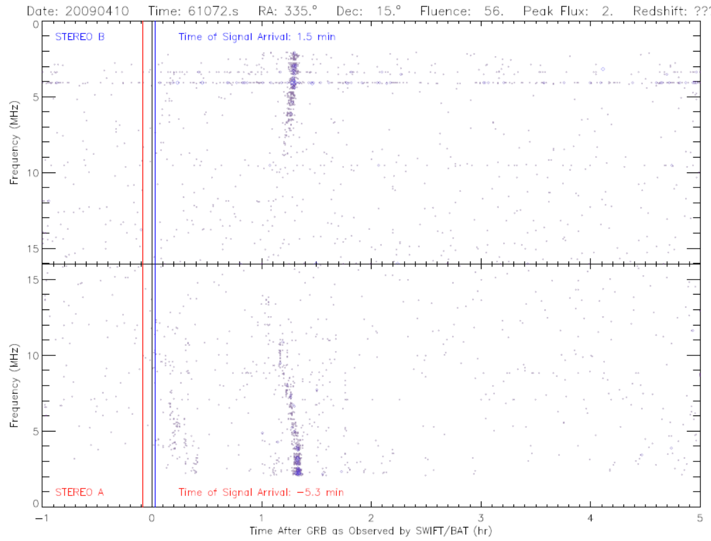


Figure RH 7

Example of the low frequency radio power spectrum observed by the two STEREO spacecraft in the time after a GRB. Vertical lines show when the GRB was seen at Earth (black) and when it should have been seen at STEREO-A (red) and STEREO-B (blue). The symbols indicate statistically significant emission in individual power measurements as a function of time.

Community Development

We participated in the development of a new paper for ROLSS led by Joseph Lazio and presented ROLSS at conferences including the 2009 Lunar Science Forum (Ames), the 2009 Lunar Exploration Analysis Group, and at the Fall meeting of the American Geophysical Union.

Heliophysics Radio Array Development

Traceability

Our first task under this element was to refine the Radio Observatory for Lunar Sortie Science (ROLSS) science requirements and trace the science requirements to instrument performance requirements. Our work in year one under this task consisted to developing more sophisticated tools for predicting the patterns of emission on the sky near the Sun as a function of frequency and time due to a Coronal Mass Ejection (CME)-associated Type-II burst or a Type-III burst of energetic electrons. Our main result so far is that simulations of the corona suggest that the emission ROLSS will observe will be oblate and aligned with the streamer belt, which changes orientation with respect to the solar equator of time.

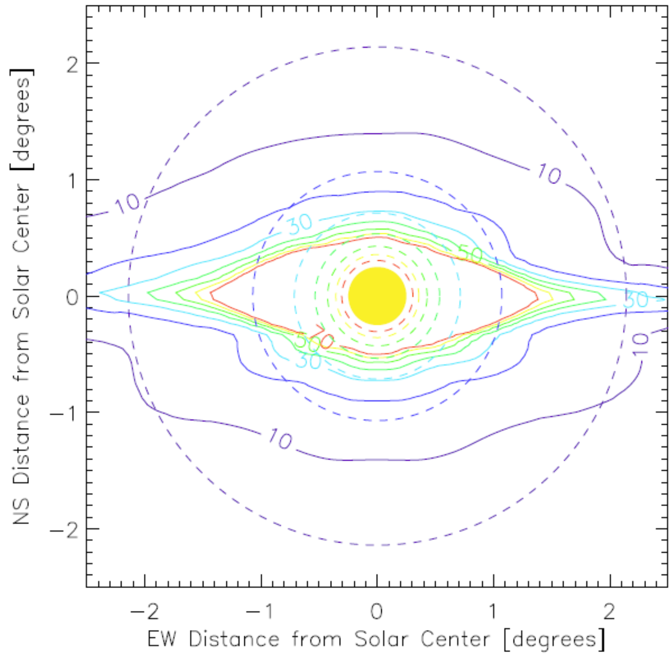


Figure RH 8

To refine the performance requirements for ROLSS we developed a framework for predicting the spatial patterns of solar radio emission from Type-II (shocks) and Type-III (relativistic electron beams) near the Sun using a realistic 3D MHD simulation of the solar corona to predict the fundamental and first harmonic frequency of emission. The solid lines indicate the location of emission as a function of frequency and the dashed circles indicate the resolution of the array at 300 m spacings. This framework will be used to optimize the spacings between antennas.

Simulations

We also plan to adopt the MIT Array Performance Software (MAPS) written for the Murchison Widefield Array (MWA) for simulating a lunar radio array. The modification of MAPS was delayed due to increased manpower allocated to the MWA in order for that project to meet short-term performance goals. It is expected that this work will start in force in March as MWA ramps down activity for a period of RFI characterization.

Analysis of Similar Observations

Our plan is to use observations from the 32-tile prototype of the Murchison Wide-field Array to obtain examples of solar disk images and solar radio transients with a resolution similar to that expected from the lunar array. While the MWA prototype has made some early observations, it has not yet produced detections of solar bursts due to low levels of solar activity. We continue to monitor the situation.

Antenna Design

We have continued to support the monthly antenna design telecons.

Antenna Deployment

Our goal for this has was to work on autonomous antenna deployment strategies and identify possible missions that these methods would be consistent with. Our model for lunar surface pathfinders for the Lunar Radio Great Observatory (LGRO) is as follows: 1) antenna test system (ATS); 2) small test observatory; 3) fully-functional solar radio observatory, such as ROLSS, on earthward side of moon; 4) phase one of LGRO on far side of moon; and 5) subsequent phases of LGRO. When the opportunity provided by an early lunar lander avails itself, we should deposit an ATS on the surface of the moon, to validate our antenna system concept. The ATS package, mostly located on the exterior of the lander, will deploy several antennas, without use of a rover deployer. For this purpose, we require the simplest, lowest mass deployer, to impact the host lander as minimally as possible. At GSFC, we are currently working on and testing such a design, intended to be carried to the lunar surface by any available lander, like Chandraayan II or Chang'e-3 or whatever opportunity exists

Antenna-Film Mutual Inductance

We expect to start this work in the coming Spring in coordination with NRL.

Electronics Development

After evaluating the needs of the team and the available work that has been performed on components such as batteries for lunar surface activities, we decided that the most useful thing to investigate for power consumption for a lunar radio array was the actual performance of Field Programmable Gate Array (FPGA)-based astronomical correlators. Large N ultra low power correlators are required for lunar applications, such as the Dark Ages Lunar Interferometer (DALI), and the Lunar Radio Array (LRA). In this initial study, we use current terrestrial technology FPGAs (Virtex 5 family), noting that Xilinx has a contract to radiation harden the Virtex 5. This means that the Virtex 5 is a very likely candidate for any lunar radio array within the next decade. Our objectives are to examine the relationship between total power consumption and the correlator architecture, number of stations, bandwidth, correlator bit-width, and clock rate.

In our existing design trade studies for the correlator component of radio arrays we have assumed simple scaling relationships for power consumption as a function of the array capabilities listed above. There are actually many properties internal to a given FPGA that can be adjusted to optimize the performance of the device for a specific correlator. The required Nyquist bandwidth, for example, sets the sampler clock. However the digital signal processor (DSP) clock, which processes the data, can be set to a sub-multiple of the ADC clock by demultiplexing the sampled data, and providing parallel processing paths in the FPGA. Thus a tradeoff can be made between the power scaling due to processing in the parallel paths, and that due to processor clock rate. The overall architecture of the correlator plays a large role, of course. For large-N applications it is typical to employ a FX architecture; even so we will also examine the possibility of using a lag architecture (XF).

