A Search for Energetic Neutrinos that Impact the Moon: Blending Frontier Science with Advanced Instrument Development

PI: Rich Bradley, NRAO Charlottesville
Co-PI: Glen Langston, NRAO Green Bank
Co-I: Tim Hankins, NRAO Socorro
Co-I: Bob Mutel, University of Iowa

April 15, 2007

Executive Summary

We propose constructing a feed array, multi-beam receiver, combined with existing FPGA back-end hardware to address a fundamental question of Cosmology and Particle Physics. The 2003 NRC review document, "Connecting Quarks with the Cosmos," identifies eleven top questions for the new Century. The NRC document posses the following question: "What Are the Masses of the Neutrinos, and How Have They Shaped the Evolution of the Universe? Cosmology tells us that neutrinos must be abundantly present in the universe today...:" Our experiment will address the question of abundance of primordial neutrinos and those generated by Super Novas and Gamma Ray Bursts. The receiver will detect very short duration (20 nano-second) pulses of emission produced by the decay of charged particles created when a extremely high energy neutrino interacts with the Lunar surface.

We propose use of the 43-Meter telescope as the radio emission is predicted to have peak emission at 1 GHz, where the telescope beam is well matched to the angular size of the Moon. Our detection system will phase signals both on and off of the Moon simultaneously, to distinguish Lunar transient events from terrestrial RFI

We will obtain follow-on funds for scientific studies to isolate and characterize neutrinos from other sources, e.g. the Department of Energy. The technical developments associated with this instrument are well-matched to the longterm R&D initiatives at the NRAO. The requested amount for this project is $291,000.

1 Overview

High-energy neutrinos are unique messengers of some of the most extreme processes occurring throughout the universe. The detection of neutrinos with energies greater than 10^{12} eV, which is as high as current terrestrial accelerators reach, would enable the discovery of new astrophysical systems and possibly new physical processes. The lack of strong and electromagnetic interactions gives neutrinos the special ability to traverse the universe unimpeded by magnetic fields and thus point directly back to their sources. However, this same feature of the neutrino also makes them extremely difficult to detect. To date, no high-energy cosmic neutrinos have been detected.

A neutrino is detected indirectly by the energy released after it strikes a nucleon. The debris, consisting of an electron or hadrons depending on the neutrino type and mediation boson involved, produces a shower within the detector, which creates a short pulse of optical or radio radiation by way of the Cerenkov effect. To achieve sufficient sensitivity for the detection of high-energy neutrinos from distant sources, experiments require a huge amount of detector mass. The Lunar regolith provides a detector volume that is many orders of magnitude greater than can be achieved using terrestrial instruments.

Several research groups have attempted to observe such pulses from the Moon using radio telescopes, but none have been successful. We understand the limitations of these past efforts and propose to develop an instrument that is highly optimized for Lunar pulse detection and use it on the Green Bank 43-Meter telescope in a search experiment. The instrument is a 900 MHz cryogenic, full-sampling, beam-forming array. The array will be capable of synthesizing four, independent, dual-polarized beams using analog beam-forming techniques. Two beams will point directly at the Moon, a third slightly offset to the east of the Moon, and the fourth slightly offset to the west. The back-end electronics will consist of an eight-channel, high speed data sampler providing 1 ns time resolution. A real-time threshold detector will search for coincidence events in real-time and store appropriate data for further analysis.

Our primary scientific goals are threefold: 1) maximize our chances of detecting a pulse originating from the Lunar surface, 2) unambiguously differentiate these pulses from other sources, and 3) localize the direction of the incoming cosmic ray. The design of the instrument, including beam characteristics, operating frequency, bandwidth, time resolution, coincidence sampling, appropriate threshold level, duty cycle, and low receiver noise, will be optimized to efficiently achieve our goals. However, to determine what frac-

tion of these pulses are actually from neutrino events will require a follow-on observation to search for coincident events between the 43-Meter system and a conventional receiver on a larger telescope such as the GBT that is pointing at the central region of the Moon. However, no GBT time is requested as part of this proposal. Funding to support the isolation and characterization of neutrinos will be sought from other sources such as the Department of Energy.

