PROJECT DESCRIPTION

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 increasingly 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 basically follow a power law, in which the flux of particles incident on the Earth falls off as $1/E^3$. 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, the Telescope Array [1] (Utah), and the Auger Observatory [2] (Argentina) now in operation 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 techique which has been pioneered at Utah is the "fluorescence" method, in which light from molecular deexcitations within the extensive airshower (EAS) are 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 proton. At this ionization level the plasma frequency is roughly 50 MHz (corresponding to the low-VHF) in which range reflection will occur. 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.

In this proposal, we seek to advance the radar technique by building 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 airshowers by conventional and radar techniques. The Long Ridge flourescence detector is where we will locate the recieving station, although we may eventually construct a simple mobile detector system. The sample of events thereby detected will facilitate further study of radar models as well as enable understanding of energy thresholds and geometrical resolutions.

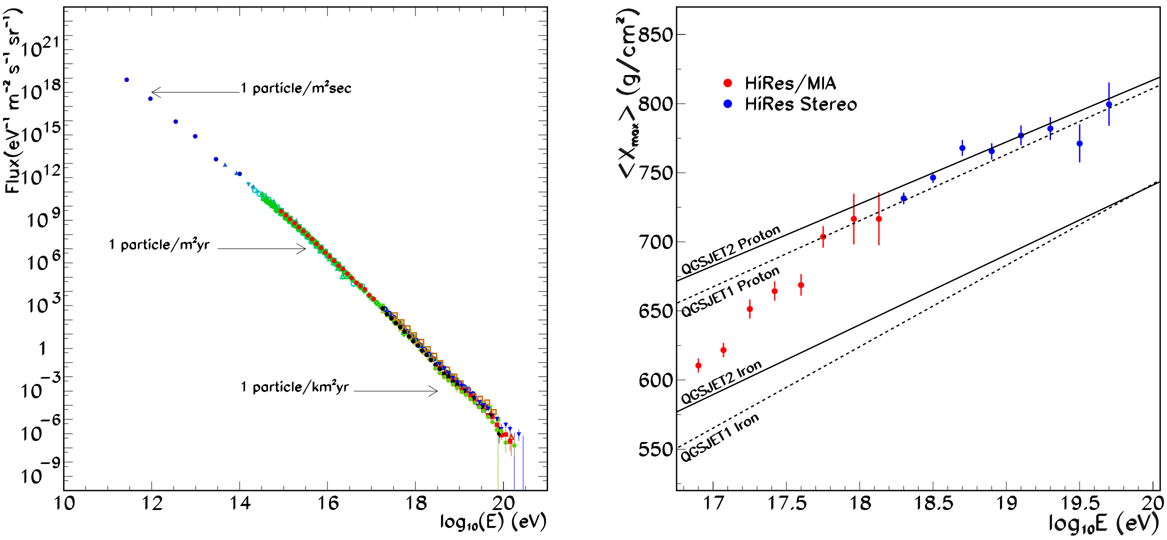

Figure 1: *Left:* The cosmic ray all-particle spectrum. *Right:* Recent HiRes results [3] on depth of mean shower maximum X_{max}, compared with the predictions of CORSIKA [6] using the QGSJET1 and QGSJET2 high-energy hadronic models. A mean X_{max} of 770 g/cm^2 at 10^{19} eV translates to a mean height above ground at Telescope Array altitudes of approximately 3 kilometers.

2 UHECRs and Extensive Air Showers

Our current picture of EAS began with the work of Heitler [4] who first formalized a model for development of electromagnetic cascades. Photons undergo e^+e^- pair production, while electrons and positrons emit bremsstrahlung photons, resulting in 2^n secondary particles at each of the n generations of shower development. This process will continue until the average energy of the leptons drops below the critical energy ξ_c, below which energy lost to collisional processes exceeds bremsstrahlung energy losses. The depth in the cascade at which this occurs is known as shower maximum, typically expressed as X_{max}.

More complete models exist which include the effects of the primary *hadronic* interaction present in actual air showers (*e.g.* Matthews [5]), and there is a small industry devoted to detailed Monte Carlo simulations of airshowers [6]. But the oversimplified picture of Heitler still predicts two important features of electromagnetic cascades, namely that the total number of particles at shower maximum X_{max} is directly proportional to the energy of the primary particle, and the depth of mean X_{max} is logarithmically proportional to the energy of the primary particle.