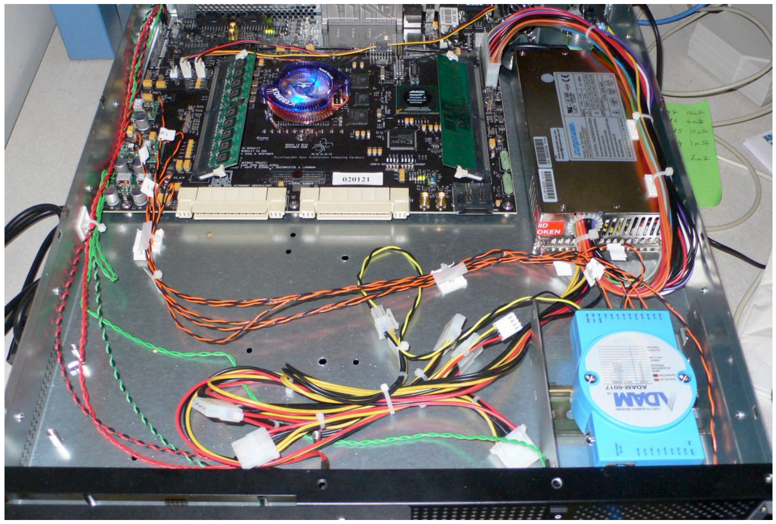


Figure RH 9

The instrumented ROACH hardware. The ADAM module right front measures the voltage drops across the current sense resistors to which it is wired with orange-black twisted pair.

To expedite our analysis we are using the UC Berkeley Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) Xilinx Virtex 5 Reconfigurable Open Architecture Computing Hardware (ROACH) FPGA boards, and high speed analog-to-digital converters (ADCs). We are equipped with a fast quad core development workstation running the latest CASPER tool flow software to expedite bit code generation. We are using the SX-95 version of the Virtex 5 chip to correlate a subset of the baselines and investigate the capabilities, and power-consumption, of a single chip. Scaling up to the full correlator is not necessarily straightforward as truly large (N ~ 1000) designs require multiple FPGAs and fast corner turn switching. In CASPER methodology, this corner turn is usually implemented with an off-the-shelf 10Gbps packetized network switch.

An Actual current measurement system is built into the ROACH hardware, but has rather coarse resolution, and thus is unsatisfactory for our purposes. So, we instrumented our ROACH with a networked multichannel DVM made by ADAM. The inputs of the ADAM unit are wired directly to the ROACH current sense resistors, which are in suitably large SMT packages.

Since we plan to generate a large number of comparative measurements, a graphical user interface has been designed, and the downloading of bit streams and taking of measurements have been scripted.

The objective is to estimate only the power consumption of the FPGA running a correlator bit stream in isolation. However the voltage rails on which the current sense resistors are placed in series supply hardware on the ROACH board, which is peripheral to the FPGA. Early on we noticed a puzzling characteristic, that on loading and running a correlator bit code into the FPGA the total power consumed actually decreased. On looking at the power consumed on each of the power rails separately, it was apparent that while the 1V rail power increased, the 1.8V rail decreased. Only on separating the programming and running events did the nature of what was going on become clear.

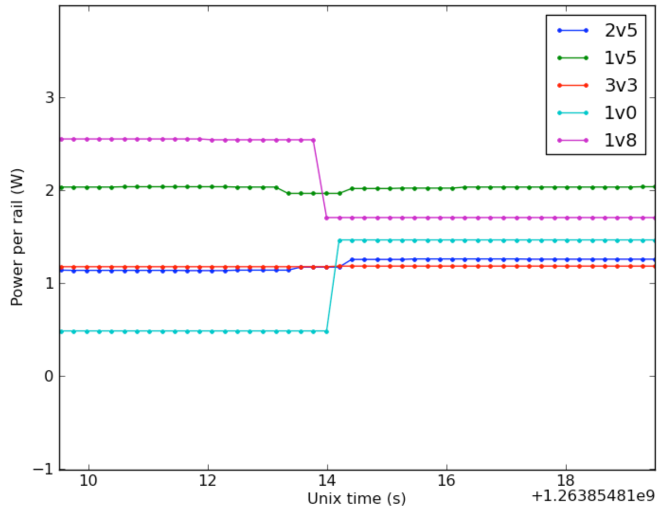


Figure RH 10

Programming the FPGA while holding the state machine in a disabled state - note the step increase in 1V current and step decrease in 1.8V current. We are investigating the root cause of this decrease.

We investigated this observation in the case of the XF correlator by loading the FPGA with a correlator bit stream (this takes the FPGA out of suspend mode), while holding the correlator state machine in a disabled state. We then measure the step increase in power consumption at the moment when the correlator is enabled. The user interface provides a streaming plot of the power consumed on each of the five power rails (1.0, 1.5, 1.8, 2.5 & 3.3V) supplied to the FPGA. It turns out that the step decrease in 1.8V current was associated purely with the programming event. Starting the correlator state machine results, purely, in a step increase in the 1V current, which is the rail, which primarily powers the FPGA fabric. Some more research is needed to separate systematic errors from true correlator consumption, i.e. we need to understand exactly what the cause of the step decrease in 1.8V power is. We further suggest that it is appropriate to add the power step on 1 V when the FPGA is programmed to the power step when the state machine is enabled, to get the full FPGA power consumption number. The pedestal of 1 V before the FPGA is programmed is 1 V consumption by other elements on the ROACH board.

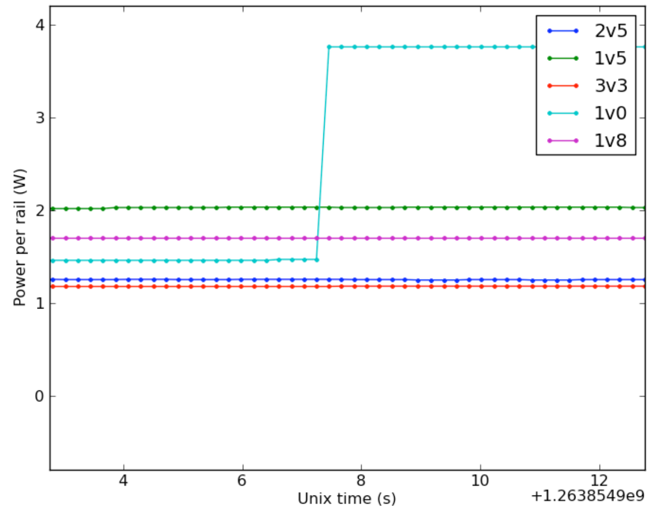


Figure RH 11

Current step on 1V through enabling event - starting the correlator.

Our first result with this setup is a comparison of an XF architecture power consumption (to a similarly capable FX. In these figures, the programming step (which takes the FPGA out of suspend mode) and the state machine-enabling step are combined. In the case of the XF architecture, there is a short delay between the step increase in 1 V power due to programming the FPGA and the step increase due to starting the state machine. Because there is no way to hold the state machine inactive in the FX case this delay cannot be observed. We take as a proxy for the FPGA power consumption of the correlator the step increase in the 1 V power between FPGA in suspend mode, and the correlator programmed and running. Measuring the step size, we estimate that the XF correlator consumes about 3.5 W, while the FX consumes about 1.9 W.