The technical developments leading to this search instrument will make significant contributions to research and development initiatives at the NRAO. These include the development of a compact, low noise cryogenic receiver element and a closely-packed array of such elements on the focal plane. In addition, by adopting the Berkeley-CASPER IBOB/BEE2 high-speed data acquisition and signal processing system for this project, we will build on already planned efforts with this FPGA-based platform at NRAO. The array itself could also be used on the GBT for other scientific applications, and many of the technical developments leading to a successful design are applicable to the Square Kilometer Array.

In this proposal, we provide the scientific justification for a neutrino search and the motivation for using radio techniques. A short description of the proposed instrument is presented along with specifications and a summary of the data analysis objectives. Finally, we include a work plan, significant milestones, and a budget estimate.

2 Scientific Justification

What are the Masses of the Neutrinos, and How Have They Shaped the Evolution of the Universe? How Do Cosmic Accelerators Work and What are They Accelerating? What is Dark Matter? These are three of the eleven questions posed in the report Connecting Quarks with the Cosmos [1] that may, in part, be addressed by exploring the nature of cosmic neutrinos. The potential sources of high-energy neutrinos can be classified into several broad categories: astrophysical point sources, diffuse cosmic backgrounds, and new physics sources [2]. The leading candidates for high-energy neutrino point sources are extragalactic objects such as active galactic nuclei (AGNs) powered by supermassive black holes, and gamma-ray bursters (GRBs). Some AGNs can maintain high luminosities for relatively long periods of time (weeks or months) while transient objects such as GRBs can reach higher peak powers but only over short periods (10s of seconds).

An important class of AGNs are the blazars which produce high-energy

gamma radiation with a relativistic jet. If relativistic hadrons are accelerated with power comparable to that of the gamma rays, then detectable fluxes of neutrinos would be produced in the jet through pion production by nuclear and photo-hadronic interactions. When the jet is aligned with the direction of the Earth, we could detect neutrinos having energies as high as 10^{15} eV. However, if inelastic nuclear interactions are important, the neutrino spectrum is expected to reflect the spectrum of relativistic particles that reach 10^{20} eV or higher.

The observation of cosmic rays with energies in excess of 10^{20} eV reaching Earth isotropically from all directions indicates that hadrons are accelerated to ultrahigh energies in extragalactic sources. A number of ultrahigh energy accelerators, proposed to explain the origin of the highest energy cosmic rays, could also be sources of detectable neutrinos.

Some other proposed relics of the early universe, such as topological defects, can be copious emitters of neutrinos along with gamma rays and cosmic rays. The neutrinos would reach us unimpeded while the others would be severely depleted when propagating across the universe. Finally, departures from the Standard Model predictions on energy scales above 10^{12} eV might also be inferred by studying the neutrino cross-section on hadrons.

A very large collector mass is required for the detection of neutrinos. A large U.S. project currently under construction at the South Pole is IceCube. Here, one cubic kilometer of Antarctic ice is used at the detecting medium. Neutrino interactions produce upward-going muons that generate Cerenkov light that propagates through the ice to light sensors (photomultiplier tubes) spread throughout the volume. There are efforts in Europe as well, including ANTARES which makes use of Mediterranean sea water as the detecting medium. Both IceCube and ANTARES should be sensitive to neutrinos having energies up to 10^{18} eV. They are limited by the small size of the detector volume, the propagation characteristics of light through the medium, and the diffuse background neutrino flux from our atmosphere. The Pierre Auger Cosmic Ray Observatory is capable of detecting tau neutrinos but with limited visibility [3].

Neutrino interactions produce different types of showers depending on the neutrino flavor and on whether the interaction is mediated by the $W^{\pm}$ or a Z boson [4]. In deep inelastic scattering charged-current interactions of electron neutrinos, the electron produced initiates an electromagnetic shower. The debris of the nucleon initiates a hadronic shower which is superimposed on the electromagnetic shower. In the 1960's, Askaryan [5] hypothesized that during the development of a high energy electromagnetic cascade in normal matter, Compton scattering knocks electrons from the

material into the shower. In addition, positrons in the shower annihilate in flight. The combination of these processes should lead to a net 20%-30% negative charge excess for the body of particles that carry the bulk of the shower energy. Askaryan went on to show that this charge excess should lead to strong coherent radio and microwave Cerenkov emission for the showers that propagate within a dielectric. The effect was first observed in 2000 by Saltzberg *et al.* [9] using the SLAC Final Focus Test Beam into a 3.5 ton silica sand target. Zas *et al.* [6] determined the electric field strength and frequency spectrum of the electromagnetic radiation as a function of neutrino energy.

