The Lunar University Network for Astrophysics Research (LUNAR)
2010 Annual Report to NLSI/NASA

March 1st 2011

Table of Contents:

- **Executive Summary** *(page 2)*
- **Low Frequency Cosmology and Astrophysics** *(page 10)*
  - **(DARE) Dark Ages Radio Explorer** *(page 22)*
- **Radio Heliophysics** *(page 28)*
- **Gravitational Structure and Lunar Laser Ranging** *(page 42)*
- **LUNAR Workshop. "Robotic Science From the Moon: Gravitational Physics, Heliophysics and Cosmology"** *(page 54)*
- **Education and Public Outreach** *(page 55)*
- **Publications and Colloquia** *(page 59)*

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, outreach, and community development to advance *Science 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, alternative models of gravity, and core of the Moon. 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 unites 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: This project 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 of the hydrogen signal from the Dark Ages. 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 conceivable by a low radio frequency telescope on the farside of the Moon (Figure 1).

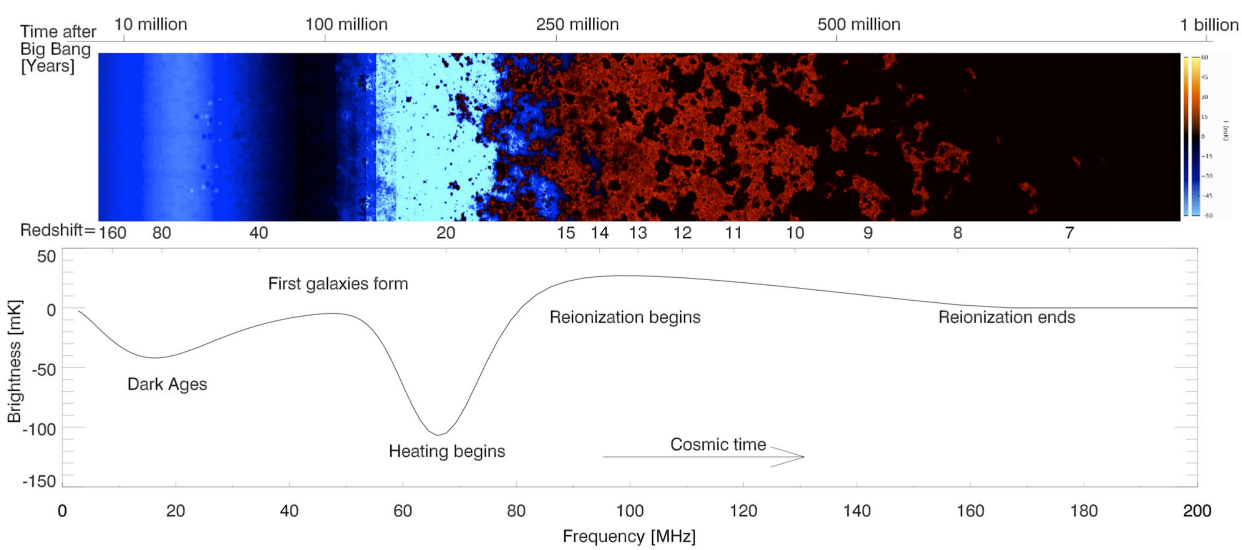


Figure 1: *Modeling by* ***Pritchard*** *and* ***Loeb*** *show the turning points of the Universe by tracing*

the 21cm signal from the hyperfine transition of hydrogen.

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 simulations, laboratory experiments to simulate the harsh conditions with which antennas will experience on the Moon, and testing how well the antennas can detect the hydrogen signal.

Theoretical Tools: Over the past year we have collectively been studying the "Epoch of Reionization". Most of this work is focused on developing models to help constrain the unexplored periods between Reionization and the Dark Ages. A Fisher matrix formalization for calculating the sensitivity of such instruments to the 21cm signal from Reionization and the Dark Ages has been developed. We also developed a parameterization of the 21cm global signal in terms of frequency and amplitude of key turning points in the sky-averaged signal, which correspond to key moments in history of the Universe such as the beginning of star formation or X-ray heating from the first accreting black holes. Simulating X-ray heating is very important to understanding the radiative feedback that dictate the time scales of the epochs of Reionization and the Dark Ages. In a continuation of work from year one, the 21cmFAST semi-numeric code, which can predict the 21cm hydrogen spin-flip signal has been made available to the public and is being utilized by multiple groups to generate predictions for forthcoming telescopes. In order to physically detect the high redshift 21cm signal, understanding the bright radio foregrounds is vital to the success of any futures observations. To facilitate this, we have continued to investigate foreground subtraction algorithms as well as studying the impact on power spectrum measurements.

Array Concept & Algorithm Development: Work in Year 2 continued to solidify the requirements for the Lunar Radio Array. As new terrestrial radio telescopes come online, we are able to test some of our designs and concepts. These new observing platforms provide robust heritage (EDGES, LWA & LOFAR) from which the Lunar Radio Array will be constructed. 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: The Lunar Radio Array will require a large number of science antennas, so that high sensitivity per unit mass is a key requirement. In our second year, we have been able to move away from the design concepts to fabrication and physical models to test. We have deployed a proof of concept polyimide film antenna just outside of Washington, DC. We have also moved forward on testing the polyimide film in the vacuum chamber at the University of Colorado. These stress tests of the film and associated electronics confirm that array components can survive and operate in a simulated lunar environment with a comfortable margin of safty.

Dark Ages Radio Explorer (DARE): DARE is a proposal for a lunar orbiting mission designed to track the impact of the first stars and black holes during the Dark Ages and the Cosmic Dawn of the Universe (Figure 2).

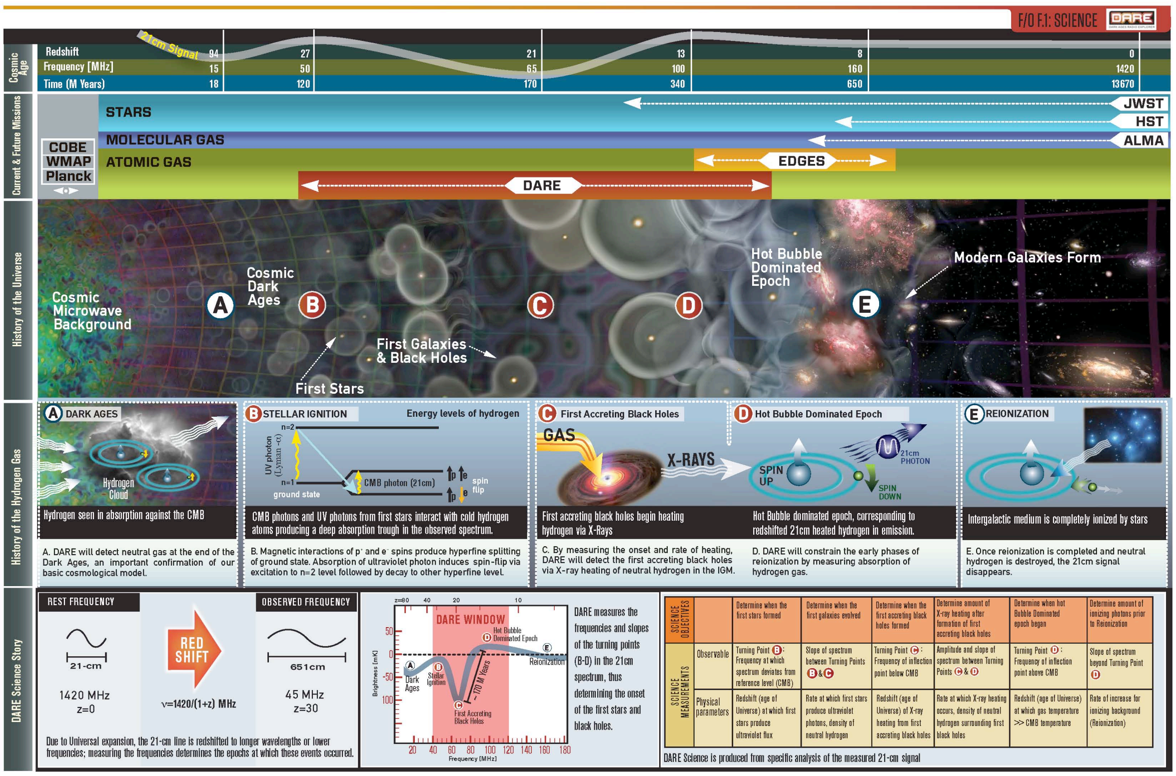


__Figure 2:__ This diagram conveys the scientific case for designing DARE to observe the Dark Ages from the farside of the Moon.

DARE will provide an important confirmation of our basic cosmological model, and the first indirect evidence of the earliest objects to illuminate the cosmos. DARE will answer two fundamental questions identified in the recent Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*: **What are the first object to light up the Universe, and when did they do it?** DARE accomplishes this by constructing the first sky-averaged spectrum of the hyperfine transition of neutral hydrogen at redshifts 11-35 corresponding to frequencies between 40 and 120 MHz. DARE was submitted to NASA headquarters in February, 2011 in response to the NASA Explorer AO.

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 Radio 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 (Figure 3).

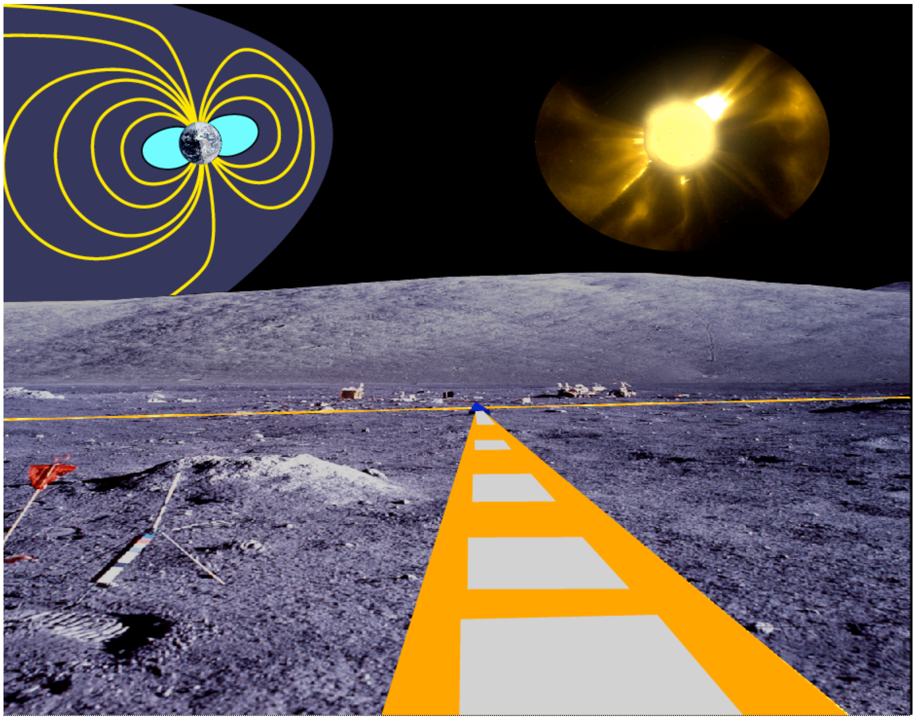


Figure 3: *This show the ROLSS concept (Radio Observatory on the Lunar Surface for Solar studies). This array would be comprises of single radio dipoles embedded within polyimide kapton film.*

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.

Radio Emission from Space: Our year two efforts use existing radio observations from spacecraft focused on DC-10MHz electric field and radio observations by the WAVES antennas on the two STEREO spacecraft. We are working on two tasks: the ability of radio receivers in space to study dust, and the use of imaging at low frequencies to detect unknown radio transients. For our dust study, we examined high resolution time series of changes in the electric field near a spacecraft produced by plasma generated by the impact of dust particles. Our results, submitted for publication in the Planetary and Space Sciences journal, show that radio receivers may be used to measure the flux of dust from nanometer to micron sizes. In particular, we believe we have made the most accurate measurements of micron-sized dust from interstellar space to date. Based on our results, we showed how small changes to the design of lunar radio arrays would enable them to conduct fundamental studies of the science of interplanetary and interstellar dust.

Designing a Solar Imaging Radio Array: A key goal of the Radio Heliophysics effort is to optimize the design of a lunar surface solar imaging radio array. For this task, we are using software and observations from the Murchison Widefield Array, a low frequency radio array in Western Australia that is a useful analog for the performance we would achieve at lower frequencies with a lunar array. We have successfully observed and imaged solar radio bursts at low frequencies with the MWA, and are now using these data to simulate lunar observations at lower frequencies.

Technology Development for a Lunar Radio Array: In year two, the technology development portion of the Radio Heliophysics effort focused on advancing the readiness of our proposed Radio Observatory on the Lunar Surface for Solar studies (ROLSS). The ROLSS concept uses dipole antennas deposited on rolls of Kapton® film, which would be compactly stored for flight and easily deployed on the lunar surface by unrolling. Recently, the effort has focused on three areas. An analog-digital converter was tested to -250° C as the introduction to placing active components on the Kapton film to provide pre-amplification of the signal at the antennas. A pathfinder concept to test the ROLSS antenna-film system on the lunar surface was developed and the first version of the design was built and tested successfully. Finally, ROLSS was presented in various talks and papers, including a white paper to the NASA Heliophysics Decadal Survey and a submission to the Proceedings of Planetary Radio Emissions VII.

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 LLR team of the LUNAR group has been addressing the design, fabrication and emplacement of the next generation of retro-reflectors for the Moon (Figure 4).

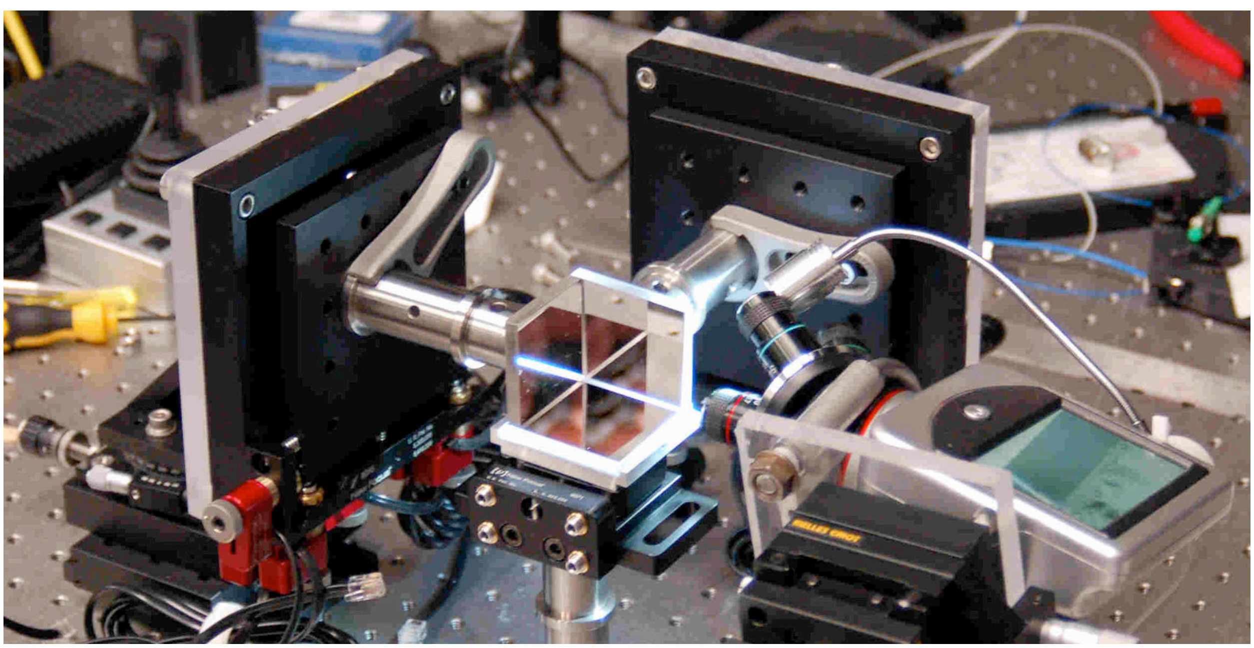


Figure 4: *This is one of our next generations of Corner Cube Reflectors CCR to help constrain our distance measurements from the Earth to the Moon.*

These can improve the accuracy, and thus the impact of the measurement of GR science, by a factor of more than 100.

From the previous year's testing of commercial hollow corner cubes, it was concluded that the currently available cubes are unlikely to perform well when scaled up to the size required for new lunar retro-reflectors. Therefore, efforts were focused on developing in-house capabilities for assembling hollow cubes using a technique known as hydroxide-catalysis bonding.

The once lost Russian lunar over Lunokhod 1 was found by the Lunar Reconnaissance Orbiter (LRO). This rover was installed with retro-reflectors different from those deployed by Apollo Astronauts. The Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) was able to use the reflectors of Lunokhod 1 to further refine our distance measurements to the Moon and help constrain theories about the structure of the lunar interior.

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 Spring of 2010. This call requested the following types of proposals:

- *Instrumentation*: The development of prototype instruments, which could potentially be used for lunar astrophysical observations.
- *Concept Studies:* The development of concepts for astrophysical observatories.
- *Technology Development*: The advancement of technologies that will be required for future lunar based telescopes.
- *Theory*: The study of possible astrophysical observations in the lunar environment from a theoretical perspective.

Proposals were peer-reviewed for potential yearlong subcontracts. The following project was selected for funding: "Development and Testing of the Light Weight LLRRA-21 Emplacement System"; Principle investigator Kris Zancy, PhD, Honeybee Robotics. The goal of this project is to design and fabricate a pneumatic drill system and to test it under realistic conditions for lunar laser ranging deployment (~1m penetration in compacted lunar regolith simulant, and vacuum). This effort will include the evaluation of a system to assure that the deployment is vertical and that it maintains an accurate azimuthal orientation. In addition, this project will evaluate structure of the dust cloud raised by the gas during drilling, the ballistic behavior of the dust particles in vacuum, and the design and testing of dust covers.

Robotic Science From the Moon Workshop: On October 5th and 6th 2010, LUNAR hosted its first national, interdisciplinary workshop in Boulder, CO with over 60 registered participants. The workshop discussed robotic science from the Moon that could be conducted over the next decade in the areas of gravitational physics, heliophysics, and cosmology. The workshop was co-sponsored by the NLSI, Lockheed-Martin Corporation and Ball Aerospace

Corporation.

Domestic and International partnerships: Over the past two years the LUNAR team has begun collaborations with international partners and with other NLSI funded teams.

The Low Frequency Cosmology and Astrophysics Key Project has been interacting with the Dynamic Response of the Environment At the Moon (DREAM) team led by Dr. Bill Farrell. Most notably, LUNAR has collaborated with DREAM on the science case for a future lunar radio telescope, and on the impact of the lunar environment on future lunar radio telescope antennas.

One of the suggestions for the reduction in the return signal of the Apollo lunar laser ranging stations is the possibility that high velocity dust particles have pitted the surface. To evaluate this, LUNAR members have begun collaborating with the Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS) team led by Dr. Mihaly Horanyi on a "dust accelerator" to reproduce surface weathering in the laboratory.

Over the past two years, there has been a continuing close collaboration with INFN-LNF in Frascati, Italy. LUNAR members and INFN-LNF have jointly designed a thermal vacuum facility for the test and evaluation of Lunar Laser Retroreflector packages. In this INFN-LNF facility, tests of next generation lunar retroreflectors were conducted in 2010. In addition, there has been a close collaboration on thermal modeling of the retroreflectors.

In the Radio Heliophysics project, a paper describing measurements of interplanetary and interstellar dust submitted this year involved contributions from European colleagues, including the Paris Observatory in France.

Education and Public Outreach (E/PO): Year 2 consisted of running K-12 teacher workshops in conjunction with the annual Astronomical Society of the Pacific (ASP) conference in Boulder, CO. We worked with "Cosmos in the Classroom" to provide activities and teaching materials to regional K-12 teachers. We are also deep into production of our children's planetarium show, "Max Goes to the Moon", based on an award wining book by Dr. Jeff Bennett. The EPO work plan calls for us to recruit a second school to build a lunar-antenna deploying robot this year. Thanks to NLSI central, we received enough funds to support 3 schools. As of early 2011 we have a request from 3 teachers and are buying Kapton film to distribute to them along with funds for parts to build robots to model the deployment of ROLSS-like arrays. We took advantage of the December 2010 Lunar Eclipse to give talks to the general public on the Moon and eclipses. This was the largest outreach event ever hosted at Fiske Planetarium at U. Colorado, with over 1400 people in attendance (Figure 5).

Figure 5: *A picture our planetarium theater full of people to hear a talk at our outreach event celebrating the Dec. 2010 total lunar eclipse.*

Following our first annual “Robotics Science From the Moon” workshop, it was deemed important for LUNAR to design and print its own brochure for use at workshops, conferences and other EPO activities; the new brochure was distributed widely at the American Astronomical Society meeting in January, 2011.

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 has led to the anticipated work being different than what was proposed originally. For technology development, no rover development work will be executed, per NASA HQ direction.