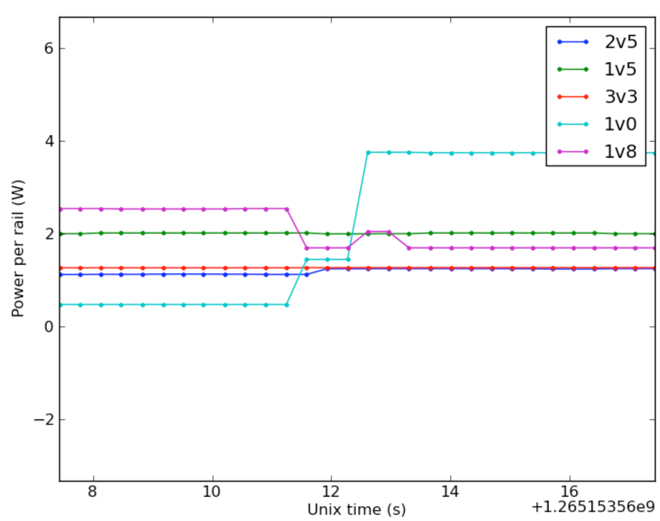


Figure RH 12

Power consumption of 16 baseline XF correlator. Programming of the FPGA (which brings it out of suspend) and enabling steps are done sequentially under software control, hence the slight delay between the step increase due to programming, and that due to starting the state machine.

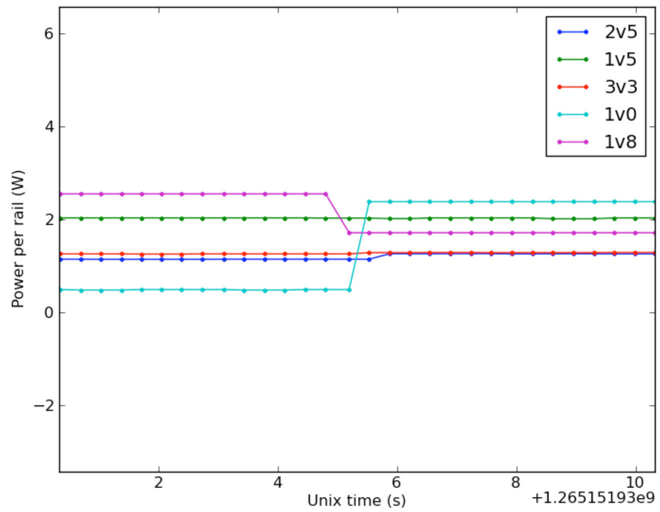


Figure RH 13

Power consumption of 15 baseline FX correlator. Programming of the FPGA (which brings it out of suspend) and enabling of the state machine are constrained to be combined for this design because the CASPER Fourier Transform block cannot be disabled.

In summary, we have created a powerful system for automated reprogramming and reconfiguration of FX and XF correlator architectures on a Virtex 5 FPGA. We can modify parameters such as the number of baselines, bandwidth, and correlator settings, and the measure directly the power consumption when the correlator is processing artificial signals. In the subsequent year we will use this system to identify the optimum configuration of a single Virtex 5 and verify the scaling relationships between bandwidth, number of baselines, and other parameters with power consumption.

Gravitational Physics & Lunar Structure

This report describes the activities of the Lunar Laser Ranging Team (LLRT) over the past year. This will address the work within the original Statement of Work (SoW) as well as activities that have arisen since.

University of California at San Diego

At UCSD, year-one activities have concentrated on three themes: 1) study of the apparent degradation of the Apollo reflectors; 2) preparation and initial attempts at two-way laser ranges to the Lunar Reconnaissance Orbiter (LRO); 3) work with the developers of the Planetary Ephemeris Code (PEP) at Harvard-CfA. These three topics are treated in turn in the following three paragraphs. On its face, this differs from the year-one UCSD work plan, which included a) assessment of modeling tools; b) refinement of science case for sub-millimeter LLR; c) review of transponder architectures. Yet item (3) maps to (a), item (2) relates to (c), and item. (1) Is more closely mapped to later goals of the study, in which assessment and mitigation of dust on the lunar surface will be a key issue.

A surprising result of the Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) is that the reflector arrays show a clear signature of degradation that is exacerbated at full moon--likely due to enhanced thermal gradients imposed by dust or abrasion. The full-moon signal reduction is roughly a factor of ten, on top of a suspected factor-of-ten reduction at all lunar phases. This discovery comes at a crucial time in the design phase of next-generation corner cubes. Doug Currie (LUNAR CoI) is trying to replicate the observation in an attempt to better understand the source of the problem and ultimately a mitigation strategy. A publication is currently under review.

The upcoming attempts to obtain two-way ranges to LRO relate to both the degradation issue and the transponder work. The strength of return from a pristine and well-characterized corner cube array compared to an adjacent measurement of the Apollo reflector return (same observing conditions) will be an interesting check on the overall degradation of the Apollo reflectors. The work is related to transponders in that several groups around the world are performing one-way laser ranging to a receiver on board the LRO spacecraft, which provides range information when compared against the on-board clock. This technique is very similar to the asynchronous transponder technique (representing half of it). By comparing the clock-independent two-way ranges from APOLLO, we will validate the one-way technique and assess its precision. This work involves a strengthened interaction between LUNAR teams at UCSD (Murphy) and at GSFC.

Finally, in collaboration with the PEP team at Harvard, we have determined that lunar orientation is the tallest pole in the PEP code at present. Attempts to improve the gravity field model and the model of the interior structure are underway. This effort still seeks funding, and is unable to go as fast as we would like at present.

NASA/Godard Space Flight Center

Much of the effort during the first year of LUNAR at GSFC was spent refining the science case for new lunar laser ranging capabilities. In collaboration with Co-I Nordtvedt, we started investigating the possibility of testing Chern Simons modified general relativity using lunar laser ranging. We also produced a number of white papers that were submitted to the Astro2010 Astronomy and Astrophysics Decadal Survey and the Planetary Science Decadal Survey:

1. "Opportunities for Probing Fundamental Gravity with Solar System Experiments" (Turyshev and Murphy contact)
2. "Next Generation Lunar Laser Ranging" (Merkowitz contact).
3. "Science from the Moon: The NASA/NLSI Lunar University Network for Astrophysics Research (LUNAR)" (Burns contact).
4. "The Moon as a Test Body for General Relativity" (Merkowitz contact).

5. “Lunar Science and Lunar Laser Ranging” (Williams contact).

Merkowitz also presented a response to specific questions from the Astro2010 Particle Astrophysics and Gravitation (PAG) panel at their June 2009 meeting and gave a presentation on LLR at the April 2009 APS meeting in Denver, CO. Finally, Co-I Merkowitz started putting together a review of lunar laser ranging for publication in *Living Reviews in Relativity*.

The original GSFC work plan called for further thermal-vac testing of commercial 1.5” hollow cubes over the temperature range of the lunar surface. However, after investigating commercial cubes further, we concluded that the currently available cubes are unlikely to perform well when scaled up to the size required for new lunar retroreflectors. We, therefore, refocused our efforts on developing an in-house capability for assembling hollow cubes using a promising new bonding technique being used for the LISA and LISA Pathfinder missions. A team of engineers is being assembled for this effort and we’ve partnered with scientists working on the LISA mission to leverage off of their efforts using this technique. In preparation for testing these cubes, we also began upgrading our far-field test bed so that it can accommodate large cubes.

In calendar year 2009 the laser clean room at the 1.2m Telescope Tracking Facility at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt Maryland was converted to support the capture and analysis of cube corner far field diffraction patterns (FFDP). This laboratory with remote access to the telescope Coude’ room originally housed high power short pulse lasers for satellite laser ranging (SLR) operations. Although the laboratory is not operated as an ultra clean facility its HEPA filters with laminar airflow and positive pressure help keep optical surfaces dust free. FFDP instrumentation including laser, collimator, test cube, reference flat, and readout device is mounted on a 2’ by 5’ NRC optical breadboard. **Figure LR 1** is a photograph of the FFDP breadboard with laser, collimating optics and readout device.

