Phase II Proposal Instructions
Research Programs

Cover Page

Please submit this information as the cover to your proposal

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Title of Project: A Radar Detector for the Universe's Most Energetic Particles

Project Time Period: from 12/2010 to 12/2013

Total Cost of Project: $1,456,985

Total Amount Requested: $899,750

THE
UNIVERSITY
OF UTAH

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President

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August 14, 2010

Dr. Maria Pellegrini
Executive Director for Programs
W. M. Keck Foundation
550 South Hope Street, Suite 2500
Los Angeles, California 90071

Dear Dr. Pellegrini:

The University of Utah respectfully submits the enclosed Phase II application, *A Radar Detector for the Universe's Most Energetic Particles*, for your review. This request represents a top institutional priority for the University of Utah and has been endorsed by the University's W.M. Keck Advancement Committee.

The University of Utah is deeply committed to cultivating an academic environment rooted in the highest standards of intellectual integrity and scholarship. This project, at its core, reflects this commitment and enhances the academic capacity of the University beyond just the sciences. By allowing students and researchers the opportunity to explore the application of novel technologies to one of the most pressing problems in fundamental astrophysics – the origin and nature of the highest energy cosmic rays – the University continues to contribute to and expand the larger arena of academic inquiry.

The W.M. Keck Foundation is known and admired for its support of bold endeavors to advance scientific knowledge. The University of Utah would be honored to partner with the Foundation on this important project. I fully endorse the submission of this proposal to the Foundation.

As always, we are deeply grateful for the Foundation's tremendous support for the University and for your consideration of this proposal.

Sincerely yours,

Michael K. Young

MKY/lm
Enclosure

Project Overview
Research Programs

Organization: University of Utah

Project Objectives/Aims	Implementation Timeline
Confirm results of Long Island pilot studies using a low power (700 W) transmitter under our control and a more capable conventional cosmic ray detector (the Telescope Array).	First half year one: Install and commission low-power transmitter equipment at Millard County Cosmic Ray center in Delta, Utah. Install crossed dipole antenna adjacent to Telescope Array (TA) site. Develop “pipeline” for processing recorded data, identifying coincidences with cosmic ray detectors and categorizing events.
Accumulate cosmic ray radar echo “event” statistics, in order to understand energy thresholds and geometric effects.	Second half year one: Collect and analyze low-power data. Perform offline studies relating cosmic ray energy, core location, and geometry (as determined by TA detector) to strength, duration, and detection efficiency of radar echoes. This process will be repeated with successively higher power transmitters in years two and three.
Develop the infrastructure and expertise required to operate a high power (20 kW) radar transmitter.	Second half year one: In parallel to collecting data with low-power transmitter, begin work with transmission engineer on installation of 2 kW system and antenna mast. The goal is to commission this transmitter by the end of year one. Year two: Work on installation of 20 kW transmitter, with the goal of completion by the end of year two.
Develop equipment for multi-antenna receiver stations and offline reconstruction techniques to determine cosmic ray airshower geometry and longitudinal profiles from radar echo information.	Year 1: Take data with crossed dipole antennas and GNU radio receivers. Study Doppler shift effects by comparing data collected in multiple frequency bands to calculations. Year 2: Develop multi-antenna receiver station to apply interferometric techniques. Year 3: Deploy an array of multi-antenna receiver stations to cover a substantial portion of the Telescope Array active detector area.
	Evaluation: Present results of studies to external advisory committee at end of years 1, 2 and 3.

Project Abstract

Earth is being bombarded by energetic cosmic radiation, likely created in the Universe's most violent processes. Current understanding of cosmic rays comes from detectors covering thousands of square kilometers of the Earth's surface and costing tens of millions of dollars, thus the sheer scale of these observatories is becoming a limiting factor to our understanding. We aim to develop a technique in which a portion of the Earth's surface is "covered" remotely, by an array of antennas detecting the radar echo of cosmic-ray induced plasma trails. This will allow high energy cosmic ray research to proceed into the next generation of sensitivity. Under the support of the Keck Foundation we will test the bistatic radar technique with a donated television transmitter and an array of radio receiver stations operated in coincidence with the Northern Hemisphere's largest cosmic ray detector, Utah's *Telescope Array*. Bistatic radar has been successfully employed in the study of micrometeorites, and our preliminary measurements indicate that western Utah is an ideally radio-quiet location. But differences between micrometeorite and cosmic ray-induced atmospheric plasmas including altitude, duration, and speed introduce high-risk uncertainties into the outcome of our efforts. A funding source able to support research in the face of these risks is essential to realizing this new cosmic ray detection paradigm.

Executive Summary

Methodology/Implementation: A cosmic ray observatory based on the bistatic radar technique requires the development of both a powerful transmitter station and a sensitive receiver scheme. The transmitter must be sufficiently powerful that the radar echoes produced by the cosmic ray ionization, or "extensive air shower" will stand out well above both galactic and anthropocentric sources of radio noise. The receiver must be capable of not only detecting the echoes, but of reconstructing astrophysically interesting properties of the incident cosmic ray such as arrival direction and air shower size and shape.

The commissioning of the transmitter station will be straightforward, given the generous donation of powerful 2 kW and 20 kW transmitters by Salt Lake City's KUTV Channel 2, and contacts we have already made with transmission engineers involved in both the design and operation of the transmitters we have in hand. We have obtained an experimental FCC license to broadcast at 54.1 MHz at low power (up to 700 W), and obtaining a higher power license will not be a problem due to the recent vacancy of the low-VHF band. The University of Utah owns a building, the Millard County Cosmic Ray Center in Delta, Utah, with sufficient space to house our transmitter facility and adjacent land suitable for installation of a transmitting antenna mast. We have obtained clearance from Delta city authority to construct the antenna mast and operate the transmitter.

A more challenging aspect of the project lies in the development of receiver stations, data acquisition, and offline analysis schemes capable of identifying and reconstructing the properties of cosmic ray air showers. Although bistatic radar has successfully been employed in tracking aircraft and meteors, there are key differences between tracking these objects and tracking developing air showers. The air shower signals are short-lived: approximately 50 microseconds in duration. The sampling rates required to extract the necessary information from such signals can result in potentially unwieldy data volumes, if the data cannot be filtered in real time. An added complication is that the high speed of the developing showers may result in substantial Doppler frequency shifts of 10 MHz or more. Receivers capable of covering such a wide bandwidth are approaching the limits of currently available technology.

We will develop the bistatic radar observatory in three stages, each stage lasting approximately one year. In each stage, we will aim to advance both the transmitting and receiving components of the observatory. In *Stage One*, we will deploy a low-power (700 W) transmitter with a conventional rooftop Yagi antenna. We will chiefly be concerned with establishing and characterizing a cosmic ray signal, which will be confirmed with the co-located Telescope Array, a conventional cosmic ray observatory. On the receiver end, we will compare the response of various antenna designs and begin developing software tools for the software-defined GNU radio receiver system.

In *Stage Two* we will begin commissioning of the 2 kW transmitter, which will also require erecting a standalone mast for the transmitting antennas. We will continue to develop the GNU radio software, and begin working with multi-antenna receivers for interferometry.

Stage Three will see the deployment of the 20 kW transmitter, using the same transmitting antenna as the 2 kW system. Thirteen multi-antenna receiver stations will be deployed in order to demonstrate the feasibility of a full-scale cosmic ray observatory based on the radar technique.

Key Personnel: The principal investigators, their expertise and roles in the project are as follows:

- John Belz (Project Leader) has 15 years experience in experimental particle physics and 12 years in cosmic ray physics, and has been investigating the use of radar in observing cosmic rays for two years. John will serve as project manager, supervise transmitter deployment and facilities maintenance. He will supervise one postdoctoral fellow, one graduate student and two RF engineers.
- Behrouz Farhang-Boroujeny is a professor of electrical engineering with a general interest in applying signal processing to communications. He has done research in the area of adaptive filter analysis and algorithm design and signal processing techniques in magnetic and optical recording. He is the author of a book on signal processing with software defined radio. Behrouz will supervise a student and focus on developing code for GNU radio, signal recognition and online filtering of data.
- Pierre Sokolsky has 29 years experience in cosmic ray physics. He won the 2008 Wolfgang Panofsky Prize in experimental particle physics for his work in developing the nitrogen fluorescence technique for reconstruction of cosmic ray air showers. He will serve as senior advisor to the project and participate in data analysis.
- Helio Takai has 24 years experience in experimental high-energy physics, and has been searching for the radar echoes of cosmic rays since 2005 with the MARIACHI project. Helio will supervise a student and investigate receiver antennas and receiver station hardware, and also work on the simulation of radar echo signals.
- Gordon Thomson has 25 years experience in experimental particle physics and 11 years experience in cosmic ray physics, and has been investigating the use of radar in observing cosmic rays for three years. He is an expert in analysis of Telescope Array surface detector data. Gordon will supervise a student and focus on the analysis of data.

Additional personnel include Isaac Myers, *graduate student, Utah*; three undesignated graduate students in physics and electrical engineering from Utah; one undesignated postdoctoral research associate from Utah; Gregory Best, *RF Engineer, Consultant*; William Ramsay *Transmission Engineer, KUTV Channel 2*; and the Telescope Array Collaboration, *24 institutions and 119 physicists*.

Budget: The total cost of the project is $1,456,985, of which we are requesting $899,750 in support from the W. M. Keck Foundation. The project will also benefit from the donation of $290,000 in radio frequency transmission equipment from KUTV Channel 2 in Salt Lake City, and benefit from existing University of Utah infrastructure. Several of the investigators are also recipients of $270,000 in National Science Foundation (NSF) grants awarded for pilot studies in this field.

Of the Keck Foundation support, $424,810 will be for personnel support including one month each for two Principal Investigators, a postdoctoral fellow and two graduate students. Two additional students will be supported by the NSF. $289,740 is for equipment, including modifications and additions to University of Utah facilities to accomodate the transmitter and receiver stations. Operations costs totalling $185,200 include travel expenses, funds for support of consulting RF engineers, electrical power and satellite internet communications.

Project Narrative

1 Introduction

Understanding the sources and chemical composition of the most energetic extraterrestrial radiation or cosmic rays is a major thrust of current astrophysical research. Particles with energies far exceeding what is believed possible through supernova shock acceleration regularly strike the Earth from within our galaxy and beyond. Understanding the origins of these particles will require accurate models of the most violent processes in the universe.

The study of high-energy cosmic rays is also a field of study requiring financial and manpower resources on a scale colloquially known as "big science". The reason for this is contained in the cosmic ray energy spectrum itself, illustrated in Figure 1 (left panel). The spectrum is known to approximately follow a power law, in which the flux of particles incident on the Earth falls off as $1/\mathrm{energy}^3$. Thus at the highest energies, detectors with apertures of hundreds or thousands of square kilometers are required in order to obtain reasonable event rates. For example, the two largest detectors now in operation, the Telescope Array [1] (Utah), and the Auger Observatory [2] (Argentina) utilize ground arrays covering 800 km^2 and 3,000 km^2 respectively. Absent new technologies, the costs required to build observatories at significantly higher sensitivity are prohibitive.

There is therefore a strong incentive to develop detection methods which can cover large areas of the Earth's surface without requiring the detectors themselves to physically occupy a large area. One such technique which has been pioneered at Utah is the "fluorescence" method, in which light from molecular de-excitations within the extensive air shower (EAS) is captured by fast ultraviolet cameras many kilometers distant. This technique is limited however in that fluorescence observations are only possible on clear, moonless nights, corresponding roughly to a 10% duty cycle. Further, atmospheric scattering and absorption of UV light limit the seeing distance of fluorescence detectors to less than about 50 km.

Recently, there has been interest in exploiting the Radio Frequency (RF) portion of the electromagnetic spectrum for this purpose. This is possible because ionization densities of the order of 10^{13} m^{-3} can be reached in the shower core for an $E = 10^{18}$ eV primary cosmic ray. At this ionization level the plasma frequency is roughly 50 MHz (corresponding to the low-VHF). Near this frequency the plasma will reflect radio waves. Provided backgrounds are sufficiently low, EAS ionization is detectable using radar techniques to capture reflected RF radiation. This technique can be used 24 hours a day, in a sufficiently radio-quiet environment. Since radio waves are only weakly absorbed by the atmosphere, reflected radio waves can be observed over distances of hundreds of kilometers.