Theoretical Tools and Science Development

Over the past year, **Pritchard** and **Loeb**, collectively and individually, studied the "Epoch of Reionization" science to be explored by the LUNAR mission (Figure 1). The details of this work help in optimizing the design of the mission for getting its best scientific yield. New research results were published in following papers:

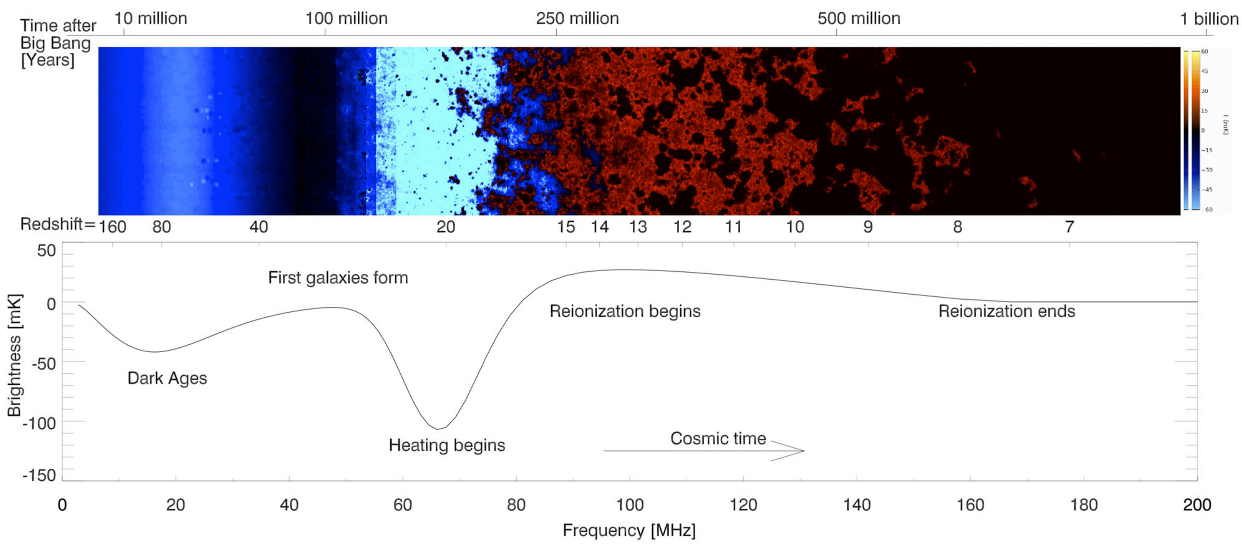


Figure 1: *Modeling by* ***Pritchard*** *and* ***Loeb*** *show the turning points of the Universe by tracing the 21cm signal from the hyperfine transition of hydrogen.*

"Constraining the Unexplored Period between Reionization and the Dark Ages with Observations of the Global 21 cm Signal" (Pritchard & Loeb): Observations of the frequency dependence of the global brightness temperature of the redshifted 21 cm line of neutral hydrogen may be possible with single dipole experiments. A Fisher matrix formalism for calculating the sensitivity of such instruments to the 21 cm signal from reionization and the dark ages has been developed. Also developed was a parametrization of the 21 cm global signal in terms of the frequency and amplitude of key turning points in the signal, which correspond to key moments in the history of the Universe such as the beginning of star formation or X-ray heating. Rapid reionization histories with duration $\Delta z < 2$ can be constrained, provided that local foregrounds can be well modeled by low order polynomials. It was then shown that observations in the frequency range of 50–100 MHz can feasibly constrain the Lyman-α and X-ray emissivity of the first stars forming at z = 15–25, provided that systematic temperature residuals can be controlled to less than 1 mK. Detecting the 21 cm signal from the dark ages before star formation is likely to be significantly more difficult.

"The Universe Was Not Ionized Abruptly" (Pritchard & Loeb): When and how the first galaxies ionized the primordial hydrogen atoms that filled the early Universe is still unknown. Observations with a single radio dipole are opening a new window on the first billion years of the Universe and providing greater exposure for the potential of future 21-cm astrophysics and cosmology observations. This was the cornerstone paper used for the scientific motivation for the Explorer proposal: Dark Ages Radio Explorer (DARE).

"Measuring the Redshift of Reionization with a Modest Array of Low-Frequency Dipoles" (Bittner & Loeb): The designs of the first generation of cosmological 21-cm observatories are split between a low-cost single dipole, which integrates over the entire sky in order to find the global (spectral) signature of reionization, and interferometers with arcminute-scale angular resolution, which aim to measure the 3D power spectrum of ionized regions during reionization. Intermediate scale instruments, such as MWA 32T, are considered and are found to be capable of placing new constraints on reionization. The global redshift of reionization can be measured from the variance in the 21-cm signal among multiple beams on large angular scales as a function of frequency, instead of the conventional approach of measuring the entire 21-cm power spectrum. The beam-to-beam variance in the differential brightness temperature peaks when the average neutral fraction was around 50%, providing a convenient flag of the redshift of reionization. A low angular resolution of order 1° is needed to exploit the physical size of the ionized regions and maximize the signal-to-noise ratio. Thermal noise, foregrounds, and instrumental effects should be manageable, as long as the u-(Fourier) coverage is complete within the compact core required for low-resolution imaging. We find that z_{reion} can potentially be detected to within a redshift uncertainty of 1 or better in 500 or more hours of integration on the existing MWA prototype (with only 32 ×16 dipoles), operating at an angular resolution of roughly 1 degree and a spectral resolution of 2.4 MHz. The prospects for such a detection are generic to similar 21-cm observatories (e.g., LOFAR) that have good u-v coverage after Earth-rotation synthesis for baselines corresponding to more than roughly 1º.

"Inflation and the Scale Dependent Spectral Index: Prospects and Strategies" (Adshead et al.): The utility of large scale structure in combination with CMB observations to improve constraints on inflationary parameters and the evolution of the very early Universe was considered, with the goal of assessing the extent to which different slow roll inflationary models can be distinguished and degeneracies with the post-inflationary equation of state can be broken. Surveying a collection of simple single field inflationary models, the magnitude of the running of the spectral index is relatively consistent, unlike the tensor amplitude, which varies by orders of magnitude. The running is potentially detectable by future large-scale structure or 21 cm observations, such as those on the Moon, but that only the most futuristic measurements can distinguish between these models on the basis of their running. For any specified inflationary scenario, the combination of the running index and unknown post-inflationary expansion history induces a theoretical uncertainty in the predicted value of the spectral index. This effect can easily dominate the statistical uncertainty with which *Planck* and its successors are expected to measure the spectral index. More positively, upcoming cosmological experiments thus provide an intriguing probe of physics between TeV and GUT scales by constraining the reheating history associated with any specified inflationary model, opening a window into the "primordial dark age" that follows the end of inflation.

"Probing the First Galaxies with the SKA" (Santos et al.): The extent to which pathfinders for the Square Kilometer Array (SKA) can constrain star formation at redshifts $z \approx 20$ from the effect of Lyman-a fluctuations on the 21 cm signal was explored. Their results are likely to affect the design of a future lunar radio telescope.

Holzbauer and **Furlanetto** have been studying inhomogeneities in the ultraviolet radiation background during the era of the first galaxies. This background is crucial for "turning on" the spin-flip background that a low-frequency lunar telescope would search for, and it is also crucial for modulating the transition from exotic (and very massive) Population III stars to their more normal descendants. They have built a new model to describe fluctuations in this background analytically. They have shown that, in the most straightforward scenarios, the backgrounds are uniform at the 10% level (Figure 6).

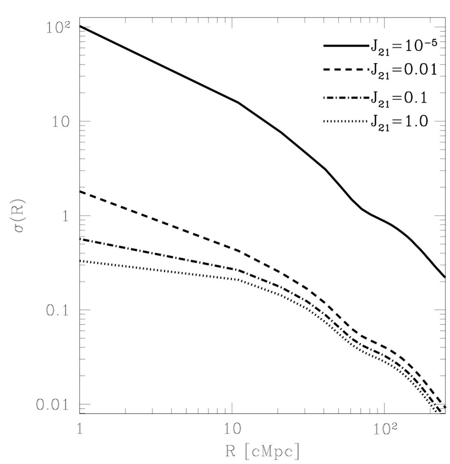


Figure 6:* *Holzbauer* *and* *Furlanetto *developed a new model looking at the relative uniformity of UV sources in the early Universe.*

This has two important implications for low-frequency telescopes. First, it means that a measurement of the *mean* intensity (through such telescopes) provides an excellent measure of the transition time between these two stellar populations across the entire Universe. Also, it means that these exotic stars are likely confined to the earliest phases of cosmic history, so that telescopes like a lunar array are essential to understand their properties. The paper will be submitted by 2011 March.

Furlanetto and **Mesinger** continued collaboration, including the further development of the 21cmFAST semi-numeric code (Figure 7).

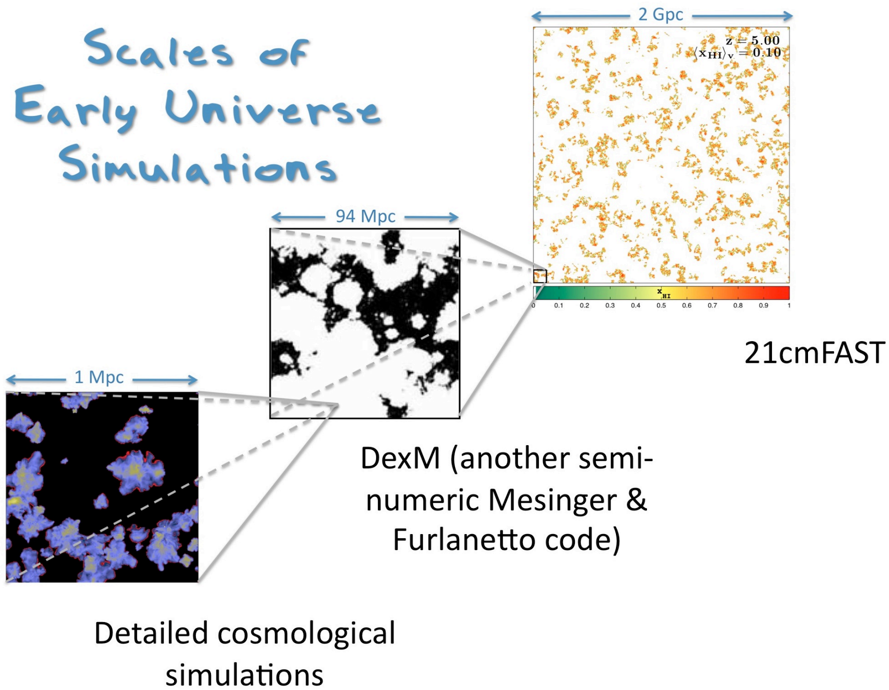


Figure 7: *This 21cm FAST semi-numeric code has been developed which can predict the 21-cm hydrogen spin-flip signal under a wide range of models.*

The code is now public and is being utilized by multiple groups to generate predictions for forthcoming telescopes. With **Crociani** (Bologna), Furlanetto and Mesinger also completed a project using these tools to study the role of recombinations in the late phases of reionization, one of the least understood aspects of that process (and hence of the spin-flip signal). The work showed that recombinations do not radically alter the topology of the intergalactic medium or the spin-flip signal.

Bowman, **Furlanetto**, and **Jones** organized a week-long workshop ("The First Billion Years") at the Keck Institute for Space Studies, Caltech, during 2010 August. Twenty-two researchers from nine US and international institutions attended, with broad participation from theorists, instrument builders, and observers. The focus was on radio spectral signatures of the early Universe, including those from space and the Moon, and the group worked together to develop new observational ideas. A final report from the workshop, describing scientific goals and experimental opportunities in early-epoch cosmology (EoR and earlier) will be published in early 2011. The workshop site http://www.kiss.caltech.edu/workshops/billion2010/ contains links to several of the presentations (Figure 8).

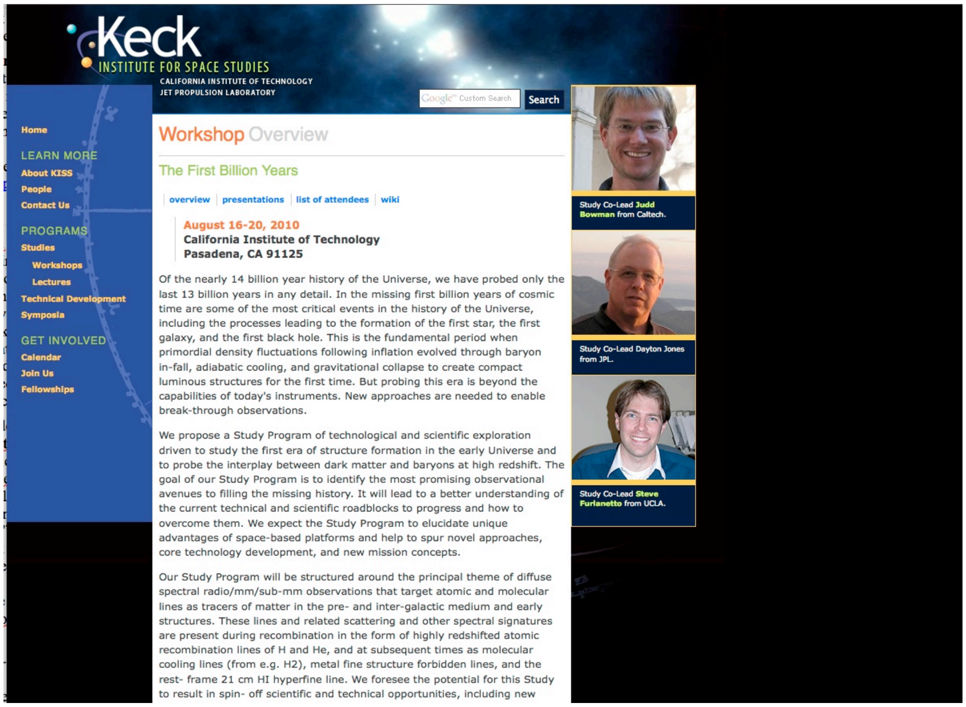


Figure 8: *This image represents the efforts made my LUNAR collaborators to run a week-long workshop called "The First Billion Years".*

LUNAR Postdoctoral Fellow **Harker** continued to investigate foreground subtraction for the LOFAR epoch of reionization experiment, studying its impact on power spectrum measurements and on imaging. The imaging regime is sometimes neglected for first-generation epoch of reionization arrays, since the low signal-to-noise ratio implies that only a very low resolution can be achieved. The 21-cm signal contains structures on extremely large scales, however, and so images potentially contain valuable information. The simple treatment of the instrument response using previous work has been made more realistic by incorporating the effects of a realistic, frequency-dependent primary beam and *u*-*v* coverage, and the large-scale signal simulations using the code developed by Mesinger & Furlanetto have replaced the earlier simulations with more limited dynamic range. The methods developed for LOFAR extend naturally to the lower frequencies that could be probed by a lunar array.

In the past year, graduate student **Mirocha**, under the supervision of **Burns** and in collaboration with **Hallman** and **Furlanetto**, has developed capabilities to more realistically create populations of active galactic nuclei (AGN) in large-scale cosmological simulations, while studying in detail the radiative feedback from individual X-ray sources and their impact on the highly redshifted 21-cm signal from the Dark Ages and Epoch of Reionization (Figure 9).

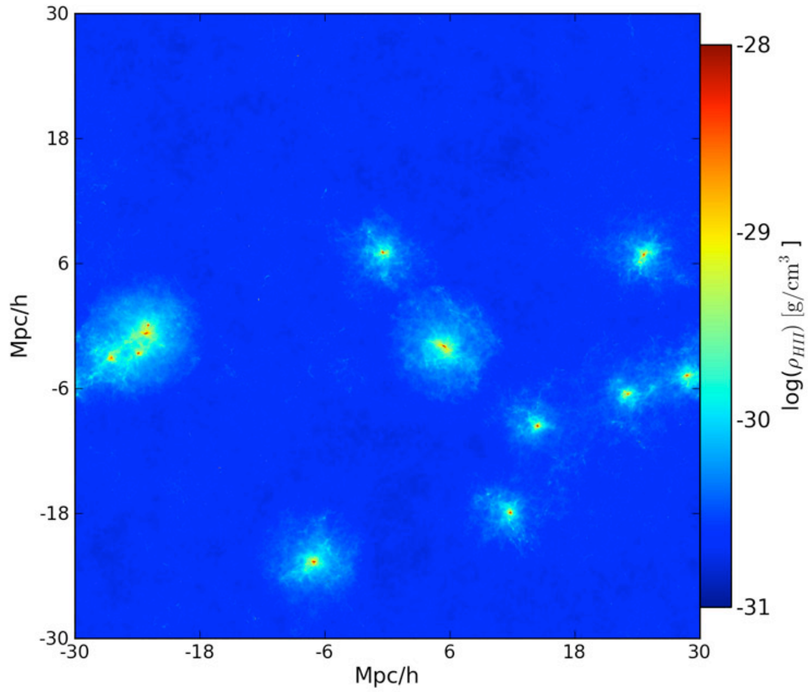


Figure 9: *This is a snapshot of the Enzo code showing the radiative transfer of X-ray emission in the early Universe.*

In order to study the effects of X-ray heating on the 21-cm signal, past authors have often formed all AGN in the simulation volume in a “burst” at a single redshift. Now, having integrated the capabilities of an inline friends-of-friends dark matter halo finder with new radiative transfer modules in the cosmological code Enzo, these simulations can generate a population of AGN that evolve naturally in tandem with the dark matter density field. X-ray emission from these AGN is propagated using an adaptive ray-tracing algorithm and is coupled to the hydrodynamics and chemistry solvers within Enzo, allowing the study the resultant heating and ionization (and thus 21-cm signal) in detail.

In order to refine these large-scale simulations and reflect recent work in the area of radiative feedback, focus has shifted temporarily to high-resolution simulations of individual X-ray sources. Simulations by other groups have hinted at the possibility of an early bottleneck in black hole growth due to negative radiative feedback, which may have a unique impact on the 21-cm signal. This work is in its early phases and is focusing on the environments surrounding Population III stars and their remnant black holes, with a particular emphasis on the resultant 21-cm profiles. Progress continues in this area with the goal of a publication in 2011, followed by adaptation to larger cosmological volumes capable of addressing the impact of X-ray heating on global 21cm measurements.

Most recently, Mirocha has performed 1D radiative transfer calculations to study the consequences of poor frequency resolution in the spectra of UV and X-ray sources in radiation-hydrodynamical simulations. The results of this work will allow for more accurate determinations of the neutral hydrogen spin temperature, and ensure that synthetic 21-cm observations are actually representative of the underlying models assumed. This work will be ready for publication in the next 6 months. Postdoctoral researcher **Skory** will collaborate with Mirocha on simulations of X-ray heating.

Burns has been studying the acceleration of electrons at shock fronts thought to be responsible for radio relics, extended radio features in the vicinity of merging galaxy clusters. By combining high-resolution Adaptive Mesh Refinement Hydro/N-body cosmological simulations with an accurate shock-finding algorithm and a model for electron acceleration, the expected synchrotron emission resulting from cosmological structure formation was calculated. From these simulations, radio, Sunyaev-Zel'dovich effect (SZE) and X-ray images for a large sample of galaxy clusters along with radio luminosity functions and scaling relationships were produced. Upcoming radio arrays, including a future lunar farside radio telescope, should detect an abundance of radio emission associated with merger shocks in the intracluster medium. By producing observationally motivated statistics, predictions have been developed that can be compared with observations to further our understanding of electron shock acceleration and kinematic structure of galaxy clusters.

Lazio was involved in developing further related aspects of the science case for a future lunar radio telescope, work that resulted in two publications. In the first, he and ***Farrell*** (NLSI DREAM team) reported on observations of the planet HD 80606b. Analogous to Jupiter's decametric emissions, extrasolar giant planets should produce intense radio emissions as a result of an interaction between the planet's magnetic field and the host star's stellar wind. Although their results are upper limits, continued observations of this planet at optical wavelengths now provide information about the planet's rotation rate so that a robust estimate can be made of the characteristic emission frequency from this planet. In contrast, for essentially all other extrasolar planets, assumptions must be made about their rotation rates. For HD 80606b, its magnetospheric emissions should become intense below about 100 MHz, a prime region of the spectrum for a future lunar radio telescope.

Lazio was also part of a team that reported on a survey for radio transients with the Long Wavelength Development Array (LWDA) at a frequency of 74 MHz. Time-domain astronomy was recognized recently as a key science frontier discovery area in the *New Worlds, New Horizons* Decadal Survey in Astronomy & Astrophysics. The LWDA illustrated the all-sky capabilities that a dipole-based low-frequency radio telescope, such as future lunar radio telescope, can offer. While the LWDA did not detect any celestial radio transients, it did detect reflections of distant TV stations from ionized meteor trails in the upper atmosphere, emphasizing that radio frequency interference from extremely distant human-generated emissions can be problematic, even if not in the direct line of sight to the telescope. The lunar far side will be an excellent location for a future radio telescope, not only because there should be few or no human-generated transmitters there, but there would be no ionosphere off which radio signals could reflect. This work was recognized on the cover of the *Astronomical Journal* (Figure 10).

ISSN: 0004-6256

THE ASTRONOMICAL JOURNAL

Founded by B.A. Gould
1849

VOLUME 140 | 2010 December ~ No. 1860 | NUMBER 6

Published for the
American Astronomical Society
by
IOP Publishing

Figure 10: *Work done by our Deputy Director Dr. Lazio was recognized on the cover of the Astronomical Journal.*

Array Concept & Algorithm Development

Taylor continued configuration studies for arrays of dipoles in a future lunar radio telescope (Figure 11).

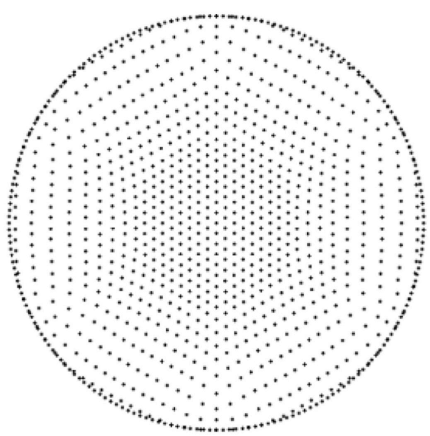


Figure 11: *This show work done to study what the optimal array configurations should be for a farside lunar radio array*

These dipoles are assumed to be distributed in a "pseudo-random" configuration that is optimized to reduce sidelobe levels. Elements are digitized to allow for independent pointings of beams and to allow for all-sky snapshot imaging. Using 919 dual polarization antennas, the beam shape is very robust against random failures of elements, but more susceptible to systematic failures.

Taylor was also involved in taking data from the first Long Wavelength Array (LWA) station, a collection of 256 dual polarization antennas located on the Plains of San Agustin in New Mexico. During Year 2, the signals from 20 antennas could be processed to generate crude images of the sky. Beam forming experiments have been conducted, and it will soon be possible to compare theoretical configurations with results obtained from a real station.

