Project Description

a. Instrument Location and Type

- Instrument Location: Millard County, Utah, U.S.A.
- Instrument Codes: MRI-61

b. Research Activities to be Enabled

Motivation

Understanding the sources and chemical composition of the most energetic extraterrestrial radiation or "cosmic rays" is a major thrust of current astrophysical research. Indeed, early in the last decade, the Turner Panel [1] listed the origins of high-energy cosmic rays among the top eleven science questions for the 21^{st} century: 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 [2] (TA, Utah), and the Auger Observatory [3] (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.

The Opportunity

The investigators behind the current proposal have a unique opportunity to capitalize on existing assets and expertise and create the first radar observatory for cosmic rays. This observatory will be the first to utilize a

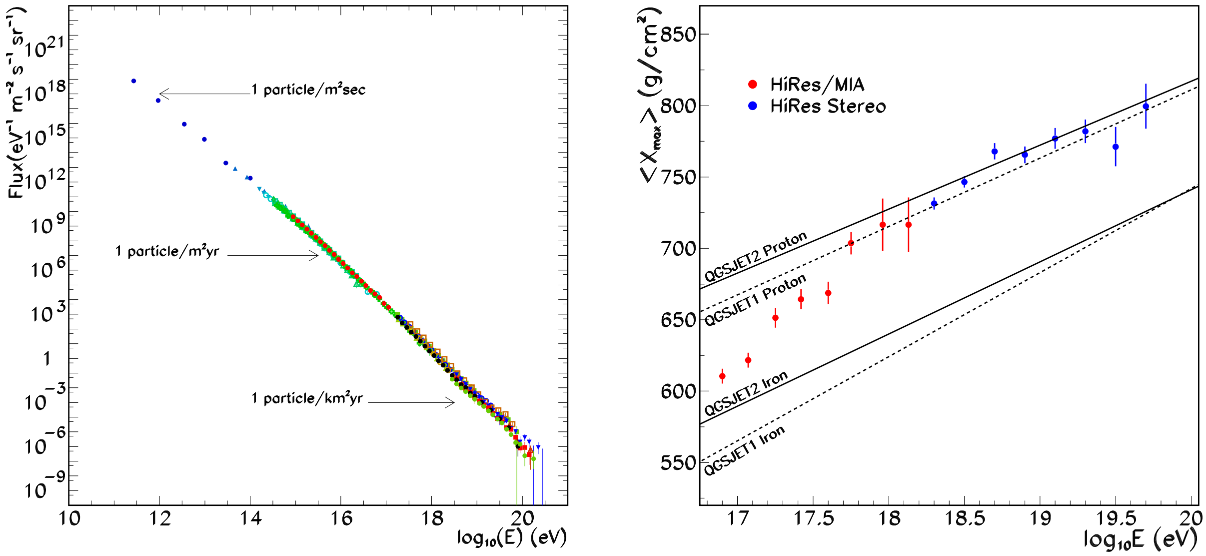


Figure 1: ***Left:*** **The cosmic ray all-particle spectrum.** ***Right:*** **Recent HiRes results [4] on depth of mean shower maximum X_{max}, compared with the predictions of CORSIKA [5] using the QGSJET1 and QGSJET2 high-energy hadronic models. A mean X_{max} of 770 g/cm^2 at 10^{19} eV translates to a mean height above ground at Telescope Array altitudes of approximately 3 kilometers.**

remote sensing technology with a 100% duty cycle, and do so at a cost per unit area far lower than that of the current generation of cosmic ray detectors.

The physical assets we have at our disposal include (1) a donated high-power television transmitter (2) the *Telescope Array* cosmic ray observatory, and (3) the *Electron Light Source*, a 40 MeV electron linear accelerator deployed in the west Utah desert.

Following the June 2009 analog-to-digital switch of commercial television broadcasts in the United States, the University of Utah received as a donation two low-VHF analog television transmitters (2 kW and 20 kW) and a high-power transmitter antenna from Salt Lake City KUTV-2. Recently, another local television provider, ABC4, has offered a second 20 kW transmitter than can be tuned to broadcast in the frequency range of interest. This equipment, which would cost over $1M each if purchased new, previously provided television service to the entire Salt Lake Valley and several adjacent valleys. By simply broadcasting a "carrier" signal at 54.1 MHz, these transmitters can provide powerful illumination of the skies over the Telescope Array in a spectral region ideal for cosmic ray radar observations. Due to the vacancy of the analog Channel 2 band, it was straightforward to obtain an experimental station license (WF2XHR) from the FCC. See the station permit in the attached supporting documentation.

In order to understand the meaning of the radar signals, it is essential that the first studies of the radar technique are carried out in coincidence with conventional cosmic ray detectors. The $20M Telescope Array (TA) observatory in western Utah provides such a complete suite of detectors, plus several additional desirable properties.

The Telescope Array is a hybrid observatory, employing both scintillation detectors as a ground array and three air fluorescence stations. See Figure 7. 507 scintillator detectors, each 3 m^2 in area, occupy approximately 800 km^2 of desert real estate on a 1.2 km grid. The three fluorescence stations each span about 120° in azimuth and elevation angles between 3° and 34°, in providing fluorescence coverage over the full aperture of the ground array detectors.