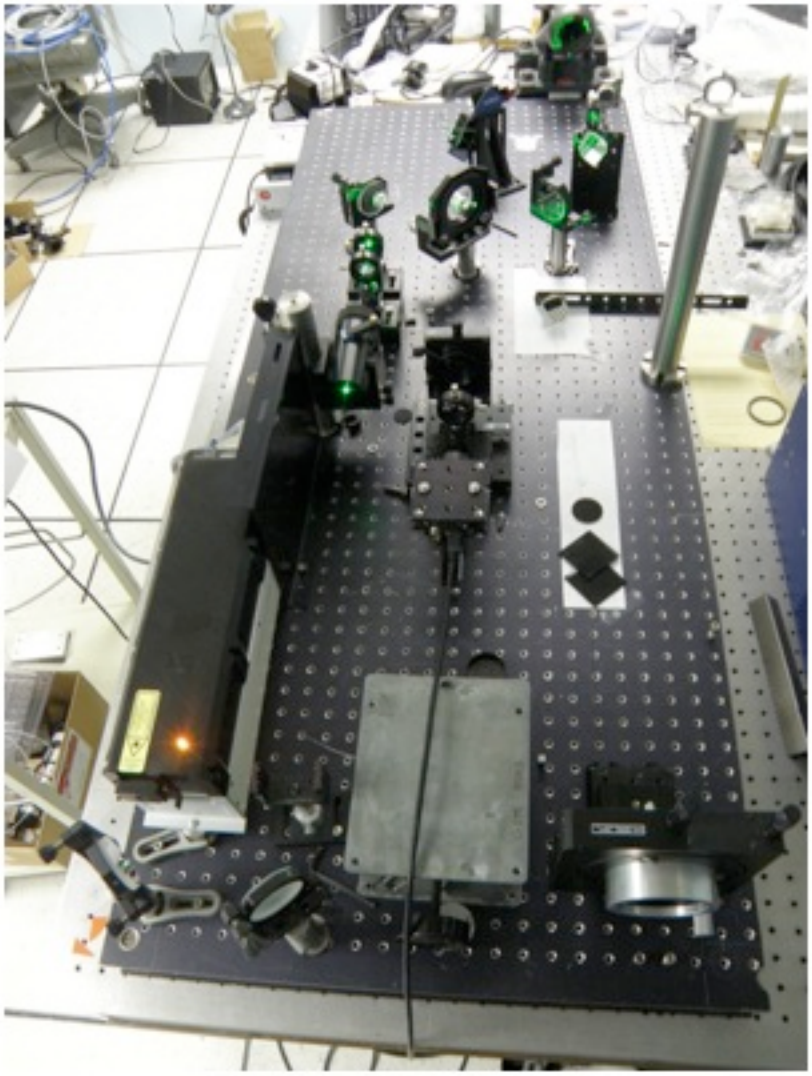


Figure LR 1

FFDP optical breadboard with laser, spatial filter, beam expander, transmit/receive splitter, 3” off axis collimator, test cube and reference flat.

Transportability of the breadboard was desired to extend cube corner testing to other laboratories adding thermal vacuum chamber test capabilities. Early cube corner testing revealed unacceptable floor vibrations coupled through the legs up into the 4’ by 10’ support table. Vibration isolation was added in 2009 by installing and operating NRC air bladder supports in the 4 legged table support system. Also observed in early testing was a significant amount image distortion due to air turbulence caused by the laser cooling fan and air handling system in the laboratory. Not shown in Figure 1 are the air baffles and plastic tent used to minimize air turbulence effects.

The laser source used is a JDS Uniphase Dual Chip NanoLaser operating at 532nm with a 1 nanosecond pulse-width and 30 KHz repetition rate. The beam is expanded and spatially filtered before illuminating the 3-inch off axis collimating optic as depicted in **Figure LR 2**. Test cube corner and reference flat are in collimated space in the upper left corner of the figure. A Basler Scout CCD camera model SCA640-70FM is used for image capture. Imaging software provided by the camera manufacturer is run on a Windows XP operating system computer.

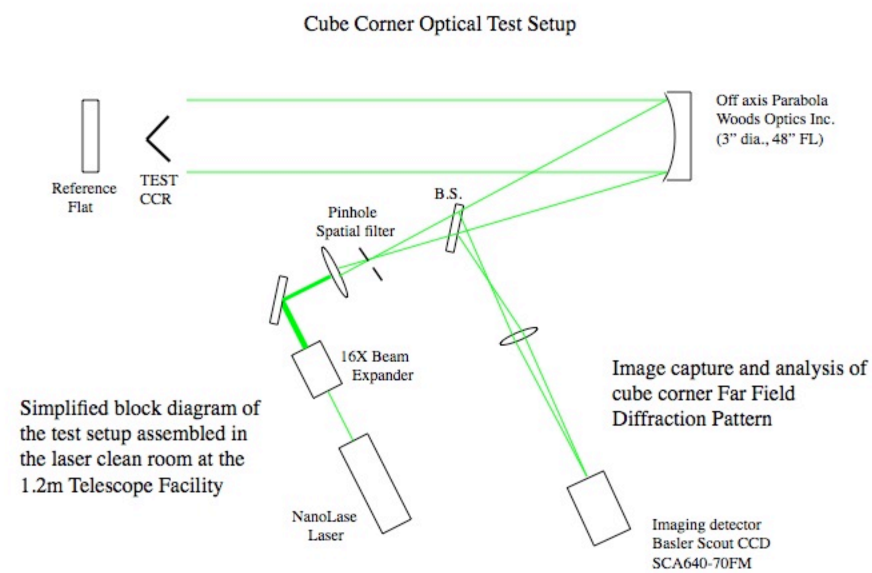


Figure LR 2

Block diagram of the Far Field Diffraction Pattern test setup showing the laser pulse source, beam expanding optics and spatial filter, off axis collimator, test cube and reference flat, and readout device.

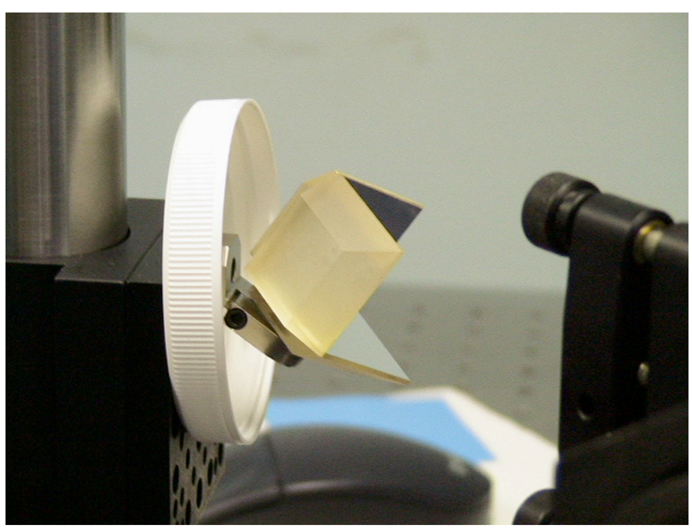


Figure RH 3: PLX 1.5" diameter zerodur cube corner

Of the four 1.5” PLX cubes tested two were fabricated of Pyrex and two of zerodur. The most telling data is that of the 1” diameter Lambda/40 reference flat. At the current limitation of 10 bits digitization in the Basler camera the airy disk pattern is not discernable. This may not be a camera limitation at all but rather the limit to the “seeing” conditions in the laboratory. Dust particles are obviously present on the imaging CCD device yielding multiple “bull's eye” patterns on all images. Air turbulences are also present making precise imaging more difficult. These disturbances are present in all FFDP images and mask cube performance. (**Figure RH 4 a & b**) shows the FFDP of the 1” calibration flat and a 1.5” diameter zerodur cube.