Figure 1 (right panel) shows the most recent mean X_{max} results obtained through analysis of stereoscopic data collected by the High Resolution Fly's Eye (HiRes) [3]. From these data we can predict the location of the densest part of the shower, which at 10^{19} eV will be located approximately 3 kilometers above ground level for the Telescope Array surface detectors. This height will be important in radar experiment design considerations to be discussed below.

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 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 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 [7]. 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 airshowers may be observed from distances approaching 50 km. A major drawback to fluorescence detection is that it can only be employed 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 [8, 9, 10]. 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 Radio Detection of Cosmic Ray Airshowers

The concept of radar detection of EAS was introduced in the early 1940's by Blackett and Lovell [11] and has been revisited over the years [12, 13]. 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.

This technique is upon first consideration quite similar to the radar detection of meteors [14, 15, 16], and one can use this fact as a starting point in understanding the radar response of cosmic ray airshowers. 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. The lower altitudes will effect the lifetime of the ionization because of the free electron attachment to molecular oxygen. While the process itself is well known the exact value for the lifetime will depend on the kinetic energy of ionization electrons produced in the shower. At airshower altitudes below 10 km the plasma lifetime can be expected to be less than 100 ns [17].

The power incident on a radio-reflective surface P_S can be expressed as

$$P_S = \frac{P_T G_T}{4\pi R_T^2} \times S_{eff} \tag{1}$$

where P_T is the transmitter output power, G_T is the transmitter gain, R_T is the distance between the transmitter and the surface and S_{eff} is the effective surface area. Then, the power P_R detected at the radar receiver station will be

$$P_R = \frac{1}{4\pi R_R^2} \frac{\lambda^2}{4\pi} G_R \times P_S \tag{2}$$

where R_R is the distance from the reflective surface to the receiver, λ is the wavelength of the reflective radiation, and G_R is the receiver gain.

We estimate the received power of an airshower-reflected radio signal by treating the airshower as a series of segments of area S_{eff}, each of which is a partially reflecting mirror. This assumption is necessary because electrons will undergo multiple scattering with air molecules. One can estimate the power loss by multiple scattering assuming that electrons accelerated by the impinging electric field are elastically scattered N times, with N determined by the mean free path of air molecules at a given altitude. This was first done by Suga in Reference [12]. The mirror reflective efficiency is about 0.3 at the position of shower maximum.

The estimate assumes that each mirror segment will appear as the shower develops at the front and then disappear at some distance from the front because of the electron capture process. Typical lifetimes for electrons are taken from Reference [17]. As the mirror apparent position moves the receiver antenna is illuminated briefly by bursts of scattered waves that combine forming a phase-modulated signal. The resulting signal is similar to a meteor signal, albeit with a compressed time scale due to differences in formation velocity. We also impose the condition that reflections are present when the ionization density is larger than 1×10^{13}/m^3.

This calculation best done numerically, to properly account for shower directions and phase additions. Typically, we expect for the TA setup (described in more detail in Section 5 below), with a transmitter of effective radiated power 10 kW illuminating a 10^{19} eV airshower, a received power that is 40 dB above galactic noise [18] for a 100 kHz bandwidth system. The same calculation returns a signal duration of 30 microseconds.

The same calculation applied to the Long Island measurements (Section 4.1) results in a signal 25 dB signal above galactic noise for a narrow bandwidth radio system.

4 Results of Preliminary Studies

In this section, we report on preliminary studies conducted in Long Island, NY 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 detection 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, NY

The MARIACHI [19] 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, NY. The key concept for the proof of principle is to detect simultaneously a radio echo and an extensive airshower by conventional means.