In this proposal, we seek to advance the radar technique by making use of an analog television transmitter donated to the University of Utah by Salt Lake City's KUTV Channel 2. We will build a transmitter station at the Millard County Cosmic Ray center, where it will illuminate the sky above the Telescope Array surface detectors and allow simultaneous detection of cosmic ray air showers by conventional and radar techniques. The sample of events thereby detected will facilitate further study of radar models as well as enable understanding of energy thresholds and geometrical resolutions.

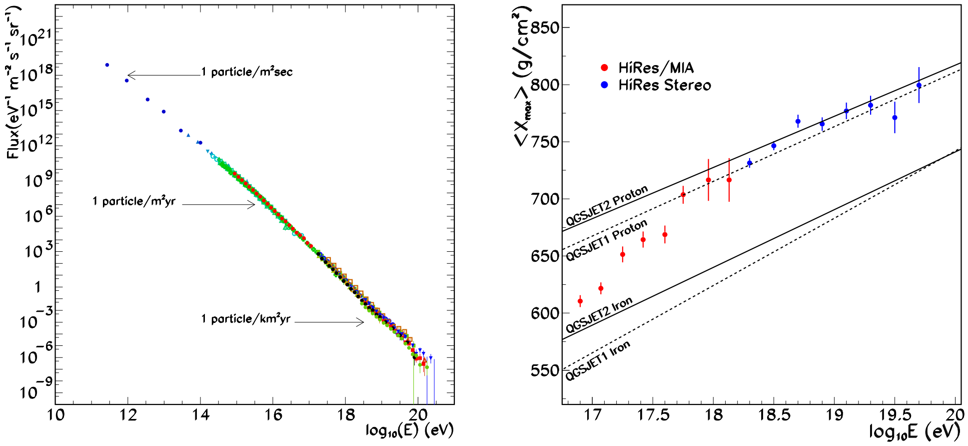


Figure 1: *Left:* The cosmic ray all-particle spectrum. *Right:* Recent HiRes results [3] on depth of mean shower maximum X_{max}, compared with the predictions of CORSIKA [4] using the QGSJET1 and QGSJET2 high-energy hadronic models. A mean X_{max} of 770 g/cm^2 at 10^{19} eV translates to a mean height above ground at Telescope Array altitudes of approximately 3 kilometers.

2 UHECRs and Extensive Air Showers

Modern observatories studying Ultra-High Energy Cosmic Rays (UHECR) primarily make use of two technologies. Both of these technologies rely on making indirect inferences about the nature of the primary cosmic ray by observation of the EAS which the primary cosmic ray triggers in the atmosphere. The surface detector technique makes use of scintillator or Cherenkov detectors to directly observe those shower particles which arrive at the ground. The fluorescence technique traces the full development of the shower via the nitrogen fluorescence excited by the charged particles in the shower. The Telescope Array in Utah is an example of a *hybrid* observatory employing both the surface detector and fluorescence fetector techiques simultaneously.

The surface detector technique, while directly detecting shower particles, suffers from several shortcomings. Surface detectors are only sensitive to particles striking the ground. Full reconstruction of air showers including such parameters as primary energy and shower maximum (X_{max}) relies on model-dependent assumptions about the showers themselves. Finally, the sensitivity of a surface detector is ultimately limited by the area of the Earth's surface which it is financially and practically feasible to instrument.

The nitrogen fluorescence technique directly addresses these shortcomings. The full shower development is observed in fluorescence light, which is known to be proportional to the energy deposited by the shower [5]. Thus there is minimal model dependence in determining the air shower energy or X_{max}. Further, detection of nitrogen fluorescence is a remote sensing technique as air showers may be observed from distances approaching 50 km. A major drawback to fluorescence detection is that it can be employed only on clear moonless nights, resulting in a duty factor of approximately 10%.

Over the past several years, new techniques have also begun exploiting the Radio Frequency (RF) emissions of EAS with ground arrays consisting of radio receivers sensitive to downward directed emissions [6, 7, 8]. These arrays however face many of the same drawbacks as more traditional ground arrays, particularly in that they still require the full aperture on the ground to be instrumented. The radar detection of UHECR induced EAS however has promise as a remote sensing technique without the inherent limitations of a 10% duty cycle. In the sections which follow, we outline the physics behind this technique, the results of preliminary feasibility studies and a plan for full development of the radar technique in conjunction with the Telescope Array observatory in Millard County, Utah.

3 Theory of Radar Detection of Cosmic Ray Air Showers

The concept of radar detection of EAS was introduced in the early 1940's by Blackett and Lovell [9] and has been revisited over the years [10, 11]. Conceptually the technique is simple. Particles with energy larger than 10^{17} eV produce large primary ionization densities that would scatter electromagnetic waves up to $f \sim 100$ MHz permitting their detection. The scattered amplitude is known to be greatest in the forward direction (see below), thus we believe that the best chance of observing air showers by radar lies with the use of the *bistatic* or "two station" technique.

3.1 Bistatic Radar

Figure 2 (left panel) is a comparison of two calculations of received power for scattering off of a cylinder 40 m long (corresponding to the free electron lifetime) and 10 m in diameter (corresponding to the dense plasma region of a high-energy airshower). In one case (points) we integrate the contributions of a series of two nanosecond "slices" of the cylinder. In the other case, the cylinder is taken as a whole and the radar cross section of the object is taken from the scattering approximation given by Glaser [12]. No normalization has been performed between the calculations. The two calculations are in reasonable agreement, and both show a strong peaking of the RCS at angles within 15° of the forward direction. This result is the essential motivation for the bistatic radar technique.

The bistatic radar technique is upon first consideration, quite similar to the radar detection of meteors [13, 14, 15], and one can use this fact as a starting point in understanding the radar response of cosmic ray air showers. However, ionization produced by cosmic rays will happen at much lower altitudes than that produced by meteors. EAS typically form at less than 10 km above sea level and meteor ionization occurs at altitudes above 80 km. At air shower altitudes below 10 km the plasma lifetime is expected to be less than 100 ns [16].

3.2 Estimates of Received Power

To evaluate the signal strength we integrate the contribution from each segment in the shower making an assumption that all electrons are concentrated in a cylinder along the shower axis. The initial power from a small cylindrical section is given by:

$$dP_R = \frac{\kappa P_T G_T G_R \sigma_e sin^2\gamma \; qds}{64\pi^3 R_T^2 R_R^2} \tag{1}$$

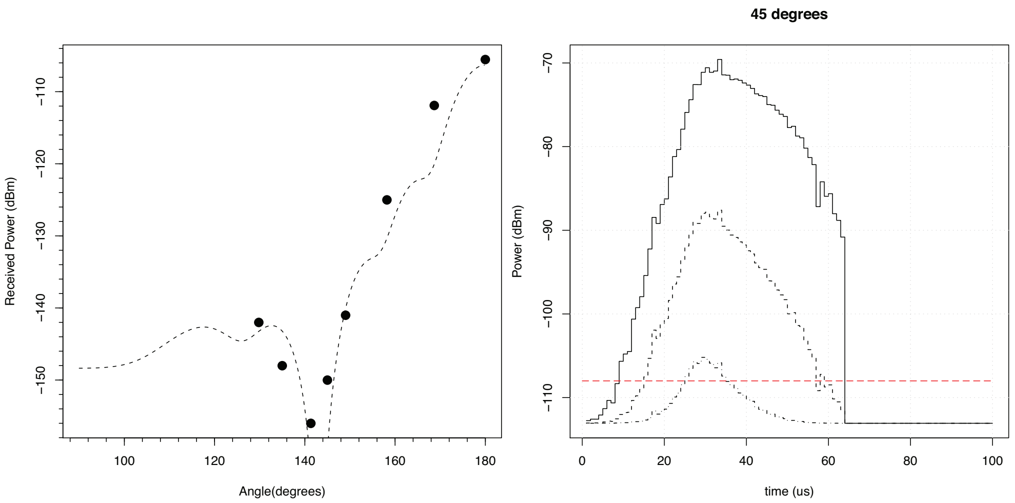


Figure 2: *Left:* Forward scattered power for an ionization cylinder of 10 meters diameter and 40 meters long. Dashed line is for a geometrical optic calculation using Reference [12]. Dashed lines are results from a Thomson scattering calculation where all the phases were taken into account. A considerable enhancement is observed at forward directions ($180°$). For this calculation the transmitter power is 2kW, and the antenna gains are 10 dBi. *Right:* Calculation of received power (referenced to milliwatts) for air showers initiated by 10^{20} eV (solid), 10^{19} eV (dashed), and 10^{18} eV (dot-dashed) primary cosmic rays. See details of the calculation in the text. The red (dot dashed) line is 5 dB above galactic background noise [17], a conservative threshold for signal detection.

where P_T is the transmitter power, G_T and and G_R and the transmitter and receiver antenna gains, σ_e is the single electron Thomson cross section, $\sin\gamma$ is the polarization at the receiver, q is the value for the electron number density, R_R and R_T the distance from the receiver and transmitter to the scattering point. q is calculated using the NKG shower parameterization [18, 19] and assuming that every track ionizes air in the minimum ionizing regime. κ is the attenuation factor due to multiple scattering of electrons by neutral molecules estimated following K. Suga [10]. The electron density will diminish because of the large attachment cross section to molecular oxygen. We take values given by Vidmar [16] that are strongly dependent on altitude. To integrate we take into account all geometrical phases and phases due to the transmitter. For the integration we assume the TA geometry of 50 km baseline. The transmitter power is assumed to be 20 kW, and the antenna gains 10 dBi and 17 dBi (directional Yagi with ground reflector) respectively for transmitter and receiver.

We integrate the contribution of each segment numerically using segments of $2\ ns$ that is approximately 1/10 of the transmitter frequency, 54.1 MHz. The resulting waveform is then segmented in $1\ \mu s$ bins and power in each bin extracted. To estimate noise, we used sky temperatures given by Cane [17]. This is a good assumption for the location of the TA, it being a remote site and free of anthropogenic noise with the exception of the installation itself. The results are shown in Figure 2, for showers inclined at $45°$. The red line shown in the graphs are located at 5 dB above the background noise, and we consider signals above this line to be detectable. Therefore we conservatively estimate that the detection threshold is 5×10^{18} eV.

3.3 Doppler Shift of Received Signal

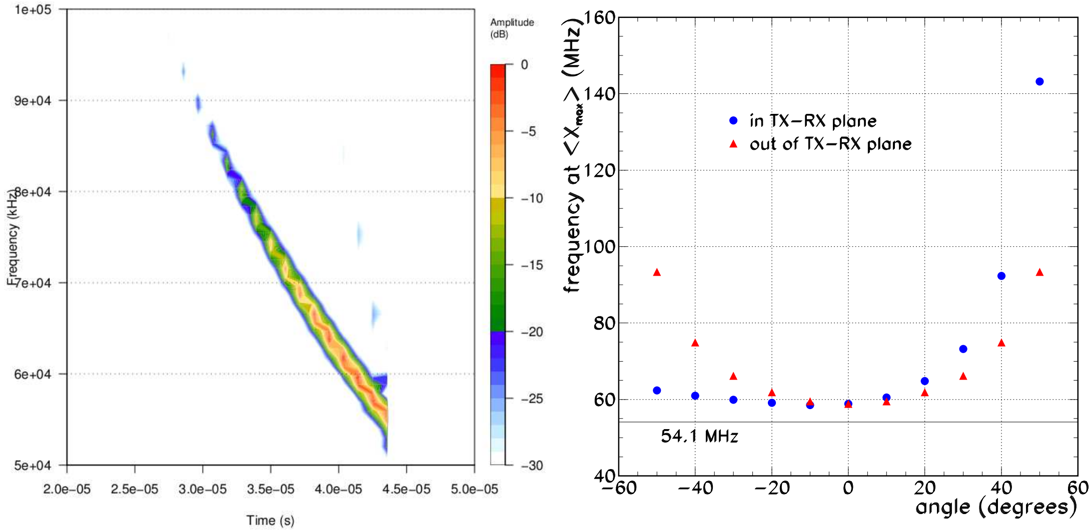


Figure 3: *Left:* Spectrogram of "chirp" for simulated airshower, initiated by vertical 10 EeV cosmic ray midway between 54.1 MHZ transmitter (TX) and receiver (RX), located 50 km apart. *Right:* "Doppler" shifted frequency at height of mean shower maximum (greatest return power) versus angle for 10 EeV showers midway between TX and RX. Angles in (circles) and out (triangles) of TX-RX plane are considered, a positive-angled shower has its top inclined towards the TX.