The fact that TA is the largest cosmic ray observatory in the Northern Hemisphere make it a prime candidate as choice for radar studies. In addition, TA's locale is extremely radio quiet (Figure 6). The Auger Observatory (Argentina) and Antarctica are also radio quiet, but are considerably more difficult to access than TA, which is a mere 140 miles from Salt Lake City. The Telescope Array site in western Utah is clearly the ideal place to carry out the proposed radar studies.

Telescope Array possesses an additional asset which will prove invaluable to the radar effort as well, the world's only anthropogenic air shower creator, known as the Electron Light Source (ELS). The ELS linac, which fires pulses of 10^9 40 MeV electrons vertically, is primarily designed to calibrate the TA fluorescence detectors. It is a great asset to the radar project as well, both as a known source of atmospheric plasma and as a tool to measure the free electon lifetime in air, a critical parameter in predicting the air shower radar echo.

Objectives of this Proposal

In this proposal we seek to advance the radar technique by making use of the donated 20 kW analog television transmitters, and by building a series of state-of-the-art receiver stations to detect the air showers' radar echoes. We will build a transmitter station at the Millard County Cosmic Ray center in Delta, Utah, where it will illuminate the sky above the Northern Hemisphere's largest cosmic ray detector, the Telescope Array. We will collect information from the conventional cosmic ray detectors — a surface array and three air fluorescence telescopes — simultaneously with the radar echoes. The large sample of events thereby detected will facilitate further study of radar models, and enable the development of data processing algorithms for air shower reconstruction.

Project Personnel

Chris Allen (Kansas) Chris Allen is a professor of electrical engineering specializing in radar systems for remote sensing applications. He is involved in polar ice sheet characterization through NASA's Operation Ice Bridge and NSF's Center for Remote Sensing of Ice Sheets. Chris has experience with antennas, signal processing, digital waveform generation, system calibration and is working closely with David Besson on antenna and system assessment issues.

John Belz (PI, Utah) has a background in fixed-target elementary particle physics and in cosmic ray physics with the High-Resolution Fly's Eye and Telescope Array. His recent research has focused on cosmic ray chemical composition studies and on the use of bistatic radar in cosmic ray observations. John will serve as project spokesman and manager, supervise transmitter deployment and facilities maintenance.

David Besson (Co-PI, Kansas) specializes in the use of radio techniques to detect ultra-high energy cosmic ray neutrinos. He is involved in the IceCube and balloon-borne ANITA projects to observe neutrinos at the South Pole. He is Principal Investigator of the RICE experiment to detect ultra-high energy neutrinos based on measurements of long-wavelength Cherenkov radiation, and spokesman for the Askaryan Radio Array (ARA) project. David is developing receiver antennas and working on simulation of the radar signal.

Behrouz Farhang (Co-Pi, Utah) 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 filters, 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 the book *Signal Processing Techniques for Software Radios*. Behrouz will focus on developing algorithms for software-defined radio, signal recognition and the online filtering of data.

Ilya Kravchenko (Nebraska) has been pursuing research in high energy physics at collider experiments as well as cosmic ray physics. In both of these, he has been involved in data acquisition, and has played a key role in developing, deploying, and maintaining the DAQ of the RICE/NARC experiment on neutrino detection at the South Pole Station. Ilya will work on DAQ R&D and commissioning, as well as data processing.

Shane L. Larson (Utah State) has a background in theoretical astrophysics. His primary research is in gravitational wave astrophysics and compact object dynamics. Shane is the lead faculty member on the HARBOR high altitude balloon project in Utah, and will lead the balloon calibration flights.

Pierre Sokolsky (Co-PI Utah) has 29 years experience in cosmic ray physics. He is spokesman for the HiRes and Telescope Array experiments, and is currently Dean of the College of Science at University of Utah. Pierre 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 (Co-PI, Brookhaven) 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 is co-convener of the ATLAS experiment Heavy Ion Physics group and a member of the ATLAS physics coordination team. He has been a QuarkNet Mentor since 1999 and is a mentor for the Laboratory Science Teacher Development program. Helio will supervise development of the receiver stations and work on the simulation of radar echo signals.

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

Additional personnel include Isaac Myers *graduate student, Physics, Utah*; Mohamed Osman, *graduate student, EE, Utah*; Samridha Kunwar *graduate student, Physics, Kansas* and an additional undesignated graduate student in physics from Utah; one undesignated postdoctoral research associate from Utah; William Ramsay *consultant, Transmission Engineer KUTV Channel 2*; and the Telescope Array Collaboration, *24 institutions and 120 physicists*.

Results from Prior NSF Support

MARIACHI: The MARIACHI [6] project made the first detection of cosmic ray air showers by means of radar. These important results are described in greater detail below under *Preliminary Measurements*.