Figure RH 4a & b

The FFDP of the 1” diameter calibration flat is show in the left image and a zerodur pattern in the right image.

Improvements need to be made in the test setup to better resolve image patterns while minimizing distortions. A larger image or higher magnification is required to discern more image detail. This can be done by increasing the magnification in front of the Basler imaging camera or moving to a longer focal length off axis parabola. The second option of replacing the collimating mirror with a longer focal length optic is preferred since a larger diameter collimator is also desired. The current 3” diameter collimator will be upgraded to a 6” diameter optic this year. Eliminating the additional magnifying optic in front of the imaging camera will also eliminate that source of distortion. To improve the Basler camera imaging capability new driver software will be written to recover the full 12-bit intensity resolution of that device. Additional air baffling and air tents will be investigated and a thorough cleaning of all optical surfaces as well as the imaging camera will be conducted.

University of Maryland

The general objective of the effort at the University of Maryland at College Park is to advance the status of the “Lunar Laser Retroreflector Array for the 21st Century” (LLRRA-21) that was initiated almost three years ago under a LSSO grant from NASA. This program is to define and develop a retroreflector package that will increase the accuracy of the lunar emplacement by several orders of magnitude.

The work at the University of Maryland will be presented in comparison with the SoW (denoted in italics), followed by a few additional items that have been addressed and/or accomplished during the past year.

a) Evaluation of Multiple Shields to Control Pocket Radiation

i) Simulation, SCF Thermal Vacuum Testing and Comparison of Modeling vs. Test Results

In order to simulate the overall performance of the LLRRA-21, the thermal properties of the lunar regolith, the housing of the CCR and the CCR have been modeled. This has been done using data on the regolith from the Apollo missions and the properties of the elements of the housing and the fused silica of the CCR. These parameters have been incorporated into Thermal Desktop, a thermal modeling program created by C&R Technologies. The most important figure of merit in the current simulations is the temperature difference between the tip of the CCR and the front face of the CCR. **Figure UMCP-1** illustrates the results of modeling the regolith, housing and CCR for one instant in the simulation of the thermal behavior through a lunar cycle (after running the model for 1,000 lunation's to reach equilibrium). **Figure UMCP-2** illustrates the temperature distribution in the CCR for one instant. Finally, **Figure UMCP-3** illustrates the tip to face temperature distribution during a lunar cycle. This distribution is satisfactory for maintaining the quality of the return laser beam and providing proper signal strength for the lunar laser ranging. This provides a return that is about 50% of the return from the Apollo 11 array.

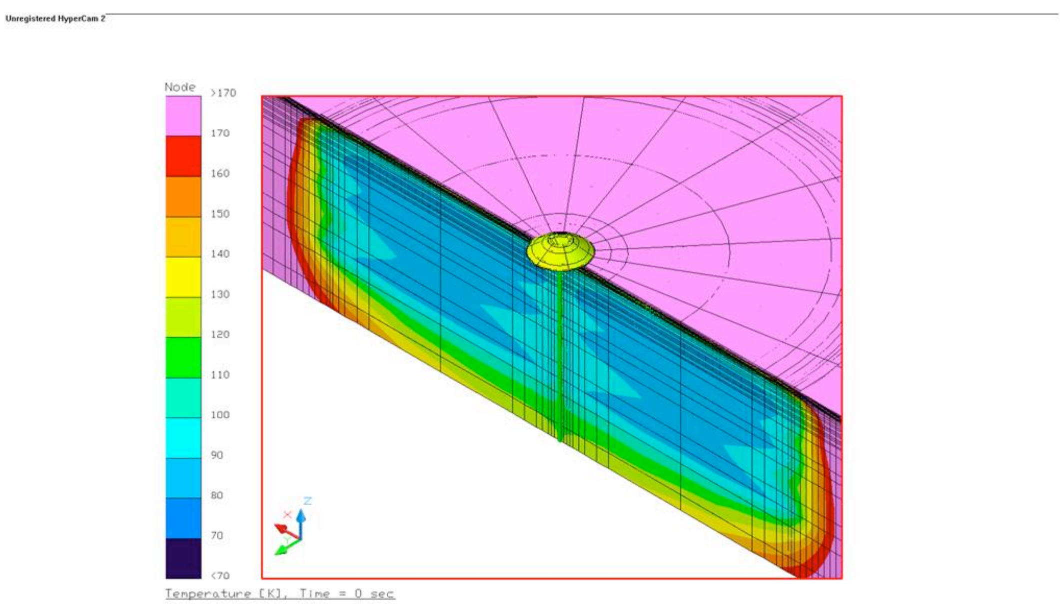


Figure UMCP-1

This illustrates the complete model used in these simulations. There is an extended region of regolith that extends beyond the thermal blanket and down to 3 meters, to cover the 1 meter support rod.

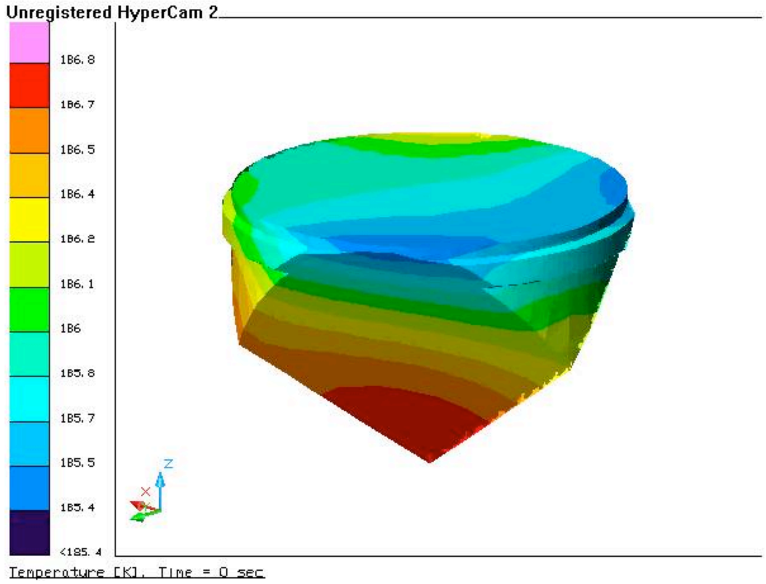


Figure UMCP-2

This illustrates the temperature changes during a lunation of the CCR within our initial design of the housing (the "mushroom" housing).

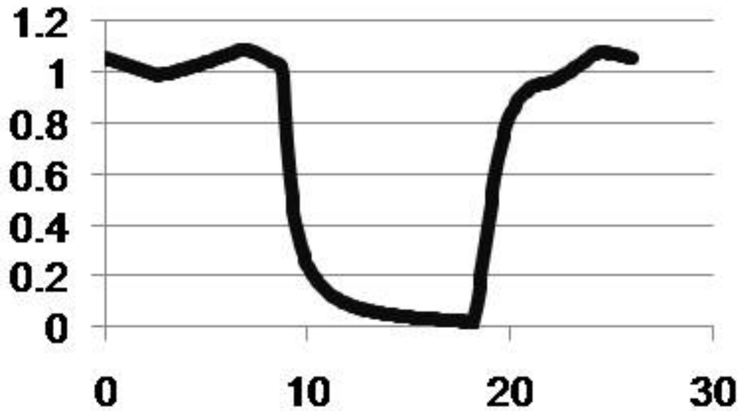


Figure UMCP-3

b) *Definition of Velocity Aberration Correction*

i) Simulate Effects of Single Face and 2 Face Angle Offsets and Select Optimal Configuration

Due to the velocity aberration, the optimal return occurs when one or more of the angles between the back faces of the CCR have a value different than the nominal 90 degrees. In order to investigate this effect and determine the optimal angle, we simulate the return (or more technically, the "radar cross-section") of the retroreflector for various "offset" angles. In the table below, we see the variety of offset angles that are simulated. On the right, we see the relative return (as a percentage of the ideal return to be expected from the Apollo 11 array). One sees that the angular combinations in bold type give the highest returns. The “top” and “bottom” refer to the orientation of the CCR with respect to the relative velocity between the CCR and the ground station. Thus for 0, -0.2 and -0.2, we have excellent return, each proposed 100 mm CCR provides ~60% of the return of the Apollo 11 array.