In the detection of bistatic radar reflections from airshowers, a complication arises due to the large (essentially that of light) speed of the developing shower. One can consider the shower as a series of segments, each segment deflects unique rays from the transmitter towards the receiver in succession. Due to their rapidly changing path lengths, the relative phase of successive rays at the receiver will evolve with time. This time-dependent phase change manifests itself as a Doppler-like shift in frequency from the transmitter output.

This effect has been considered before [20]. Here, we present the results of our own calculations. Figure 3 (*left*) is a spectrogram (power spectrum versus time) of a radar echo off of a simulated 10 EeV vertical shower lying midway between a 54.1 MHz transmitter and a receiver separated by 50 km. The shower evolves longitudinally according to the Gaisser-Hillas [21] parametrization. The atmospheric ionization is assumed to persist for 10 ns to 40 ns (dependent on altitude [16]) after passage of the shower. The simulation shows the expected signal is a downward chirp covering 30 MHz in approximately 15 microseconds, with peak signal at airshower maximum occurring at roughly 60 MHz.

The frequency shift will of course be geometry dependent, as illustated in Figure 3 (*right*). Plotted are received frequencies at airshower maximum as a function of angle of track, both in and out of the transmitter-receiver plane. In the zenith angle range where the Telescope Array surface detector reconstructs air shower characteristic best, below about 40° zenith angle, Figure 3 shows that the largest radar reflections will occur with shifts between 55 and 75 MHz. Clearly it will be necessary to operate our radio receivers at bandwidths covering tens of MegaHertz in order to reconstruct the airshowers producing the echo, and real-time sparsification will be needed in order to reduce data volume to reasonable levels.

4 Results of Preliminary Studies

In this section, we report on preliminary studies conducted in Long Island, New York and Millard County, Utah. The focus of the Long Island studies was to use commercial television signals as a radar source, along with an array of high school cosmic ray detectors, in an attempt to confirm the detectability of EAS reflections with a conventional cosmic ray detector. In Utah, we aimed to characterize the radio environment of the west desert area, in order to assess its suitability for further radar studies.

4.1 Measurements in Long Island, New York

The MARIACHI [22] experiment was set up to test the concept of using forward scattering radar for the detection of ultra high energy cosmic rays. To prove the concept, parasitic forward scattering radar stations together with 12 mini-shower detectors were set up on Long Island, New York. The key concept for the proof of principle is to detect simultaneously a radio echo and an extensive air shower by conventional means.

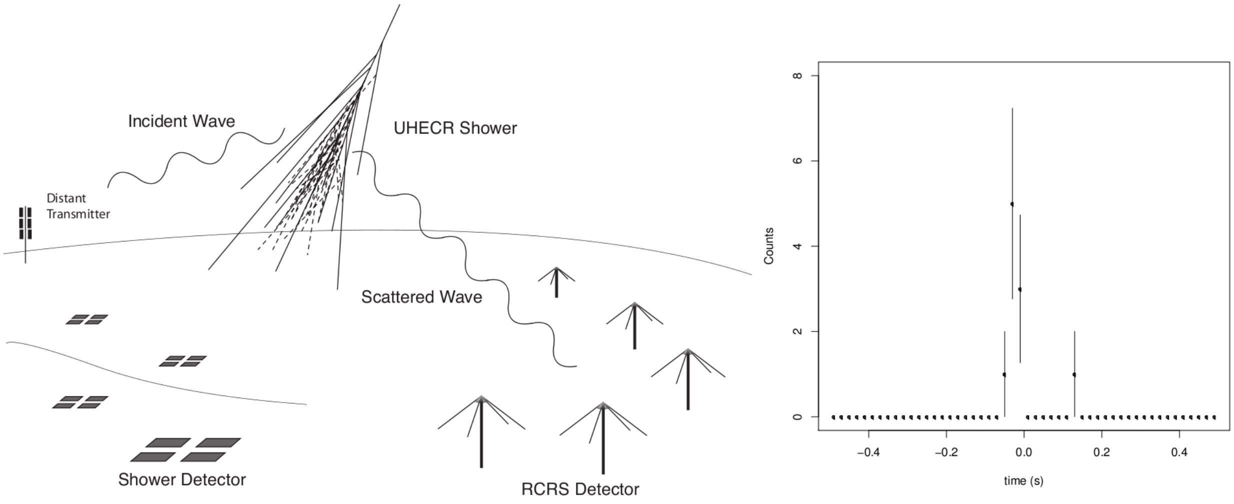


Figure 4: *Left:* The MARIACHI experiment. Small shower detectors are used to tag the presence of showers while Radio Cosmic Ray Scattering (RCRS) stations listen to forward scattered echo. Typical distances between RCRS stations and scintillators is 40 to 80 km. *Right:* Histogram of events found in coincidence with the scintillator sites in a period of 2 weeks. The offset from zero is due to data acquisition timing issues.

With the MARIACHI geometry Channel 4 analog (67.26 MHz) provided good illumination from a few kilometers above sea level to an estimated 120 km. The closest stations were in Pittsburgh, PA and Chapel Hill, NC, both with a nominal 100 kW power, of which 25% goes into the VHF carrier itself.

The mini shower detectors are five sets of scintillators placed at high schools. When a 4-fold coincidence is detected the event time is recorded using a GPS clock. The time accuracy for the GPS clocks is 100 ns and the units purchased are specifically designed for time tagging. The radar station is two inverted VEE dipoles placed orthogonal to each other to obtain direction information, albeit with ambiguity. Each dipole arm is fed into a commercial narrow band PCR1000 receiver and recorded using a high end sound card.

The MARIACHI experiment collected data with a radar station at the Custer Institute and 5 scintillator stations for a total of 8 weeks. The radar station was located 40 km from the closest shower station and about 70 km from the furthest. For the analysis sequence we opted for searching for coincidence signals using the GPS timing information from the scintillators.

The procedure to search for signals used the times given by the shower array as an offline trigger for the radar stream. With a pulser system we verified that our dipole system has directionality as expected for a simple dipole system. For each shower detection time a window of $\pm 1s$ was examined in the radar stream for the presence of a signal.

The search for coincidences was done for a period of two weeks when the system was considered to be running at its prime. Data for other periods as mentioned above exist but a better understanding of calibration issues is required. These schools cluster at an average distance of 60 km to the location of radar. Because the scintillator energy threshold is low, we scanned for about 30,000 triggers and found 10 events that satisfied the presence of a signal that matched expectations. With one exception, the observed signals are all clustered (See Figure 4, right panel) at 50 ms prior to where the coincidence would be, *i.e.* at zero. This time lag is due to the data acquisition system that takes on average that amount of time to start recording data. The events found vary in duration which is translated to a characteristic frequency response. These events constitute a rate of approximately 0.7 events per day. For a threshold energy of 5×10^{18} eV we expect a coincidence rate of ~ 1 per day. We hand-surveyed how many cosmic ray like signals per hour we would expect, and determine that we have an accidental coincidence rate of approximately 1.8 events in the period of 2 weeks. We conclude that we have seen approximately 8 “true” coincidences between scintillator and radar.

It is possible to infer the signal bearing based on the signals observed at both dipoles with the caveat that a single dipole system does have ambiguities. The absence of stations to the east of the radar station reduces the ambiguity to two quadrants, NW and SW. Unfortunately it is difficult to eliminate either because there are equal number of stations in both. However, if one arbitrarily neglects the NW direction the estimated bearing angles of the 9 clustered events point towards the trigger scintillator station within $\pm 5^\circ$. The event at $\Delta t = +0.15$ seconds was 15° from the nearest scintillator station.

We have observed coincidences for a class of events that we classify as cosmic rays based on hardware simulated signals. The coincidences are observed between any of the 5 scintillators and the radar station at the Custer Institute that is located on average 60 km from the scintillator stations. There is also indication that the signal bearing would point towards the trigger scintillator. In spite of these evidences we are at this point unable either confirm or dismiss these events as cosmic ray echo. The fact that coincidences exist is an indication that signals were generated at the same time and it could be generated by other means, e.g. short glitches in the power grid. To pursue this research further in the urban area which profits from the abundance of TV and FM radio stations, a minimum of two radar stations would be required. At the same time careful monitoring of other electromagnetic events via e.g. VLF or direct line monitoring would be desirable. However, a better strategy is to attempt the detection of coincidences between radio echo and cosmic ray shower at a well established cosmic ray experiment such as the Telescope Array.

4.2 Measurements in Millard County, Utah

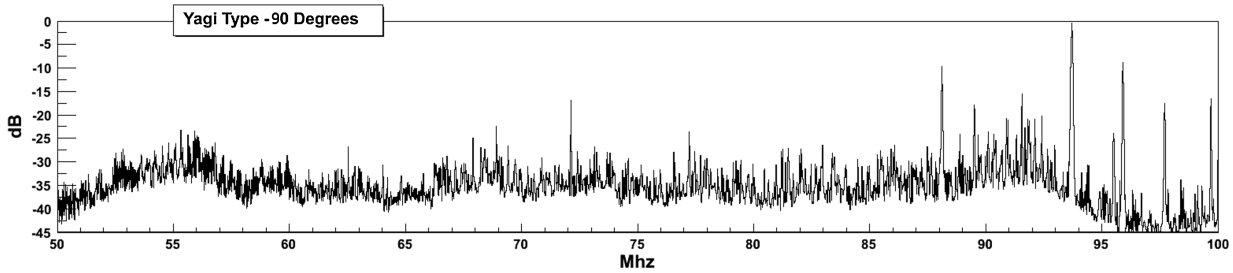


Figure 5: Radio frequency background, as measured with a 6-element Yagi antenna antenna located at the Millard County Cosmic Ray Center, pointing due East. This is roughly the direction a receiver station placed at Long Ridge would face overlooking the TA surface detector. See text for measurement details. The radio skies over TA are extremely quiet in the low-VHF band, particularly since analog-to-digital switch in June 2009. “Spikes” in the background starting at approximately 88 MHz are FM radio stations. The largest, at 93.7 MHz is a 500 W translator station 71 km distant, for which line-of-sight is obscured by terrain.

The focus of studies in Utah thus far has been to characterize the electromagnetic noise environment in the low-VHF frequency range, in order to determine the suitability of Millard County for the development of the radar technique.

The ideal geometry for the detection of cosmic ray air showers is one in which the atmosphere a few kilometers above ground is illuminated by the RF source, but the receiver antennas on the ground are shielded from direct signals by mountains or the curvature of the Earth.

Long Island is situated in a relatively flat region where Earth-curvature effects dominate and there are abundant suitable RF signal sources. Millard County, Utah and the Telescope Array observatory sit at the bottom of a geographic “bowl” ringed by mountains up to and exceeding 3 km MSL. RF stations and repeaters within the bowl tend to illuminate the ground within the bowl, and hence our receiver antennas as well. Transmitters located outside the bowl illuminate the sky tens or hundreds of kilometers above ground level but not at shower maximum.

As a consequence, since the low-VHF portion of the spectrum was vacated in the analog to digital television conversion of June 2009, the skies in the vicinity of the Telescope Array are extremely radio quiet in the 50 MHz band. This point is illustrated with data we collected during summer 2009, which is shown in Figure 5. A broadband Yagi Antenna [23] was pointed in an easterly direction, and its signal was read out using a Universal Software Radio Peripheral (USRP) [24] device with a clock rate of 64 MHz. An FPGA operating as a digital down-converter (DDC) decimated the sampling by a factor of eight, corresponding to a digital bandwidth of 8 MHz being read out by PC. The USRP was set to sweep in 2 MHz steps, sampling for 10 seconds per step, and in the PC an FFT is applied to each sweep. The data is then “stitched” together to achieve the full spectrum shown.