MARIACHI was funded by a Cyberinfrastructure E&O grant from NSF-CI TEAM to Co-PI Takai. With the grant, MARIACHI was able to set up a system of shower array detectors in 12 Long Island high schools, in order to detect shower arrival times. Three radar stations collected data to search for coincidences over a period of roughly two weeks, during which time ten radar echoes were observed in coincidence with the surface detector activity, with an expected random background of 1.8 events.

Detection of Cosmic Rays by Bistatic Radar: Three of the senior personnel on the present proposal (PI Belz, Co-PI Takai, Thomson) are recipients of a grant to commence the study of the bistatic radar technique in Utah. Work supported under this grant began in July 2010, and has focussed on three areas (1) commissioning of a 2 kW television transmitter at the Millard County Cosmic Ray Center, (2) deployment of a simple

Figure 2: **Station WF2XHR, broadcasting a 54.1 MHz carrier wave at 2 kW from Delta, Utah. *Left:* "Low" power analog TV transmitter as installed in the Millard County Cosmic Ray Center. *Right:* Outdoor view of Cosmic Ray Center with mast and 6-element Yagi antenna. Work on this transmitter station was completed January 2011, just prior to submission of this proposal.**

receiver station at the Telescope Array Long Ridge fluorescence observatory, and (3) modeling the scatter of radio waves by air shower targets,

We have obtained an FCC experimental-class license to broadcast a 54.1 MHz carrier wave at up to 2 kW (8200 W ERP), under callsign WF2XHR. (See supporting documentation.) Commissioning of the 2 kW transmitter is complete (Figure 2) with the device first going on-air in January 2011, just prior to submission of this proposal. As of this writing, we are completing assembly of a receiver station using an oscilloscope-based data acquisition system which will be able to detect radar echoes and duplicate the MARIACHI results in conjunction with the Telescope Array surface detector.

At the same time, we have been simulating expected air shower radar echoes, in order to better understand the challenges of using the bistatic technique to perform astrophysical measurements. These results are described in further detail in the next section of the proposal.

MRI: Askaryan Radio Array (ARA): Co-PI Besson is also spokesperson for the Askaryan Radio Array (ARA) experiment. This multi-national collaboration seeks first observation of the so-called diffuse GZK neutrino flux, using a 1332-channel array of radio frequency (110-900 MHz) antennas embedded in the Antarctic ice sheet at South Pole, to depths of 250 m. As the acronym suggests, the detection scheme is based on the Askaryan effect, in which a neutrino undergoing a charged current interaction with matter (in this case, ice) initiates an hadronic particle shower which produces high-amplitude, coherent Cherenkov radiation at 0.1–1 m wavelengths.

Initially proposed in August, 2009, with funding beginning in January, 2010, ARA is currently in the midst of its first operational season at South Pole. This first-stage deployment consists of a 14-channel receiver array at a depth of 40 meters below the surface, with two additional radio frequency antennas on the surface. In addition, three high-power (3 kV amplitude, 100 ps rise time) transmitters have been parasitically attached to IceCube strings at ice depths of 1450, 1475 and 2450 meters into the ice sheet. Slaved to a high-precision rubidium clock, these transmitters will permit not only extensive inter-array calibration, but will also allow first-ever radioglaciological studies along a horizontal chord. All three transmitters and all 16 receivers are currently fully operational.

The primary task assigned to the University of Kansas for this MRI is successful commissioning of a power delivery system. Owing to the remoteness of the site, as well as the large areal coverage (approximately 10 square km., with plans to increase that by a factor of 100), it is impractical to bring power from the South Pole Station, via cable, to the array. As of this writing, we are therefore installing three wind turbines at South Pole; these turbines will be monitored in real-time using an extensive suite of diagnostic electronics designed and built at the University of Kansas. In addition to primary performance characterization (wind speed, charge controller voltage, etc), we will also extract information allowing us to map the wind velocity with height-above-surface, as well as bearing viscosity inside the main turbine housing itself. In parallel, a simulation has been developed that should permit a reliable projection of anticipated ARA downtime, etc, assuming the turbine effort is successful.

As our first prototype station is only now being commissioned, quantitative information on downtime is not yet available.

c. Description of the Research Instrumentation and Needs

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 [7] and has been revisited over the years [8, 9]. 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.

Figure 3 (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 air shower). 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 [10]. No normalization has been performed between the calculations. The two calculations are in reasonable agreement, and both show a strong peaking of the radar cross section (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 [11, 12, 13], 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 [14].