2.1 Previous Attempts at radio detection of Neutrinos

A radio instrument based on the Askaryan effect is RICE - the Radio Ice Cerenkov Experiment [7], deployed in the ice at the South Pole. It is a set of radio receivers designed to detect electron neutrinos with energies greater than 10^{15} eV. RICE complements IceCube by extending into the electron neutron sector (as opposed to tau neutrinos) and offering a detection strategy for ultra-high energies. The ratio of the effective volume of a radio receiver compared with a photomultiplier tube grows with energy such that a radio receiver offers an effective volume ten times larger than a photomultiplier for 10^{18} eV neutrinos. Although RICE is non-responsive to background muons, its sensitivity, and that of IceCube, are limited by diffuse neutrino flux within our atmosphere. To date, no clear neutrino candidates have been observed.

Askaryan was the first to suggest that the Moon could be used as a cosmic ray detector [5], [8]. The pulse duration is on the order of nanoseconds but will be dispersed to tens of nanoseconds as it propagates through the Earth's ionosphere. Detailed analysis of using the Moon as a neutrino detector is given in [4]. Two important figures are borrowed from the paper and reproduced here. The left-hand panel of Fig. 1 is a graph of the expected flux density as a function of energy for a given bandwidth. Fig. 2 shows the aperture of the Moon for cosmic ray and neutrino detection.

The first attempt to detect such pulses using a radio telescope was performed by Hankins *et al.* [10] using the Parks 64-meter in 1996. They observed th Moon for ten hours using two 100 MHz wide receiver channels spaced 200 MHz apart (around 1400 MHz) and attempted to use ionospheric dispersion to identify pulse events. No pulses were detected that met the detection criteria. Another attempt was made by Gorham *et al.* [11] (project GLUE) who searched for coincident pulses from two NASA Deep Space An-

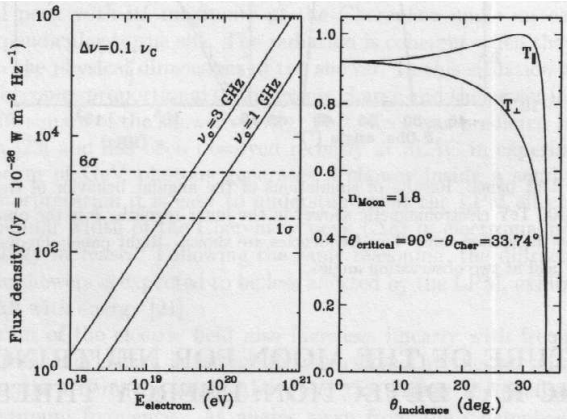

FIGURE 2. Left panel: Flux density at Earth emitted by an electromagnetic shower of energy $E_{\text{electrom.}}$ for two central frequencies and a bandwidth $\Delta\nu = 0.1\nu_C$. Also shown is the flux density of the thermal noise in NASA/JPL Goldstone DSS 14 radiotelescope. Right panel: Transmissivity ($\text{Power}_{\text{transmitted}}/\text{Power}_{\text{incident}}$) of radio waves at the Moon-vacuum interface as a function of the incidence angle with respect to the perpendicular to the local surface of the Moon.

Figure 1:

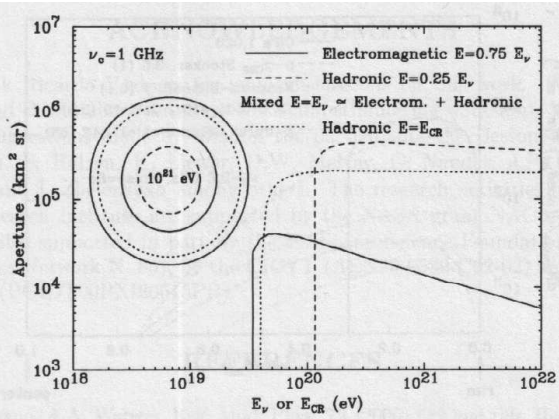

FIGURE 4. Aperture of the Moon for cosmic ray and neutrino detection. For neutrino initiated mixed showers the aperture is the sum of the solid and dashed curves (not drawn). The inset represents the surface of the Moon. The lines correspond to the same lines in the legend. The region between each line and the outermost solid line is the surface where cosmic ray or neutrino detection is expected at $E = 10^{21}$ eV.