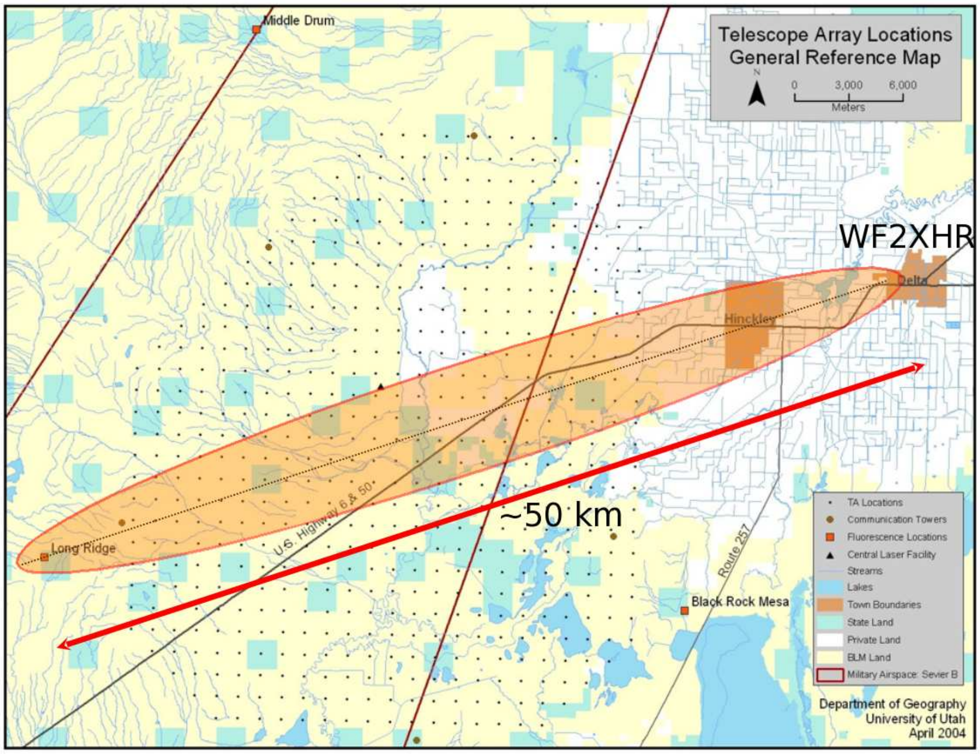


Figure 6: Map of Telescope Array (TA) site and proposed radar observatory. Points represent TA Surface Detectors (SDs), red squares represent TA Fluorescence Detectors (FDs). The transmitter, operating under FCC license as station WF2XHR will be located at the Millard County Cosmic Ray Center in Delta, Utah. The initial receiver station will be located at the Long Ridge FD. The shaded ellipse region shows the region in which forward scattering will produce the largest bistatic radar signal.

With the exception of the FM radio signals (the largest is a 500 W, 93.7 MHz FM translator 71 kilometers away in Nephi, Utah which is blocked from line-of-sight by terrain) beginning at about 88 MHz, Figure 5 shows the low-VHF environment in Millard County to be very quiet, and ideally suited to radar studies with a controlled transmitter located with in Millard County, operating in this frequency regime.

5 Scope of Proposed Research

Under the proposed grant we will seek to validate the bistatic radar technique for cosmic ray airshower detection, by installing a series of successively higher-powered low-VHF transmitters in the vicinity of the Telescope Array surface detector and by deploying receiver stations on the far side of the array (Figure 6). The objectives are to detect radar signals in coincidence with the surface array, test models of received power and frequency response, and to learn to use bistatic radar reconstruction techniques to find air shower position, geometry, and longitudinal profiles.

5.1 Transmission Facility

The Millard County Cosmic Ray Center (CRC) is a 4,000 square foot single-story commercial building in Delta, Utah, which is owned by the University of Utah. It is the center for Telescope Array operations and data acquisition, and its considerable floor and surrounding outdoor space has been used for detector assembly, testing and repair. It is also the Telescope Array visitor center, and serves as the public face of the Telescope Array collaboration. The Cosmic Ray Center will be a high-profile location for the proposed Keck Radar Transmission Facility. (See attached Recognition Statement.)

We will install the transmitters at the CRC. Initially, we will use a modified ham radio transmitter purchased with NSF funds to achieve 700 W in output power at 54.1 MHz. We have already obtained an FCC experimental-class license to broadcast under callsign WF2XHR (see supporting documents). Installing this transmitter first will enable us to rapidly get up and running so that we can begin searching for radar echoes. We will also make use of GPS-tracked reflective balloons and small airplanes as radar “targets”, to test our ability to predict received reflected power from well-defined scatter centers.

In the second and third stages of this project, we will upgrade to donated commercial television transmitters. (See the letter of donation from KUTV Channel 2 in the supporting documentation.) These transmitters are solid state devices from the Harris [25] Platinum series, and will be operated in 2 kW and 20 kW output mode. Each transmitter is approximately 25% efficient and hence will require respectively 10 kW and 100 kW of of power from the grid to operate. We will only broadcast a single frequency carrier signal (again at 54.1 MHz). This will greatly simplify the “plumbing” by eliminating the need to merge video and audio signals via waveguides and hybrid combiners.

The RF signal will be piped via flexible foam-core waveguide to the antenna — a segmented Kathrein directional dipole [26] — which will be attached to a 50 foot tall mast located in a field behind the CRC. We have obtained permission to erect this mast at the CRC site (supporting documentation). As this mast is located on flat ground, the curvature of the Earth as well as local terrain features will attenuate the signal at ground level on the far side of the surface array, approximately 50 kilometers distant.

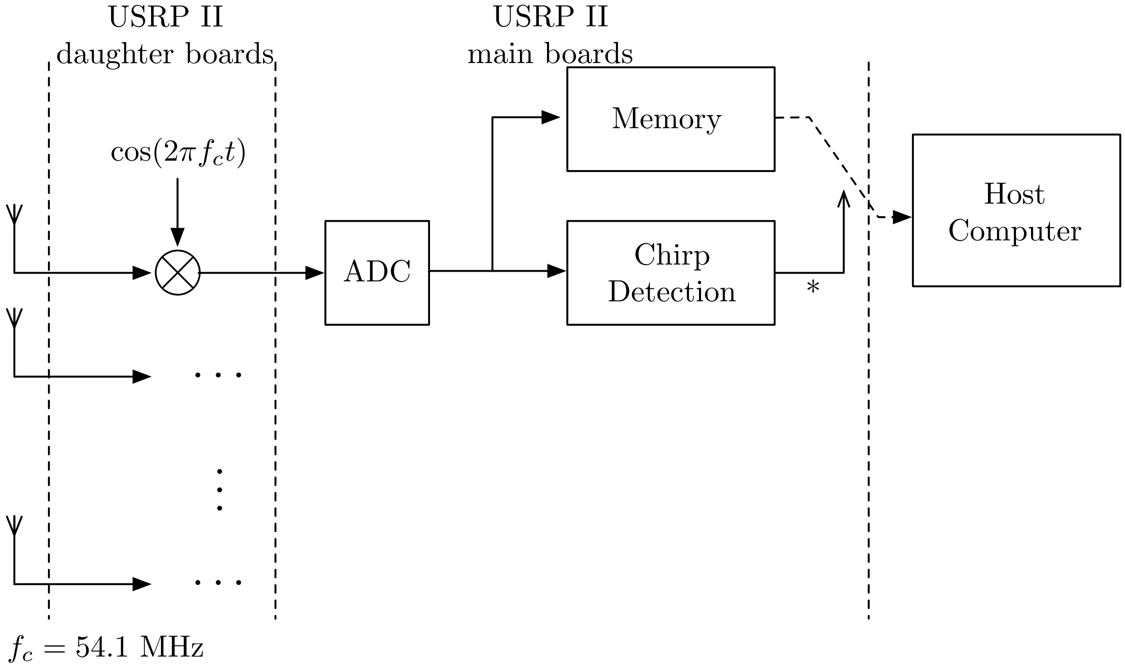
The transmitter station will be assembled with the help of an engineering consultant, Mr. Greg Best, who is one of the designers of the Harris Platinum transmitter, and Mr. Bill Ramsay who operated the equipment on behalf of KUTV.

The broadcast antennas will be aligned so as to have maximum emitted power in a west-southwesterly direction, in order to illuminate the sky above the center of the TA surface detector array.

5.2 Receiver Stations

A radar receiving station will be composed of four antennas, associated electronics and a host computer. The first receiver station to be deployed will be co-located with and tethered to the Long Ridge fluorescence detector station. At latter stages our goal is to have a station that is autonomous as far as both power and internet connectivity. The autonomous station will be a prototype for future large-scale radar observatories beyond the current proposal. It will make use of solar power and satellite internet communications. Receivers, computers and anciliary electronics will be housed in a radio hut that should be thermally insulated due to large swings in temperature in Utah's West Desert.

Four towers, each 24 feet in height, will be erected near the hut to minimize cable runs. We plan on using RG-8, 50 Ohm cable to connect each log periodic antenna to the digital receiver module (discussed further below). A single computer will be required to communicate with all receivers. As we acquire experience with the tethered station, we will move to install solar power and satellite internet services.



* Transfer the content of memory to the host if a chirp is detected.

Figure 7: Block diagram of the radar receiver.

A crucial component to the execution of this project — and the key to dealing with the large Doppler excursions in frequency — is a flexible radio receiver to (i) receive the reflected signals from the airshowers, (ii) identify the occurrence of each airshower and capture the corresponding signal samples, and (iii) store the captured signal in a host computer. To implement a radio that can be adapted to these requirements, we propose to develop a software-based radio (often called software defined radio — SDR). We will use the Universal Software Radio Peripheral (USRP); the USRP-II, in particular, of Ettus Research LLC [24].

Figure 7 depicts a block diagram of the SDR-based receiver that we propose for our radar system. The received signal at each antenna is demodulated to baseband using the carrier frequency $f_c = 54.1$ MHz. The demodulated signal passes through an anti-aliasing filter and sampled at a rate of 100 MHz, using an analog-to-digital convertor (ADC); available on USRP-II. A signal analysis algorithm (implemented on the USRP-II FPGA) is then performed to identify the presence of a chirp spectrum (see Figure 3, left) in the sampled signal. If a chirp is identified, a fixed window of, say, 100 μs of the captured signal is passed to the host computer for storage. Using this approach, we are assured that only those portions of the received signal that are *likely* to contain reflections from airshowers are stored. This reduces our storage needs from a prohibitive size to a very manageable size. Without getting into details, here, we only note that without such intelligent mechanism our storage need per 24 hours would be in the order of a few tens of terabytes. We will reduce this number to less than 100 megabytes; a reduction factor in the order of 1/100,000.

5.3 Plan of Analysis

Analysis of the radar and surface detector (SD) data will proceed in parallel with hardware development. Early on, we will focus on understanding the response of the radar receivers with easily identifiable targets such as reflective balloons and a small airplane. While the wide-bandwidth "chirp" detector is under development, we will also seek to detect coincidences between SD events and narrow-bandwidth receiver data at select shifted frequencies.

With the deployment of the multi-antenna array and chirp detector receiver, we will begin to take data containing utilizing the full ADC sampling rate. We will be able to compare the observed chirps with the predictions of phase shift models. We will use both the Dopper shifts and the relative phase information from the several receiver stations to reconstruct air shower geometries. Finally, we will seek to correlate the received power of the echo signals with the energy of the incident cosmic ray.

6 Summary

In this Project Narrative, we have explained the need for an observatory with the ability to remotely detect airshowers induced by high energy cosmic rays. We showed that the properties of airshowers and radio frequency scattering make bistatic radar a viable candidate for a remote detection technology.

We presented results of preliminary studies in Long Island, New York showing that cosmic ray airshowers can indeed by "seen" in radar echo, and that Millard County, Utah is ideally suited for the studies we propose. Indeed, the unusually radio quiet environment, access to the Northern Hemisphere's largest cosmic ray observatory and opportunistic receipt of donated high-power transmitter equipment present us with the ideal situation to carry these studies forward.

As presented, the three-stage plan for deployment of successively higher-powered transmitters and more sophisticated receiver stations is achievable within the three-year scope of the proposal, and is a realistic path towards overcoming the technical obstacles. The assembled team of cosmic ray physicists and electrical engineers is the right group of people to successfully carry out this project with the support of the W. M. Keck Foundation.