Jones studied concepts for low-mass transmission lines that could be used with passive (DALI-like) low frequency antennas on the lunar surface. Numerical analysis of field strength as a function of transmission line geometry, and of ohmic, radiation, and substrate losses, resulted in three basic conclusions: First, a balanced two-conductor geometry with square-profile conductors spaced as closely as possible is desirable; second, passive antennas operating far below resonance produce high loss due to excessive VSWR and the resulting multiple reflections along the line; and third, ohmic losses dominate for frequencies above about 10 MHz and consequently either active electronics at the antenna feed points or the use of high-temperature superconductors will be required. A passive antenna and transmission line design for ROLSS will be viable within a factor of 2–3 of antenna resonance.

Technology Development (Science Antenna)

Bradley, **Czekala**, **Klima**, and **Boyd** have fabricated a proof of concept helical antenna, furthering the development of the Self-Tending Array Node and Communication Element (STANCE) concept, first introduced under NASA Award NNX08AM30G (Figure 12).

Figure 12: *The antenna was constructed using #18 gauge copper wire supported by a dielectric framework of PVC tubing.*

Figure 13: *A low noise amplifier and a 50-to-75 W transformer were mounted inside of a weather-proof enclosure and connected to the antenna terminals from beneath the ground plane.*

This system was deployed at the Beaver Creek field station near Charlottesville, VA, where it was connected to the ORBCOMM satellite receiving system used to measure the antenna's beam pattern relative to that of the reference dipole antenna. Data were acquired, and analysis of the beam pattern is pending.

Stewart, **Hicks**, **Polisensky**, **Weiler**, **Lazio**, and **MacDowall** (*Radio Heliophysics*) deployed a proof-of-concept polyimide film antenna at a site in suburban Washington, DC. The antenna is composed of two 4-m long segments of copper-coated Kapton segments. The segments have a 1-m long taper to their feedpoints. The total length (tip-to-tip) is 8 meters, so that the resonance wavelength is 16 m (frequency of 18.75 MHz). It is connected to a receiver, previously constructed for tests of the Long Wavelength Array and which operates over the frequency range 0–30 MHz. The intent was to collect drift scan data as the sky rotated overhead; because of the emission from the Milky Way Galaxy, there should be a diurnal variation in the power levels recorded at the receiver. A total of 49 hr of data was collected between 2010 November 12 and 14. (Figure 11)

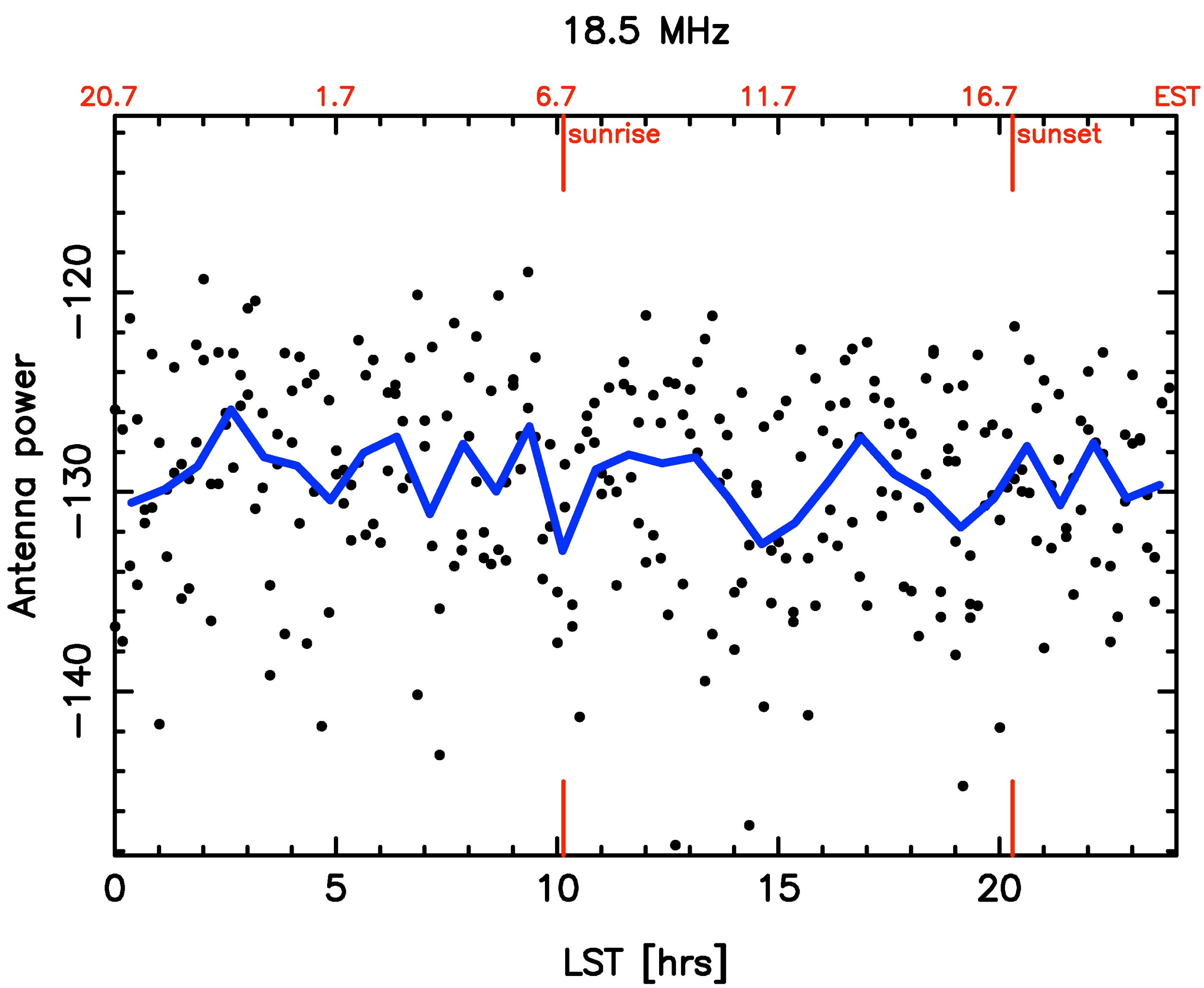
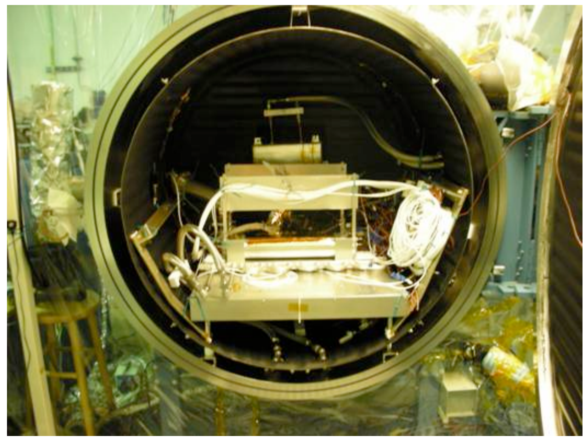


Figure 11: *Shows representative drift scans; analysis of these is continuing.*

Burns, **Kruger**, **Alfaro**, and **Lettang** are currently designing and carrying out experiments to investigate the feasibility of using Kapton, a polyimide film, as the framework for a lunar telescope array. This telescope will be placed on the far side of the Moon to study the Dark Ages of the universe, particle acceleration around Jupiter, heliophysics, and other astronomical phenomena. The telescope will be subjected to harsh conditions such as temperature variation from about −150 C to 100 C and ultraviolet radiation. The series of experiments conducted this year investigated any changes in the Kapton's properties. They performed two experiments, each lasting one month. The vacuum chamber ("lunar simulation facility") used was taken down to high vacuum (10^{-7} Torr) and cycled down to −150 C for 24 hours and then up to 100 C for 24 hours (Figures 15 and 16).



Figures 15 & 16: *(left) shows some of our undergraduate and graduate students working on our experiments outside the vacuum chamber. (right) shows the experiment inside the vacuum chamber prior to simulating the lunar environment.*

This was repeated for one month, simulating one lunar year. For the first test, a piece of Kapton was wound around an aluminum roller to model transportation of the array to the Moon. Once we lowered the temperature to −150 C, the Kapton was unrolled and left undisturbed for the rest of the test. We measured the film's temperature over the course of the experiment to determine how rapidly the Kapton would reach the ambient temperature. It cooled and heated quite slowly, as expected since it is an insulator. This result is encouraging as the dipoles embedded in the array would not be subjected to rapid temperature swings. We also measured the change in tensile strength before and after the test. It decreased by about 8%. From this first experiment, it appears that Kapton may indeed be a viable material. Results of this work were presented at the NASA Lunar Science Forum 2010 (Kruger et al.) and were awarded 3rd prize in the student paper competition at the Forum. In the second test, a Kapton (Minco) heater was used to simulate the electronics possibly associated with each dipole antenna. A constant current was run through the heater, which was monitored for any change in resistivity. The circuit is being redesigned to eliminate problems uncovered by an earlier circuit design from tests in the vacuum chamber. The heater showed no sign of de-lamination under a microscope. This experiment will be repeated during next year with the previously mentioned modifications. A "micro-rover" is also being designed that will be placed under the same conditions in the lunar simulation chamber. It will unroll the film, much as a robot on the Moon would. This experiment is intended to illustrate the challenges might arise during the Kapton's deployment.

Dark Ages Radio Explorer

The Dark Ages Radio Explorer is a proposal for a lunar orbiting mission designed to track the impact of the first stars and black holes on the neutral intergalactic medium (IGM) via the highly redshifted hyperfine (21-cm) line from hydrogen (H I). The proposal was submitted in 2011 February in response to the Explorer 2011 Announcement of Opportunity. A new and significant effort was expended by members of the LUNAR Cosmology & Astrophysics Key Project on the DARE mission proposal during this past year. The proposal team is led by LUNAR Director, **Jack Burns**, and Deputy Director, **Joseph Lazio**, as PI and Deputy PI, respectively. The DARE Science Team is composed of many LUNAR members including **Burns**, **Lazio**, S. Bale (University of California, Berkeley), **Bowman**, **Bradley**, **Carilli**, **Furlanetto**, **Harker**, **Loeb**, and **Pritchard**. The overall Project Management is at NASA/Ames Research Center, the Spacecraft project management is at Ball Aerospace in Boulder, and the Science Instrument project management is at JPL. The University of Colorado will oversee DARE Mission Operations and the Science Data Center.

The DARE Mission supports the NASA Astrophysics goal, "Discover how the Universe works, explore how the Universe began and developed into its present form…" It also addresses "How did the Universe originate and evolve to produce the galaxies, stars, and planets we see today?" DARE will provide the first direct evidence of neutral gas during the *Dark Ages*, an important confirmation of our basic cosmological model, and the first indirect evidence of the earliest objects to illuminate the cosmos. DARE's science objective addresses:

- When did the first stars form?
- When did the first accreting black holes form?
- When did the Hot Bubble Dominated Epoch and Reionization begin?
- What surprises do the end of the *Dark Ages* hold (e.g., Dark Matter decay)?

DARE will answer two fundamental questions identified in the recent Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics:* ***What were the first objects to light up the Universe, and when did they do it?*** The birth of the first stars and black holes is one of the truly transformative events in the history of the Universe.

DARE uniquely complements the efforts of the Wilkinson Microwave Anisotropy Probe (WMAP), the James Webb Space Telescope (JWST), and the Atacama Large Millimeter Array (ALMA) by bridging the nearly billion-year gap between the smooth Universe seen via the Cosmic Microwave Background and the rich web of galaxy structures imaged at more recent times.

Science Case

Developing the science case for DARE occupied the time of a number of LUNAR members, notably **Loeb**, **Furlanetto**, **Pritchard**, and **Harker**. Figures in the proposal were developed from a *Scientific American* article on the "Dark Ages" that **Loeb** published in 2006. **Pritchard** and **Harker**, in particular, developed theoretical models of the 21 cm signal for use in optimizing the basic requirements for DARE to ensure that it would return important science on the first galaxies.

DARE's proposed observations are challenging because the 21-cm signal strength is predicted to be much fainter than various foregrounds. However, DARE eliminates the most intense foreground, namely human-generated radio frequency interference (RFI). DARE orbits the

Moon for a baseline mission of 3 years and takes data above the lunar farside, the only location in the inner solar system proven to be free of RFI. The smooth frequency response and differential radiometry of DARE are effective in removing the remaining foregrounds (i.e., the Galaxy and solar system objects).

The theoretical models developed by **Pritchard** and **Harker** have been incorporated into a broader simulation pipeline designed to demonstrate DARE's ability to remove foregrounds successfully and extract the 21 cm signal, building in part on work by Pritchard & Loeb (2010). The result is that the number of model parameters has been increased to the point that Markov-Chain Monte-Carlo techniques were needed to explore the likelihood surface. In combination with extended modeling of solar system sources of radio emission from the Sun, Moon, and Jupiter, this software was used to produce predictions for the DARE proposal and provide specifications for the required integration time and scanning strategy (Figure 17). They are continuing to extend this simulation software to form a complete data pipeline for DARE.

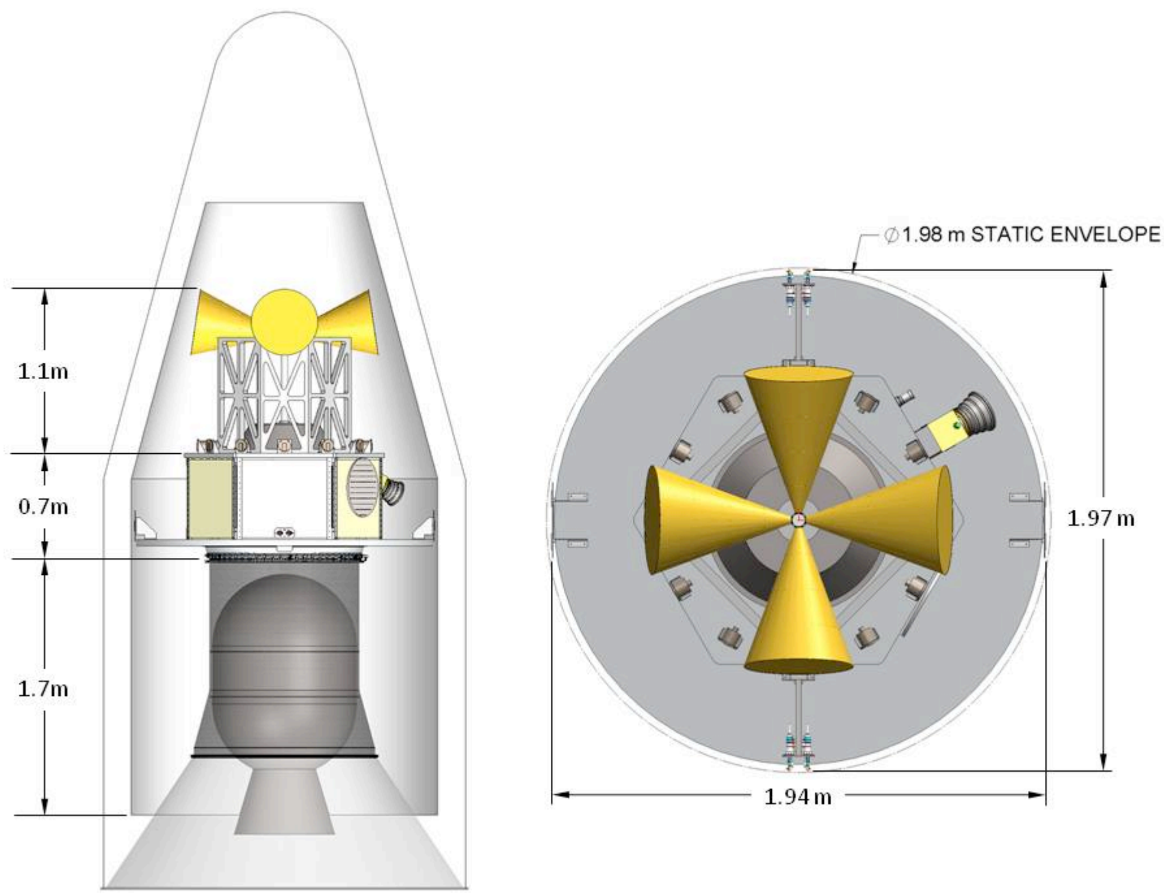


Figure 17: *(left) Shows DARE's launch configuration inside the faring of its launch vehicle and the instrument layout (right).*

In connection with DARE, **Harker** also investigated the possibility of conducting cosmic ray and neutrino science from such a satellite by detecting low-frequency radio emission caused by the Askaryan effect, but it was determined that the necessary modifications would add unacceptable cost and risk to a mission primarily designed for low-frequency cosmology.

Science Instrumentation

Members of the LUNAR team were also responsible for developing the concept for the Science Instrument for the DARE Mission. Lead members were **Bradley** and **Bowman**, with **Lazio** assisting to involve engineers from the Jet Propulsion Laboratory, which is the institution responsible for delivering the instrument (Figure 18).

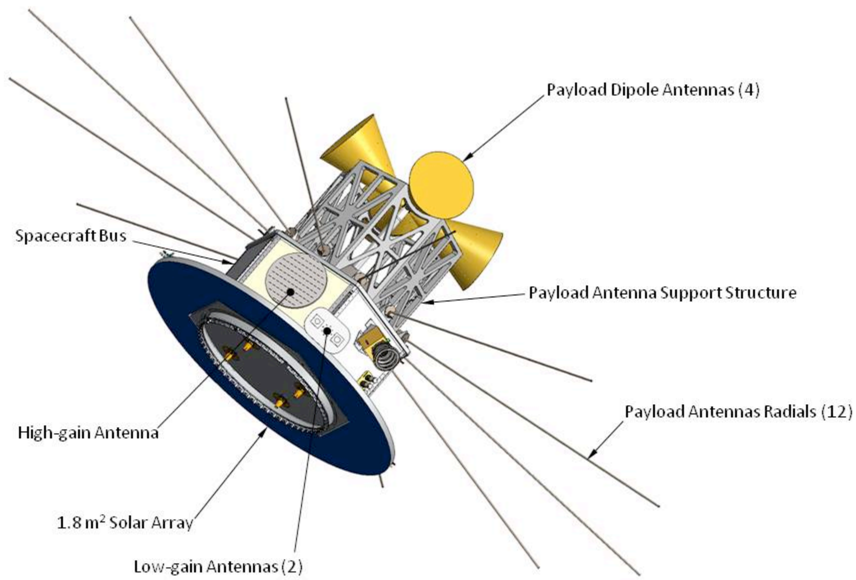


Figure 18: *This shows DARE in its operational configuration.*

The two major subsystems of the Science Instrument considered were a wide-bandwidth antenna and the receiver. While various configurations were explored to cover the 40–120 MHz band of interest, the design culminated with a pair of orthogonal, bi-conical dipoles located adjacent to a ground plane. Due to deployment constraints, the ground plane was formed by a set of metal rods emanating radially from the spacecraft bus. The electromagnetic properties of the antenna were modeled using CST Microwave Studio. The beam pattern and terminal impedance were found to be smoothly varying functions of frequency in accordance with the science requirements (Figure 19).

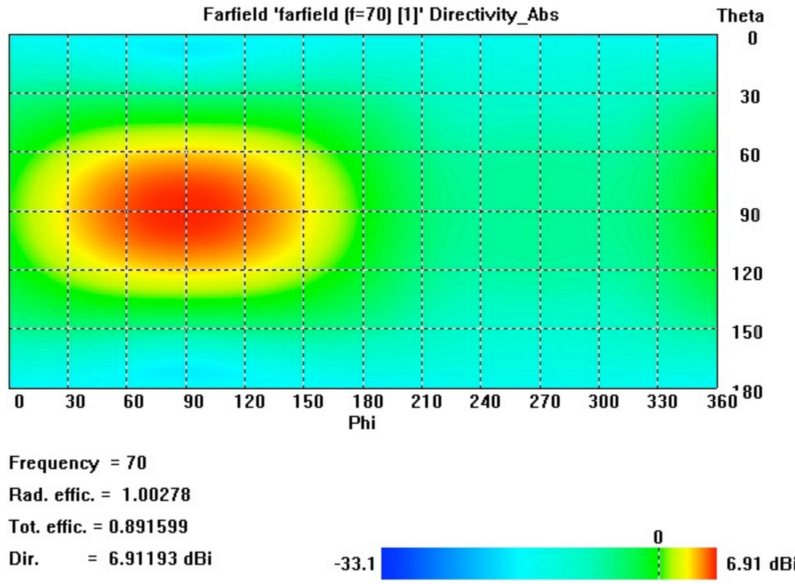


Figure 19: *Shows a typical beam pattern of the DARE instrument.*

While Figure 20 shows the terminal impedance as a function of frequency plotted on a Smith Chart. A full-scale, field evaluation model of this antenna, which will be used to verify the functional dependence of the terminal impedance, is currently under construction.