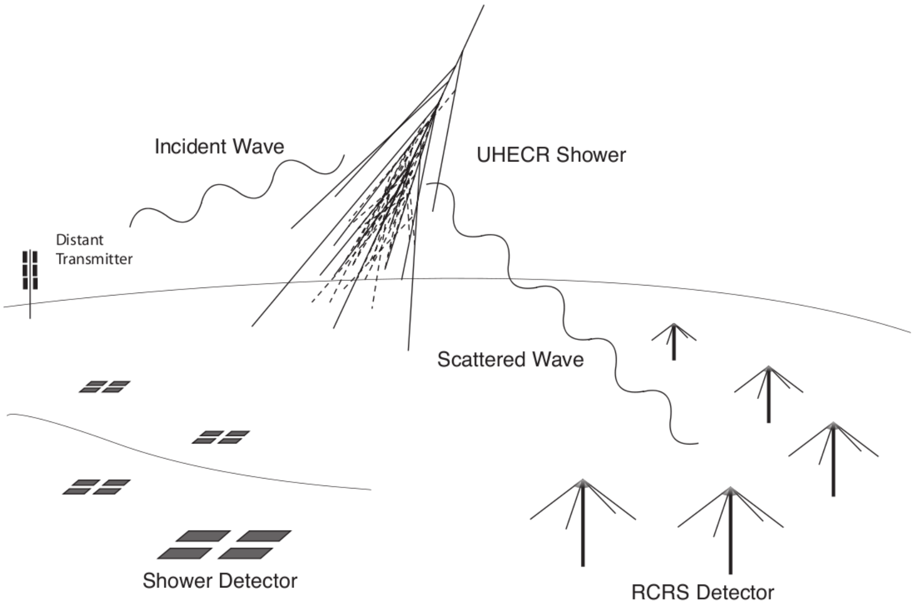

Figure 2: The MARIACHI experiment. Small shower detectors are used to tag the presence of showers while Radio Cosmic Ray Scattering (RCRS) stations listen to forward scattered echo. Typical distances between RCRS stations and scintillators is 40 to 80 km.

In radio meteor scatter it is customary to chose commercial transmitters that are of the order of 1000 km from the detection station. The most powerful stations are generally analog television (TV) stations [1], which provide good illumination of the skies over the Eastern United States. In particular, 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 VHF signal propagation, especially in the low band, is a complex process that involves ground propagation and other indirect processes. We estimate that five stations contributed to the illumination

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[1] Unfortunately, these were discontinued on June 12,2009.

at the altitudes where cosmic ray showers are present, and up to twelve stations contribute for meteor detection. The closest stations for us are in Pittsburgh, PA and Chapel Hill, NC, both with a nominal 100 kW power, of which 25% goes into the VHF carrier itself.

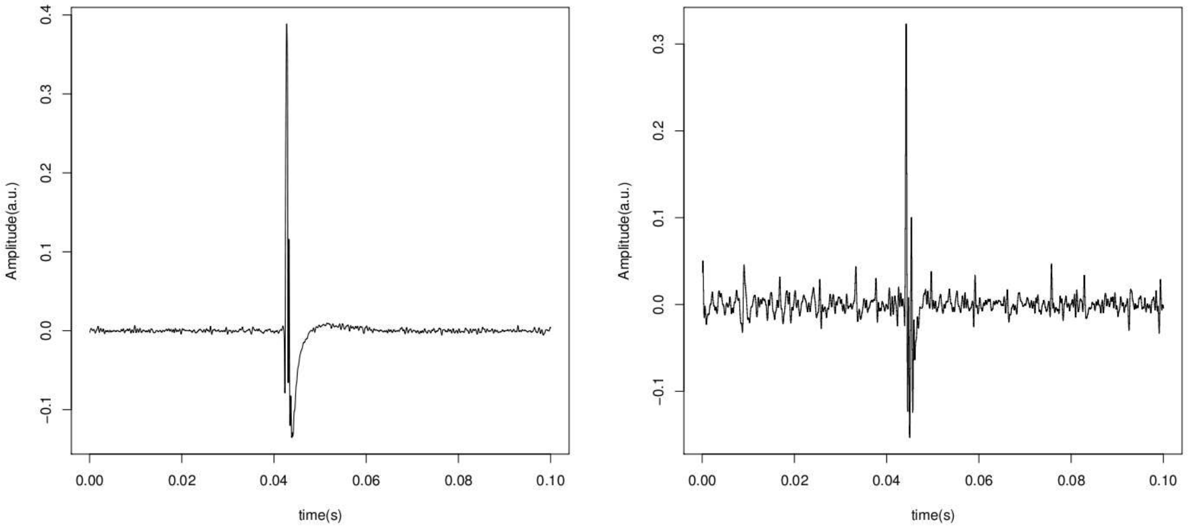

Figure 3: *Left:* Calibration signal taken with a 53 microsecond long pulse mimicking a cosmic ray signal. *Right:* Cosmic ray candidate signal found in coincidence with a scintillator trigger.