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:

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

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 [15, 16] and assuming that every track ionizes air in the minimum ionizing regime. κ is the attenuation factor due to multiple scattering of electrons

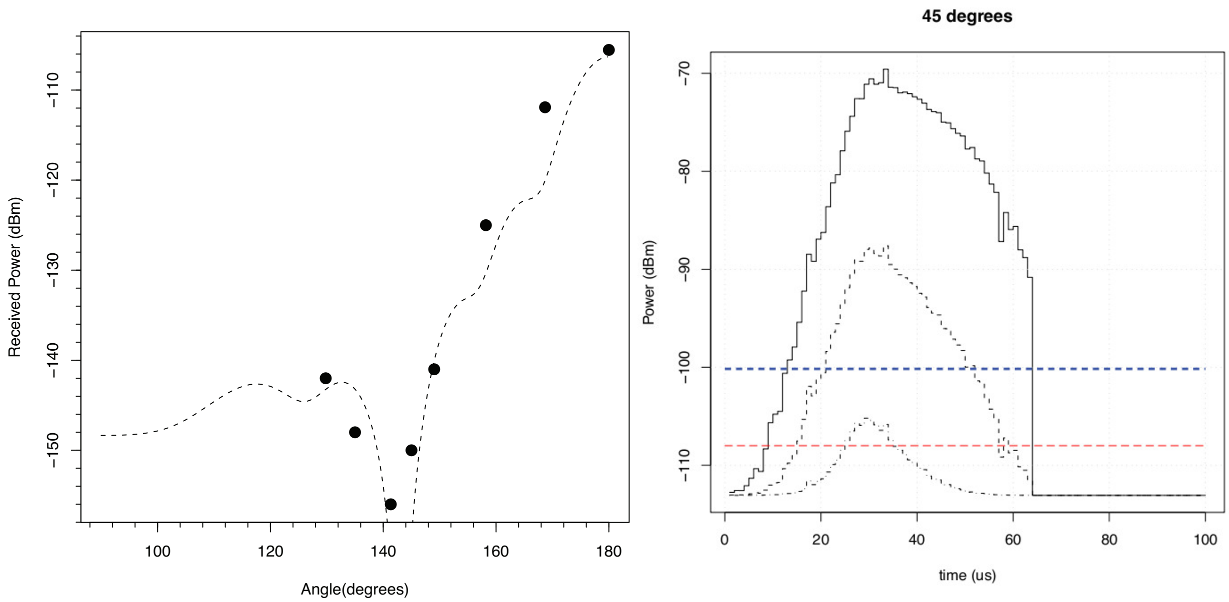


Figure 3: ***Left:*** **Forward scattered power for an ionization cylinder of 10 meters diameter and 40 meters long. The dashed line is for a geometrical optics calculation using Reference [10]. Points are results from a Thomson scattering calculation where all the phases were taken into account. A considerable enhancement is observed at forward directions** $(180°)$**. Vertical scale is arbitrary.** ***Right:*** **Calculation of received power (referenced to milliwatts) for echoes off of air showers initiated by** 10^{20} **eV (solid),** 10^{19} **eV (dashed), and** 10^{18} **eV (dot-dashed) primary cosmic rays. Transmitter power is assumed to be 20 kW. The air shower is midway between transmitter and receiver separated by 50 km. The horizontal red line is the background from thermal noise [17] integrated over a 4 MHz bandwidth. The horizontal blue line is the background including electronics and sky noise.**

by neutral molecules estimated following K. Suga [8]. The electron density will diminish because of the large attachment cross section to molecular oxygen. We take values given by Vidmar [14] 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, which is approximately 1/10 of the wavelength at a transmitter frequency of 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 3, for showers inclined at $45°$. For comparison, two background estimates are also included.

In the detection of bistatic radar reflections from air showers, 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 [18, 19]. Here, we present the results of our own calculations.