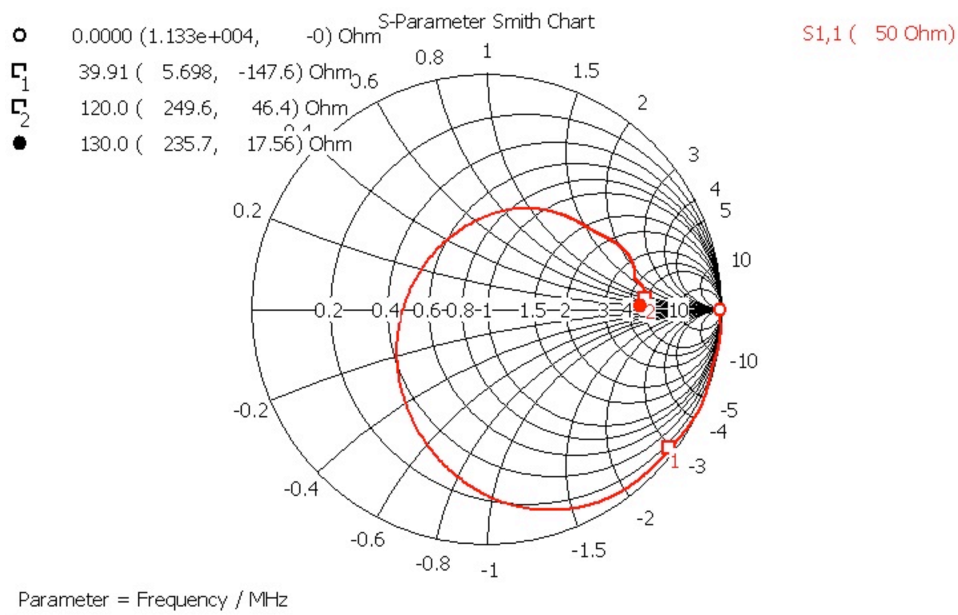


Figure 20: *Shows the terminal impedance as a function of frequency plotted on a Smith Chart.*

The receiver concept consists of a front-end module located in the vicinity of the dipoles and a filter module located inside the spacecraft bus. These modules are connected together by a pair of coaxial cables. The front-end incorporates load switching for spectral calibration. It operates in the 50W environment after the low noise amplifiers to reduce structure to the spectrum imposed by the switch itself. Sensors are used to monitor the physical temperature of these amplifiers to correct for gain drift, if necessary. **Bradley** has been modifying a PAPER balun to assess the performance (Figure 21).

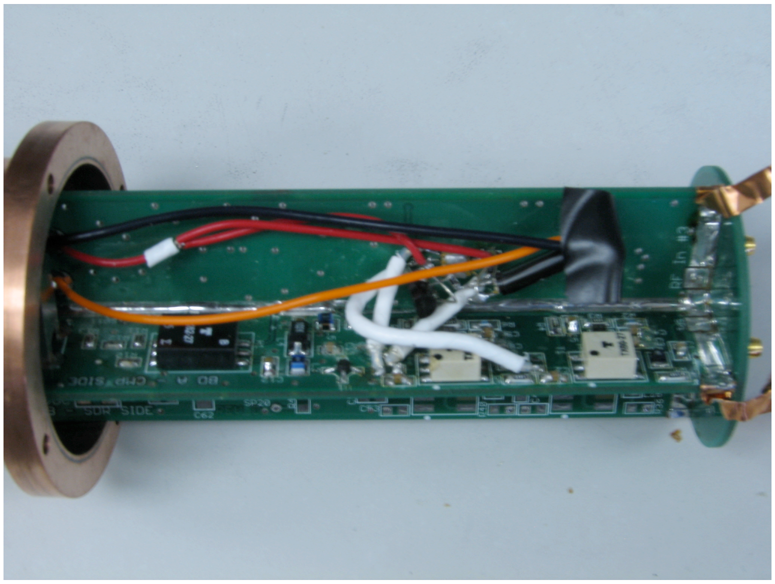


Figure 21: *This image shows one of the instruments used to measure the performance of low noise amplifiers.*

Bradley, **Bowman**, and **Lazio** also developed an Instrument Verification Plan to address outstanding issues in the Science Instrument package and retire risks during Phase A of the project. The Plan will verify the antenna's smooth, frequency dependent impedance and beam pattern, confirm adequate receiver stability, confirm proper operation of the digital signal processor, and evaluate the effectiveness of system integration. A full size model of the science antenna and a 50% scale, electromagnetic model of the spacecraft together with the science antenna will be constructed and utilized in the evaluation process.

Cross-Team Interactions

The Low Frequency Cosmology & Astrophysics Key Project of LUNAR has been interacting with other NLSI teams, most notably the Dynamic Response of the Environment At the Moon (DREAM) team. The most significant interactions have been on the science case for a future lunar radio telescope and on the impact of the lunar environment on future lunar radio telescope antennas.

- **Lazio** and ***Farrell (DREAM)*** published a paper on radio observations of the extrasolar planet HD 80606b. While unable to detect it, they showed that the most likely frequency at which this planet would emit would be below 100 MHz, which is in the likely frequency range for a future lunar cosmology radio telescope (Lazio, Shankland, Farrell, & Blank 2010).
- ***Farrell (DREAM)*** et al. presented a poster, on behalf of the DREAM and LUNAR teams, at the Lunar Science Forum 2010 reporting on a preliminary investigation of the plasma

environment on the performance of lunar radio antennas, particularly those constructed of polyimide film (“Lunar Environmental Effects and Astrophysical Platforms”).

Related Work

Undergraduate student **Simmons** (MIT) worked with **D'Addario** (JPL) to develop concepts for lower-power digital cross-correlators for lunar-based low frequency arrays. This work was funded through a proposal titled “An Ultra-Low-Power Digital Correlator for a Lunar Radio Interferometer” by **Lawrence**, **D'Addario**, **Hewitt**, **Jones**, and **Lee** to the JPL Strategic University Research Partnership program in 2010. This work has led to improvements in low-power design for other large radio arrays as well, including the SKA.

Bowman, **Lazio**, and **Jones** submitted a Strategic University Research Partnership (SURP) proposal for collaboration between JPL and ASU to implement and perform preliminary tests on a prototype lunar orbit dipole receiver.

A number of LUNAR investigators led by **MacDowall** (*Radio Heliophysics*) submitted a proposal to the NASA Moon Mars Analog Mission Activities (MMAMA) program (“High-Fidelity Field Testing for ROLSS and Other Lunar Radio Astronomy Observatories”), part of the Research Opportunities in Space and Earth Science for 2010. The goal is to improve the technical readiness of polyimide-based antennas for the Radio Observatory for Lunar Sortie Science (ROLSS) mission, and other low frequency lunar radio arrays. Antenna deployment and performance testing will be conducted in desert areas with very low soil moisture, loose sandy surfaces, and a range of terrain features. This proposal was not selected for funding.

Radio Heliophysics

Radio Emission from Space

Lunar low frequency radio arrays would explore the region of the electromagnetic spectrum inaccessible on Earth, either due to complete ionospheric cutoff at frequencies below 2-10 MHz, or due to strong terrestrial radio frequency interferences at frequencies below 100 MHz. In the Radio Heliophysics Key Project we use existing low frequency observations to conduct path finding scientific investigations in order to develop the scientific case for a radio heliophysics array on the moon. Examples of precursor observations that we have used include dynamic power spectra from 1-10 MHz on the STEREO and Wind spacecraft, and images and power spectra from the 80-300 MHz Murchison Widefield Array 32-tile prototype array in Western Australia. These existing observatories have a significantly limited capability compared to a full lunar radio array, lacking the imaging capability in the case of STEREO and Wind or the really low frequencies in the case of MWA, but they provide a valuable first look at what a fully capable lunar array would be able to observe. In the second year, radio emission work focused on the novel use of radio measurements to characterize interplanetary and interstellar dust, automated searches for planetary and extra-solar radio transients, and the imaging quality of radio arrays with small numbers of antennas.

Interplanetary and Interstellar Dust

For a long time, dust has been known to exist in interplanetary and interstellar space in the micro-meter size range, through the remote observation of the zodiacal light produced by the scattering of sunlight by interplanetary dust particles. Since the first space exploration missions, in-situ dust detection has been an important observational goal. Most of these measurements have been performed with instruments specifically designed to characterize dust particles. In the last several years several new studies have shown that radio receivers on spacecraft are be able to (although not designed to) measure electric signals associated with individual dust grains impacting the spacecraft body at high speed. This discovery was based on an analysis of dynamic radio spectra measured by the WAVES electric field antennas on the STEREO spacecraft, which showed that individual dust impacts on the spacecraft produce a strong signal at frequencies below 1 MHz. The STEREO spacecraft were launched in 2008, and these results appeared in the literature in the last two years.

We realized in year one of the LUNAR project that the fact that dust produces a detectable signal in a radio receiver in space potentially opens an entire new field of scientific investigation for a lunar radio array. The lunar array would have a significantly larger collecting area than an antenna on a single spacecraft, and could therefore make much more sensitive surveys of the distribution of interplanetary dust as a function of mass. If the individual signals produced by dust impacts produce a distinct signal, we could also optimize the lunar array to improve the accuracy of the derived dust properties. Finally, we needed to characterize the rate and intensity of dust signals. This is needed to ensure that there would be no impact to our primary goals of imaging the quiet and active Sun, along with our secondary goal of making an all sky survey at low frequencies. We decided to use measurements from the two STEREO spacecraft, and investigate three questions: If we look at the actual electric field waveforms instead of the power spectra reported previously, how much information can we derive about individual dust impacts? Over what range of masses can a space-based radio array study dust? What would the event rates be for a lunar radio array due to dust impacts, and is that a scientific opportunity or a threat to our other observation plans?

This investigation was conducted at SAO by **Kasper** and postdoctoral associate Arnaud **Zaslavsky**, along with LUNAR collaborator **Bale** and European colleagues. Initial results were presented in talks at the LUNAR-organized Robotic Science From the Moon forum in October 2010 titled "Heliospheric Dust and Consequences", at the Fall American Geophysical Union meeting in December 2010 titled "Interplanetary dust fluxes measurements using the Waves instrument on STEREO", and at a LUNAR Webinar in February 2011 titled "Recent results in solar bursts and heliospheric dust with lunar radio Analogs". A paper describing all of the results, titled "Interplanetary dust detection by radio antennas: Mass calibration and fluxes measured by STEREO/WAVES", by Zaslavsky et al., was submitted to Planetary and Space Sciences in February 2011.

Previous studies had shown that when a dust particle strikes the STEREO spacecraft it generates detectable noise at frequencies below 1 MHz. For this project, we used the Time Domain Sampler (TDS) portion of the STEREO/WAVES instruments to look at the electric field as a function of time as recorded by the three antennas on STEREO. The TDS system continuously records the electric field waveform observed by each antenna. A trigger system searches for transient events and telemeters snapshots of the electric field waveform surrounding these events. One example of a TDS waveform given in **(Figure 22),** which shows the sampled electric signal on the X monopole of STEREO A during a series of dust impacts captured on January 1, 2009.

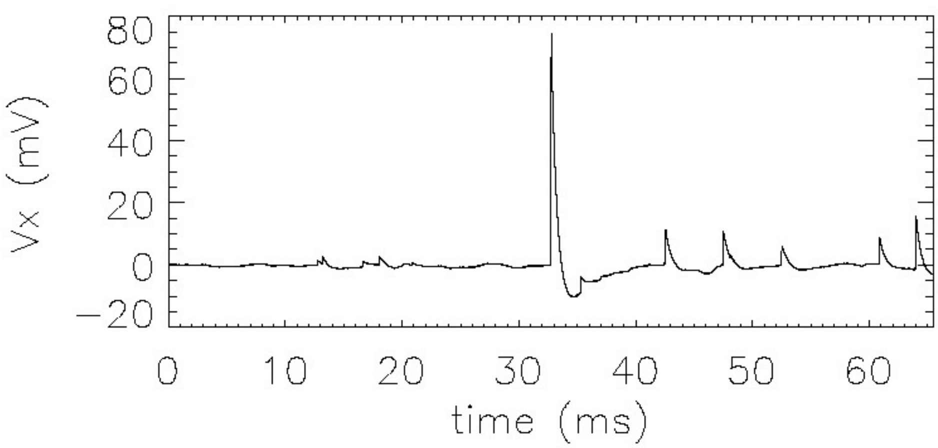


Figure 22: *Shows data of dust impacts measured from the WAVES instrument onboard the STEREO A & B spacecraft.*

We built up a catalog of hundreds of thousands of dust impact events, and then constructed a model of the electron cloud produced by a dust impact, in order to relate the maximum electric field seen by TDS to the mass of the incident particle. The detailed derivation of the dynamics of the plasma cloud are given in the Zaslavsky et al. paper. Briefly, when a high velocity dust particle strikes a target it excavates a volume of material roughly proportional to dust particle mass and proportional to the particle speed to 3.5 power. This material is immediately ionized, and the electrons stream away from the impact site, creating a potential difference. Within a few ms, the electrons are pulled back to the impact site by the resulting electric field, and the impact site becomes neutral. With an appropriate model for the dust particles and their speeds, and the details of the STEREO antennas and the plasma cloud dynamics, we can relate the incident particle mass to the resulting number of freed electrons and electric field strength (Figure 23)

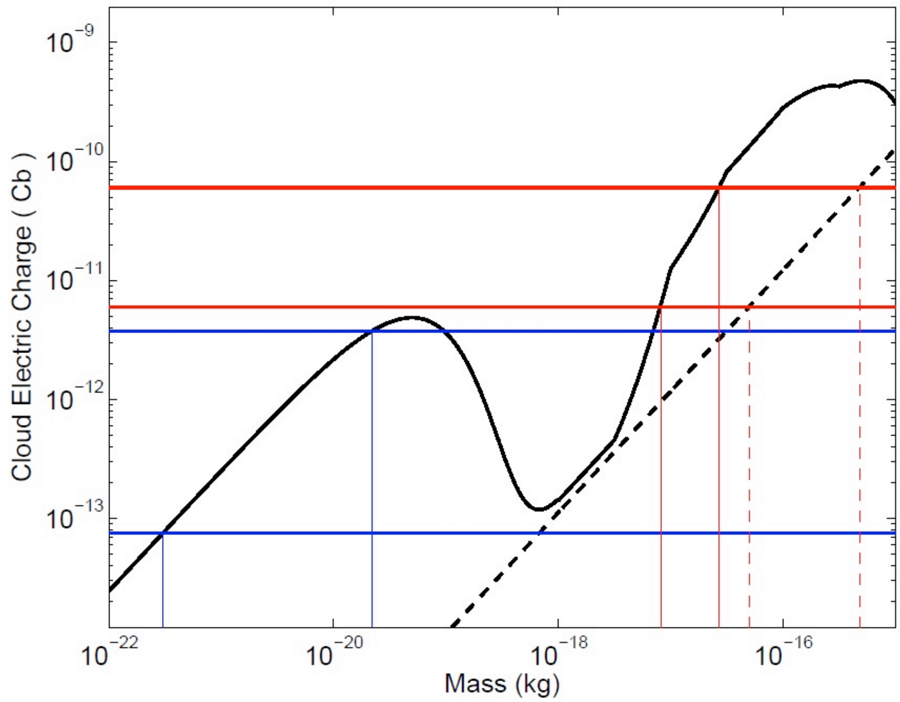


Figure 23: *illustrates our mapping between freed charge and initial dust particle mass for the STEREO spacecraft.*

The total charge Q released by a given dust impact as a function of the mass of the impinging particle is plotted in black. The dashed curve shows the charge generated by an interstellar dust impact when the spacecraft longitude is equal to the interstellar dust upstream or downstream longitude. Depending on the particle mass, the signal due to the impact will be seen by all three of the spacecraft antennas or just one. The red and blue lines present the TDS detection range when the signal is generated by the cloud's electrons recollection and through a direct electric field measurement on a single antenna. The vertical lines show the grain mass range scanned when looking at triple (red) and single (blue) hits. The considered voltage detection interval is 15−150 mV for the red lines and 3 −150 mV for the blue lines (Figure **24)**

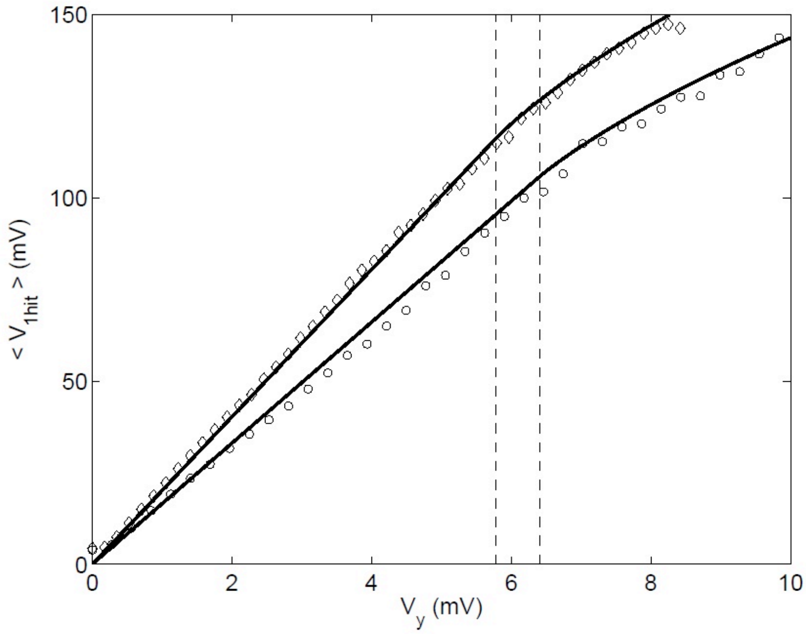


Figure 24: *we demonstrate the success of our model for the dynamics of the expanding plasma plume created by a dust impact in predicting the weak signals seen on other antennas when one antenna records a strong signal.*

The average of the amplitude on the X (Z) monopole on STEREO A (B, respectively) is represented by diamonds (circles, respectively) as a function of the amplitude detected on the Y monopole (which is proportional to the charge Q in the plasma cloud) (Figure **25**).

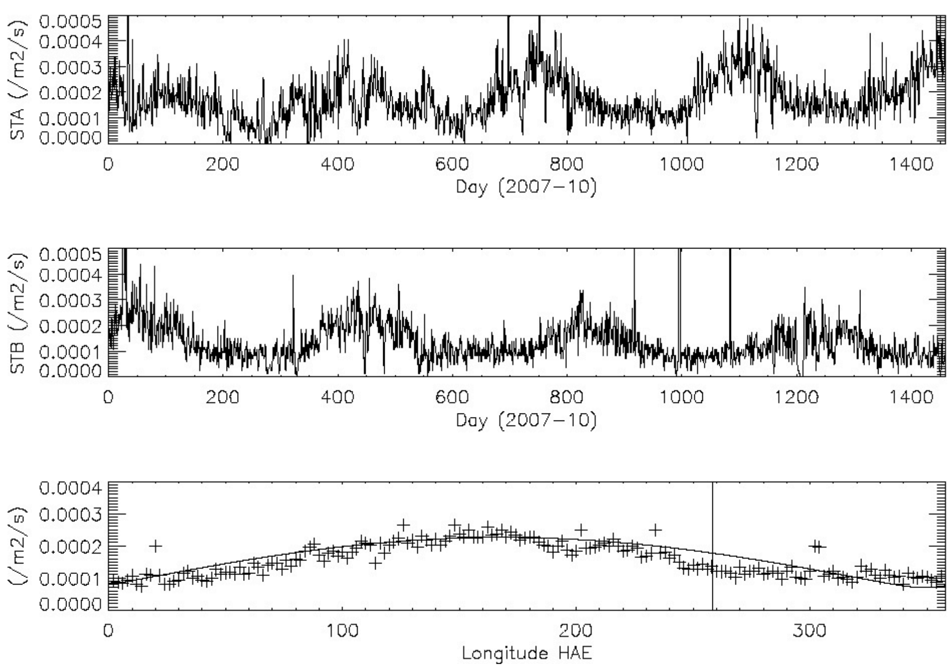


Figure 25: *shows our calibrated dust flux calculated with daily resolution each day for STEREO A and B.*

The observed fluxes present a modulation depending on the solar longitude. The bottom panel presents the averaged flux measured by both spacecraft as a function of the solar ecliptic longitude (the average is performed on 2 deg bins). The vertical line shows the upstream direction of the interstellar dust flow, and the best fit of the data using our model of interstellar and interplanetary dust is over-plotted with the solid line.

Comparison of the flux measurements derived in this study using the S/WAVES TDS, and a classical dust flux model (given by the solid curve), is shown in (Figure 26).

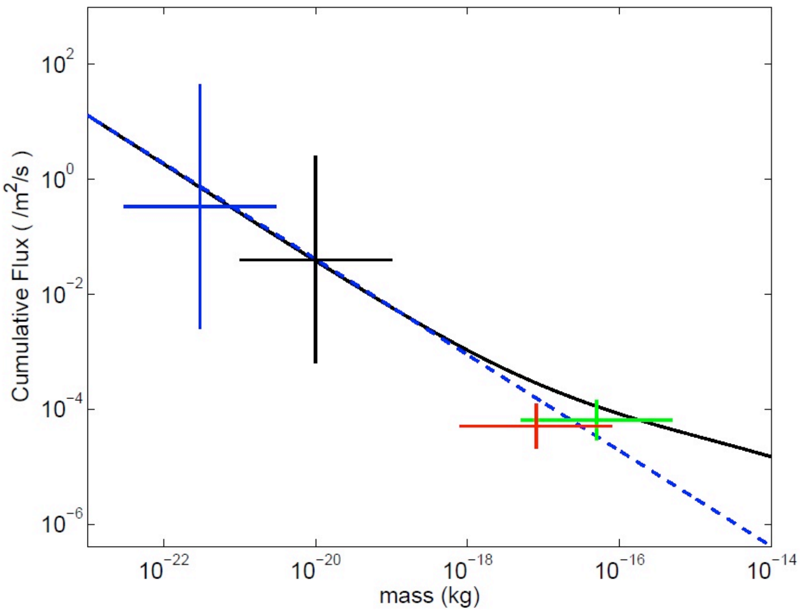


Figure 26: *Described above.*

The dashed curve is the extrapolation of the model with a m−5/6 power-law, from the small bodies fragmentation equilibrium theory. The red cross shows the ⍰ 0.1 µm flux measurements. The green cross shows the result derived from the 0.1 −0.3 µm interstellar dust measurement. The blue cross shows the 3−12 nm measurements (4-year average). The black cross shows the earlier result of Meyer-Vernet et al using just the power spectrum of the dust signature.