The mini shower detectors are five sets of scintillators placed at high schools, Stony Brook university and at the Selden campus of the Suffolk County Community College. 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. Each radar station is set up as in a radio meteor scatter experiment. Two inverted VEE dipoles are placed orthogonal to each other to obtain direction information, albeit with ambiguity. The antennae were tested for resonant frequency using an antenna tester and also for design impedance of 50Ω. Each dipole arm is fed into a commercial narrow band PCR1000 receiver and recorded using a high end sound card. The receiver was tested for the detection of very narrow signals and was found to be sensitive down to a 5 μs pulse with considerable distortion. This distortion is observed up to signals of 50 ms width. Other radio receivers such as WinRadio G3100i that process the signal digitally were verified not to be sensitive to short signals.

The MARIACHI experiment collected data with 3 radar stations and 12 scintillator stations for a total of 8 weeks. Not all the stations were collecting data all the time and therefore there is an overall efficiency of about 50%. After the fact analysis has also shown that the data from the BNL and SCCC radar stations were noisy and although meteors could be identified, it was not possible to extract lower signals. Therefore the overall data available for analysis comprises 12 mini-shower stations and one radar station located at the Custer Institute in Southhold, NY. The radar station is located at 40 km from the closest shower station and about 70 km from the furthest. It is a location that is relatively radio quiet for Long Island but with difficult access from the point of view of data transfer that was done using large removable disks. 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. To guide the pattern recognition we used an arbitrary function generator to illuminate the antenna with short signals mimicking the expected signals (Figure 4, left panel). We pulsed the system with signals of 5 μs to 100 ms duration. This exercise allowed us to look for a specific class of signal, recognizable through their time versus frequency characteristics. With the pulser system we have also 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 similar to those simulated by a pulser. The signal length can potentially be longer than those predicted if the lifetime values are different than those assumed. It is not expected that they will be longer than 1 ms, as that would require elevated temperatures. Therefore we accept signals that are up to 200 μs long in the searches. We have also ascertained that meteor signals are not shorter than 100 ms. From the ~ 30000 triggers examined, the majority of the coincidences are accidental coincidences with meteor signals or anthropogenic noise. Only a small fraction ($< 1\%$) contain a candidate signal.

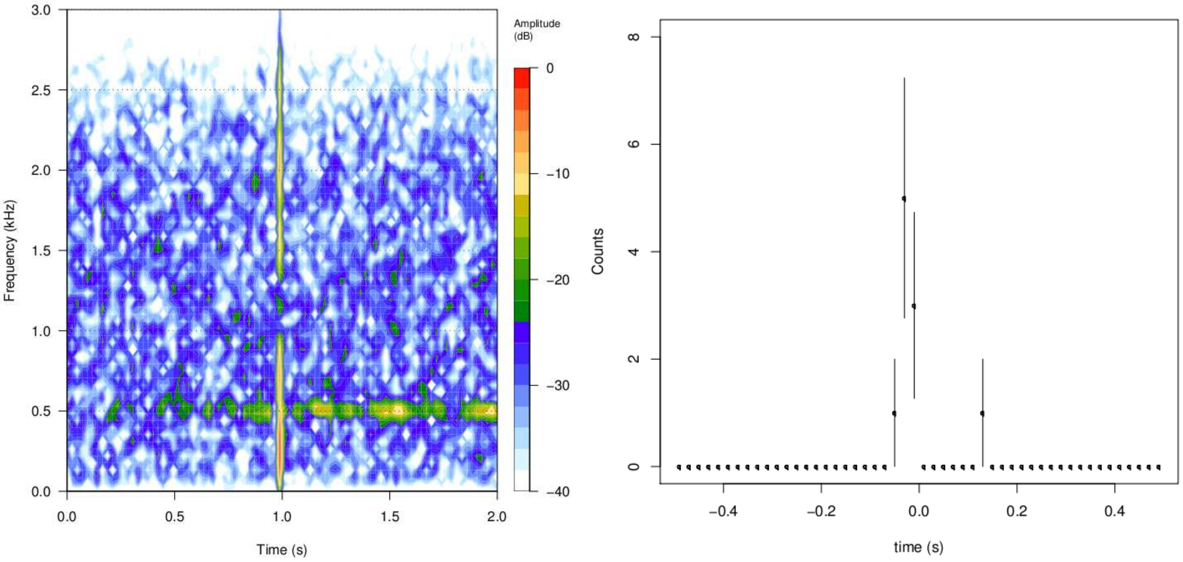

Figure 4: *Left:* Spectrogram, frequency vs time for a candidate cosmic ray signal. *Right:*Histogram of events found in coincidence with the scintillator sites in a period of 2 weeks. The offset from zero is due to data acquisition timing issues.