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[25] **http://www.broadcast.harris.com**

[26] **http://www.kathrein.de/**

Biographical Sketch: John W. Belz

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University of Utah
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Education

Postdoctoral	Rutgers University (G. Thomson and S. Somalwar)
Ph.D. (Physics)	Temple University (1993) (K. McFarlane)
B.A. (Physics)	Temple University (1987)

Recent Professional Positions

2009–	Research Associate Professor, University of Utah
2006–2009	Research Assistant Professor, University of Utah
2005–2006	Visiting Assistant Professor, University of Utah
2002–2006	Assistant Professor, University of Montana
1999–2002	Research Assistant Professor and Adjunct Instructor, Montana State University

Research Experience

15 years	Experimental high-energy physics (at BNL, FNAL, SLAC)
12 years	Cosmic ray physics (with High Resolution Fly's Eye, Telescope Array)

Selected Recent Publications

- *Indications of Proton-Dominated Cosmic Ray Composition above 1.6 EeV*,
  by the HiRes Collaboration, R. Abbasi et al., Phys. Rev. Lett. **104** 161101 (2010).

- *Measurement of the Flux of Ultra High Energy Cosmic Rays by the Stereo Technique*,
  by the HiRes collaboration, R. Abbasi et al., Astropart. Phys. **32** 5360 (2010).

- *Cosmic Rays: The Second Knee and Beyond*,
  Douglas R Bergman, John W. Belz, J.Phys. G34:R359., (2007).

- *Observation of the GZK Cutoff by the HiRes Experiment*,
  by the HiRes Collaboration, R. Abbasi et al., Phys. Rev. Lett. **100** 101101 (2008).

- *Comparison of Air Fluorescence and Ionization Measurements of E.M. Shower Depth Profiles: Test of a UHECR Detector Technique*,
  by the FLASH Collaboration (J. Belz et al.), Astropart. Phys. **25** 57 (2006).

BIOGRAPHICAL SKETCH

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EMPLOYMENT

July 2004 -	Professor, ECE Department, Univ of Utah.
Aug. 2000 – June 2004	Associate Professor, ECE Department, Univ of Utah.
June 1998 – Aug 2000,	Associate Professor: ECE Department, National Univ of Singapore.
Sept 1989 – June 1998,	Senior Lecturer: ECE Department, National Univ of Singapore.
Sept 1983 – Sept 1989,	Assistant Professor, Isfahan Univ of Technology, Isfahan, Iran.

EDUCATION

Ph.D.	Communications, Elec. Eng. Dept., Imperial College, University of London, 1981.
M.Eng.	System Test Technology, University of Wales, Institute of Science and Technology, U.K., 1977.
B.Sc.	Elec. Eng. Dept., Tehran University, Iran, 1976.

PROFESSIONAL ACTIVITIES

Associate Editor, IEEE Trans. Signal Processing, 2002 - 2005.
Associate Editor, IEEE Signal Processing Letters, 2008 - .
Vice Chair IEEE SP/COM Society-Utah Chapter, 2001-2003.
Chairman IEEE SP/COM Society-Utah Chapter, January 2004 – December 2005.

RECENT SELECTED PUBLICATIONS

[1] B. Farhang-Boroujeny, Signal Processing Techniques for Software Radios. BOOK, self-published at Lulu publishing house. This book is widely used in amateur radio community.

[2] Peiman Amini, E. Azarnasab, Pooyan Amini, S. Akoum, and B. Farhang-Boroujeny, "An Experimental Cognitive Radio for First Responders," 3rd IEEE Symposium on Dynamic Spectrum Access Networks, DySPAN 2008, 14-17 Oct. 2008, pp. 1 – 6.

[3] S.A. Laraway and B. Farhang-Boroujeny, "Implementation of a Markov Chain Monte Carlo Based Multiuser/MIMO Detector," IEEE Trans. On Circuits and Systems, Jan. 2009.

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ADDRESS

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EDUCATION:

University of Chicago	Physics	B.A. 1967
University of Illinois	Physics	Ph.D 1973

PROFESSIONAL EXPERIENCE:

1973	Research Associate, University of Illinois
1973-1975	Research Associate, Columbia University
1975-1981	Assistant Professor, Columbia University
1981-1988	Associate Professor, University of Utah
1988-present	Professor, University of Utah
1994	Distinguished Visitor, University of Adelaide, Adelaide, Australia
2003-2007	Chair, Physics Dept., University of Utah
2007-present	Dean, College of Science, University of Utah

RESEARCH ACTIVITIES:

Study of ultra-high energy cosmic rays using atmospheric fluorescence technique. Worked on Fly's Eye experiment, High Resolution Fly's Eye (HiRes) experiment (spokesman), Telescope Array collaboration (co-spokesman), Pierre Auger experiment, FLASH (experiment to measure air-fluorescence efficiency at Stanford Linear Accelerator Center).

HONORS:

Sloan Foundation Fellow, 1977-1981
Distinguished Visitor, University of Adelaide, 1994
Japan Society for the Promotion of Science Fellow, 1996
Distinguished Research Award, University of Utah, 1999
Guggenheim Foundation Fellow, 2002-2003
Fellow, American Physical Society, 2002
Governor's Medal For Science and Technology, 2006
W.K.H. Panofsky Prize in Experimental Particle Physics, American Physical Society, 2008

SELECTED RELEVANT PUBLICATIONS:

"Extremely High Energy Cosmic Rays", with B. Dawson and P. Sommers, Physics Reports, **217** (1992).

"Evidence for Correlated Changes in the Spectrum and Composition of Cosmic Rays at Extremely High Energies", with D. J. Bird *et al.*, Phys. Rev. Lett. **71**, 3401 (1993).

"Measurement of pressure dependent fluorescence yield of air: Calibration factor for UHECR detectors", with J.W. Belz et al, Astropart. Phys. **25** 129 (2006).

"First Observation of the GZK Cutoff by the HiRes Experiment", with R. U. Abbasi et al., Phys. Rev. Lett. **100** 101101 (2008).

"Indications of a Proton Dominated Cosmic Ray Composition Above 1.6 EeV", with R. U. Abbasi et al., Phys. Rev. Lett. **104** 161101 (2010).

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Education:

B.Sc.	Physics	University of São Paulo, Brazil, 1980
M.Sc.	Physics	University of São Paulo, Brazil, 1982
Ph.D.	Physics	University of Rio de Janeiro, 1986

Employment: Adjunct Professor, Physics Department, SBU (2005 - to present)
Physicist, Physics Department, BNL (1995 - to present)
Associate Physicist, Physics Department, BNL (1992-1995)
Assistant Physicist, Physics Department, BNL (1990-1992)
Research Associate, Physics Department, BNL (1989-1990)
Research Associate, Dept. Phys. & Astronomy, Pittsburgh (1986-1989)

Others: Outstanding DOE Mentor, 2003 and 2006
Fellow of the Royal Astronomical Society (2004)
Convener of the ATLAS experiment Heavy Ion Physics Group (02-06)
Mentor for QuarkNet, (2000 - to present)
Mentor for DOE Educational Programs - LSTPD, SULI and PST
Mentor for Stony Brook URECA and Simmons program.

Relevant Publications:

1. M. F. Bugallo, H. Takai, et al; *MARIACHI: A multidisciplinary effort to bring science and engineering to classroom.* ICASSP 2008
2. M. F. Bugallo, H. Takai, et al; *Hands-on engineering and science: Discovering cosmic rays using radar based techniques and mobile technology, in IEEE ICASSP 2009 Proceedings.*
3. T. Terzella, J. Sundermier, J. Sinacore, C. Owen, and H. Takai, *Measurement of g using a Flashing LED*. Phys. Teach. 46, 395 (2008)
4. S. Aronson et. al.; *A nuclear physics program at the ATLAS experiment at the CERN large hadron collider*. ArXiv:nucl-ex/0212016
5. A. Berntson, V. Stojanoff and H. Takai; *Application of a neural network in high throughput protein crystallography*. Journal of Synchrotron Radiation 10, 445(2003)

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Department of Physics and Astronomy,
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Education

B.S.	Illinois Institute of Technology, with Distinction	1965
M.A.	Harvard University	1968
Ph.D.	Harvard University	1972

Recent Positions

Rutgers University	Assistant Professor	1980-1986
Rutgers University	Associate Professor	1986-1996
Rutgers University	Professor I	1996-2003
University of Utah	Visiting Scholar	1999-2000
Rutgers University	Professor II	2003-2009
University of Utah	Professor	2009-present
University of Utah	J.W. Keuffel Chair in Experimental Astrophysics	2009-present

Areas of Research

Cosmic Ray Physics, 11 years experience
Experimental High Energy Physics, 25 years experience

Five Publications Related to the Proposed Project

1. R.U Abbasi *et al*., [The High Resolution Fly's Eye Collaboration], "Indications of Proton-Dominated Cosmic Ray Composition above 1.6 EeV", accepted for publication by Phys. Rev. Lett.
2. R.U. Abbasi *et al*., [The High Resolution Fly's Eye Collaboration], "Analysis of Large-Scale Anisotropy of Ultrahigh Energy Cosmic Rays in HiRes Data", accepted for publication by Ap.J. Lett.
3. R.U Abbasi *et al*., [The High Resolution Fly's Eye Collaboration], "First Observation of the GZK Cutoff by the HiRes Experiment", Phys. Rev. Lett. **100**, 101101 (2008).
4. R.U Abbasi *et al*., [The High Resolution Fly's Eye Collaboration], "Search for Correlations between HiRes Stereo Events and Active Galactic Nuclei", Astropart. Phys. **30**, 175 (2008).
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July 11, 2010

Dr. John Belz
Department of Physics and Astronomy
University of Utah

Dear Dr. Belz

The Brookhaven National Laboratory's Physics Department enthusiastically supports the participation of Dr. Helio Takai in the proposal *A Radar Detector for the Universe's Most Energetic Particles* to the W. M. Keck Foundation. Dr. Takai has first introduced the concept of using bistatic radars for the detection of ultra high energy cosmic rays at our laboratory. Your plans to implement a dedicated radar at the Telescope Array facility at Utah will permit a definitive test of this concept and this is quite exciting. Dr. Takai's direct contribution to your effort will be on the development of radar instrumentation.

In support of the proposed project here at BNL we will support a fraction of Dr. Takai's time to participate in the project. We will provide him with access to our infrastructure with laboratory and workshop space. We will also encourage Dr. Takai's supervision of graduate students in this project.

Best of luck in your application,

Sincerely

Robert Ernst
Administrator, Manager
Physics Department
Brookhaven National Laboratory

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July 11, 2010

Dr. John Belz
Department of Physics and Astronomy
University of Utah

Dear John,

I am very happy that we are submitting this proposal to the W. M. Keck foundation. As you well know, we started pursuing the idea of implementing a bistatic radar for the detections of the ultra high energy cosmic rays about five years ago. From its beginnings to today our collaborative effort has led us to a stage where we feel confident of its implementation. Our preliminary tests and experiments has led us to the development of a mature idea of how to implement a radar system that will detect the universe's most energetic particles. Personally, I think that this is one of the most exciting projects I have been involved in my professional career. This project is truly transformational in nature as it may open a window for the implementation of a detection system to explore the nature and origin of the most energetic particles known by mankind. This facility will also open up the possibility to explore the existence of high energy neutrinos and other exotic energetic particles yet to be discovered. This grant from W.M. Keck will certainly make our ideas a reality, and that is very exciting. I am delighted to be part of this collaboration and I am looking forward to a successful implementation of the bistatic radar.