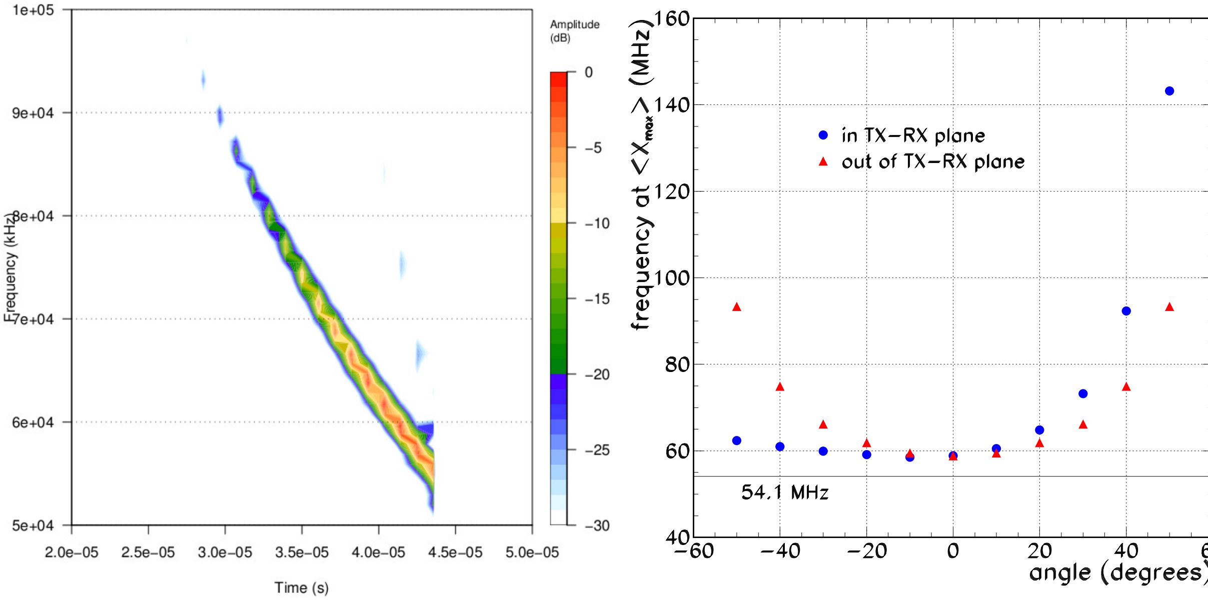


Figure 4: ***Left:* Spectrogram of "chirp" for simulated air shower, initiated by vertical 10 EeV cosmic ray midway between 54.1 MHZ transmitter (TX) and receiver (RX), located 50 km apart. *Right:* "Doppler" shifted frequency at height of mean shower maximum (greatest return power) versus angle for 10 EeV showers midway between TX and RX. Angles in (circles) and perpendicular to (triangles) the TX-RX plane are considered, a positive-angled shower has its top inclined towards the TX.**

Figure 4 (*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 [20] parametrization. The atmospheric ionization is assumed to persist for 10 ns to 40 ns (dependent on altitude [14]) 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 air shower maximum occurring at roughly 60 MHz.

The frequency shift will of course be geometry dependent, as illustated in Figure 4 (*right*). Plotted are received frequencies at air shower 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 4 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 air showers producing the echo, and real-time sparsification will be needed in order to reduce data volume to reasonable levels.

Preliminary Measurements

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 (*i.e.* operating in "parasitic" mode), 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.

The MARIACHI [6] 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.

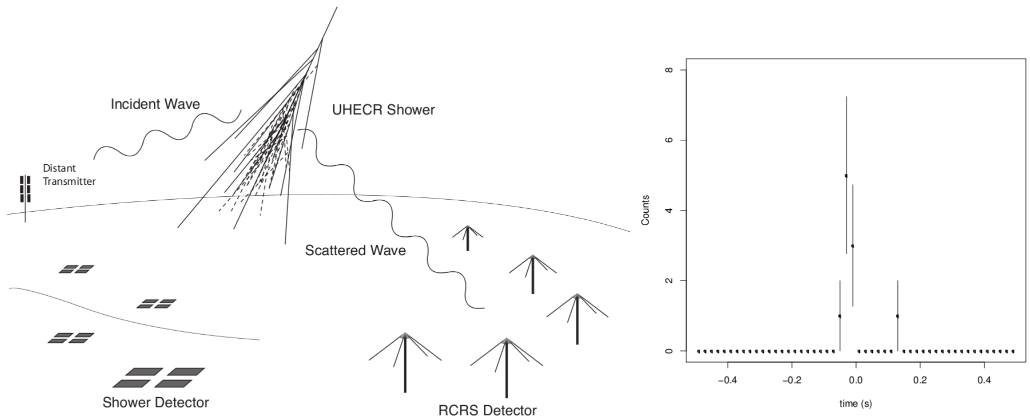


Figure 5: ***Left:* The MARIACHI experiment. Small shower detectors are used to tag the presence of showers while Radio Cosmic Ray Scattering (RCRS) stations listen to forward scattered echo. Typical distances between RCRS stations and scintillators is 40 to 80 km. *Right:* Histogram of events found 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 5, 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 $\pm 5°$. 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. 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.

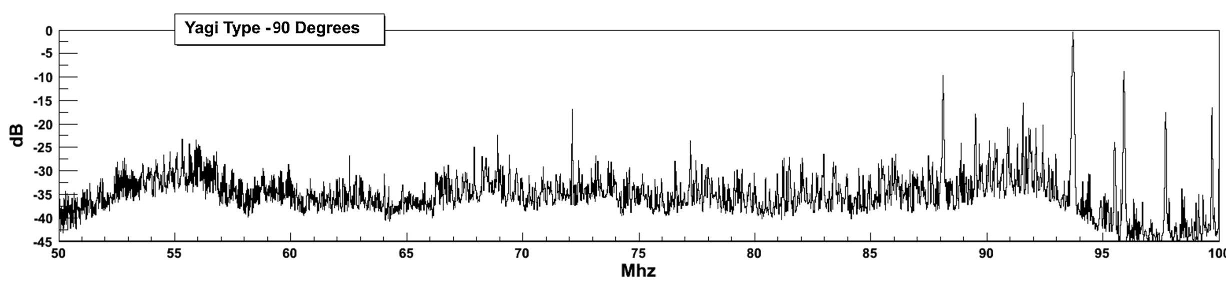


Figure 6: **Radio frequency background, as measured with a 6-element Yagi antenna antenna located at the Millard County Cosmic Ray Center, pointing due East. This is roughly the direction a receiver station placed at Long Ridge would face overlooking the TA surface detector. See text for measurement 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 6. A broadband Yagi Antenna [21] was pointed in an easterly direction, and its signal was read out using a Universal Software Radio Peripheral (USRP) [22] 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.

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 6 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.