Figure 2:

tennas at Goldstone separated by 22 km, operating at 2.2 GHz. A nominal 100 MHz of bandwidth was used. No positive detections were found after 120 hours of operation. Triggering issues, narrow bandwidths, and short observing times limited the effectiveness of these experiments.

2.2 Recent Tests with the MIT/LL Feed and 43-Meter

The NRAO 43-Meter telescope has been refurbished by the MIT/LL group to perform wide bandwidth observations of the Earth's Ionosphere. The existing Kildal feed (Chalmers University, Sweden) has a frequency range of operation of 0.15 to 1.7 GHz. In the frequency range 0.5 to 1.1 GHz the receiver system has an effective system temperature of 90K. The telescope has existing RF system that allows transmitting the signals to the Jansky Lab. Langston has written software that allows convenient tracking of the Moon when the system is not otherwise in use by the MIT/LL group.

We have also been experimenting with a rudimentary pulse detector developed by a graduate student under Bradley's guidance and supported by a small research grant from Sigma Xi. A pair of RF channels from the wide bandwidth front-end currently on the 43-Meter was filtered to 750-950 MHz and amplified. A dual-channel digital oscilloscope samples these channels at a cadence of 2 ns and stores these data on a PC. This system gave us first hand experience with threshold detection and related transient signal processing techniques. Although a few short pulses were observed, the tiny duty cycle and lack of coincidence detection limited the effectiveness this system.

Based upon this experience and a careful study of past activities, we have defined a new search instrument that will provide the best possible opportunity for the successful detection of Lunar pulses from primary sources greater then 10^{20} eV. Considering the power spectral density of the expected Cerenkov pulse and RFI concerns, the center frequency was chosen to be 900 MHz. Simulations have shown that the spectral power at 1 GHz is less dependent on observation angle that at 3 GHz [4].

The proposed system would be used in conjunction with the 43-Meter radio telescope since its beam width at 900 MHz closely matches the solid angle of the Moon in order to maximize the detector volume. The noise temperature of our receivers should be under 50 K so that the thermal background of the Moon (200 K [12]) sets the sensitivity of our detector. The sample rate of 1.2 GHz and the receiver bandwidth of 400 MHz (smoothing on time scale of 2.5 ns) is chosen so as to nearly resolve the Cerenkov pulse.

The simultaneous sampling of the four, independent, beams will permit

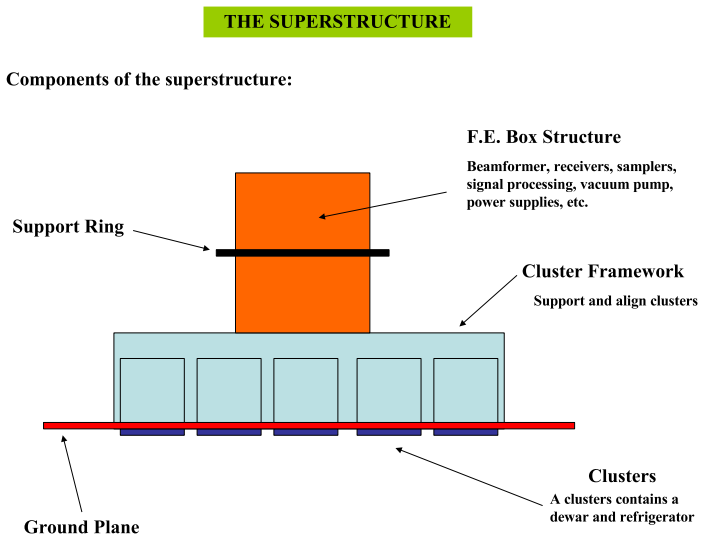

Figure 3: Diagram of the neutrino search instrument.

distinguishing those pulses that originate from the Moon from those occurring from cosmic ray extensive air showers in the Earth's atmosphere and RFI. The threshold level for a positive detection will be optimized to reduce the chance of a false detection due to statistical fluctuations [14]. The back-end signal processing system will be designed to search for and save only those coincidence signals that rise above the threshold level and discard all others so that observing time is maximized. The receivers will be dual-polarization so that the orientation of the linearly polarized Cerenkov radiation, corrected for Faraday rotation, can be determined. This information, together with the geometry of the Cerenkov cone and refraction at the regolith-vacuum interface, will permit us to localize the direction of an incoming cosmic ray that strikes the Moon.