Sincerely,

Helio Takai

Dr. Helio Takai
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Research Programs Project Budget

Organization Name: University of Utah

Category	Year 1		Year 2		Year 3		Cumulative		Totals
Personnel (Salary + Fringe Benefits)	**WMKF**	**Other Sources***	**WMKF**	**Other Sources***	**WMKF**	**Other Sources***	**WMKF**	**Other Sources***	**All Sources**
Principal Investigators (2)	$23,050		$23,740		$24,460		$71,250		**$71,250**
Postdoctoral Fellows (1)	$60,000		$62,000		$64,000		$186,000		**$186,000**
Graduate Students (4)	$42,560	$42,560	$43,840	$43,840	$45,160	$45,160	$131,560	$131,560	**$263,120**
Other (undergraduate students)	$12,000		$12,000		$12,000		$36,000		**$36,000**
Personnel Subtotal	**$137,610**	**$42,560**	**$141,580**	**$43,840**	**$145,620**	**$45,160**	**$424,810**	**$131,560**	**$556,370**
Equipment									
700 W transmitter, antenna		$46,500						$46,500	**$46,500**
2 and 20 kW transmitter, antennas		$290,000						$290,000	**$290,000**
transmitter facility, mast	$41,700						$41,700		**$41,700**
receiver stations (13)		$17,170	$41,340		$206,700		$248,040	$17,170	**$265,210**
Equipment Subtotal	**$41,700**	**$353,670**	**$41,340**		**$206,700**		**$289,740**	**$353,670**	**$643,410**
Operations									
Consumable supplies	$1,000		$1,000		$1,000		$3,000		**$3,000**
Satellite network			$1,200		$6,000		$7,200		**$7,200**
Travel/symposiums	$12,000		$12,000		$12,000		$36,000		**$36,000**
Contracted services	$14,000		$14,000		$5,000		$33,000		**$33,000**
Renovations	$1,000		$1,000				$2,000		**$2,000**
Facilities/Overhead		$13,665		$13,998		$14,342		$42,005	**$42,005**
Other (transmitter power)	$3,250		$35,750		$65,000		$104,000		**$104,000**
Other (computing)		$10,000		$10,000		$10,000		$30,000	**$30,000**
Operations Subtotal	**$31,250**	**$23,665**	**$64,950**	**$23,998**	**$89,000**	**$24,342**	**$185,200**	**$72,005**	**$257,205**
Totals	**$210,560**	**$419,895**	**$247,870**	**$67,838**	**$441,320**	**$69,502**	**$899,750**	**$557,235**	**$1,456,985**

* Other includes institutional and external forms of support

† List major pieces and/or categories

Revised 01/10/07; June 2007 cycle

Revised 01/10/07; June 2007 cycle

Project Budget

Budget Justification: Line-by-line justification of the project budget is given below.

Personnel
We request a total of $424,810 from W.M. Keck for personnel expenses. These include one month salary for two of the principal investigators (J. Belz and B. Farhang), support for one postdoctoral researcher at the standard University of Utah rate, and support for two University of Utah graduate students. We also request funds of $12,000 per year for support of undergraduate research assistants. Two graduate students will also be supported on this project from an NSF award.

Equipment
A substantial part of the equipment costs for this project are borne by the private donation by KUTV Channel 2 of nearly $290,000 in television transmitter equipment and broadcast antennas. The cost of buying this equipment new would be over $1M. See attached letter of donation. Equipment for the Phase-I transmitter, including radio equipment, antennas and lightweight mast, oscilloscope and spectrum analyzer have been purchased with NSF money.

The equipment costs to Keck for the 2 and 20 kW (Phase-II and -III) transmitter facility are broken down in the following table. The antenna mast cost is based on a quote for the Trylon *Super Titan* model [1], the cost of the hazardous duty rigging crew is taken from similar antenna mounting operations by KUTV. The remainder of construction costs are based on similar projects performed in Delta, Utah.

Item	Cost
antenna mast	$28,700
antenna rigging crew	$ 6,000
concrete bed for mast	$ 2,000
chain link safety fence	$ 2,000
coaxial waveguide, misc. connectors	$1,500
modifications to CRC power	$1,500
TOTAL	$41,700

Table 1: Transmitter facility costs.

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[1] www.trylon.com

Equipment, continued

In Table 2 we summarize the costs of the receiver stations which we will deploy. We assume the first station will be "tethered" to the TA Long Ridge fluorescence detector, and thus not require remote operations capability. (This station will be purchased with NSF funds.) Subsequent stations (12) will require solar power, and because the land is federally owned we will be required to perform plant, animal, and archaeological surveys on the receiver sites. The full battery of receiver stations will cover an area comparable to the entire TA SD array. The primary expenses for the receiver stations (described in more detail in Section 5.2 of the Project Narrative) are for the USRP-II software-defined radio receiver, host computer, and log-periodic antennas required to detect the broadband chirp signal. The cost of the satellite network communications which are required for the remote sites is listed separately under "Operations".

Item	Unit Price	Total
antenna (log periodic)	$500	$2,000
tower (24" stand alone)	$480	$1,920
cables		$250
hut for receiver equipment		$500
USRP-II GNU radio receiver	$1,500	$6,000
computer (e.g. Panasonic Toughbook)		$4,000
miscellaneous hardware		$500
concrete pad		$2,000
total "tethered"		$17,170
site surveys		$1,300
solar cells and batteries		$2,800
total "untethered"		$20,670

Table 2: Costs for single radar receiver station.

Operations

The largest operations costs are for electrical power, particularly to operate the 20 kW transmitter. We assume 25% efficiency and current rural Utah power rates in our power estimates. It is assumed that the 2 kW transmitter will operate one half of year one, year two will be one half 2 kW and one half 20 kW transmission, and year three is 100% 20 kW transmission.

Other costs include travel at $12,000/year, for both trips to Delta, Utah and conferences. $33,000 is for contracted services in the form of the two RF engineers who will help us install and maintain the transmitter systems. In years two and three, we include costs for remote satellite network links at the rate of $600 per station per year. $3,000 is alloted for supplies, and $2,000 is included for renovations to the Cosmic Ray Center to enhance the "visitability" of the Keck radar transmision facility. The NSF grant will provide $10,000 per year for computing and data storage.

Other Funding: To date, funding has been sought and secured for pilot studies validating the feasibility of the technique. In Long Island New York, approximately $130,000 was obtained from the NSF for equipment, student salary and travel for the MARIACHI project. Using this high-school based cosmic ray ground array in conjunction with two radar stations, Co-P.I. Helio Takai has detected approximately ten radar echos in time and spatial coincidence with cosmic ray showers.

The University of Utah provided seed grant funds totalling $34,689 for the support of a graduate student and equipment, in order to characterize the radio-frequency environment at the Telescope Array site in Millard County, Utah. Based on this work as well as the MARIACHI events described above, we have obtained additional funding totalling $270,000 from the NSF for support to operate a low power (700 W) modified ham radio transmitter and receiver station in Millard County.

The goal for the NSF-supported part of the project is to essentially duplicate the Long Island pilot studies using our own transmitter as opposed to ambient radio frequency emissions. We expect to be able to improve on the “statistics” obtained in Long Island as well. However the NSF grant has limited funds for development of more sophisticated receiver stations — which will be needed in order to do astrophysics with this technique — and not nearly enough support for the engineering, construction and power required in order to utilize the high-power KUTV transmitters.

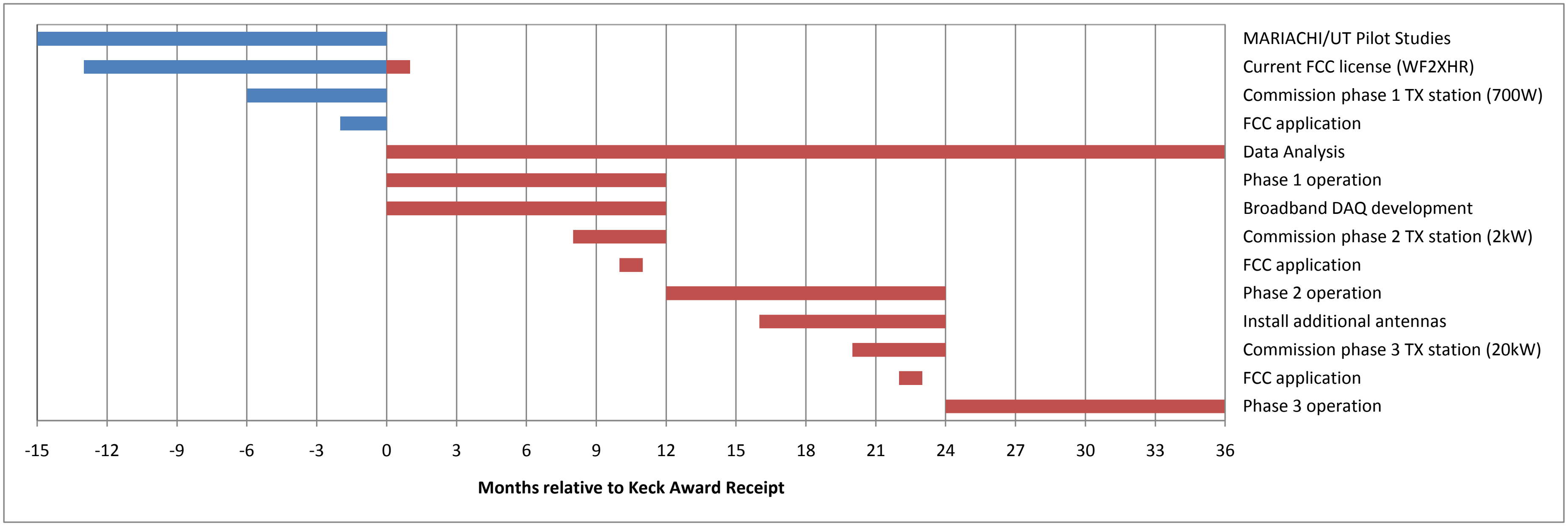
In terms of the three-stage plan outlined in our proposal, the NSF grant covers part of Stage-I. Given the uncertainties, Stage-I is not likely to provide definitive evidence that the technique can work. Therefore the Keck Foundation’s role is actually pivotal.

This project received a large boost from the donation of high-power 2 kW and 20 kW transmitters from KUTV Channel 2 in Salt Lake City. The estimated depreciated value of these transmitters is $290,000. They would cost $1,050,000 if purchased new.

Finally, this project can count among its assets several facilities owned by the University of Utah. These include the Millard County Cosmic Ray Center in Delta, Utah, a $160,000, $4,000 square foot facility with adjacent lot space which will house the transmitters. Also, the Telescope Array cosmic ray observatory, constructed for roughly $20M with funds from the Ministry of Science and Education in Japan and the U.S. National Science Foundation will provide crucial information on the cosmic ray air showers which produce the radar echoes under study.

Keck Foundation Support is Essential: Cosmic rays are one of the most important areas of astrophysics research. First detected early in the 20^{th} century, cosmic rays were a source of many early discoveries in elementary particle physics until man-made accelerators took over this role after World War II. Today, cosmic rays are studied to learn about their astrophysical sources and the interstellar and intergalactic media through which they propagate before reaching Earth.

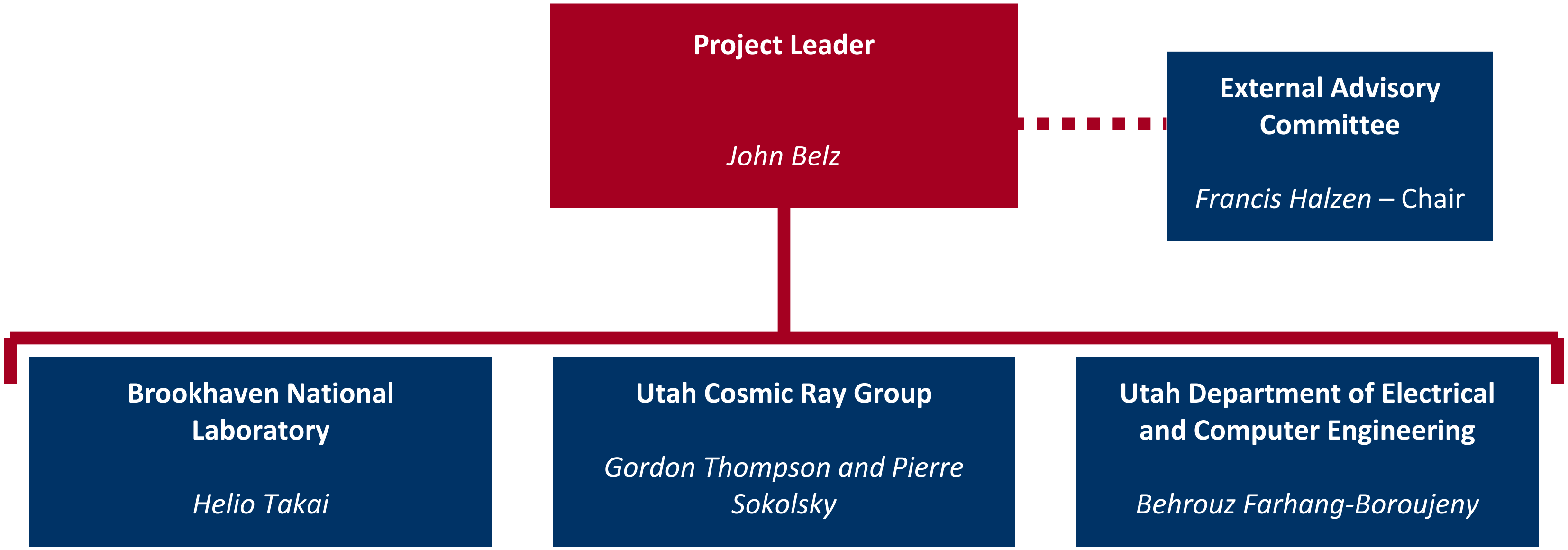
Because the highest energy particles are so rare, we have nearly come to the end of this study using standard techniques. The extension of conventional detectors to new levels would be prohibitively expensive. New technologies are needed in order for the field to progress beyond the current generation of observatories. The bistatic radar technique is a prime candidate. However while the idea appears promising it has yet to be proven viable in this role. The support of a funding source willing to invest in an unproven yet potentially transformative technology is essential.