In summary, in this year two activity, we have demonstrated that a low frequency radio receiver such as the S/WAVES instrument on STEREO, or a future lunar radio array, can be used as a dust detector with convincing results both in the nanometer and sub-micrometer size ranges. In the latter case, the orbital motion of the spacecraft allows us to distinguish between interstellar and interplanetary dust components. Our results reasonably agree with previous studies and with current dust flux models and suggest that a lunar radio array could successfully add the sources, variability, and mass distribution of interplanetary dust as a key science goal. On the basis of this study, we have three recommendations for ROLSS. The addition of an automated dust counter that registers the amplitude and time of each impacts would greatly reduce the error bars on the flux measurements, especially in the nano-size range where the fluxes are high. A larger dynamical range (S/WAVES TDS saturates at ⍰ 170 mV) would enable ROLSS to scan a larger (and different) mass range. The use of well-separated antennas in ROLSS would allow us to gather more information about single-hit dust impacts, specifically allowing us to determine the dust grain velocity vector.

Searches for Radio Transients

We continue to use the WAVES receivers on the twin STEREO spacecraft to conduct blind searches radio transients within the solar system and for emission outside of the solar system, including prompt low frequency emission from Gamma Ray Bursts. This work is being conducted by **Kasper**, along with Harvard University Department of Astronomy graduate student Bennett **Maruca** and post-doctoral associate Arnaud **Zaslavsky**. Initial results were presented by Maruca at the 2010 Lunar Science Forum at NASA Ames in a talk titled “Searching for Extra-Solar Bursts of Decameter Radiation” by Maruca, and in a poster presentation at the Robotic Science From the Moon meeting in October 2010.

The WAVES radio receivers on the twin STEREO spacecraft measure the dynamic power spectrum of radio emission from 1-10 MHz every 40 seconds. The STEREO spacecraft are in heliocentric orbit at about 1 AU, with one spacecraft leading and one trailing Earth, drifting apart tens of degrees per year in solar longitude. By January of 2011, the spacecraft are 180 degrees apart about the Sun, and a signal at the speed of light takes more than 15 minutes to travel between the two spacecraft. We can take advantage of this propagation delay to search for transient emission in the sky. In a real lunar radio array a transient would be separated from background emission by generating images of the sky. We can use the STEREO spacecraft as a proxy for this capability by looking for prompt emission seen by both spacecraft, and then comparing the delay in arrival time at the two spacecraft with expected values for known radio sources in the solar system. There are two main types of time delays. For short duration emission from a single point in space, the expected time delay is calculated by assuming the emission travels in an expanding plane wave. For continuous emission produced by a rotating object, for example emission created by the Jupiter-Io system, the time delay is a function of the orbital rotation rate of that system (Figure 27).

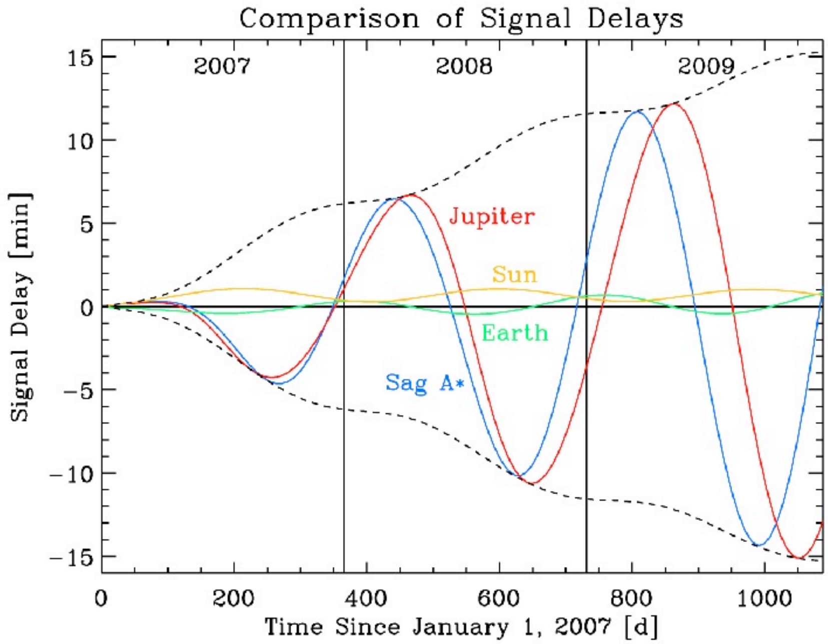


Figure 27: *indicates the expected delays for the main objects in the solar system known to produce prompt radio emission.*

The time resolution of the WAVES observations, combined with the location of the two spacecraft, now permits 8 degree resolution on the sky for the arrival direction of prompt emission.

In the first year of LUNAR we wrote code that looked for any coincident detection of signals above noise levels on both STEREO spacecraft. That code produced a large database of candidate transient events, but there were many false positives and the events had to be examined by hand. In the second year, we worked to expand and refine the code that automatically searches for events in the STEREO/WAVES data to reduce the rate of false-positives. We modified the code to search for emission from the Jupiter-Io system specifically. We decided to start with Jupiter-Io emission since it is the most frequent type of event in the data. The code generates a list of possible events from the data of each spacecraft, estimating the beginning, middle, and end of each candidate. Then, it compares the events from the two spacecraft, looking for ones that are separated by a time period about equal to the expected delay in a signal from Jupiter-Io. The same code also looks to see if the timing of an event is consistent with pure beamed emission from Jovian rotation, solar emission, terrestrial emission, and emission from Saturn. (Figure 28)

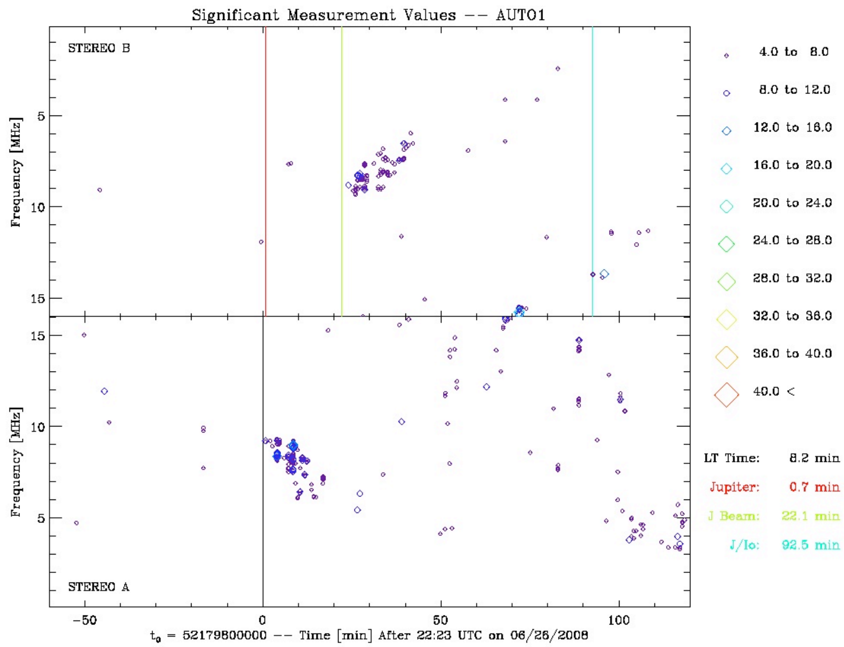


Figure 28: *is an example of a detection produced by this code.*

The size and color of the diamonds indicate the signal to noise ratio (SNR) of transient emission detected by each spacecraft in the highest resolution time and frequency intervals. The black vertical line indicates the starting time of the emission as seen by STERERO A, and the series of colored vertical lines indicate the time the emission should have arrived at the second spacecraft for a variety of emission mechanisms. In this case, the delayed emission is clearly most consistent with the delay expected by Jovian rotation, as indicated by the yellow-green line. This analysis has resulted in a large database of emission from Jupiter and the Jupiter-Io system, along with a few events that seem inconsistent with those sources. In year three we will work on explaining these additional results, and complete our analysis of detection thresholds for radio emission associated with Gamma Ray Bursts.

Designing a Solar Imaging Radio Array

Our second year task two involves work on the design of a solar imaging radio array for the lunar surface. This is separate from the third task of conducting technology development for the array, which is described in the next section.

Work on the design of a lunar radio array in the second year of the LUNAR project involved studies of the number of antennas needed to successfully image solar radio emission. The more antennas, and the larger the separation between the antennas, the higher quality the resulting images, in terms of both angular resolution and point spread function, or dynamic range. However, more antennas would directly lead to higher resources required for the array, and mass will likely be the largest single constraint on a lunar array. We are studying both how the quality of solar images depends on the number of antennas, and developing software and analysis techniques to improve the quality of the resulting analysis. Work on this topic is based on the Murchison Widefield Array, specifically a prototype system consisting of 32 tiles of antennas built in Western Australia. The 32-tile prototype (32T), has 300m baselines and observes from

80-300 MHz. This is very close to the number of antennas under consideration for a lunar solar array. While the 32T prototype operates at slightly higher frequencies than a lunar array, the antennas are more closely spaced, resulting in very similar angular resolution and image quality.

Work in this task was conducted at SAO by Kasper and scientist Daniel **Mitchell**. Initial results were presented in a LUNAR Webinar in February 2011 and a draft manuscript is under preparation for publication in the third year of the project.

Our requirement for the observational portion of this task has been for the 32T prototype, which is operated on an occasional basis, to observe solar radio bursts. This occurred in August 2010, and an initial summary of the observations was published this year by Oberoi et al, "First Spectroscopic Imaging Observations of the Sun at Low Radio Frequencies with the Murchison Widefield Array Prototype". Now that we have the observations in hand we have begun analyzing the same dataset with different numbers of antennas. We are also looking at data collected at night during the same period to evaluate how well such a small array can produce a detailed sky survey. Results of this part of the task are expected in year three.

In parallel with the analysis of observations, we have also been developing software algorithms to form higher quality images. Our focus has been in developing ways to subtract the bright unpolarized emission from the Sun in order to prevent the Sun from contaminating images of polarization from solar bursts or from other objects in the sky. These techniques will be essential for both a solar array and for concepts for larger cosmology-focused arrays on the far side of the moon, since low frequency arrays inherently have large fields of view, and must be able to cope with bright sources anywhere in the sky. Mitchell has produced an eigen value method for extracting the solar contribution to images in real time. We are evaluating the technique with the MWA data, and plan on submitting an article on the results in year three.

Technology Development for a Lunar Radio Array

The technology development task for the Radio Heliophysics Key Project consists of demonstrations of deployment techniques for a lunar radio array, testing of radio antennas designs, and work on low temperature low power electronics. This work is led by LUNAR team members at Goddard Space Flight Center (GSFC). In year two, the radio-heliophysics effort at Goddard Space Flight Center (GSFC) focused on advancing the readiness of our proposed Radio Observatory on the Lunar Surface for Solar studies (ROLSS). The ROLSS concept uses dipole antennas deposited on rolls of Kapton® film, which would be compactly stored for flight and easily deployed on the lunar surface by unrolling. Recently, the group at GSFC has focused on three areas. An analog-digital converter was tested to -250° C. as the introduction to placing active components on the Kapton film to provide pre-amplification of the signal at the antennas. A pathfinder concept to test the ROLSS antenna-film system on the lunar surface was developed and the first version of the design was built and tested successfully. Finally, ROLSS was presented in various talks and papers, including a white paper to the NASA Heliophysics Decadal Survey and a submission to the Proceedings of Planetary Radio Emissions VII.

1) Components of the ROLSS system: Throughout the LUNAR team, activities are taking place to advance the technologies required to make ROLSS or larger lunar radio arrays a functioning reality. One concern about the original concept for ROLSS (Figure 3) is that the

antenna-transfer line system was passive, i.e., there was no pre-amplification at the antennas in order to avoid having to provide power to such components.

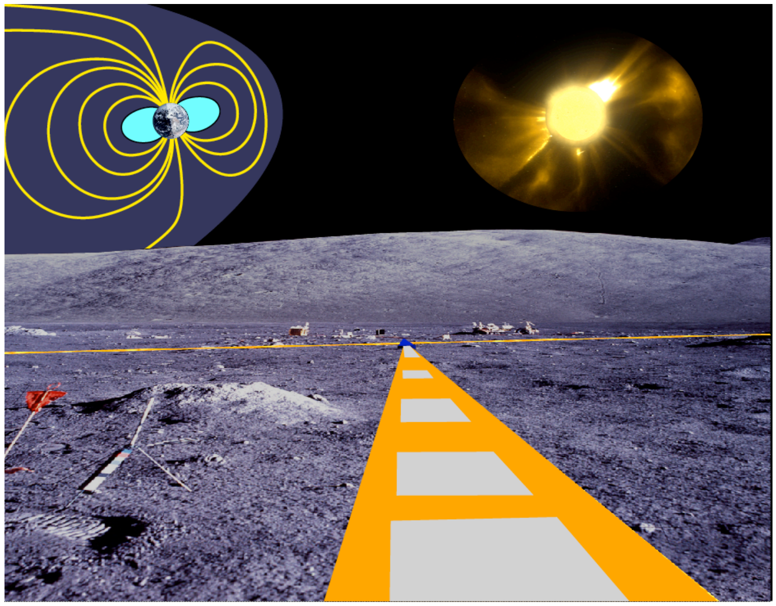


Figure 3: *This show the ROLSS concept (Radio Observatory on the Lunar Surface for Solar studies). This array would be comprises of single radio dipoles embedded within polyimide kapton film.*

Amplification would occur when the signals arrived at the Central Electronics Package, but the losses from the antennas 500 m away would be substantial – up to 25 dB. While this might be acceptable for the more intense solar radio bursts, it is clearly problematic for weak signals, such as those of cosmic origin.

To deal with the resulting signal loss, we are working on the concept of active components on the film at or near the individual antennas. A key concern for ROLSS, which only operates during the lunar day, is will such components survive the thermal cycling imposed by the Moon's rotation. For cosmic radio observatories planning to observe at night, the question becomes will the components function at lunar night temperatures, or how much power is required to heat them.

As the first step in answering these questions, **MacDowall** and **Yeh** tested the functioning of a Texas Instruments (TI) 16-bit ADS5483 analog digital converter (ADC) to -250° C. Such an ADC would likely not be used for the interferometric data, given the excess number of bits calculated, but it could be used as the total signal amplitude monitor used to monitor the full range of solar and other radio signals received at the ROLSS site. The setup for this test is shown in (Figure 29).

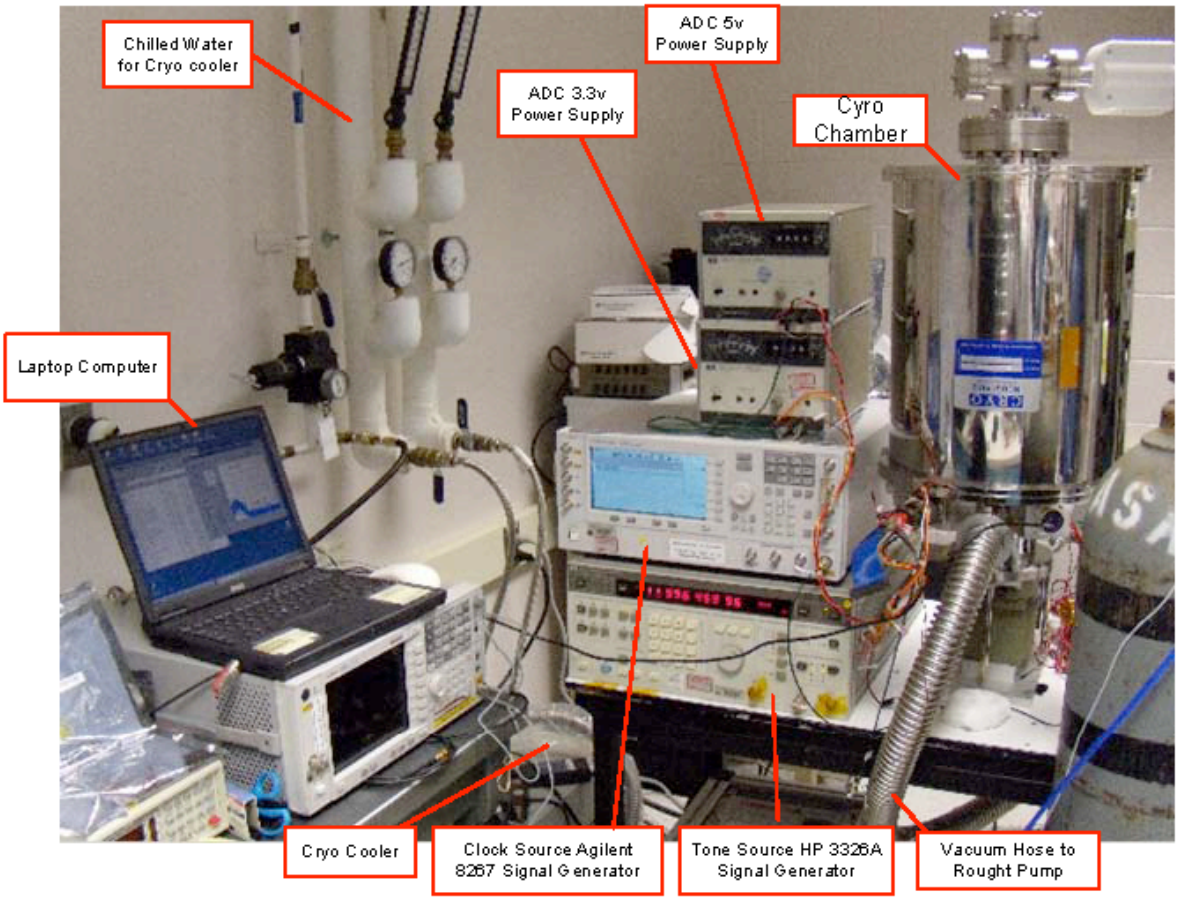


Figure 29: *Show the testing of the analog to digital converters needed for a lunar low frequency radio array.*

The parameter used to describe the quality of the ADC function is the "effective number of bits" (ENOB); the noise of the test system reduced the measured ENOB at room temperature to ~10 bits, as shown in (Figure 30).

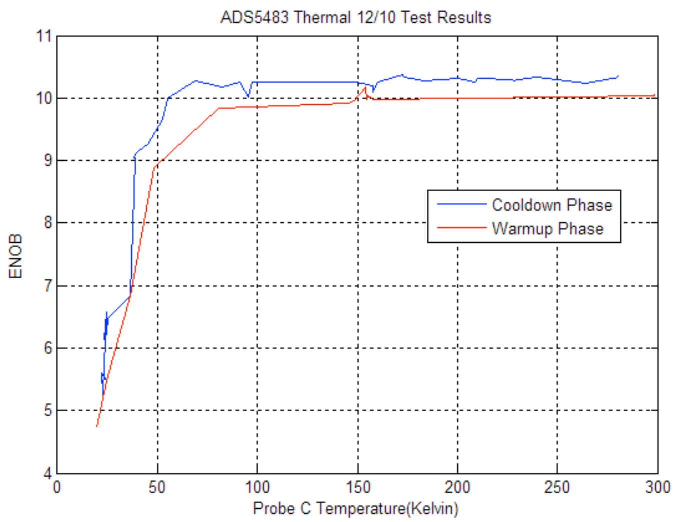


Figure 30: *Described above.*

This level of function was maintained down to -200° C, below the typical lunar night surface temperatures. We will next cycle the ADC repeatedly over thermal ranges analogous to the change in lunar surface temperatures near the lunar equator to determine survivability.

The TI ADS5483 has been previously tested at GSFC for radiation response to protons and heavy ions. It performed well in both tests, suggesting that it could function and survive without shielding in the lunar environment.

2) Although ROLSS may be thought of as a small lunar radio observatory, the new design elements that it would require to work on the lunar surface, in particular, the antenna-transmission line system deposited on polyimide film would necessarily be tested by a pathfinder mission. For this purpose, MacDowall, Espley, Rozmarynowski, and Sheppard at GSFC are working on a small, light weight package that could fly as a secondary payload on an unmanned lunar lander to deploy ~50 m of film with two dipole antennas and transmission lines for testing the deployment and other aspects of the film (Figure 31).

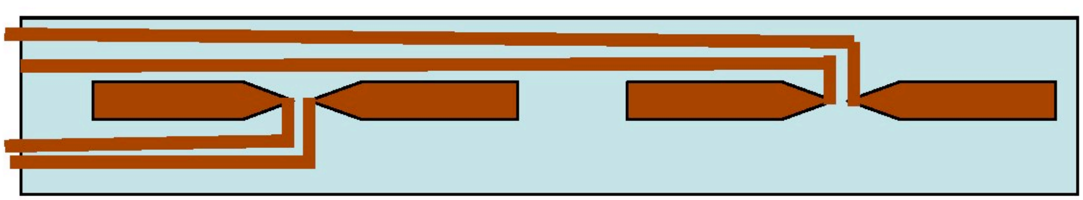


Figure 31: *Described above.*

A number of options have been considered with our current efforts being focused on a system where an anchor is spring-launched to >50 m and the line through the anchor is pulled in by a small motor, thereby pulling out the film (Figure 32).

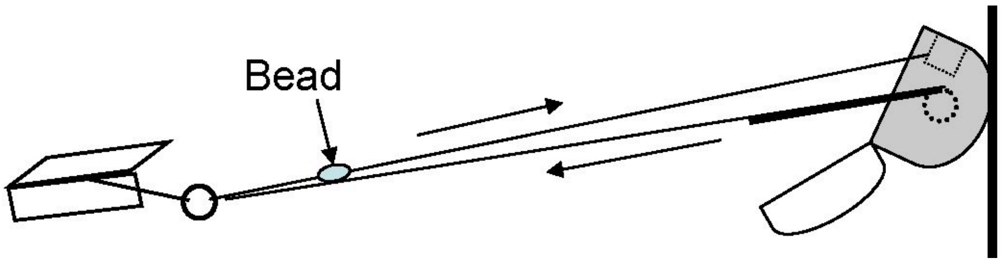


Figure 32: *Described above.*

Our first implementation of this concept was a "backyard" design. As shown in (Figures 33-35), this test was conducted in an environment with a surface rather different from the range of lunar surfaces; however, this is a weakness that is relatively easy to rectify. What is important is that the technique – spring launch of anchor, then line through anchor pulls out Kapton film analog – worked well.