3 Technical Description

A diagram of our neutrino search instrument is shown in Fig. 3 It is based upon the fully-sampled focal-plane array technology pioneering by Fisher and Bradley [13]. The entire system will be housed in a standard Green Bank front-end box that is mounted at the prime focus of the 43-Meter radio telescope. This phased-array approach is necessary not only to comply with

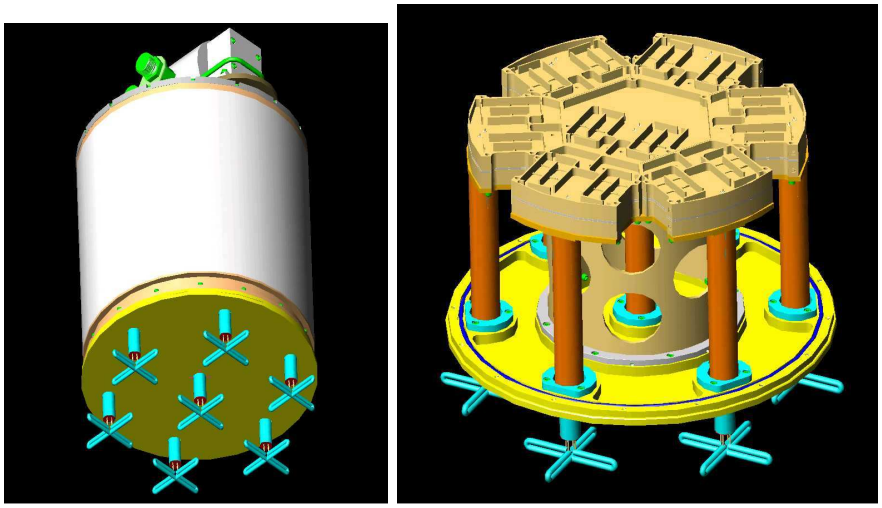

Figure 4: Left Panel: Sketch showing a cryogenic array cluster illustrating one possible configuration for the dipoles, amplifiers, and refrigeration system. Right Panel: Inside of dewar showing amplifiers and feeds.

size and weight constraints, but also to form two co-located independent beams. Thirty-seven low noise, cryogenic elements, tuned for 900 MHz, are located on a framework assembly that is fastened to box. The elements form a close-packed array with $\lambda/2$ spacing between elements. Each will consist of a folded dipole encapsulated in foam insulation and integrated with a low noise active balun that resides in a small cryostat. Other dipole variants will also be explored. The amplifier and feed are cooled together by a closed-cycle refrigeration system to obtain a physical temperature of 15 K. Several configurations will be studied; an example of which is shown in Fig. 4. The clusters would be arranged on the focal plane as shown in Fig. 5.

Four independent, dual-polarization beams are synthesized by amplifying, filtering, and combining the signals from subsets of the thirty-seven elements using a conventional delay-and-sum analog multi-beam-former [15]. Careful study and measurements on the Green Bank antenna range will be required to finalize the design. However, it is anticipated that a subset of nineteen elements will be required to form each beam so that adequate reflector illumination is achieved while mitigating spillover noise and unwanted coupling between beams. Good performance will be required over the entire 400 MHz bandwidth.

The MIT/LL group and the NRAO in GB and at the CDL are cur-

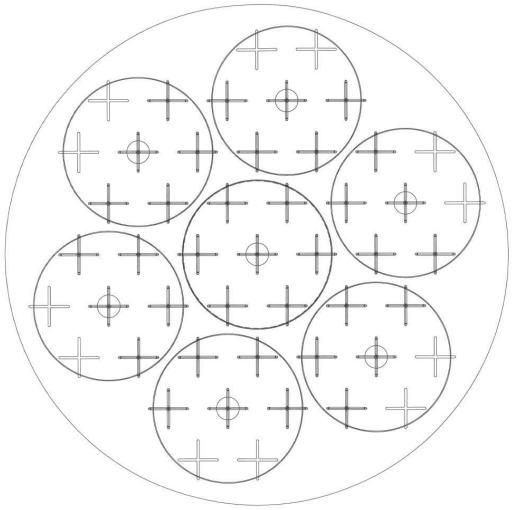

Figure 5: Array of dewar clusters forming the entire array. Only the central 37 elements are active.