			Percentage of Peak Intensity of A11			
angle 1	angle 2	angle 3	top equator	top 45º	bottom equator	bottom 45º
0	0	0	48	40	45	36
0.2	0	0	30	33	28	29
0	0.2	0	46	30	36	18
0	0	0.2	39	22	42	26
0.2	0.2	0	26	23	18	13
0.2	0	0.2	21	15	22	19
0	0.2	0.2	39	18	36	15
0.2	0.2	0.2	18	10	15	7
-0.2	0	0	58	39	55	35
0	-0.2	0	46	45	51	53
0	0	-0.2	56	57	42	42
-0.2	**-0.2**	**0**	50	41	**58**	51
-0.2	**0**	**-0.2**	**60**	53	46	37
0	**-0.2**	**-0.2**	52	**62**	49	**58**
-0.2	-0.2	-0.2	53	55	50	52

Note that we will use these data to define another run with a finer grid about the 0, -0.2, 0.2 configuration. Since this data is for a single polarization of the incident laser beam, we will also run the fine grid for the other polarization.

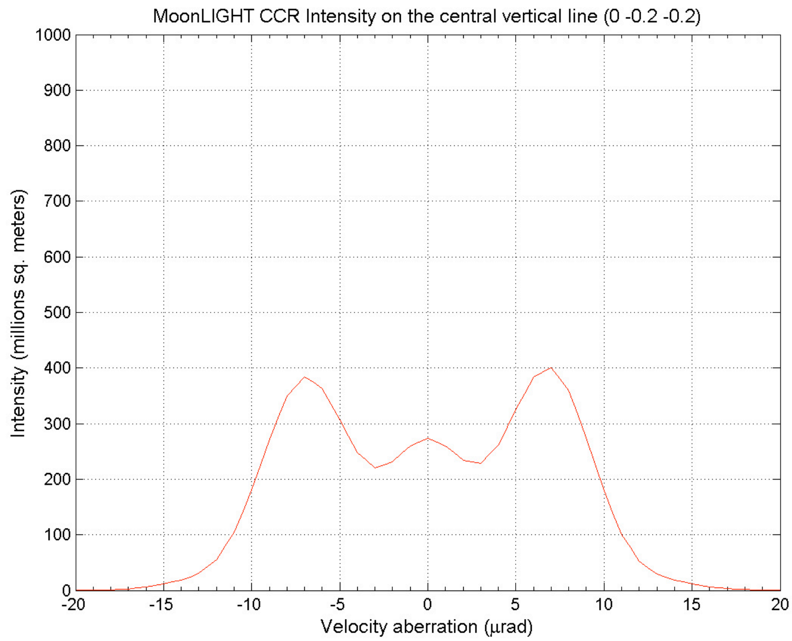


Figure UMCP-4

This is the far field diffraction pattern for the 0.0, -0.2, -0.2 configuration in the above table. Note the strong return for the offset position defined by the velocity aberration.

c) Mitigation of Effect of Lunar Day/Night Thermal Variation on Optical Performance

i) Simulation and Optimization of Figuring the Front Face of CCR

The effects of figuring the front face of the CCR have been investigated by a simulation using Code 5. In particular, the Far Field Diffraction Patterns (FFDP) for a spherical curvature of the front face have been explored for a range of spherical curvatures. In particular, the magnitude of the wave front curvature is defined by the difference in phase between the phase at the center and the phase at the edge. These values range from plus one wavelength to minus one wavelength. The primary effect of this simulated figuring is to produce a spherical wave front, which in turn produces a focusing of the return beam. This is the same optical distortion as the first order effect of the thermal distortion caused by the absorption of the solar radiation within the CCR. Thus this figuring will be used to optimize the signal return between the day and night.

ii) Effect of Tolerancing Combined Simulation with Velocity Aberration Correction

This item has not yet been address within the first year. It was felt that certain other items (addressed below) were more important to understand at this time. These items were:

1) Evaluation of multiple IR shields to control pocket radiation. We have purchased the IR shields and will test them in April 2010. Therefore, we needed to develop the simulations to define the parameters of the thermal vacuum test. These simulations will also be used to compare to the results of the test.

2) Create and Implement a Plan for Test Concepts for Drilling into Regolith with a simulated housing of the CCR. This was an items in the SoW for year 2. Initial tests have been performed at the laboratory of Honeywell and at the NASA/CSA/DRL 2010 Mauna Kea Lunar Analog Test Program.

3) Address the mitigation of the dust on the CCR due to electrostatically lifted dust.

d) ***Further Computer Simulation - esp. of SCF Tests***

i) Detailed Simulation of Thermal Vacuum Chamber Tests

The "ideal" configuration of the thermal vacuum test in the SCF at INFN-LNF in Frascati, Italy that was conducted during April 2009 has been has been simulated using Thermal Desktop. This simulation addresses the expected performance of the CCR in the presence of the LN2 walls of the chamber, the warm entrance window for the solar simulator and the limited accuracy of the solar simulation.

(1) Warm and Hot Front Entrance Window with Control of Window Temperature

To address issues of the front entrance window, the window has been equipped with thermocouples to determine the temperature of the window and a coil for circulating water to control the temperature. Thus one can keep the window at a known fixed temperature

(2) Effect of Relatively Warm (LN2) Chamber Walls w.r.t. Cold Space

This effect has been addressed and is negligible for our current series of tests

(3) Results of Absorption of Simulator Lens and Front Window

The window on the solar simulator and the optics of the solar simulator absorbs most of the infrared radiation. Although the former is fabricated of a variety of fused silica that transmits extended infrared radiation, it still cuts off before the solar radiation becomes negligible. Thus the accuracy of the solar simulation is not as good as we might wish. On the other hand, the infrared radiation is absorbed on the front surface of the CCR and does not penetrate to the interior of the CCR. This heat is radiated out to space and thus does not, to first order, contribute to the temperature gradient in the CCR and thus to the optical distortion.

(4) Impact on Comparison of Simulation and Testing

Due to technical difficulties, the April 2009 test was not conducted in a manner to achieve an equilibrium thermal state in a manner that matched an achievable simulation. Thus only a rough comparison has been made between the simulation and the test observations. It is expected that the March 2010 tests will allow a better comparison.

e) ***Define Drilling Requirements***

In order to address the drilling requirements, the regolith has been simulated and the effect of the thermal blanket on the temperatures of the regolith below the CCR and around the support rod has been simulated in Thermal Desktop. Using this, the temperature changes of the INVAR support rod have been computed and the resultant vertical motion of the CCR during a lunation has been determined. When combined with the design of a compensation procedure within the CCR housing, the resultant motion of the CCR through a lunation is about ten microns. This is based upon a meter drill depth.