Development Strategy

Under the proposed grant we will take the next step in developing the bistatic radar technique by (1) commissioning a transmitter powerful enough to allow air shower reconstruction from the received echos, (2) devising a set of trigger algorithms to identify candidate radar echoes in real time, so as to allow for reasonable data volume and (3) adapting bistatic radar reconstruction techniques to the development of software tools for offline air shower reconstruction.

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.

We will install the 20 kW transmitter (see the letter of donation from KUTV Channel 2 in the supporting documentation) at the CRC. We have already obtained an FCC experimental-class license to broadcast under callsign WF2XHR (supporting documentation). The transmitter is a solid state device from the Harris [23] Platinum series. It is approximately 25% efficient and hence will require 80 kW of of power from the grid to operate, not including the costs of air cooling. We will only broadcast a single frequency carrier signal (54.1 MHz). This will greatly simplify the “plumbing” by eliminating the need to merge video and audio signals. The transmitter station will be assembled with the help of an engineering consultant, Mr. Bill Ramsay, who operated the equipment on behalf of KUTV.

The RF signal will be piped via flexible foam-core waveguide to the antenna — a segmented Kathrein directional dipole [24] — 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 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.

Receiver Stations: A radar receiving station will be composed of array of four two-polarization log-periodic

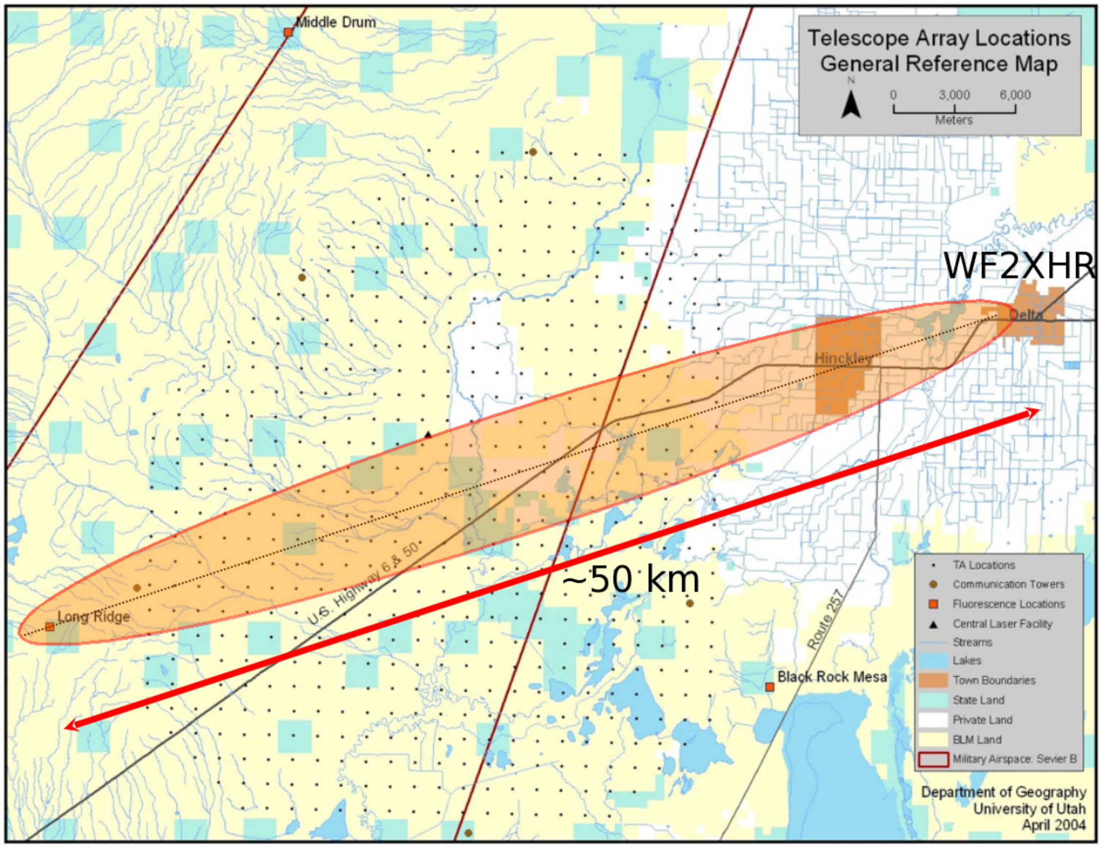


Figure 7: **Map of Telescope Array (TA) site and proposed radar observatory. Points represent TA Surface Detectors (SDs), red squares represent TA Fluorescence Detectors (FDs). The transmitter, operating under FCC license as station WF2XHR will be located at the Millard County Cosmic Ray Center in Delta, 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.**

antennas (to detect wide-bandwidth signals with uniform gain), 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 (Figure 8). At later stages, our goal is to have three receiving station that are autonomous, distributed over a wide area, and connected to a fusion center through a local area network (LAN). The autonomous stations and the fusion center are envisioned as the prototype of a large-scale radar observatory, beyond the scope of the current proposal. They will make use of solar power and a LAN. Receivers, computers and ancillary electronics will be housed in a radio hut that should be thermally insulated due to large swings in temperature in Utah's West Desert.