Figures 33-35: *(upper-left) shows the launching platform. (upper-right) show the deployment of the array. (bottom) show the anchor itself.*

Given the success of this design to date, we are building a more robust, flight-like model to test deployment on surfaces that are better analogs of lunar surfaces. The critical element is the anchor, which must hold adequately on the range of surfaces anticipated. For this purpose, we anticipate an anchor like that shown in (Figure 36), which will hold on dusty or rocky surfaces.

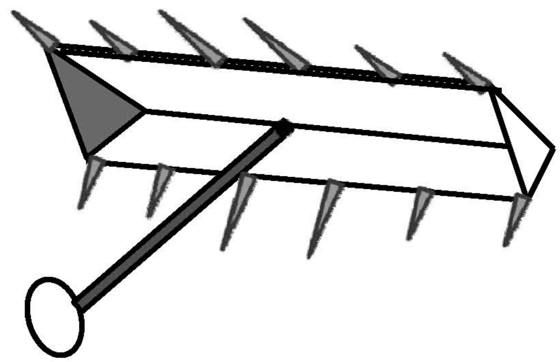


Figure 36: *Described above.*

Lunar Laser Ranging

The lunar laser ranging (LLR) effort within LUNAR has seen some interesting developments in the last year: The long-lost Lunokhod 1 rover/reflector was found in March 2010 by the LRO spacecraft, and subsequently ranged by Murphy and colleagues the following month. The coordinates---previously unknown at the 5 km level---are now pinned down to within a few cm. Surprisingly, the Lunokhod 1 reflector performs about four times more strongly than its twin on Lunokhod 2. This provides an interesting wrinkle in the story of degradation of the reflectors, as reported in the first annual report for LUNAR. Lunokhod 2 was once comparable in strength to Apollo 15, but is now ten times weaker than Apollo 15. Lunokhod 1, by contrast, is only a factor of two weaker than Apollo 15. Since the two Lunokhod reflectors share the same design, we are faced with the mystery of why Lunokhod 2 has degraded much faster than has Lunokhod 1 (meanwhile, the Apollo 15 array has degraded significantly as well). The location of Lunokhod 1 on the moon---the closest reflector to the apparent limb---makes it the most sensitive probe of lunar orientation. Having five available reflectors on the moon bolsters our ability to map tidal distortions of the lunar figure. Finding Lunokhod 1 is also a useful trial case of "installing" a new reflector on the moon, and adapting analysis efforts to utilize the new data.

A total lunar eclipse on 2010 December 21 provided an opportunity to test ideas about the observed LLR signal deficit at full moon (reported in last LUNAR annual report). In marginal observing conditions, the APOLLO project was able to confirm beyond any doubt that the removal of sunlight resulted in far better signal performance than has been previously seen by APOLLO at full moon. It also appears that the signal improves early in the eclipse, then gets worse, and briefly becomes strong again when the light returns. This matches expectations if solar absorption at the corner cube front surface establishes a thermal gradient that causes the signal degradation. When the sunlight is removed, the gradient temporarily disappears, then changes sign as the corner cube prism cools by radiating to space. When the light returns, the gradient swings through zero again as it re-establishes a warmer front surface. This new information will help constrain models of what causes the deficit, and will contribute to the next-generation reflector designs that seek to avoid a similar fate.

Murphy spent a sabbatical quarter at Harvard/CfA in the fall of 2010, with the aim of becoming proficient at using the PEP LLR model in line with the LUNAR work plan, so that we might begin to evaluate science capabilities of next-generation LLR. While some progress was made (acquiring, compiling, running code), the full goals were not realized---mostly due to unexpected equipment damage to APOLLO at the Apache Point Observatory, the remedy for which consumed considerable time. The most significant advance on the modeling front was a two-day workshop convened in Cambridge 2010 December 9-10, aimed at revitalizing the LLR modeling effort and performing an assessment of capabilities. LUNAR paid for the travel of two of the participants. We had representation from PEP, JPL (by phone only), a German group and a French group. The weeks before saw a rush of effort to outline model content/details, and to produce APOLLO residuals for inter-comparison. The results were very illuminating, showing the JPL code to be in the clear lead--especially with regard to lunar interior models (impacting lunar orientation). It became clear where the other models need to work to improve, and the PEP and European groups established a set of stepwise exercises to carry out a meaningful comparison between codes/models. The workshop, therefore, kick-started a qualitatively new level of interaction and collaboration on the LLR analysis community, which will no doubt benefit the LUNAR objectives.

Much of the effort during the second year of LUNAR at GSFC was spent establishing the alignment and bonding technique to produce hollow corner cubes, procuring the necessary facet flats, and making improvements to the existing capture and analysis setup to study the far field diffraction patterns (FFDPs) of the corner cubes.

From the previous year's testing of commercial hollow corner cubes, it was concluded that the currently available cubes are unlikely to perform well when scaled up to the size required for new lunar retroreflectors. Therefore, efforts were focused on developing in-house capabilities for assembling hollow cubes using a technique known as hydroxide-catalysis bonding. This technique uses a small amount of sodium silicate solution to produce a thin bond between glass materials while providing significant strength over a large temperature range. A considerable amount of work during the second year was done to determine how the bond will change the positions of the facet flats as the bond sets, characterizing the bonding technique to determine the amount of solution to be used and how to administer the solution, and establishing the alignment procedure using hydroxide bonding.

Although the hydroxide bonding technique can be used to bond glass to glass with significant strength, most of the bond areas that have been tested are typically less than 500 mm^2. Larger bond areas will be needed if construction of 6" cubes is to be successful. For this reason, investigations into bonding larger surface areas was done, and strength measurements were performed to determine the feasibility of using larger surface areas. Successful bonds with surface areas of 2500 mm^2 were achieved with tensile breaking strengths of over 1 MPA.

To determine how the facets move as the bond cures, light from a fiber-coupled laser was passed through a power beamsplitter and onto a mirror that was held in place by a positioner that will be used to make the cubes (Figure 1 shows the positioners). The light is then reflected from the mirror and again by the beamsplitter onto a position sensitive photodiode. Another mirror is placed horizontal to the optical table and is aligned such that it sits flush with the mirror that the light is being reflected off of to produce an L-shaped set of mirrors. The bonding solution is placed where the two mirrors meet and the position of the reflected beam is measured over time. Current measurements put the angular displacement at less than 10 arcseconds, although this is believed to be limited by the experimental setup. Improvements are being made to lower this upper bound.

After the characterization of the hydroxide bonding technique was done, an alignment setup and procedure was established to produce cubes up to 6". This will be done using micrometer platforms in conjunction with 6-axis piezo aligners to give both rough and fine alignment capabilities to position the facet flats in the correct position while being able to monitor the FFDP at the same time (Figure 4). Once the correct FFDP has been achieved, the sodium silicate solution will be injected to solidify the positions of the mirrors. Two inch facet flats have been procured and will be used to assemble a cube soon, while fabrication of 6” cubes is currently being investigated.

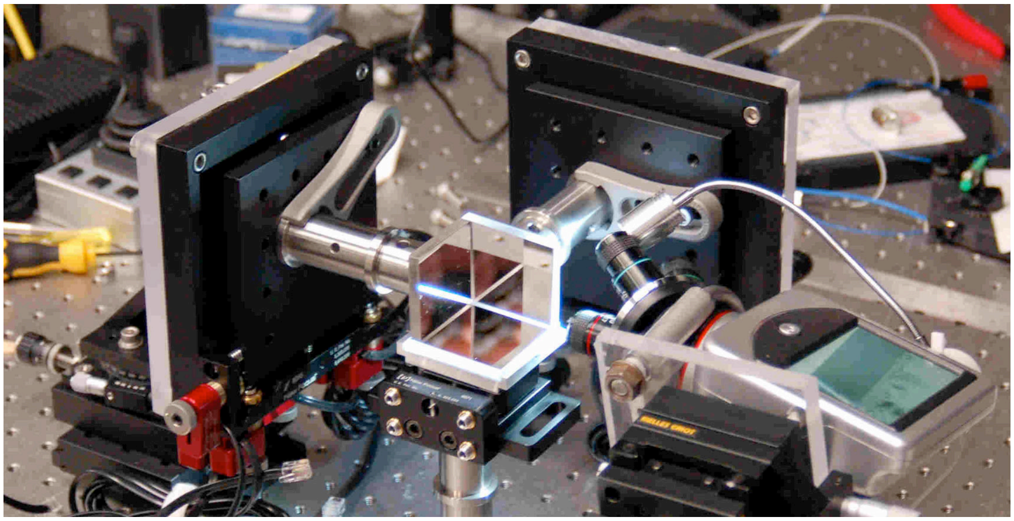


Figure 4: *This is one of our next generations of Corner Cube Reflectors CCR to help constrain our distance measurements from the Earth to the Moon.*

In addition to characterizing the bonding technique, modifications were made to improve the stability of determining the FFDPs of corner cubes. In calendar year 2010 the laser clean room setup at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt Maryland was upgraded significantly to support the capture and analysis of cube corner FFDPs. The original plan of using a transportable NRC breadboard which could be moved from lab to lab was abandoned because of instability and unneeded complexity of the optics. Future FFDP thermal vacuum chamber tests of cube corners will require a portable thermal vacuum chamber be brought to the GGAO.

The optical setup has been improved by replacing the off axis parabola (OAP) of the collimator with a larger diameter and longer focal length mirror and simplifying the transmit and receive optics. The new OAP is a Space Optics Research Lab (SORL) 8-inch diameter and 120-inch focal length mirror. The longer focal length mirror yields a larger pattern in the camera image plane. A fiber optic delivery system for the laser illumination was installed to replace laser optics and the spatial filter. By using a 10 meter long 3 micron diameter single mode fiber for delivery, the laser can be placed in a remote location eliminating its contributions to air turbulence. Additional unneeded optics in both transmit and receive paths were eliminated to make the measurements as clean and undisturbed as possible. Shown in (Figure 37).

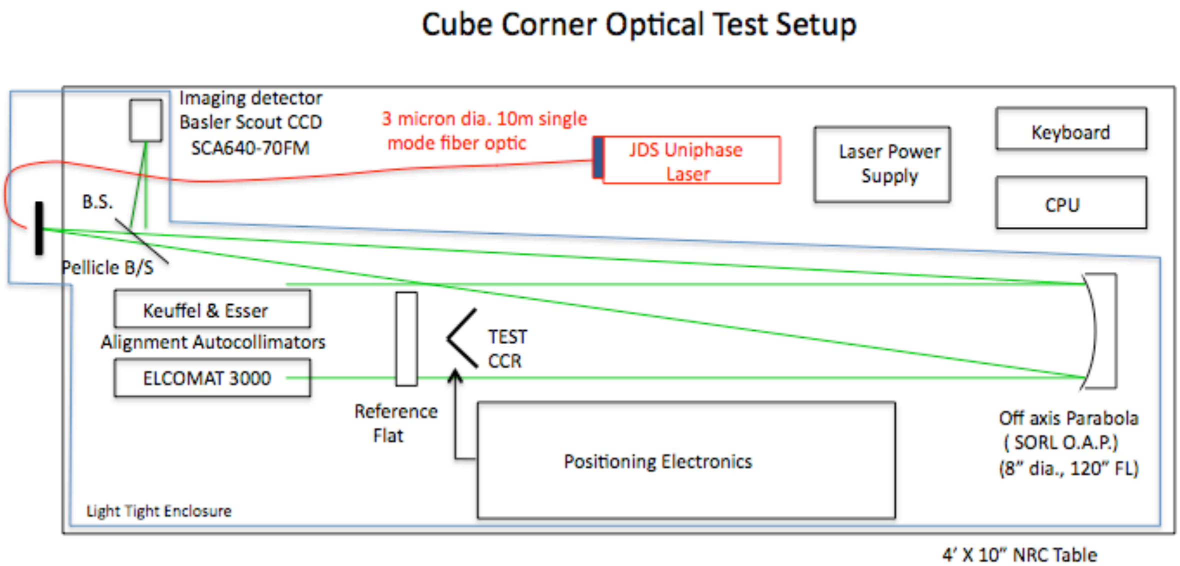


Figure 37: *is a simplified block diagram of the cube corner test setup.*

Laser illumination is brought in through the fiber, through the pellicle beam splitter, to the OAP and to the test cube corner. On the return path the pellicle beam splitter reflects 50% to the imaging Basler Scout CCD camera for capture and analysis. (Figure 38) shows photographs of the FFDP setup with laser, OAP, alignment autocollimators, pellicle beam splitter, and readout device.

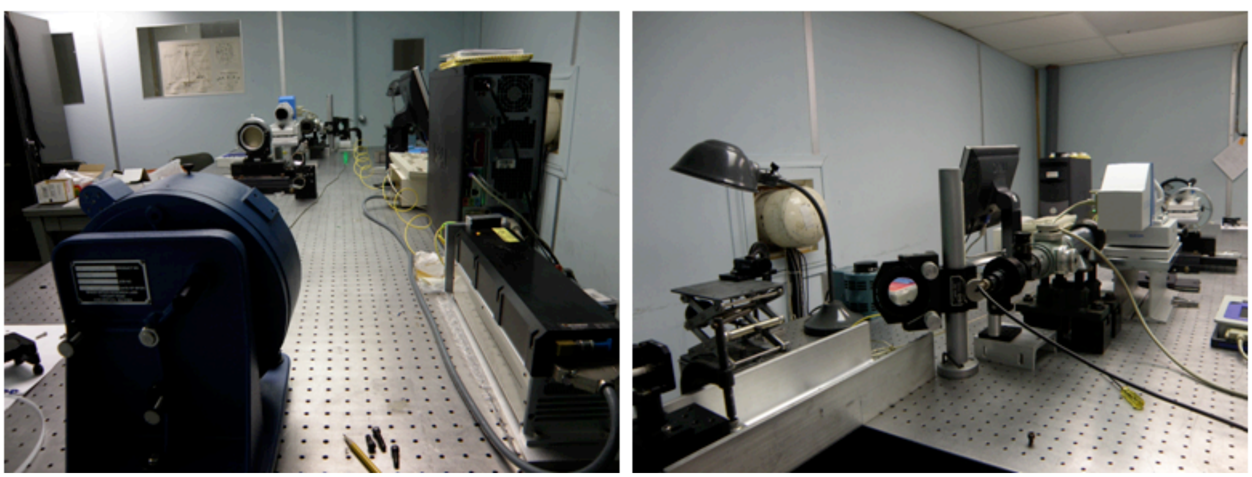


Figure 38: *Described above.*

The laser source used is a JDS Uniphase DualChip NanoLaser operating at 532nm with a 1 nanosecond pulsewidth and 30 Khz repetition rate. The output of the 3 micron fiber is placed 120-inches from the OAP at the 4-inch off axis position. This illuminates the full aperture of the OAP and yields a well collimated, uniformly illuminated beam. Test cube corner and reference flat returns are split at the pellicle and imaged in the Basler Scout CCD camera model SCA640-

70FM. Imaging software provided by the camera manufacturer is run on a Windows XP operating system computer.

Cube corner testing to date reveals moderate floor vibrations coupled through the legs up into the 4’ by 10’ support table as well as significant image disturbance due to air turbulence caused by the laser and computer fans, the air handling system in the laboratory, and movement of personnel. Vibration isolation will be improved by floating the NRC table on its air bladder. Air turbulence will be minimized by moving the sources of the airflow (laser and computer fan) to remote locations, and enclosing the entire beam path with a Plexiglas cover.

A 1-inch diameter λ/40 flat was tested in the FFDP setup as a reference and is shown in (Figure 39).   At the current limitation of 10-bits intensity digitization in the Basler camera the airy disk pattern is just barley visible.   The poor “seeing” conditions are also contributing to the image quality since the light tight air baffle enclosure is not yet in place.

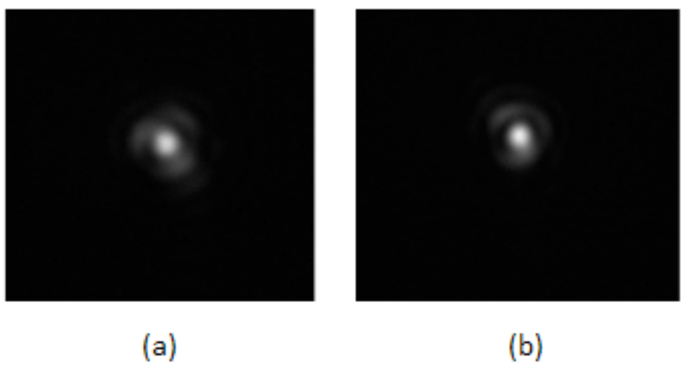


Figure 39: *Described above.*

The LAGEOS cube FFDP is shown in (Figure 40).

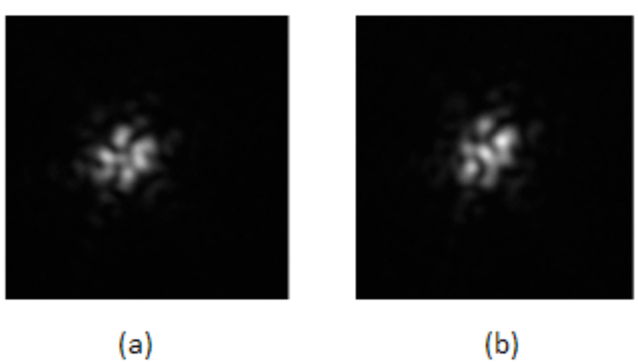


Figure 40: *Also tested was a flight spare LAGOES 2 cube.*

Image quality improvements will be made in the near future. These include accessing the full 12-bit intensity resolution of the CCD camera, completing the light tight air baffle system to reduce air turbulence, and removing the source of the air turbulence to a remote location.

We have also reached a nominal final design for the Lunar Laser Ranging Retroreflector Array for the 21st Century, a.k.a. LLRRA-21 has been achieved that has an acceptable performance over the range of thermal environments on the lunar surface. To illustrate this, (Figures 41)

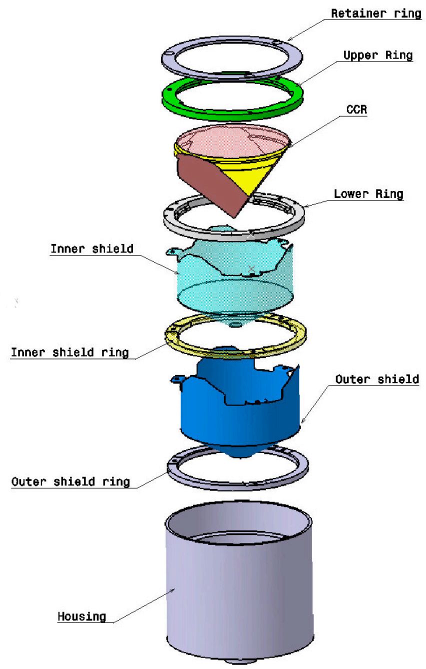


Figure 41: *Described above.*

(Figure 42) *below.*

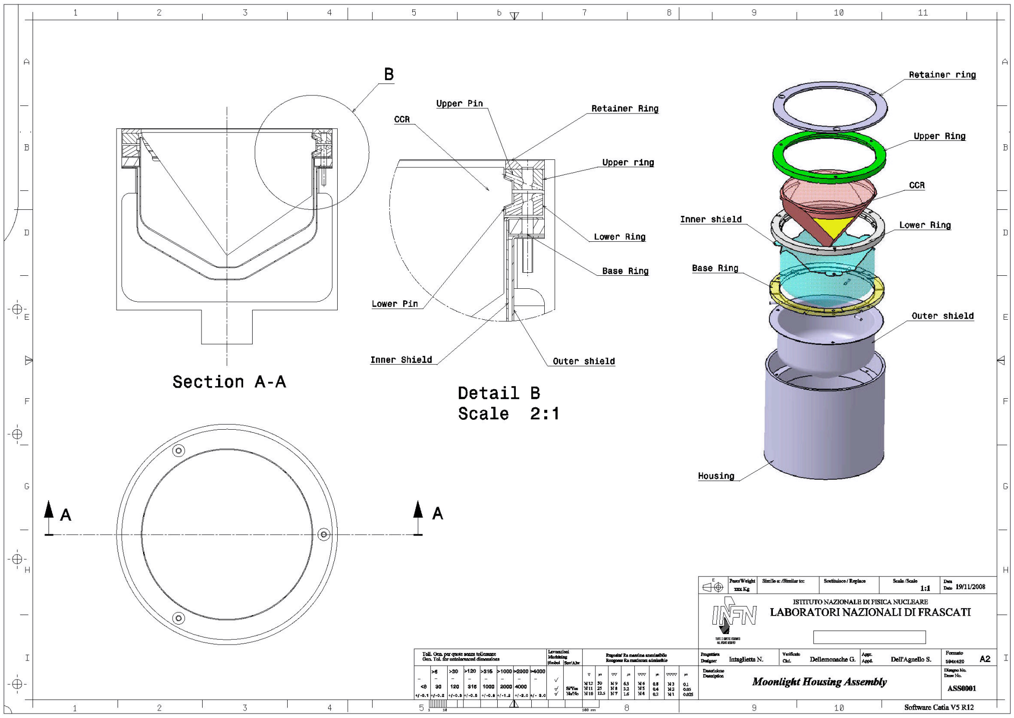


Figure 42: *Shows more of the design specifications for the LLRRA 21 package.*

describe the complete model used in these simulations. To date, the model address the "package", that is the CCR, the housing and the sunshade without addressing the mode of deployment. In this case, the LLRRA-21 package sits 10 cm above a four meter diameter representing the lunar surface. The simulated lunar surface goes though the known temperature range during a lunation. The model addresses an extended region of regolith that extends beyond the thermal blanket and down to 3 meters, to cover the 1 meter support rod.