The following are item that were not included in the SoW for the first year. In general, these were expected to be address in years 2 and 3.

f) Evaluation of Multiple IR shields to Control Pocket Radiation

With the proper design of the housing, one of the main contributors to the thermal gradients that distorts the optical performance of the CCR is the volumetric absorption of the solar radiation within the CCR. This radiation than transfers' thermal energy between the CCR and the thermal shields that protect the CCR. In this section, we address the advantages of the thermal shields. Such an evaluation must include:

- CCR Volumetric absorption
- Conductive heat flow from the mechanical interfaces (KEL-F rings)
- IR Radiation from the housing/IR shields

Experience from the Apollo era demonstrated that to maximize performances of reflectors, the heat flow from the hardware must be limited as much as possible because, in principle, at steady state it must be radiated toward space from CCR entrance face, generating an axial thermal gradient.

For the above reason the design of the LLRRA-21 experiment at this stage allows the mounting of up to two IR shields, to prevent the infrared radiation from the sun and the regolith to pass between the CCR and the pocket, that is, the thermal shields lining the pocket.

To evaluate effectiveness of using more than one shield a simple model has been prepared. In the model the CCR is made with a cone and the infrared radiation on the CCR has been "simulated" by directly applying a heat load on one half of the external housing. This is to check for some radial induced thermal gradient in the set up that would occur during sunrise or sunset. This is the time when the nominal sun radiation on the housing is maximum. No volumetric absorption load is considered in this model.

Results are shown in the following tables, where the case of having no infrared shield has been added to check the performance of the model.

	Mean T [K]	Heat from CCR [W]	Heat from inner shield [W]	Heat from outer shield [W]	Heat from housing [W]	Thermal gradient [K]
CCR	115	-	inactive	inactive	**0.063324**	0.3
inner shield	inactive	inactive	-	inactive	inactive	-
outer shield	inactive	inactive	inactive	inactive	inactive	-
housing	199	**-0.063324**	inactive	inactive	-	-

Table 1 CCR assembly heat loads – no IR shield case

	Mean T [K]	Heat from CCR [W]	Heat from inner shield [W]	Heat from outer shield [W]	Heat from housing [W]	Thermal gradient [K]
CCR	88	-	**0.020943**	inactive	0.000889	0.1
inner shield	160	**-0.020943**	-	inactive	0.021039	-
outer shield	inactive	inactive	inactive	inactive	inactive	-
housing	201	- 0.000889	-0.021039	inactive	-	-

Table 1 CCR assembly heat loads – one IR shield case

	Mean T [K]	Heat from CCR [W]	Heat from inner shield [W]	Heat from outer shield [W]	Heat from housing [W]	Thermal gradient [K]
CCR	80	-	**0.013945**	0	0	0.06
inner shield	145	**- 0.013945**	-	0.012700	0	-
outer shield	182	0	-0.012700	-	0.012827	-
housing	201	0	0	- 0.012827	-	-

Table 6 CCR assembly heat loads – two IR shields case

Data of the radiating heat on the assembly components are quite representative of what will be the real situation on the various assembly components (at fixed housing temperature); whilst the gradient induced in the CCR must be considered only for reference to evaluate contribution of infrared radiation.

In the future this analysis can be extended to the orbital case, but some work is required since such option is not ready to use in the Thermal Desktop software.

g) Create Plan for Test Concepts for Drilling into Regolith and Deploying CCR and Housing

One of the tasks for the second year is to address the drilling problem with tests.

We have had the opportunity to address this task during the first year. If the CCR were placed directly on the lunar regolith, as was the case of the Apollo arrays, there would be a very significant error in the range due to the heating and cooling of the regolith during a lunation. This causes a mechanical expansion and contraction of the regolith. In order to remove this source of ranging error one must provide a mechanical anchor to the layer of the regolith which has no significant temperature variation through a lunation or through a year. This requires drilling to 0.7 to 1.0 meters and anchoring the support rod at this depth. Although similar drilling was accomplished during the Apollo landings, this was not an easy task. However, the discovery of a new drilling technology makes it appear feasible not only to effectively deploy the LLRRA-21 during a manned landing but also to deploy it from a lander or on a rover mission. On the initial review, the technology of pneumatic drilling appears to be feasible for the deployment. In order to address this further, a test was conducted at the Honeybee laboratories in a compacted lunar stimulant and a CCR housing. This test was entirely successful. Based upon these results, tests were scheduled for the NASA/CSA/DLR 2010 Mauna Kea Lunar Analog Tests in Hawaii, conducted the first week in February 2010. These tests consisted of using the CCR support rod as the pneumatic drilling mechanism with the CCR housing and the CCR mounted in the appropriate configuration. These tests again were entirely successful. Without the gas flowing, an average force of 80 pounds with peaks as large as 100 pounds were required to force the support rod to a depth of one meter. With the gas flowing, the weight of the CCR and housing was enough to cause the support rod to descend into the dry volcanic regolith with no addition force. Thus the use of pneumatic drilling, at the current stage, appears to provide a quite feasible procedure for the deployment of the LLRRA-21.

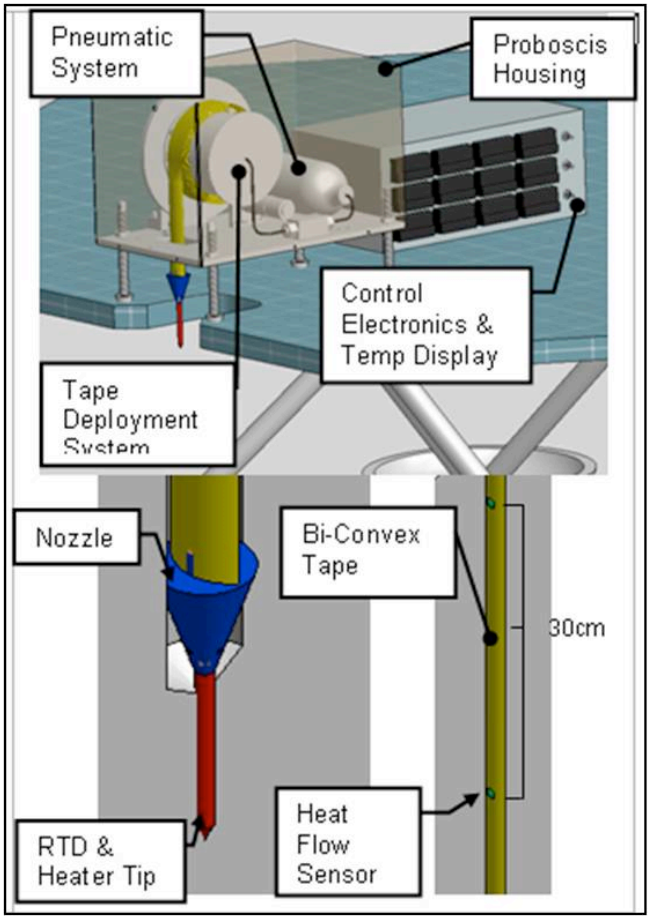


Figure UMCP-5

h) Dust Mitigation

Measurements by the APOLLO ground station in New Mexico strongly suggest that the Apollo arrays have received a layer of dust that reduces the signal by a factor of almost ten. This is addressed in more detail in the above discussion by Tom Murphy. The analysis of the LLRRA-21 signal strength has also included such a loss so that the signal magnitude will still be appropriate. That is, even assuming the deposition of a similar dust layer, the LLRRA-21 signal level will be over half of the signal from Apollo 11 array. The latter has provided suitable return for 90-95% of the time that it is targeted by the APOLLO station. However, if we can prevent or reduce the dust accumulation, we may expect a much stronger signal. To this end, we have reviewed some of the current suggestions for the mitigating of dust deposits. All of these require power and/or mechanisms in some form, which means that a lifetime that has been achieved with the

Apollo arrays (40 years) cannot be expected. To this end, we are investigating a technique that will require neither power nor moving mechanisms. Parts have been ordered and received to build a prototype for a very preliminary test. Initially, this will be tested with a stimulant of the lunar dust. Following these tests, the prototype will be evaluated in a test conducted in collaboration with Professor Larry Taylor of the University of Tennessee using real lunar dust (as opposed to a stimulant).

i) Mitigation of the Reduction in Signal for Apollo Arrays at Local Noon

The APOLLO ranging has also detected another anomaly in the magnitude of the return signal for the Apollo arrays. When the sun is directly overhead, the signal is reduced further. This is addressed in more detail in the above discussion by Tom Murphy. As with the dust, if we can mitigate this effect, we would obtain stronger signals so that the lunar ranging could be accomplished by lunar laser ranging stations using a much smaller telescope. To address this, we have accomplished some of the preliminary thermal simulations of the current candidate for the effect. We also expect to conduct thermal vacuum tests that will also address this issue.