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 (1) receive the reflected signals from the air showers, (2) identify the occurrence of each air shower and capture the corresponding signal samples, and (3) 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 plan to use a FlexRIO National Instrument FPGA board and two front-end four-channel digitizers with a sampling rate of 250 MHz. This sampling rate is sufficient to capture the air shower chirp signals whose frequency can be

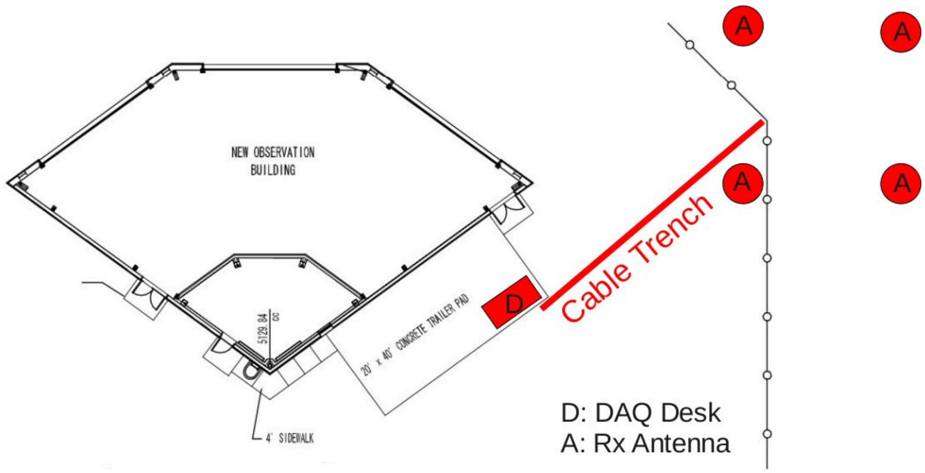
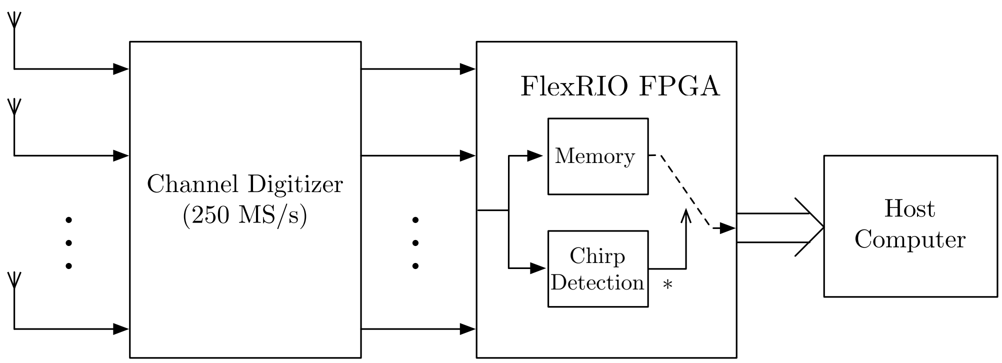


Figure 8: **Layout of first ("tethered") radar receiver station, at the TA Long Ridge Site.**



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

Figure 9: **Block diagram of the radar receiver.**

as high as 80 or 90 MHz. We believe the presence of a large Vertex-5 FPGA module and 512 MB of RAM on the FlexRIO will give us sufficient flexibility to develop a high-performance chirp detector/processor on the board.

Figure 9 depicts a block diagram of the SDR-based receiver that we propose for our radar system. The received signals from 4 antennas (horizontal and vertical polarization, hence 8 signals in all) are sampled and passed to the FlexRIO FPGA board. A chirp signal analysis algorithm (implemented on the Vertex-5 FPGA) is then performed to identify the (possible) presence of a chirp spectrum in the sampled signals. 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 air showers 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.

Air Shower Reconstruction: 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 using well-defined scattering targets including radar reflectors carried by GPS-tracked weather balloons. These studies will enable us to simulate our transmission patterns, as well as to confirm our forward scattering models (cf. Figure 3) in the absence of appreciable Doppler shift.

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 in order to establish energy and geometric threshold factors.

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.

d. Impact on Research and Training Infrastructure

The primary motivation behind the current proposal is the need for a remote-sensing technique for detecting and reconstructing cosmic ray air showers, without the duty-cycle limitations inherent in the fluorescence method. Absent such a new technology, the field is unlikely to advance beyond the current generation of detectors. The Telescope Array (Utah) and Pierre Auger Observatory (Argentina) surface detectors instrument areas the size of large cities, and do so at costs of tens of millions of dollars.

The savings in equipment, space and maintenance costs associated with the bistatic radar technique are substantial. We estimate that a single 20 kW transmitter and approximately 10 receiver stations (costing under $50k each) could cover an area comparable to the $5M Telescope Array surface detector. Long-term maintenance costs would also be greatly reduced, as there are fewer detector elements. The detector elements themselves are simpler in design than both surface arrays and nitrogen fluorescence observatories. Thus we expect that bistatic radar will not only enable the expansion of cosmic ray studies in Utah, but will also encourage the development of new observatories elsewhere in the world.