rently developing a next generation flexible Spectrometer and Pulsar back-end based on the UC Berkeley/Seti FPGA based hardware. The hardware consists of three major components, 1) The analog to digital sampler board (ADC), the 2) interface board (IBOB) with limited computing capabilities and 3) the BEE2 board with 5 high-end Xilinx chips and Gigabit Ethernet connections.

This hardware configuration far out-paces the capabilities off individual computers and has far greater flexibility that hardware built of discrete components. The NRAO has already installed the software development environment and is actively developing new applications for this hardware. Langston is the project scientist for the NRAO GB development effort and Bradley has extensive experience with the Berkeley hardware based on his efforts for the PAPER project.

Signals from each of the four beams (eight channels) are further amplified and sent to four ADC boards attached to two CASPER IBOBs. Here the signals are digitally mixed down to baseband. The digital electronics and RF networks will be housed in separate EMC enclosures [16].

4 Data Analysis

The signal processing tasks are divided into real-time and post-processing activities. The real-time tasks will be performed by the IBOB/BEE2 system where one second's worth of 8-bit data samples are obtained simultaneously from each of the eight receive channels. The processor will perform basic threshold tests on the four channels coming from the Lunar-pointing beams. The threshold level is critical - if set too low, the system will be swamped with false positive detections due to the system noise, but if set too high, real pulses will be missed. The optimum value will depend on the system temperature and the duration of the measurement (many months). Time-tagged data bursts from all eight channels will be stored for post-processing if coincident pulses are found from the Moon (within a small time window). An integration and dump mode on all channels will also be available for instrument test purposes.

It is important to note that the detection process does NOT rely on the anticipated dispersion of the signal through the ionosphere nor does it rely on a trigger from any other source. If the data burst is determined to not contain a coincidence pulse, it is deleted and another set of samples are obtained. This action is designed to maximum observing time and minimize data storage requirements.

The post-processing activities will determine the source of the pulse. If a coincident pulse is also found in the signals from one or the other of the offset beams, then the pulse is either due to a terrestrial cosmic in the atmosphere along the line-of-sight to the Moon, or simply RFI. Pulses determined to be of Lunar origin will be analyzed further - their spectral properties and polarization will be determined. RFI will be removed by excising frequency bins. A de-dispersion model of the ionosphere that makes use of slant electron content obtained from GPS measurements and readily available from the NOAA Space Environment Center [18], will be applied to remove the effects due to the Earth's ionosphere and correct for Faraday rotation. The characteristics of the E-field leaving the Moon can then be estimated. Analysis of the polarization and the geometry of the Cerenkov cone will allow us to localize the direction of arrival of the primary particle.

5 Work Plan and Milestones

The project will require approximately two years of effort - 17 months to develop the array, 1 month for commissioning and installation on the 43-

Meter, and 6 months for observations. The MIT/LL group plans continued ionospheric studies using the 43-Meter through September 2008. This schedule is well matched to our development plan. Front end development which should be complete a few months after completion of the MIT/LL project.

Back-end development will be done in parallel with front end work. Data processing techniques will be tested using the existing MIT/LL receiver. During the period before the feed array is complete, we will measure the transient event background, measure the RFI levels and characterize the intensity versus time variations of the known RFI sources.

The following is a list of significant milestones along with a brief description of the work leading to it. Some work activities may proceed in parallel. Graduate students from both the University of Virginia and the University of Iowa will take part in this work.

- **Low Noise Element Design** - The array work will begin with the design of the low noise element. This effort dovetails well with work recently proposed by Bradley under the NRAO Individual Engineering Research Project Initiative where a broadband (10:1) feed is integrated with a low noise cryogenic amplifier. The issues are similar to those given here regarding control of thermal loading, condensation, cooling paths, and RF loss. Details of the folded-dipole, cryostat RF feed-through, foam characterization [17], and amplifier circuitry have already been addressed and can simply be scaled for operation at 900 MHz. The noise temperature of the antenna/balun will be measured using a Y-factor method involving cold sky and an RF absorber [19].