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. The nominal design uses a sunshade that is 200 mm in length, Multi-Layer Insulation (MLI) on the exterior surfaces of the package, a special "Dark Mirror" coating on the interior of the sun shade, gold coatings on the interior and exterior of the outer conical thermal shield and the interior surface of the inner conformal thermal shield. The interior surface of the inner conformal thermal shield is coated with bare silver. As mentioned above, the modeling of this package yields an acceptable thermal gradient from tip to front face, and an acceptable Far Field Diffraction Pattern (FFDP) through an entire lunation.

Recently, the potential opportunity to obtain a ride with one or more of the Google Lunar X Prize Landers has pushed for a reduction in the envelope of the LLRRA-21 package. To this end, we have investigated the performance of a package with a sunshade that has a length of 100 mm. In particular, we address the temperature behavior of the housing (illustrated in the following graphs in a sky blue color), the CCR (grey), the inner conformal shield (red) and most important, the temperature gradient in the CCR from the back tip to the front face (black). The temperature of the first three are indicated by the axis on the left in degrees Kelvin and the temperature gradient is indicated by the axis on the right, again in degrees Kelvin.

We may first address one of the early approaches. In this case, the interior of the sun shade has a black coating (Figure 43). This has the advantage that none of the solar energy in the visible is reflected down onto the CCR. This would increase the temperature gradient.

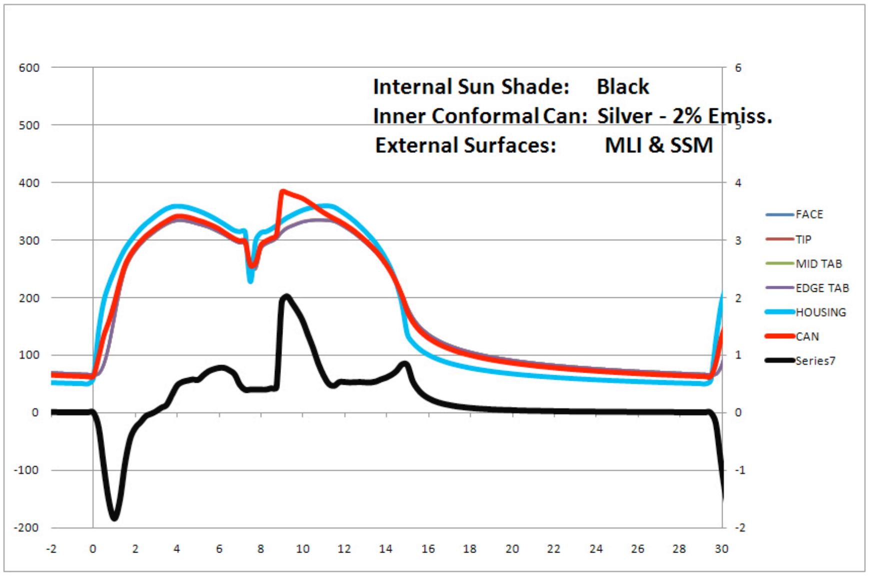


Figure 43: *Described above.*

Generally, we aim to keep the tip to front face gradient less than one degree Kelvin. The x-axis is the number of days after sun rise at the location of the package. On Day 1, there is a strong negative gradient. This is due to the sun falling on the exterior of the sun shade, rising to a high temperature, radiating this heat to the front face of the CCR, and this increase thermal energy propagation into the CCR. On Day 10 after sunrise, the sun enters the sun shade at such an angle that there is a failure of the total internal reflection at the back of the CCR. The solar energy then propagates onto the inner thermal shield and heats the shield. Despite the low emissivity of the gold coating, it reradiates to the CCR and produces a spike in the thermal gradient. Note that this is the reason we went to a sunshade that is 200 mm in length, since this reduces the breakthrough spike to less than one degree.

Our main objective is to reduce the Day 1 spike. To this end, we investigate coatings that appear black in the visible and have very low emissivity in the infrared. If we go in the other direction, that is, use gold as a low emissivity coating, we obtain the following temperatures (Figure 44).

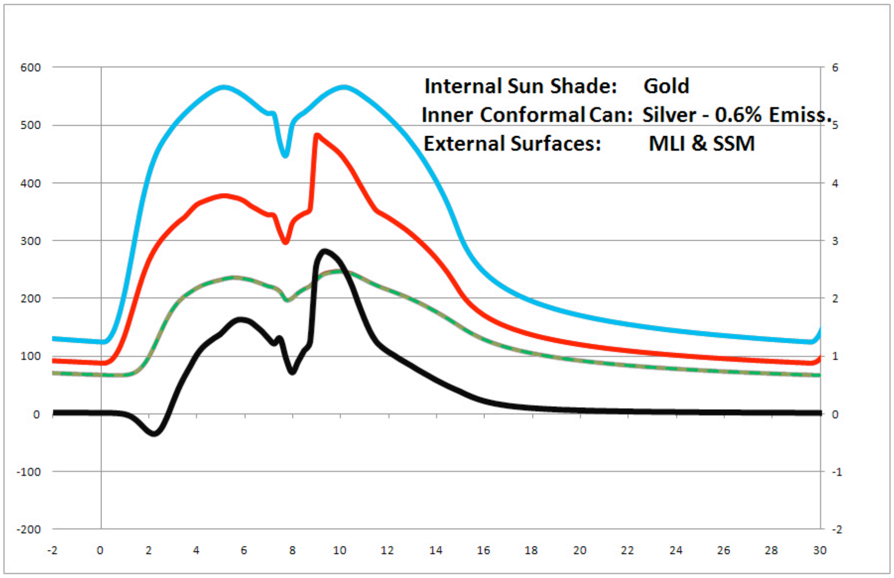


Figure 44: *Described above.*

Now we get a much worse behavior since the gold absorbs 30% of the solar radiation and then re-radiates it to the CCR. There is a coating, the GSFC Dark Mirror that has properties in this direction. However, upon discussions with the fabricators of this coating, it cannot be deposited on the inside of the sun shade. It would have to be deposited on Mylar and then fastened to the interior of the sunshade. This may create a vulnerability to the lunar environment and limit the lifetime of the LLRRA-21. This will be considered as a backup. We have also designed a serrated coating that appears to provide the properties, but has not been fully simulated. However, in order to determine the expected behavior, an initial simulation has been accomplished. We now replace the gold with a perfect Dark Mirror, that is, no absorption in the visible and no emissivity in the infrared. This Ex Dark Mirror will not be fully implemented with our serrated coating, but we will include realistic values when the full simulation of the Serrated Dark Mirror is completed (Figure 45).

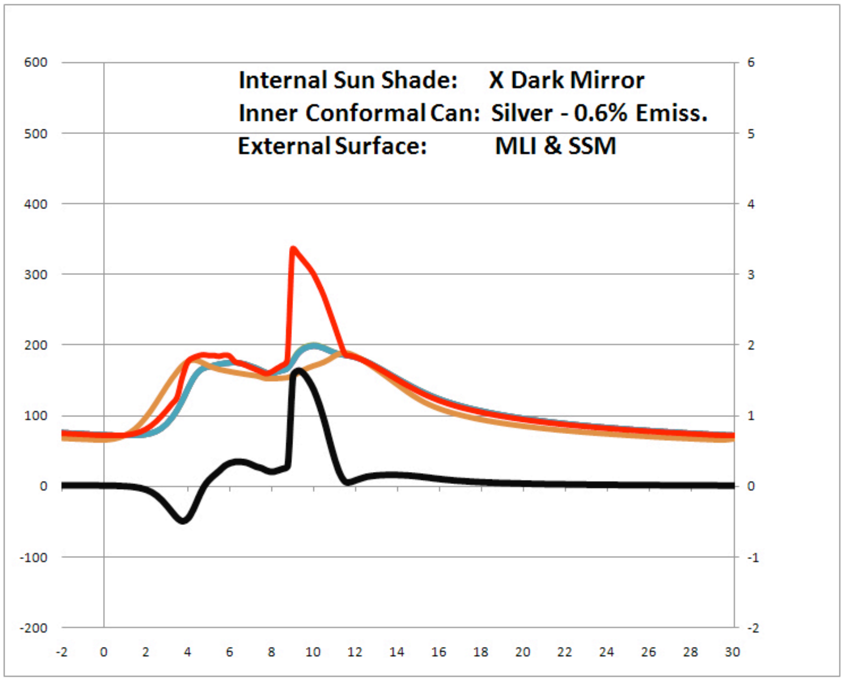


Figure 45: *Described above.*

The exterior surfaces are assumed to be covered with MLI in which the external surface is a Second Surface Mirror (SSM) with silver in the interior of the SSM. In order to determine if the MLI is necessary, we rang a simulation without the MLI but with the SSM. This is shown in (Figure 46)

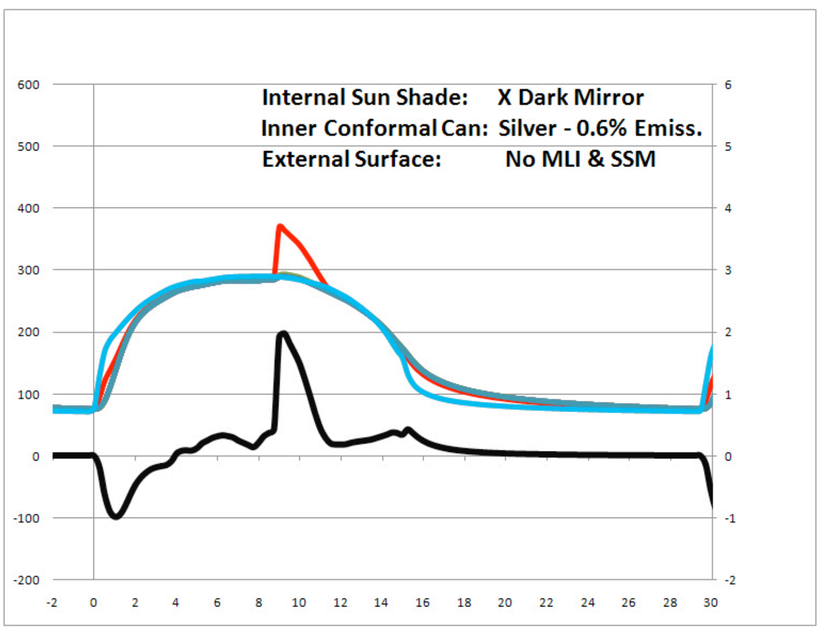


Figure 46: *Described above.*

This results in a higher overall temperature, so the MLI is providing a very useful contribution. Note that in all of these, the spike due to TIR breakthrough has remained large. This is due to the assumption of a sunshade that is 100 mm in length. The 200 mm sunshade greatly reduces the magnitude of this. Therefore, the reduction of the length of the sunshade does not seem to be advisable.

It is necessary to first define the optimal aberration correction and thermal figuring and then compare the simulations. The various angle offset have been explored, and the simulated FFDPs have been generated. This has resulted in the selection of an offset of 0.2 arc seconds. This may be done on either one or two of the back surfaces. We have also investigated the possible role of Thermal Figuring of the front face of the CCR. However, analysis and simulations indicate that this is inferior in signal return to the offset angles. And thus we will look to procure a second CCR with optimal offset angels and thermal figuring.

Currently the optimal choice of material for the CCR will be SupraSil 311 Plus, from Hereaus. We aim to independently verify the design specifications for this material. During the next thermal vacuum test in the SCF at Frascati, Italy, the uniformity of the existing flight configuration CCR will SupraSil 1, not 311 Plus. So it will be a measurement of the material that is not as uniform as 311 Plus. However, we will then have the data to scale to the uniformity of 311 Plus, using the measured data on SupraSil 1 and the manufacturer's data on both SupraSil 1 and 311 Plus. We have been in the process of running return simulations for the manufactured parameters. The aim for this is to develop and test a procedure to supplement the manufacturing procedures. Since the angles we require have been demonstrated but are at the edge of the state of the art, we want to define and test (on the next CCR to be fabricated) for the manufacturer to send us the measurements for the angles, and then by simulation, define an iterative procedure to optimize the FFDP and thus the return.

Another component of the next generation CCR has been design and testing of a pneumatic drilling system to help isolate the CCR's on the lunar surface. We have also begun designing modifications for the pneumatic drill for use on a rover. The contract to accomplish this has just recently been put in place. A preliminary design, based on another similar concept has been completed and indicates that the procedure for the LLRRA-21 should be feasible. We are investigating the fabrication of the pneumatic drill core and discussions have been held with SSG, a division of L-3 that fabricates silicon carbide. They believe that the core should be feasible, and we will be getting cost and schedule estimates from them in the near future. (Figure 47).

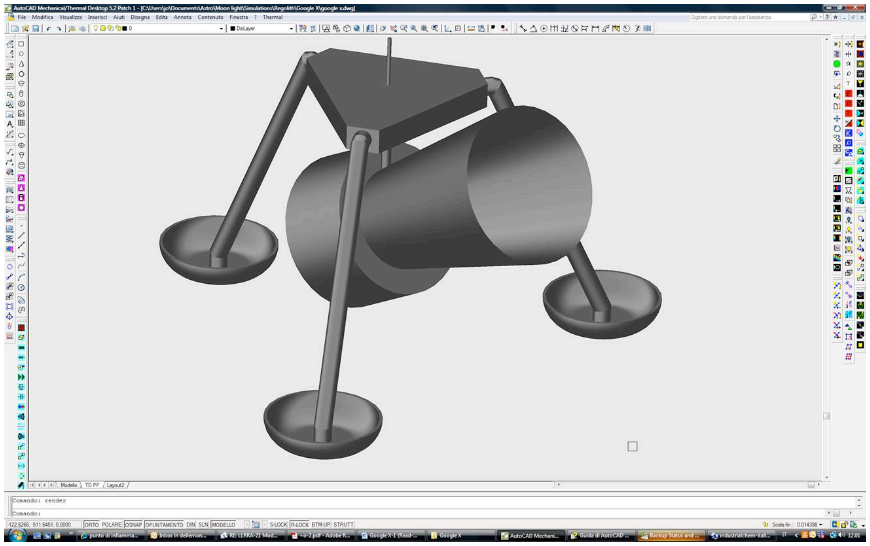


Figure 47: *Shown is a frame that has been designed for surface deployment.*

There are three angles that need to be correct to ~ 1 degree. This design automatically (by sensing the direction of local gravity) operates correctly at two. The third azimutial angle is to be adjusted by the arm of the Lander, observing the "sun dial" on the top. This is the same method that was used very successfully for the Apollo arrays. The fabrication of this Surface Deployment Frame is currently being priced and scheduled by SSG-L-3. It has been entered into the thermal analysis program, but not yet simulated. In our development to design a house away from the sub earth point we found that mushroom design was applicable. The above design is applicable to any latitude.

Although not a part of our original goals we found it necessary to develop coatings to enhance the inner shield surface. This task has been accomplished. While the GSFC Dark Mirror would be suitable, it is the best commercially available candidate. On the other hand, we have defined the serrated inner surface. However, this has not yet been optically or thermal simulated. This is in progress. We are actively performing computer simulations to evaluate different surface coatings. In addition, the use of silver coating for the interior of the inner thermal shield was proposed and verified to be the optimal coating. This reflects the excess solar energy out the CCR into space. This has been optically and thermally simulated and greatly improves the performance. A prototype of the inner thermal shield has been fabricated. The next step will be to perform thermal vacuum tests.

A field test of the pneumatic drill was performed at the CSA/NASA/DRL test site at Mauna Kea, Hawaii, Hawaii in January. This was successful. The pneumatic drill, weighted only by the CCR and the CCR housing, penetrated to about one meter when the compressed air was injected in the tip of the drill bit.

LUNAR Workshop on “Robotic Science From the Moon: Gravitational Physics, Heliophysics and Cosmology”

One of the goals of the LUNAR team, as outlined in the proposal to NLSI, was to host a series of workshops on the topic of Science from the Moon. The first such workshop, entitled "Robotic Science from the Moon: Gravitational Physics, Heliophysics, and Cosmology," was held in Boulder, CO, on 2010 October 5-6 with over 60 registrations from astronomers, planetary scientists, physicists, and engineers. The Web site for the workshop is (http://lunar.colorado.edu/workshopstuff.php), and all of the papers presented at the workshop are now archived there.

The workshop was organized into 6 sessions, with an invited lunch time talk and an evening event at the University of Colorado's Fiske Planetarium. The 6 scientific sessions focused on various aspects of the work in which the LUNAR team is engaged. Because the work of the LUNAR team is presented elsewhere in this report, highlights of presentations from people not on the LUNAR team are given here.

There were 2 sessions on cosmology and astrophysics that can be extracted from observations of the 21-cm hydrogen line originating from the intergalactic medium during and before the epoch of formation of the first stars. Talks in this session included a summary of what is known currently from observations by the Wilkinson Microwave Anisotropy Probe (WMAP, by M. Shull) and what can be expected from the James Webb Space Telescope (JWST, by R. Windhorst).

There was a well-received session on the gravitational physics that can be extracted from lunar laser ranging. Talks in this session included an illustration of how lunar laser ranging studies complement observations that will be performed by the Laser Interferometer Space Array (LISA, by P. Bender).

There was an interesting session on studies of the Sun via Radio Heliophysics. Talks in this session included an overview of what is known from current spacecraft observations and what open questions remain, such as could be answered by a future lunar radio array (by S. Bale).

There were also sessions on Education & Public Outreach and the Dark Ages Radio Explorer (DARE), both of which are covered elsewhere in this report.

The lunch time talk on the first day was on the topic of the status of the Orion capsule. While designed originally as a crew module for human exploration of the Moon, its mission has broadened due to recent changes in U.S. space policy. The main focus of the Orion capsule continues to be for human exploration, but there was also discussion about the extent to which robotic science packages might be able to be transported by it to the neighborhood of the Moon.

Finally, there was a preview of a planetarium show that is being developed by the LUNAR EPO team at the University of Colorado. This show is based on the book, *Max Goes to the Moon*. The presentation included a reading of the book by its author Jeffrey Bennett, who also explained how the story is structured to be based on the current best science while still being an exciting fictional story for children.

LUNAR EPO

Teacher Workshops

Our EPO plan called for running one teacher workshop during summer 2010, with attendance budgeted for 15 teachers. However, by joining with the Astronomical Society of the Pacific we became part of the national meeting, "Cosmos in the Classroom," which was held at the University of Colorado, with LUNAR EPO lead Doug Duncan as Chair of the Local Organizing Committee. This allowed us to draw approximately 50 teachers, and break them into elementary, middle school, and high school groups. The LUNAR team's Matt Benjamin and Doug Duncan taught at the workshops. As specified in our work plan, we created some new materials and also took advantage of good materials created by NASA and by other educators who participated in the ASP meeting (Figure 51 & 52).

Figures 51 & 52: *Shows K-12 teachers at Fiske Planetarium between workshop sessions.*

A particularly successful activity was developed to explain cosmic "lookback time," the idea that the farther astronomers look into the universe, the older the light they are seeing, but the *younger* the universe looks. This is very important to LUNAR since we hope to see the universe before any stars or galaxies formed. The activity paired photos of older and older galaxies with old photos of the astronomer leading the activity. Students recognized that "old photos show young people" and that analogy was used to explain "old light shows young objects in the universe." (Figure 53 & 54)

Figures 53 & 54: *show the workshop activity designed to help explain the concept of "lookback time".*

Every teacher who attended received an inexpensive "Galileoscope" telescope they could keep and practiced observing the moon. Activities related to understanding cosmology – and the role of observations from the moon, were also taught. The very impressive "Science on a Sphere" at Fiske Planetarium was used to display lunar data. A "NASA Nugget" was submitted about this meeting and its workshops. (Figure 55)

Figure 55: *Described above.*

<u>Total Eclipse of the Moon</u>

Although not part of our EPO plan, we decided to take advantage of the December 2010 Lunar Eclipse. Many telescopes were set up at Fiske Planetarium and Sommers Bausch Observatory at the University of Colorado. Local amateur astronomers were invited to set up more. Denver and Boulder TV stations were told about the eclipse well in advance, and decided to cover it from Fiske, rather than a location in Denver. The combined publicity resulted in crowds that overfilled the Planetarium and Observatory three times their capacity. Campus police kept order, and with so many telescopes and binoculars (and with clouds that cleared at just the critical time) everyone saw the eclipse.

As we had planned, LUNAR team member Matt Benjamin presented a program in the planetarium theater that not only explained the eclipse but also highlighted and explained the science planned by Dr. Jack Burns NLSI LUNAR team. He repeated the program three times in order to accommodate the large crowds. (Figures 5)

Figure 5: *A picture our planetarium theater full of people to hear a talk at our outreach event celebrating the Dec. 2010 total lunar eclipse.*

Planetarium program "Max Goes to the Moon"

This is a children's show. Recording of the script is being done in February 2011. Artwork and programming are to follow, with a completion date targeted for summer 2011. This is approximately 6 months behind our original schedule, but work is now proceeding. The slowdown was primarily due to determining how to show artwork when we found that there is no access to the artist who illustrated the book. We have developed the ability to "green screen" a person with any background, just like on TV, and we plan to use this to illustrate "Max."

Robotics Clubs Lunar Rovers

The EPO work plan calls for us to recruit a second school to build a lunar-antenna deploying robot this year. Thanks to NLSI central, we received enough funds to support 3 schools. As of early 2011 we have request from 3 teachers and are buying Kapton film to distribute to them along with funds for parts to build robots.