Assessment of Other Astrophysics Enabled by a Return to the Moon

Additional potential concepts for lunar-based astrophysics were assessed, via a small grants program. LUNAR solicited the astrophysics community for new ideas for lunar-based telescopes in the Fall of 2009. This call requested the following types of proposals:

- Theory: Theoretical studies as relate to possible astrophysical observations enabled by a return to the moon.
- Instrumentation: Studies to develop instruments which could be used for lunar astrophysical observatories.
- Concept Studies: development of concepts for astrophysical observatories.

Proposals were peer reviewed for potential yearlong subcontracts. Three projects were selected for funding:

1. **Scalable Superconductor Bearing System for Lunar Telescopes and Instruments: Design and Proof of Concept**

PI: Peter C. Chen, Lightweight Telescopes, Inc.

Abstract:

We propose to design and build a demonstration model of a two-axis instrument pointing system using high temperature superconductor (HTS) bearings. Unlike previous designs, this new configuration is simple and easy to implement. Most importantly, it can be scaled to accommodate instruments ranging in size from decimeters (laser comm systems) to meters (solar panels, communication dishes, optical telescopes, optical interferometers) to decameters and beyond (VLA type radio interferometer elements). We propose to study the details and characteristics of the mount structure and investigate its operational parameters and limiting factors when used on the Moon.

2. Material Development and Characterization for Instruments, Support Structures, and Large Aperture Astrophysical Observatories on the Moon

PI: **Paul Lowman, NASA Goddard Space Flight Center**

Abstract:

We propose to study a newly discovered material that shows promise as a building block for infrastructures and instrument support and perhaps as an enabling factor for future large astrophysical observatories on the Moon and in space. Our group has developed a material that uses lunar regolith to make a substance that is demonstrably harder than concrete. The fabrication process is simple, does not require water, and can take place under lunar conditions of vacuum and radiation. Preliminary tests suggest that the substance may be very stable, leading to the possibility of future *in situ* fabrication of large telescopes and radio interferometers. We propose to study how the properties of this 'lunar concrete' can be quantified and optimized, by changing the proportions of the ingredients and measuring the corresponding changes in the Young's modulus, Poisson ratio, shear modulus, and ultimate tensile strength. Measurements are also to be made of samples kept under vacuum and cooled by liquid nitrogen to simulate lunar exposure. Sets of samples are to be made using the standard JSC1-AC lunar regolith simulant as well as a newly developed high fidelity simulant.

3. **Lunar Occultation Observer (LOCO)**

PI: Richard S. Miller, University of Alabama, Huntsville

Abstract:

The Lunar Occultation Observer (LOCO) is a new gamma-ray astrophysics mission concept being developed to probe the nuclear regime (~0.02-10 MeV). It will perform an all-sky survey of the Cosmos, and will the have capability to address multiple high-priority science goals. Placed into lunar orbit, LOCO will utilize the Moon's unique environment to maximize performance relative to terrestrial endeavors. Specifically, LOCO will use the Moon to occult astrophysical sources as they rise and set along the lunar limb. The encoded temporal modulation will then be used to image the sky and enable spectroscopic, time-variability, point- & extended-source analyses. This approach enables the excellent flux sensitivity, position, and energy resolution required of the next-generation nuclear astrophysics mission. In addition, occultation imaging eliminates the need for complex, position sensitive detectors. The LOCO concept is cost effective, and has a relatively straightforward and scalable implementation.

The LUNAR team is also now coordinating the yearly science symposium as specified in our original proposal. This will include the 3 funded research teams, who will report on their progress at this symposium. The symposium is tentatively being scheduled for the early fall in Boulder, Colorado.

Education Public Outreach (EPO)

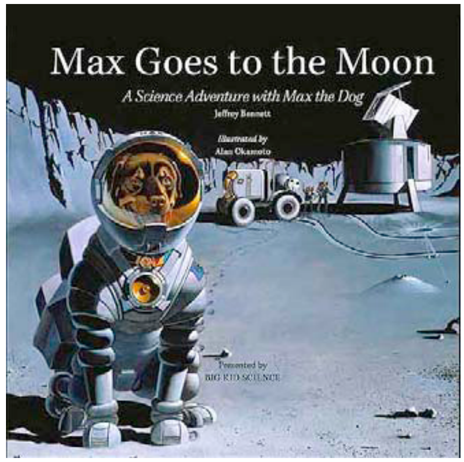
As part of LUNAR EPO we proposed to produce two planetarium programs. The first planetarium show is designed for adults and will reprise the history of the Apollo explorations of the moon and then focus on the science to be done by NLSI teams. The second, "Max Goes to the Moon," is designed for kindergarten through fifth grade students.

Because of the uncertainty of how and when we will return to the moon, we decided it would make sense to produce the children's planetarium show first, and the adult program next year, when it is more clear what NASA's plans will look like. (The children's program doesn't go into such specific details as the adult program.)

We have a complete first draft script for, "Max Goes to the Moon." The show will teach:

- The moon is a world just like the earth is a world, even though the moon has no air or liquid water.
- Humans went there once. Those people – astronauts – were welcomed as heroes by people all over the earth.
- An approximate idea of how distant the moon is from the earth. (Compared, for instance, to how far the space shuttle flies.)
- An idea of what it would be like to be on the moon: low gravity (all the fun things you might do as a kid if you could jump around on the moon), no air (the need to wear a spacesuit and bring food and water.)
- The moon shows phases as seen from the Earth; students and their parents can observe these in the sky and explain what causes them.

The plot of the show is based on the award-winning book, "Max goes to the moon.”



Max, a real dog belonging to author and scriptwriter Jeff Bennett, helps make tangible to children the story line of preparations needed for going to the moon. A nice touch is the idea that Max’s first lunar paw print will be preserved just like Armstrong's first lunar footprint.

The show will incorporate two breaks in which students will perform activities. One is shown in the first photograph. Students will learn the cause of moon phases by each using a Styrofoam moon on a stick.

Fiske staffs began interviewing for the various voice parts in January 2009 and have identified the person to be hired as the main narrator.

The 2009 management plan called for the first planetarium show to have the draft script finished by the end of October 2009. We are approximately 2 months behind that schedule.

To draw attention to the LCROSS impact and science we held a “Lunar Bagel Breakfast” with food sponsored by Moe’s Bagels. More than 200 people filled the Fiske Planetarium theater, where we broadcast NASA select TV, and others were in the lobby. (See Fig. 3). LUNAR scientists such as Dr. Jack Burns provided commentary. We arranged for good local newspaper and TV coverage, and Fiske Director Duncan also appeared on the NBC national news.

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