MARIACHI/UT Pilot Studies
Current FCC license (WF2XHR)
Commission phase 1 TX station (700W)
FCC application
Data Analysis
Phase 1 operation
Broadband DAQ development
Commission phase 2 TX station (2kW)
FCC application
Phase 2 operation
Install additional antennas
Commission phase 3 TX station (20kW)
FCC application
Phase 3 operation
-15
-12
-9
-6
-3
0
3
6
9
12
15
18
21
24
27
30
33
36
Months relative to Keck Award Receipt

A Radar Detector for the Universe's Most Energetic Particles

Project Organizational Chart

The University of Utah | 2010



Project Leader

John Belz

External Advisory Committee

Francis Halzen – Chair

Brookhaven National Laboratory

Helio Takai

Utah Cosmic Ray Group

Gordon Thompson and Pierre Sokolsky

Utah Department of Electrical and Computer Engineering

Behrouz Farhang-Boroujeny

Description of Expertise and Roles of Key Project Personnel

- **John Belz (Project Leader)** has 15 years experience in experimental particle physics and 12 years in cosmic ray physics. His cosmic ray projects have included the High-Resolution Fly's Eye, Telescope Array, and the Telescope Array Low Energy Extension (TALE). His recent research has focused on cosmic ray composition studies, and he has been investigating the use of radar in observing cosmic rays for two years.

  John will serve as project manager, supervise transmitter deployment and facilities maintenance.

- **Behrouz Farhang-Boroujeny** is a professor of electrical engineering with a general interest in various applications of signal processing to communications. In the past he has done research in the general area of adaptive filter (analysis and design of algorithms), acoustic echo cancellation and active noise control, and signal processing techniques in magnetic and optical recording. His current research activities include Cognitive Radio, Multicarrier Communications, CDMA detection techniques, and MIMO communications. He is the author of a book *Signal Processing Techniques for Software Radios*.

  Behrouz will focus on developing code for GNU radio, signal recognition and online filtering of data.

- **Pierre Sokolsky** has 29 years experience in cosmic ray physics. He is spokesman for the HiRes, Telescope Array, and Telescope Array Low Energy Extension (TALE) experiments. He is currently Dean of the College of Science at University of Utah, and won the 2008 Wolfgang Panofsky Prize in experimental particle physics for his work in developing the nitrogen fluorescence technique for reconstruction of cosmic ray air showers.

  Pierre will serve as senior advisor to the project and participate in data analysis.

- **Helio Takai** is Senior scientist at Brookhaven National Laboratory and faculty member of the Stony Brook University Physics Department. He has 24 years experience in experimental high-energy physics, and in 2005 developed the concept of MARIACHI. Helio co-Convener of the ATLAS experiment Heavy Ion Physics group and member of ATLAS physics coordination. He has been a QuarkNet Mentor since 1999 and is a mentor for the Laboratory Science Teacher Development program.

  Helio will lead the effort to investigate different receiver antennas, and develop receiver station hardware. He will also continue to work on the simulation of radar echo signals.

- **Gordon Thomson** has 25 years experience in experimental particle physics and 11 years experience in cosmic ray physics. He is currently working on three experiments studying ultrahigh energy cosmic rays, the High Resoluton Fly's Eye (HiRes) experiment (co-spokesman), the Telescope Array (TA) experiment, and the Telescope Array Low Energy Extension (TALE) experiment (co-spokesman). Gordon has been investigating the use of radar in observing cosmic rays for three years.

  Gordon is an expert in analysis of Telescope array surface detector data, and will focus on the analysis of data and air shower reconstruction.

Plans beyond proposed time period

The transmitter and receiver array to be developed under this proposal will demonstrate the feasibility of the next level of deployment beyond the scope of the Keck grant: a full-scale array of receiver antennas covering an area up to $10\times$ greater than the world's largest existing cosmic ray observatories. In initial conversations, the NSF has indicated an interest in supporting the further development of a radar observatory if the concept can be shown to work.

As an example, the thirteen receiver stations that we will deploy under this grant will "cover" an area of the Earth's surface approximately equal to the Telescope Array Surface detector. The roughly \$600,000 in Phase-III transmitter and receiver costs should be contrasted with the \$5 M cost of the TA Surface Detector itself.

Beyond the three year period of the Keck grant we will build a much larger detector, seeking support from the National Science Foundation, which has long supported particle astrophysics research in Utah. Competing projects include the Telescope Array and the proposed Northern site of the Auger Observatory. The proposed Auger North detector will cover approximately 10,000 km^2, at a proposed cost of \$120 M. Using radar technologies, we envision a detector with a similar aperture for approximately one tenth of the cost. In other words, by virtue of its cost effectiveness we expect our radar detectors to be highly competitive with other proposed astroparticle observatories.

Evaluation Plan

The search for radar reflections from ultrahigh energy cosmic ray showers will use data from the Telescope Array (TA) experiment for verification of the detection of cosmic ray showers. Therefore the radar project must be, and is, an official part of the TA experiment. Every aspect of the radar project will be reviewed by the TA collaboration on a frequent basis. In addition, the TA External Advisory Committee will review the project on a yearly basis. The first such external review of TA occurred in April, 2010, and the radar project was presented in complete detail (the report of the committee is enclosed).

The committee enthusiastically endorsed the radar project, saying

> …the committee strongly supports the investigation of new detection techniques, specifically the ongoing research on bistatic radar for which TA occupies an ideal site in the case of success. The method is familiar from meteor detection using radio waves. The key idea of the technique is to observe the electromagnetic wave reflection off the ionization cloud produced by a cosmic ray in the atmosphere.

The members of the TA External Advisory Committee, all leaders in the field of particle physics and astrophysics, are:

- Professor Francis Halzen, University of Wisconsin, chair
- Dr. John Peoples, Fermi National Accelerator Laboratory
- Dr. Nick Samios, Brookhaven National Laboratory
- Professor Eun-Suk Seo, University of Maryland
- Professor Yasushi Muraki, Konan University
- Professor Yoichiro Suzuki, University of Tokyo

Recognition Statement

In recognition of the support of the W. M. Keck Foundation, we will name the radar transmitter facility after the Keck Foundation and reference that named aspect in any publications or public presentations describing this work. The transmitter facility will include a wing of the Millard County Cosmic Ray Center (CRC), the transmitter, antenna and supporting mast.

The CRC is a 4,000 square foot commercial building which is located at 39° 21' 10" North, 112° 35' 23" West, in the town of Delta, Utah. It is owned by the University of Utah. In addition to serving as the nexus of detector construction and data collection for the Telescope Array experiment, it is also the location of the project's Visitors Center.

The CRC is visited regularly by tourists in Delta and by student and community groups as part of our scientific outreach program. The CRC contains several educational displays about cosmic rays, and more are being prepared for installation the near future. The Keck radar transmission facility would be an exciting addition to the "tour", wherein it would both contribute to our outreach efforts and publicize the support of the Foundation.

Additional Information

DELTA CITY
76 North 200 West
Delta, UT 84624
(435) 864-2759 FAX (435) 864-4313
www.delta.utah.gov

July 29, 2010

Professor John Belz
University of Utah, Department of Physics
115 South 1400 East, Suite 201
Salt Lake City, UT 84112-0830

Dear Professor Belz:

I am writing in response to your questions regarding installation of a fifty-foot antenna mast, and supporting guy wires, at the Millard County Cosmic Ray Center in Delta, Utah. It is my understanding that this mast will support transmitting antennas as part of your effort to detect cosmic rays using radar.

Inasmuch as this mast will be located on property owned by the University of Utah, there are no obstacles to construction, provided the entire installation, including guy wires, is located a minimum of ten feet from the property line. In addition, it must be fenced or have climb safety features (no access for the public).

If you have any additional questions, please contact me.

Sincerely,

Alan Riding
Public Works Director

kj

Isaac Myers, 115 S 1400 E, Salt Lake City, UT 84112,

United States of America
FEDERAL COMMUNICATIONS COMMISSION
EXPERIMENTAL RADIO STATION CONSTRUCTION PERMIT AND LICENSE

EXPERIMENTAL (Nature of Service)	WF2XHR (Call Sign)
XR FX (Class of Station)	0459-EX-PL-2009 (File Number)

NAME University of Utah Department of Physics and Astronomy

Subject to the provisions of the Communications Act of 1934, subsequent acts, and treaties, and all regulations heretofore or hereafter made by this Commission, and further subject to the conditions and requirements set forth in this license, the licensee hereof is hereby authorized to use and operate the radio transmitting facilities hereinafter described for radio communications in accordance with the program of experimentation described by the licensee in its application for license.

Operation: In accordance with Sec. 5.3(c) of the Commission's Rules

Station Locations

(1) Delta, UT - NL 39-21-10; WL 112-35-23

Frequency Information

Delta, UT - NL 39-21-10; WL 112-35-23

Frequency	Station Class	Emission Designator	Authorized Power	Frequency Tolerance (+/-)
54.1-54.1 MHz	FX	N0N	2880 W (ERP)	

Special Conditions:

(1) The station identification requirements of Section 5.115 of the Commission's Rules are waived.

(2) Licensee should be aware that other stations may be licensed on these frequencies and if any interference occurs, the licensee of this authorization will be subject to immediate shut down.

(3) In lieu of frequency tolerance, the occupied bandwidth of the emission shall not extend beyond the band limits set forth above.

(4) Operation is subject to prior coordination with the Society of Broadcast Engineers, Inc. (SBE); ATTN: Executive Director; 9247 North Meridian Street, Suite 305; Indianapolis, IN 46260; telephone, (866) 632-4222; FAX, (317) 846-9120; e-mail, executivedir @ sbe.org; information, www.sbe.org.

This authorization effective February 22, 2010 and
will expire 3:00 A.M. EST March 01, 2011

FEDERAL COMMUNICATIONS COMMISSION

NEWS
FRESH AIR

Tel 801.973.3000
299 South Main Street, Suite 150
Salt Lake City, Utah 84111

Bill Ramsay
Transmissions Engineer, KUTV Channel 2
299 S. Main Street
Salt Lake City, UT 84111
BRamsay@kutv2.com

September 21, 2009

John Belz
Research Associate Professor
University of Utah
Department of Physics and Astronomy
115 S. 1400 E. Suite 201
Salt Lake City, UT 84112-0830

Dear Professor Belz:

On behalf of Salt Lake City's KUTV Channel 2, I am pleased to donate our analog television broadcasting equipment to you and your cosmic ray research group at the University of Utah. I understand that this equipment will be used as part of a new project to detect cosmic ray airshowers by radar techniques, in conjunction with the Telescope Array project in Millard County.

The donated equipment includes a 20 kW Harris transmitter, a 2 kW backup transmitter, an 18 segment Kathrein dipole antenna, a 25 kW test termination load, hybrid combiners for the two transmitters and assorted waveguides. We estimate the total depreciated value of the donated assets at $289,629.41. The total original cost of the two transmitters was $1,049,417.95.

We at KUTV wish you the best in your efforts, and look forward to doing a news story describing your research with this equipment.

Sincerely,

Bill Ramsay

Bill Ramsay

April 11, 2010

Report of the TA/TALE Advisory Committee

Preamble

The committee met at the University of Utah on April 8 and 9, 2010. We visited the site of the experiment. The tour included one of the surface detectors (SD), one of the three fluorescence detectors (FD) sites and the transmission tower. We were also given a tour of the Cosmic Ray Center in Delta, Utah where Pierre Sokolsky made a presentation on the history of cosmic ray physics in Utah and introduced the committee to TA/TALE.