LUNAR Brochure

Following our first annual "Robotics Science From the Moon" workshop, LUNAR designed and printed its own brochure for use at workshops, conferences and other EPO activities. We had these ready for distribution for the January 2011 AAS meeting in Seattle, Washington. Electronic versions of the brochure can be found on the LUNAR website (http://lunar.colorado.edu) (Figure 56)

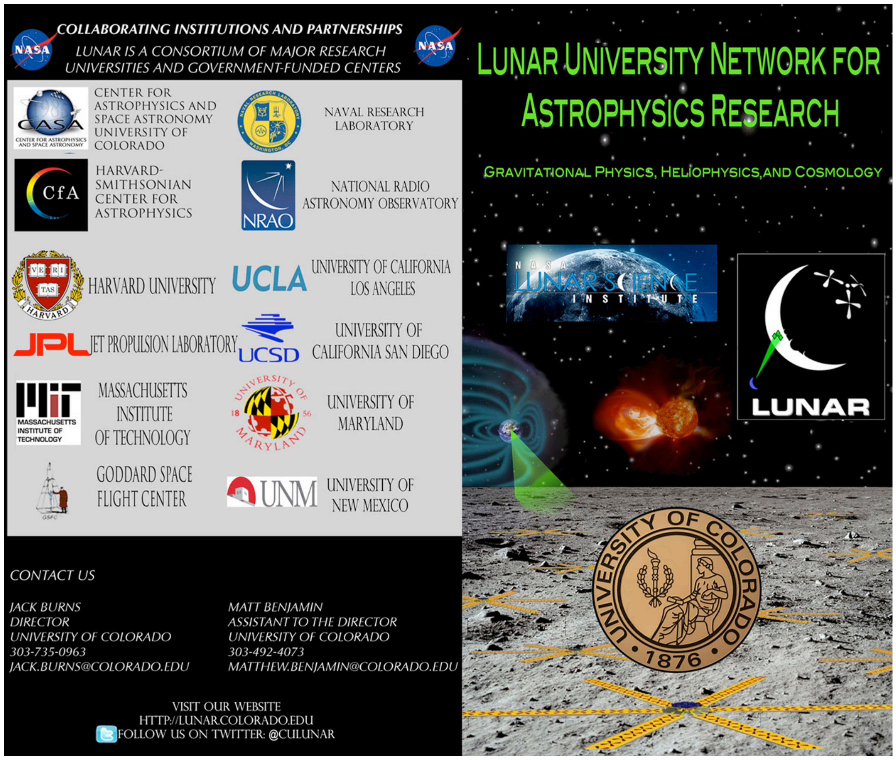


Figure 56: *Shows the front and back covers of our LUNAR brochure.*

Publications

Peer-reviewed Publications

Adshead, P., Easther, R., Pritchard, J., & Loeb, A. 2010, “Inflation and the Scale Dependent Spectral Index: Prospects and Strategies,” submitted; http://arxiv.org/abs/1007.3748

Bernardi, G., de Bruyn, A. G., Harker, G., et al. 2010, “Foregrounds for observations of the cosmological 21 cm line. II. Westerbork observations of the fields around 3C 196 and the North Celestial Pole,” Astron. & Astrophys., 522, A67

Bittner, J., & Loeb, A. 2010, “Measuring the Redshift of Reionization with a Modest Array of Low-Frequency Dipoles,” submitted; http://arxiv.org/abs/1006.5460

Bowman, J. D. & Rogers, A. E. E. 2010, “A lower limit of $\Delta z > 0.06$ for the duration of the reionization epoch,” Nature, 468, 796

Burns, J. O., Skillman, S. W., & O'Shea, B. W. 2010, “Galaxy Clusters at the Edge: Temperature, Entropy, and Gas Dynamics Near the Virial Radius,” Astrophys. J., 721,1105

Crociani, D., Mesinger, A., Moscardini, L., & Furlanetto, S. 2010, “The distribution of Lyman-limit absorption systems during and after Reionization,” Mon. Not. R. Astron. Soc, in press

Currie D, Dell’Agnello S, Delle Monache G, A Lunar Laser Ranging Retroreflector for the 21st Century Acta Astronautica 68 (2011) 667–680

Datta, A., Bowman, J. D., & Carilli, C. L. 2010, “Bright Source Subtraction Requirements for Redshifted 21 cm Measurements,” Astrophys. J., 724, 526

de Oliveira-Costa, A., & Lazio, J. 2010, “Clustering of Extragalactic Sources from 151 MHz to 232 MHz: Implications for Cosmological 21-cm Observations,” Mon. Not. R. Astron. Soc., submitted; arXiv:1004.3167

Dell’Agnello S, Lops C, Giovanni O. Delle Monache, Douglas G. Currie, Manuele Martini, Roberto Vittori, Angioletta Coradini, Cesare Dionisio, Marco Garattini, Alessandro Boni, Claudio Cantone, Riccardo March, Giovanni Bellettini, Roberto Tauraso, Mauro Maiello, Luca Porcelli, Simone Berardi, Nicola Intaglietta “Probing Gravitational Physics with Lunar Laser Ranging” a chapter for the Book *“Moon: Geological Characteristics, Physical Characteristics and Exploration”,* edited by Navapublishers press.In process

Furlanetto, S. R., Stoever, S. J. 2010, "Secondary ionization and heating by fast electrons," Mon. Not. R. Astron. Soc., 404, 1869

Harker, G., Zaroubi, S., Bernardi, G., et al. 2010, "Power spectrum extraction for redshifted 21 cm Epoch of Reionization experiments: the LOFAR case," Mon. Not. R. Astron. Soc., 405, 2492

Lazio, T. J. W., Clarke, T. E., Lane, W. M., et al. 2010, "Surveying the Dynamic Radio Sky with the Long Wavelength Demonstrator Array," Astron. J., 140, 1995

Lazio, T. J. W., Shankland, P. D., Farrell, W. M., & Blank, D. L. 2010, "Radio Observations of HD 80606 Near Planetary Periastron," Astron. J., 140, 1929

Hallman, E. J., Skillman, S. W., Jeltema, T. E., Smith, B. D., O'Shea, B. W., Burns, J. O., & Norman, M. L. 2010, "The Properties of X-ray Cold Fronts in a Statistical Sample of Simulated Galaxy Clusters," Astrophys. J., 725, 1053

MacDowall R.J, T. J. Lazio, S. D. Bale, J. Burns, W. M. Farrell, N. Gopalswamy, D. L. Jones, and K.W. Weiler, "A Radio Observatory on the Lunar Surface for Solar Studies (ROLSS)," White Paper submitted to the NASA Solar and Space Physics Decadal Review 2010.

MacDowall R.J, T. J. Lazio, S. D. Bale, J. Burns, N. Gopalswamy, D. L. Jones, M. L. Kaiser, J. C. Kasper, K W. Weiler, "Observing Solar Bursts from the Lunar Surface," Proceedings of the 7th Planetary Radio Emissions Conference, Graz, Austria, 2010.

Mesinger, A., Furlanetto, S., & Cen, R. 2010, "21CMFAST: a fast, seminumerical simulation of the high-redshift 21-cm signal," Mon. Not. R. Astron. Soc., in press

Mirabel, I. F., Dijkstra, M., Laurent, P., Loeb, A., & Pritchard, J. R. 2011, "Stellar black holes at the dawn of the universe," Astron. & Astrophys., in press

Muñoz, J. A., & Loeb, A. 2010, "Constraining the Minimum Mass of High-Redshift Galaxies and Their Contribution to the Ionization State of the IGM," Astrophys. J., submitted; arXiv:1010.2260

Oberoi, D., Matthews, L. D., Cairns, I. H., et al. 2011, "First Spectroscopic Imaging Observations of the Sun at Low Radio Frequencies with the Murchison Widefield Array Prototype," Astrophys. J., 728, L27

Ord, S. M., Mitchell, D. A., Wayth, R. B., et al. 2010, "Interferometric Imaging with the 32 Element Murchison Wide-Field Array," Publ. Astron. Soc. Pacific, 122, 1353

Parsons, A. R., Backer, D. C., Foster, G. S., et al. 2010, "The Precision Array for Probing the Epoch of Re-ionization: Eight Station Results," Astron. J., 139, 1468

Peters, W. M., Lazio, T. J. W., Clarke, T. E., Erickson, W. C., & Kassim, N. E. 2010, "Radio recombination lines at decametre wavelengths. Prospects for the future," Astron. & Astrophys., 525, A128

Pritchard, J., & Loeb, A. 2010, "Constraining the unexplored period between reionization and the dark ages with observations of the global 21 cm signal," Phys. Rev. D82, 023006

Pritchard, J., & Loeb, A. 2010, "Cosmology: Hydrogen was not ionized abruptly," Nature, 468, 772

Pritchard, J. R., Loeb, A., & Wyithe, J. S. B. 2010, "Constraining reionization using 21 cm observations in combination with CMB and Lya forest data," Mon. Not. R. Astron. Soc., 408, 57

Santos, M. G., Silva, M. B., Pritchard, J. R., Cen, R., & Cooray, A. 2011, "Probing the first galaxies with the Square Kilometer Array," Astron. & Astrophys., 527, A93

Skillman, S. W., Hallman, E. J., O'Shea, B. W., Burns, J. O., Smith, B. D., Turk, M. J. 2010, "Galaxy Cluster Radio Relics in Adaptive Mesh Refinement CosmologicalSimulations: Relic Properties and Scaling Relationships," Astrophys. J., in press

Visbal, E., & Loeb, A. 2010, "Measuring the 3D clustering of undetected galaxies through cross correlation of their cumulative flux fluctuations from multiple spectral lines," J. Cosmol. Astropart. Phys., 11, 16

Wyithe, S., & Loeb, A. 2010, "Extrapolating the Evolution of Galaxy Sizes to the Epoch of Reionization," Astrophys. J., submitted; arXiv:1011.3210

Zeiger, B., & Darling, J. 2010, "Formaldehyde Anti-Inversion at $z = 0.68$ in the Gravitational Lens B0218+357," ApJ, 709, 386

Conference Proceedings, Abstracts

Bowman, J. D., & Rogers, A. E. E. 2011, "Results From EDGES," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Bowman, J. D., & Rogers, A. E. E. 2010, "VHF-band RFI in Geographically Remote Areas," Proceedings of Science

Burns, J. O., Lazio, J., Bowman, J., Bradley, R., Carilli, C., Furlanetto, S., Harker, G., Loeb, A., & Pritchard, J. 2011, "The Dark Ages Radio Explorer (DARE)," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Burns, J., & Mirocha, J. 2010, "Preliminary Results from Numerical Simulations of Xray Heating in the Dark Ages", in Astrophysics & Cosmology with the 21-cm Background*,* Aspen Center for Physics, Aspen, CO

Burns, J. O., & Skillman, S. W. 2011, "Cosmological Numerical Simulations of Radio Relics in Galaxy Clusters: Insights for Future Observations," in Non-Thermal Phenomena in Colliding Galaxy Clusters; arXiv:1101.3361

Currie, D. G., , the LLRRA-21/LSSO Team & the MoonLIGHT/INFN-LNF Team 2010, "A Lunar Laser Ranging RetroReflector Array for the 21st Century" 40th Lunar and Planetary Science Conference, The Woodlands, TX 1

Currie, D. G., Zacny, K., 2010 Regolith Drilling for the Lunar Laser Ranging Retroreflector Array for the 21st Century, LUNAR Workshop, Cambridge MA

Currie, D. G., & The LLRRA-21 Teams 2010 "A LUNAR LASER RANGING RETRO REFLECTOR ARRAY for the 21st CENTURY" LUNAR Workshop Boulder CO

Currie, D. G., Dell'Agnello, S. & Delle Monache, G. O. 2010 A Lunar Laser Ranging Retroreflector Array for the 21st Century ISOT 2010 International Symposium on Optomechatronic Technologies, Toronto, Canada

Currie, D. G., Zacny, K., the LLRRA-21/LSSO Team & the MoonLIGHT/INFN-LNF Team 2010 "A Lunar Laser Ranging RetroReflector Array for the 21st Century" Lunar Exploration Analysis Group Washington DC.

Currie, D. G., Delle Monache & G. O. Dell'Agnello, S. 2010 "A Lunar Laser Retroreflector for the FOR the 21ST Century (LLRRA-21): Selenodesy, Science and Status" 2010 American Geophysical Union Fall Meeting San Francisco, CA

Currie, D. G., & the LLRRA-21 Teams 2011 "A LUNAR LASER RANGING RETRO REFLECTOR ARRAY for the 21st CENTURY" 2nd Lunar Laser Ranging Workshop, International Space Sciences Institute, Bern Switzerland

Currie, D. G., Dell'Agnello, S. & Delle Monache, G. O. 2011 "LUNAR LASER RANGING: FLIGHT HARDWARE SIMULATION, TESTING AND STATUS". Lunar and Planetary Science Conference, The Woodlands, TX ,

Dell'Agnello, S., Delle Monache, G. O., Currie, D. G., Martini, M., Lops, C., Garattini, M., March, R., Bellettini, G., Tauraso, R., Battat, J. B. Bianco, G., Murphy Jr., T. W. , Coradini, A., Chandler, J. F., Boni, A., Cantone, C., Maiello, M., Porcelli, L., Berardi, S., Intaglietta, N., Patrizi, G., & McElfresh D. "The Moon as a test body for General Relativity and new gravitational theories" presented at the conference European Planetary Science Congress 2010 (ESPC2010) at the Angelicum Centre – Pontifical University of Saint Thomas Aquinas, Rome, Italy.

Dell'Agnello, S. , Currie, D. G. , Delle Monache, G. O. Cantone, C. Garattini, M. Martini, M. Intaglietta, N. Lops C. , March, R , Tauraso, R, Bellettini G. , Maiello, M , Berardi, S. , Porcelli, L.; "Next Generation Lunar Laser Ranging and its GNSS Applications"; IEEE Aerospace Conference, Big Sky (MT), USA,

D'Addario, L. 2011, "A Strawman Correlator for the SKA," in 2011 URSI U.S. National Radio Science Meeting, Boulder, CO

Jones, D. L. 2011, "Low-Mass Transmission Lines for a Lunar Low Frequency Array," in IEEE Aerospace Conference 2011, Big Sky, MO

Jones, D. L. 2010, "Loss in Transmission Lines from Low Frequency Lunar Array Dipoles," in NASA Lunar Science Forum, NASA/Ames Research Center

Kassim, N., White, S., Rodriquez, P., Hartman, J., Hicks, B., Lazio, J., Stewart, K., Craig, J., Taylor, G., Cormier, C., Romero, V., & Jenet, F. 2010, "The Long Wavelength Array (LWA): A Large HF/VHF Array for Solar Physics, Ionospheric Science, and Solar Radar," in Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, ed. S. Ryan, Maui, HI

Kruger, L., Burns, J., Alfaro, R., & Lettang, F. 2010, "Exploration of the Dark Ages: An Investigation into Kapton's Suitability as a Radio Telescope Material," NASA Lunar Science Forum, NASA/Ames Research Center

Lazio, T. J. W., Shankland, P. D., Farrell, W. M., & Blank, D. L. 2011, "Radio Observations of HD 80606 Near Planetary Periastron," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Lazio, J. 2010, "Transient Phenomena: Opportunities for New Discoveries," in Joint European National Astronomy Meeting, Lisbon, Portugal

Mirocha, J., & Burns, J. 2010, "Cosmological Simulations of the Dark Ages & the Epoch of Reionization", in The High Redshift Universe*,* Aspen Center for Physics, Aspen, CO

Mirocha, J., Burns, J., Hallman, J., Wise, J., & Furlanetto, S. 2010, "Cosmological Numerical Simulations of X-ray Heating During the Universe's Dark Ages: Predictions for Observations with a Lunar Farside Radio Telescope," in NASA Lunar Science Institute Forum, NASA/Ames Research Center

Mitchell, D. A., Greenhill, L. J., Ord, S. M., et al. 2010, "The Murchison Widefield Array," Proceedings of Science

Pober, J., Parsons, A., Backer, D., et al. 2011, "The Precision Array for Probing the Epoch of Reionization," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Pritchard, J. 2010, "H I Science through Cosmic Time," Aperture Array Verification Programme 2010: Realising the Aperture Array Programme for SKA, Cambridge, UK

Pritchard, J. 2011, "Exploring the Dawn of Structure with the Redshifted 21 cm Signal," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Pritchard, J. R., & Loeb, A. 2011, "Extracting The Astrophysics Of The First Sources From The 21 Cm Global Signal," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Pritchard, J. 2010, "Lessons from constraining the global 21 cm spectrum in the presenceof foregrounds," in "The First Billion Years," Keck Institute of Space Studies, Pasadena CA

Pritchard, J. 2010, "Pre-reionization 21 cm Signatures," in Astrophysics & Cosmology with the 21 cm Background, Aspen, CO

Pritchard, J. 2010, "Extracting Science from the Global 21 cm Signal," in Astrophysics and Cosmology with the 21 cm Background, Aspen, CO

Pritchard, J. 2010, "Atomic Physics and the 21 cm Line," in DAMOP2010, Houston T Salvesen, G., Henning, J. W., Skillman, S. W., & Burns, J. O. 2011, "Shocks in Galaxy Cluster X-ray Temperature Images," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Simmons, S., & D'Addario, L. 2011, "Signal Processing for a Lunar Array: Minimizing Power Consumption," in 2011 URSI U.S. National Radio Science Meeting, Boulder, CO

Stewart, K. P., Hicks, B. C., Paravastu, N., MacDowall, R., Jones D., Gross, C., Lazio, J., & Weiler, K. W. 2010, "Numerical Simulations of the Lunar Polyimide Film Antennas," in NASA Lunar Science Forum, NASA Ames Research Center

Taylor, G. B., Tremblay, S. E., Pihlstrom, Y., et al. 2011, "An Update on the Long Wavelength Array," Amer. Astron. Soc. 217th Meeting, Seattle, WA

Traub, W. A., Lawson, P. R., Unwin, S. C., et al. 2010, "Exoplanets Forum 2008," in Pathways Towards Habitable Planets, eds. V. Coudé du Foresto, D. M. Gelino, & I. Ribas (San Francisco: Astron. Soc. Pacific) p. 21

Colloquia and Public Presentations

Burns, J. 2010, "Exploring the Cosmos from the Moon," scientific colloquium, Naval Research Laboratory, Washington, DC

Burns, J. 2010, "Exploring the Cosmos from the Moon," scientific colloquium, MichiganState University, East Lansing, MI

Burns, J. 2010, "Exploring the Cosmos from the Moon," scientific colloquium, University of Michigan, Ann Arbor, MI

Burns, J. 2010, invited public lecture, Aspen Winter Conference on The High Redshift Universe, Aspen, CO

Burns, J. 2010, invited public lecture, Florida Institute of Human & Machine Cognition, Pensacola, FL

Burns, J. 2010, invited public lecture, Nonthermal Phenomena in Colliding Galaxy Clusters, Nice, France

Czekala, I., & Bradley, R. 2010, "Calibrating Astronomical Antenna Arrays with Man Made Satellites," American Institute of Aeronautics & Astronautics (AIAA), Region I-MA Student Conference, Blacksburg, VA

Czekala, I., & Bradley, R. 2010, "Calibrating Astronomical Antenna Arrays with Orbiting Data Satellites, Atlantic Coast Conference (ACC) "Meeting of the Minds" Conference, Atlanta, GA

Currie, D. G., & the LLRRA-21 Teams 2011 "A LUNAR LASER RANGING RETRO REFLECTOR ARRAY for the 21st CENTURY" 2nd Lunar Laser Ranging Workshop, International Space Sciences Institute, Bern Switzerland

Dell'Agnello, S.; Currie, D. G.; Delle Monache, G. O.; Lops, C.; M. Martini 2010 "LLRRA21/MoonLIGHT: a 2nd Generation Lunar Laser Ranging Array for Precision Gravity Tests and Lunar Science Measurements" at the Conference Global Lunar Conference – Beijing, China.
Furlanetto, S. 2011, "Cosmic Dawn: The Birth of the First Galaxies," Santa Monica Amateur Astronomy Club, Santa Monica, CA
Furlanetto, S. 2010, "Cosmic Dawn: The Birth of the First Galaxies," Los Angeles Astronomical Society, Los Angeles, CA
Furlanetto, S. 2010, "Cosmic Dawn: The Birth of the First Galaxies," Friends of the Mt. Wilson Observatory, Altadena, CA
Furlanetto, S. 2010, "The Redshifted 21 cm Signal," The First Billion Years (Keck Institute of Space Studies, California Institute of Technology), Pasadena, CA
Furlanetto, S. 2010, "Cosmology at Low Radio Frequencies," scientific colloquium, Aspen Center for Physics, Aspen, CO
Furlanetto, S. 2010, "Cosmology at Low Radio Frequencies," cosmology & astrophysics seminar, University of Pennsylvania, Philadelphia, PA
Lazio, J. 2010, "Magnetospheric Emissions from Extrasolar Planets," scientific colloquium, National Radio Astronomy Observatory, Green Bank, WV
Lazio, J. 2010, "Magnetospheric Emissions from Extrasolar Planets," Aperture Array Verification Programme, Cambridge, United Kingdom
Loeb, A. 2010, "The First Stars," conference opening lecture, Austin, TX
Loeb, A. 2010, "The First Stars," conference banquet lecture, Pennsylvania State University, State College, PA
Loeb, A. 2010, "How Did the First Stars and Galaxies Form?" Harvard Physics Department, Cambridge, MA
Loeb, A. 2010, "How Did the First Stars and Galaxies Form?" Munich Cosmology Colloquium, Munich, Germany
Loeb, A. 2010, "How Did the First Stars and Galaxies Form?" scientific colloquium, Tel Aviv University, Tel Aviv, Israel
Loeb, A. 2010, "How Did the First Stars and Galaxies Form?" scientific colloquium, Hebrew University, Jerusalem, Israel
Loeb, A. 2010, "The First Light," Galaxy Evolution, Potsdam, Germany
Loeb, A. 2010, "The First Light," Texas Symposium 2010, Heidelberg, Germany
Pritchard, J. 2010, scientific colloquium, University of California, Berkeley, Berkeley, CA
Pritchard, J. 2010, scientific colloquium, Cambridge University, Cambridge, United Kingdom
Pritchard, J. 2010, scientific colloquium, Carnegie Mellon, Pittsburgh, PA
Pritchard, J. 2010, scientific colloquium, University of Chicago, Chicago, IL
Pritchard, J. 2010, scientific colloquium, Oxford University, Oxford, United Kingdom
Pritchard, J. 2010, scientific colloquium, Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
Pritchard, J. 2010, scientific colloquium, Yale University, New Haven, CT
Pritchard, J. 2010, scientific colloquium, University of Waterloo, Waterloo, Ontario, Canada