To encourage the spread of this technology, we are requesting in this proposal support for a workshop which we will host in the third year of this grant. We expect that this workshop will cover not only radar studies, but the wide range of radio-frequency detection techniques currently under study. We are specifically requesting travel support for students and postdoctoral scholars, whose interest and expertise will be key in promoting this "technology for the future".

The bistatic radar project itself will offer ample opportunities to motivated postdoctoral scholars and graduate students. Because of the project's close involvement with the Telescope Array, trainees will participate in both the operation and analysis of data from a "conventional" cosmic ray detector. Additionally, they will have the unique opportunity to be present at and make real contributions to the nascence of a new technique.

Within this project there are areas of investigation appropriate for both experimental physics students (*e.g.* air shower modeling, RF scattering, event reconstruction) and electrical engineering students ((*e.g.* software-defined radio programming, bistatic radar technique, antenna design). The physics and engineering students working on this project will have the unusual opportunity of working in close proximity with students from another field.

Undergraduate students have and will continue to play an important role in the project. Detector construction and maintenance and analysis software programming are ways in which undergraduates have already contributed. Under this proposal we will add the involvement of students in the HARBOR [25] student ballooning project based at Weber and Utah State Universities. HARBOR is designed as a platform for undergraduate students to learn the constraints of vehicle and experiment design in the "near space" environment. The tools that they have already developed for the launch, tracking and recovery of near space vehicles make them an ideal choice as launch platform for a radar scattering target.

e. Management Plan

The bistatic radar development project described in this proposal is tightly coupled to the established Telescope Array (TA) collaboration and observatory. TA is run by a group of approximately 120 physicists from Belgium, Japan, Korea, Russian and the United States. The spokesmen for the TA project are Pierre Sokolsky (Utah, Co-PI on the current proposal) and Masaki Fukushima (Tokyo, ICRR). TA has an executive committee consisting of the heads of the various institutes which meets monthly to decide policy issues. An External Advisory Panel consisting of F. Halzen (Wisconsin), J. Peoples (FNAL), N. Samios (BNL), E. Seo (Maryland), Y. Muraki (Konan U.) and Y. Suzuki (Kamioka) provides the experiment with feedback in the form of biannual on-site reviews.

John Belz (Utah) is PI and spokesperson for the bistatic radar effort. The organizational chart shown in Figure 10 shows the relatively simple structure of the proposed project. Project personnel are assigned responsibilities as listed above in Section b.

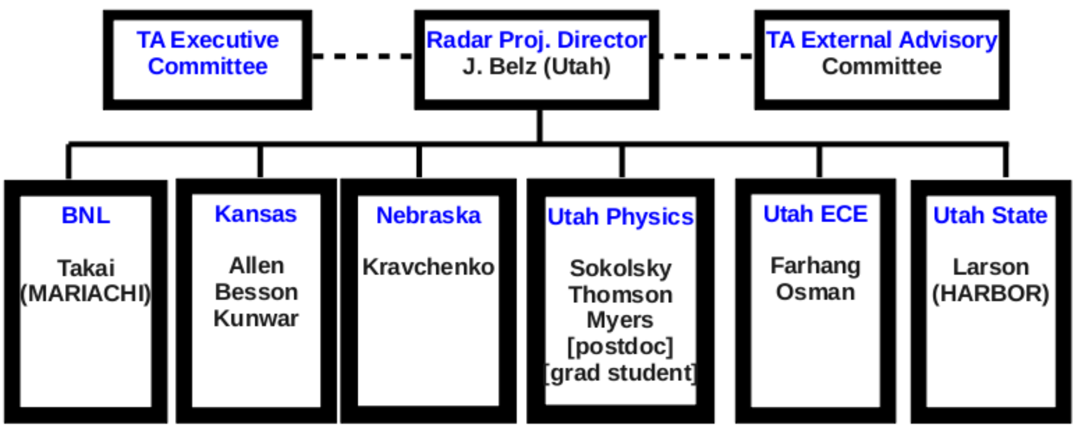


Figure 10: **Organizational Chart for Proposed Project**

The timeline of the project is envisioned as follows: During the first year, work will proceed in parallel on (1) commissioning the 20 kW transmitter and transmitting antenna (Utah Physics), (2) preparing the first receiver station hardware (BNL, Kansas), (3) preparing the data acquisition systems for the first receiver station (Nebraska, Utah ECE) and (4) modeling and mapping transmitted RF pattern (Utah Physics, Utah State).

During years two and three, the focus will be on (1) collecting data (2) analyzing data, with the focus on development of algorithms for air shower reconstruction, and (3) deployment of standalone receiver stations two and three. It is expected that during this time there will be feedback between analysis results and the hardware: For example, issues such as determining the ideal spacing of receiver antennas and understanding the effects of polarization will require actual air shower echoes to resolve.

In year three, we will sponsor a workshop on radar and radio detection techniques in cosmic ray physics, in order to propagate the techniques developed over the course of this grant. Emphasis will be on the involvement of younger researchers, particularly at the postdoctoral scholar and graduate student level.

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