- **Array Design and Mutual Coupling Study** - The array itself will be simulated using CST Microwave Studio. Beams will be formed and the effects of mutual coupling studied. Results will be compared with theoretical circuit modeling [20]. Power patterns from individual elements embedded in the array will be measured using test arrays (ambient temperature) on the Green Bank Antenna Range. Clusters of elements will be mounted into cryostats with each having its own refrigeration system. Maintenance of the array a primary design issue. Some mechanical engineering and drafting will be required.

- **Analog Beam-Former** - A multi-beam, delay-and-sum analog beamformer will be designed. Modeling of the array, mutual coupling, and beam forming will be simulated using Agilent's Advanced Design System (ADS) and CST Microwave Studio. A prototype beam-former will be constructed using microstrip circuitry and evaluated. Finally,

the full-scale beam-former, again using microstrip technology and capable of forming four, independent, dual-polarization beams, will be developed. The beam-former will be packaged in an EMC enclosure. Tests of the array with beam-former will be evaluated on the Green Bank Antenna Range. Engineering assistance will be needed here.

- **Receivers** - The receivers will be designed using ADS and fabricated in microstrip technology. These receivers will consist of MMIC-based amplifiers and bandpass filters. It may ultimately be integrated into the beam forming module. EMC enclosure around the receivers and good isolation between receiver channels will be required.

- **Front-End Box Configuration** - The entire search instrument will be mounted in a standard Green Bank front-end box. The array structure itself will be mounted to the box and can be easily removed. The box will be temperature controlled. All components with the exception of the cryogenic compressors will be housed in the box. The issue of how best to run cryogen lines will need to be addressed.

- **Signal Processor** - The signal processor will make use of ongoing development efforts at the NRAO to adopt the CASPER IBOB/BEE2 platform for general signal processing tasks. The search and detect activities are well-suited to the IBOB/BEE2. Data bursts containing coincident pulses will be transferred to a PC in the front-end box. Data will be transfered from this PC over the Internet to workstations for further processing.

- **Commissioning and Installation on the 43-Meter** - The entire array will be build in the Jansky Laboratory and run for several weeks before deployment on the 43-Meter. Noise temperatures will be measured using the outdoor receiver test facility in Green Bank. Statistical tests will be performed on the data as a function of threshold level to verify its proper setting. Deployment on the telescope will take place in steps, beginning with the front-end box followed by the array framework and cryostats. On-telescope, commissioning activities will include beam mapping, system temperature measurement on calibrator sources, and statistical checks.

- **Observations** - The observations on the 43-Meter are rather straightforward. The telescope will track the Moon during both daylight and nighttime observations. All of us will be involved in the data analysis and archiving operations that will occur offline. The observation

phase will last at least six months. The experiment will be successful if pulses are clearly determined to have originated from the Moon. Several pulses per day are expected. The coincident observations involving the GBT are NOT considered part of this initial study.

- **Beam-Forming Array Study** - The system would also be available for engineering tests. The beam-former could be expanded to accommodate additional beams. The synthesis of many course beams (using seven elements instead of nineteen) could be explored. This system will be compatible with the GBT and could be interfaced to the various back-ends. The technology development proposed is pathfinding for an array on the GBT. In addition, a 100 MHz bandwidth, 42-element beamformer using the IBOB/BEE2 platform is currently under development by the CASPER group and will be available in 2008 [21].

6 Budget Justification

The total request is for $291,000. A complete budget spreadsheet is attached. About $154,000 in materials and supplies will be needed. These include the low noise cryogenic amplifiers, test dewar for electronic devices and experimental feeds, fixtures and RF components for array measurements, analog beam-former, dewar and Model 22 refrigeration systems, receivers, front-end box refurbishment and assembly, and EMC enclosures.

Personnel costs total $137,000. This includes 18.5 weeks of engineering, 6 weeks of drafting, 30 weeks of technician assistance, and 14 weeks of machining at the estimated rate of $2,000 per week.