In a series of excellent presentations the collaboration reviewed the status of the data analysis, future plans for TALE, the research and development work on bistatic radar detection of cosmic rays and the ASPIRE outreach program.

We thank the collaboration for their excellent hospitality.

The detailed schedule of the review and the membership of the committee are listed in the Appendix.

Executive Summary

The HiRes experiment established that the highest energy cosmic rays are extragalactic in origin with the observation of their absorption by microwave photons. The appearance of the Greissen, Zatsepin and Kuzmin (GZK) absorption dip in the cosmic ray spectrum has been confirmed by the next-generation Auger experiment and resolved the long-standing controversy between the HiRes and AGASA experiment whose data, with limited statistical significance, indicated the absence of the GZK cutoff. At present a new controversy has emerged between the HiRes and Auger experiments that essentially disagree on everything else but the GZK feature: these include the detailed structure of the spectrum, the composition of the cosmic rays and whether the highest energy particles point back to their sources. Enter the Telescope Array (TA).

The Telescope Array, mostly funded by Japan, has been deployed in Millard County, Utah in record time with the help of the experienced University of Utah cosmic ray group. The local group has recently been strengthened by the move of the Rutgers HiRes faculty to Utah. The present collaboration also includes universities from Belgium, Korea and Russia. Though smaller than Auger, its concept is somewhat different: rather than operating as a hybrid surface array and fluorescence detector, the two components of TA are fully functional, separately and as one. Very experienced groups centered in Japan and Utah each independently analyze the experiment's early SD, FD and hybrid data. Results have been obtained in a very short time and presented for the first time at the SNOWPAC meeting and at the Japanese Physical Society meeting in Okayama, Japan in March, 2010. Though preliminary and of limited statistics, all analyses, SD, FD and hybrid, agree on the spectrum and are consistent with the published HiRes data.

It is now clear that the initiative to build a next-generation experiment besides Auger showed great foresight and presents the collaboration with an extraordinary opportunity. In this context the committee strongly supports the plan of the collaboration to proceed with the construction of the US contribution to TA dubbed TALE (TA Low Energy extension), and unfortunately not funded so far. It will recycle all HiRes fluorescence detectors and incorporate them into the present detector in order to not only lower the threshold but also achieve an acceptance at all energies similar to that of Auger. At high energy it will further contribute to the all-important issue of whether the cosmic rays near 10^{20} eV reveal their sources. Additionally, it will cover all features of the spectrum (the onset of the extragalactic component, presumably the knee, the second knee and the ankle as well as the e^+e^- and pion production absorption dips) with a single instrument. In the absence of "proton astronomy" the details of the spectrum are our most powerful probe of the sources.

We agree with the collaboration that the next step is a detector with an acceptance increased by at least one order of magnitude, able to deliver more that 10 events per year above 10^{20} eV. Such a detector should be based on information obtained by Auger and TA/TALE neither of which has exploited its full science potential at this time. In this context the committee strongly supports the investigation of new detection techniques, specifically the ongoing research on bistatic radar for which TA occupies an ideal site in the case of success. The method is familiar from meteor detection using radio waves. The key idea of the technique is to observe the electromagnetic wave reflection off the ionization cloud produced by a cosmic ray in the atmosphere.

The committee discussed the issue of manpower in the context of the ambitious program that includes completion of the HiRes analysis, timely delivery of quality TA data and their analysis, construction of TALE and the development of radar detection. We suggest that the collaboration consider expansion. The considerable impact of the first TA data will undoubtedly create the opportunity to attract excellent scientists to all aspects of the successful program, including experienced radio experts.

Although the committee focused on science, we observe that the management of the collaboration is based on an appropriate mixture of formal and informal planning that is clearly effective. The project management established a record of success in the construction phase of TA and is carrying this forward into the analysis phase of the experiment.

The outreach effort of the collaboration includes the ASPIRE program that has a long record of success. The committee congratulates the collaboration on all aspects of its extensive outreach program.

The committee will focus the rest of its report on the following issues:

- Status of the data analysis.

- Structure of the Japan-University of Utah collaboration.
- The future Low energy extension of TA: TALE.
- Bistatic radar R&D.

Status of the data analysis:

The analysis of the complete HiRes data set is almost complete, the end of a historic experiment. HiRes established the GZK feature in a spectrum that has now been confirmed by the next-generation Auger experiment. After initial disagreements on the cosmic ray spectrum, the Auger collaboration announced at the recent SNOWPAC meeting that their observations agree with the HiRes results within the systematic errors on the absolute energy measurement of the two experiments. Also, with higher statistics the arrival directions of the cosmic rays measured by Auger are no longer inconsistent with the isotropy observed by HiRes. We look forward to improved statistics with continued data taking. We note that the SD data is at present insufficient to establish the GZK feature in the spectrum and look forward to this important measurement in the near future.

The composition of the highest energy particles, especially as derived from the observations of shower fluctuations, is still a matter of controversy. The fluctuations in the depth of shower maximum measured by the HiRes detector is consistent with protons, while fluctuations essentially disappear (all showers are the same) for the highest energy Auger events suggesting heavy nuclei. The disagreement is extremely puzzling because, by cosmic ray standards, the comparison of the two measurements is relatively direct. The issue is important, with a heavy composition suggesting that we may be witnessing the end of the energy reach of the accelerators. Assuming that the energy to which particles are accelerated is proportional to Ze, heavy nuclei would indeed reach the highest energies. We foresee that the pressure from the community for the two collaborations to exchange data and simulations in order to resolve the issue will be considerable. We encourage this approach and note that first steps have been taken.

At this point all the important HiRes results have been published; only two papers remain to be written: one on the proton-air cross-section and one on the distribution of the widths of individual showers. We foresee very little impact on TA and TALE operations, development and analysis. While the analysis of HiRes data may be nearly finished, the relevance of the published results remains very high and, as already mentioned, the defense of the results is likely to require attention.

The Japanese contribution to TA is completely deployed and operating smoothly. Part of the Hires mirrors have been redeployed to constitute a third fluorescence detector for the TA complex. The analysis programs are in place, with refinements to be made but no qualitative changes expected. Groups on both sides of the Pacific independently analyze both the SD and FD data. We understand that the collaboration has come to a consensus on releasing preliminary analysis results. We strongly encourage this approach as well as early publication given the obvious impact of the findings in confirming the HiRes measurements with a new hybrid detector and with an independent analysis of the data by the Japanese group.

The committee congratulates the collaboration on the timely completion of the detector and the prompt delivery of results. We agree with the Utah group that it is time to move to the completion of the experiment with TALE. From now on TALE will refer to the original proposal by the TA collaboration to relocate the totality of the HiRes detectors to the TA site. Having delivered their part of the detector, the Japanese part of the collaboration is looking forward to the completion of the US contribution to the detector.

US contribution to TA: TALE

The dominant contribution of the Utah group so far has been to act as a host laboratory for the deployment of the Japnese SD and FD detectors. They prepared all infrastructure with the development of the sites, laying out the roads, implementing the inter-detector communications and creating the Cosmic Ray Center in Delta. The group did all surveys, applied for permission of land use and for wireless communications, arranged the exemptions of import tax for Japanese equipment and worked out an agreement with the USAF which uses the area as a training site. These efforts were performed with funding from the State of Utah, the University of Utah, private donations and the NSF.

While the contribution of the Utah group to the experiment has been impressive, the scientific contribution remains incomplete. Its delivery has been packaged in a proposal for the TALE components of TA. Completion of TALE calls for two additional fluorescence sites, each approximately six kilometers from the two existing Japanese FD sites. At each new site two rings of mirrors covering half the azimuth will be deployed, thus using up all available HiRes II mirrors. At one of the sites three additional rings will be built using new mirrors with three times the collecting area and covering 90° in azimuth (the Tower). In front of the Tower, a muon array consisting of buried (or sandbagged) scintillator counters spaced by 400 m will be deployed. This plan delivers an energy coverage from $10^{16.5}$-10^{20} eV, a stereo aperture at 10^{18} eV an order of magnitude larger than HiRes and an instantaneous fluorescence aperture twice that of the SD at 10^{20} eV. The muon array provides hybrid geometry and composition at lower energies.

The committee concluded that ongoing considerations for scaling down TALE imply a loss of science that is not commensurate with the financial savings. The current design of TALE calls for only one new fluorescence site and the muon detector array is replaced by additional SD's of the current design. While this down-scoped plan still provides the low energy coverage, it does so with reduced instantaneous aperture, both in stereo at 10^{18} eV and in all modes at

10^{20} eV. The loss of the muon detectors removes the possibility for an additional handle in determining the composition.

Although doing proton astronomy at 10^{20} eV remains to be demonstrated, it is the highest priority in cosmic ray physics. If successful, it represents the most direct way to identify the sources. The possibility for TALE to collect a significant sample of fluorescence events in the relevant energy region should not be abandoned. We note that the PASAG committee expressed the same opinion. In the absence of cosmic ray astronomy, either because of the dominance of heavy primaries at the highest energies or the discovery of unanticipated values of the intergalactic magnetic field, the case for TALE becomes even more compelling. The only hope to identify the sources with a cosmic ray detector would be to perform a detailed study of the spectrum and all its features with a single instrument. TALE does just that covering the transition to extragalactic particles, the knee, a possible second knee, the e+e- absorption dip and the GZK feature.

As emphasized in the introduction, TA has turned out to be a welcome addition representing a second hybrid detector complementing Auger. In this context the loss of a reduced aperture at the highest energy of the scaled-down detector is especially unfortunate.

TALE Timeline

The committee studied the timelines shown below for the completion of TALE and achieving timely progress on the development of the bistatic radar technique. The latter effort involves the BNL group that originated the research. It is likely that the effort will attract the interest from others specialized in radio detection. Noting that the analysis of TA data made an impressively smooth start, the collaboration is encouraged to proceed with the triple efforts of operating and completing TA, analyzing its data and proceeding with the effort to investigate a new technique for constructing next-generation experiments.

Cosmic ray physics has moved into an era where hybrid detectors as Auger and TA are likely to dominate the science. Next-generation detectors must be built on the findings of present instruments; it will take several years for these to emerge. During this period the opportunity arises to develop techniques for detectors that extend the aperture of cosmic ray instruments by one order of magnitude, or more. Early results obtained at Brookhaven indicate that bistatic radar represents such an opportunity. We take note of the fact that the TA site offers is ideal for the deployment of the facility with the transmitter at the center in Delta and the receivers on the far side of TA relative to Delta. Not only is the site isolated but a ridge between receivers and transmitter additionally shields the receivers from interference.

The committee concluded that it should be possible to interleave the data analysis, TALE construction, and radar R&D schedules shown below to achieve success. The collaboration is by now very experienced, so it should be able to meet the somewhat aggressive schedule. The considerable impact of the first TA data will likely attract excellent scientists to all aspects of the successful program, including experienced radio experts to help develop bistatic radar. Expansion of the collaboration would make these schedules realistic and easy to achieve.

TALE Timeline

• Year 1

o Site development for TALE site

Generators

Radio communications

Central Facility

o Begin construction of building for Rings 1-3 (HiRes-II telescopes)

o Begin refurbishment of HiRes-II telescopes for Rings 1-3

o Begin building Tower telescopes

• Year 2

o Site development for TALE site (networking, DAQ, Central Timing) o Finish construction of building for Rings 1-3

o Deploy refurbished HiRes-II (Rings 1-3) telescopes

o Begin construction for building for Rings 4&5 (Tower telescopes)

o Finish building Tower telescopes

o Begin deployment of Tower telescopes

o Begin deployment of SD Infill Array

- Year 3

o Begin taking data with Rings 1-3

o Finish deployment of Tower telescopes

o Begin taking Tower data

o Finish deployment of SD Infill Array

RADAR Timeline

- Year 1

o Install 800 W transmitter at CRC (already in progress)

o Repeat Long Island studies of Helio Takai in a radio quiet environment and a dedicated UHECR surface detector array

- Year 2

o Install 2 kW transmitter (needs the services of a professional transmission engineer)

o Being studies of detection thresholds (energy & geometry)

o Begin studies of more sophisticated receiver systems

  - Begin studies using interferometery using multiple receivers
- Year 3
  - Install 20 kW transmitter
  - Try to demonstrate the feasibility of a detector system using many receivers covering many tens of thousands of square kilometers

TA External Advisory 2010-04-08

Contact Info

Professor Francis Halzen
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