Budget Estimate

Lunar Energetic Neutrino Search (LENS)

Objective	FY 2008 Request					
	Initiative					
	M&S	Labor				
Test Dewar	$10,000	$8,000				
Low Noise Amplifiers and Feeds	$12,000	$36,000				
Array measurements on GB range	$5,000	$8,000				
Beam former	$25,000	$16,000				
Complete dewar assembly	$35,000	$32,000				
Receivers	$10,000	$7,000				
Front-end box & EMC shielding	$5,000	$14,000				
Back-end electronics & PC	$50,000	$10,000				
Commissioning	$2,000	$6,000				
Totals	$154,000	$137,000				
Totals (M&S + Labor)		$291,000				

Figure 6: Budget Estimate

References

[1] *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, National Research Council, Washington, D.C., 2003.

[2] *Neutrinos and Beyond: New windows on Nature*, National Research Council, Washington, D.C., 2003.

[3] Coutu, S. *UHE Neutrinos with Auger*, Snowmass Conference, June - July, 2001.

[4] Alvarez-Muniz, J. and E. Zas. *Prospects for Radio Detection of Extremely High Energy Cosmic Rays and Neutrinos in the Moon*, Radio Detection of High-Energy Particles, D. Saltzberg and P. Gorham, eds., AIP, pp. 128-138, 2001.

[5] Askaryan, G.A. *Excess Negative Charge of an Electron-Photon Shower and Its Coherent Radio Emission* Soviet Physics JETP, Vol. 14, pp. 441-443, Feb. 1962.

[6] Zas, E., F. Halzen, and T. Stanev. *Electromagnetic Pulses from High-Energy Showers: Implications for Neutrino Detection*, Phys. Rev. D, Vol. 45, No. 1, pp. 362-376, Jan. 1992.

[7] Adams, J. *Neutrino Telescopes in Antarctica*, Publ. Astron. Soc. Aust. Vol. 17, pp. 13-17, 2000.

[8] Askaryan, G.A. *Coherent Radio Emission from Showers in Air and Dense Media*, Soviet Physics JETP, Letters, pp. 658-659. Vol. 21, 1965.

[9] Saltzberg, D., P. Gorham, D. Walz, C. Field, R. Iverson, A. Odian, G. Resch, P. Schoessow, and D. Williams, *Observations of the Askaryan Effect: Coherent Microwave Cherenkov Emission from Charge Asymmetry in High-Energy Particle Cascades*, Phys. Rev. Lett. Vol. 86, No. 13, pp. 2802 - 2805, Mar. 2001.

[10] Hankins, T. R. D. Ekers, and J. D. O'Sullivan. *A Search for Lunar Radio Cerenkov Emission from High-Energy Neutrinos*, Mon. Not. Astron. Soc. Vol. 283, pp. 1027-1030, 1996.

[11] Gorham, P.W., C.L. Hebert, K.M. Liewer, C.J. Naudet, D. Saltzberg, and D. Williams. *Experimental Limit on the Cosmic Diffuse Ultra-High Energy Neutrino Flux*, astro-ph/0310232, v3, May, 2004.

[12] Kraus, J. Radio Astronomy, McGraw-Hill, NY, p.339 , 1966.

[13] Fisher, J.R., R.F. Bradley, and K.S. Saini, *Progress on the evaluation of a Phased Array Feed*, URSI North American Radio Science Meeting Digest, Montreal, Canada, p. 611, 1997.

[14] Skolnik, M. Introduction to Radar Systems, 2nd ed., McGraw-Hill, NY, Ch. 2, 1980.

[15] Fourikis, N. Phased Array-Based Systems and Applications, Wiley, Ch. 3, 1997.

[16] Bradley, R.F. *A Low Cost Screened Enclosure for Effective Control of Undesired Radio Frequency Emissions*, NRAO EDIR, No. 317, July, 2006.

[17] Bradley, R.B. and H. Clevenson. *Dielectric Characterization of Rigid Foam Insulation*, NRAO EDIR (in writing - draft available upon request).

[18] NOAA SEC Website: http://www.sec.noaa.gov

[19] Gawande, R.S. and R.F. Bradley. *The Inverted, Conical, Sinuous Antenna over a Ground Plane*, (Invited - to be presented) 2007 North American Radio Science Conference, Ottawa, ON, Canada, July 2007.

[20] Bradley, R.F. and J.R. Fisher. *A Linear Mutual Coupling Model for Antenna Arrays*, NRAO EDIR, (in writing - draft available upon request).

[21] Parsons, A., private communication, April 13, 2007.