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. For this analysis we chose 5 high school sites and the Custer Institute radar data stream. 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 matches the calibration signal. A typical signal found in coincidence is shown in Figure 3 together with a sample calibration signal. With the exception of one signal, they 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 $\pm 5°$. The event at $\Delta t = +0.15$ seconds was $15°$ from the nearest scintillator station. The angle is calculated as $\tan\theta = A_{EW}/A_{NS}$ where A is the signal amplitude in each arm. Because the antenna was aligned to the magnetic north a correction of 14^o was applied to obtain the geographic bearing. This is however weak evidence and a two antenna system would be the minimal configuration for the measurement.

Albeit timing issues with the Data Acquisition System 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 coincidence exists 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, UT

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 geography of Western Utah is very different from that of the East Coast of the United

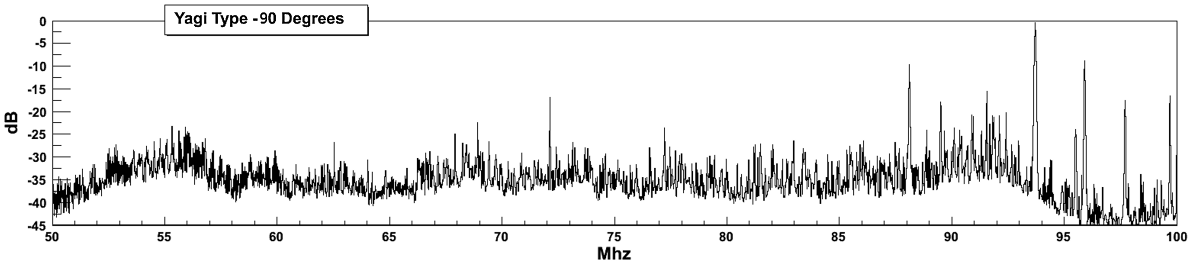

Figure 5: Radio frequency background, as measured with a 6-element Yagi antenna antenna located at the Millard County Cosmic Ray Center, pointing due East. This is roughly the direction a receiver station placed at Long Ridge would face overlooking the TA surface detector. See text for measurement details. 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.

States. The differences have several consequences for the types of RF studies we hope to perform. The ideal geometry for the detection of cosmic ray airshowers is one in which the atmosphere a few kilometers above ground (as stated previously, shower maximum is on average 3 km above the ground for a 10^{19} eV shower over the Telescope Array) 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 sits 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 (by design) 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 Winegard YA-6260 Broadband Yagi Antenna [20] was pointed in an easterly direction, and its signal was read out using a Universal Software Radio Peripheral (USRP) [21] 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 5 shows the low-VHF environment in Millard County to be very

Figure 6: *Left:* The Millard County Cosmic Ray Center (CRC). *Right:* Homebrew crossed-dipole antenna tuned to 6 m (50 MHz) band, mounted on top of CRC for radio environment tests during summer 2009.

quiet, and ideally suited to radar studies with a controlled transmitter located in Millard County, operating in this frequency regime.

5 Scope of Proposed Research

We will extend the investigations described in Sections 4.1 and 4.2 by installing a low-VHF transmitter at the Cosmic Ray Center (39.352867N,-112.589656E). We will also deploy a primary receiver station at the Long Ridge fluorescence detector (39.207901N,-113.121512E), and possibly a portable radar receiver station, for the purpose of detecting radar signals in coincidence with surface array and characterizing the response of radar signals to airshower energy and geometrical factors.

5.1 Transmission Facility

The Millard County Cosmic Ray Center (CRC, Figure 6) 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 transmitter will consist of a standard laboratory signal generator (with output power approximately 100 dBm, i.e., 100 mW) or custom oscillator circuit amplified in two stages to 500-700 W, which will require approximately 2 kW of power from the grid to operate. We will broadcast an analog signal at 54.1 MHz, which is in the channel two television band. The first stage of amplification will be a proprietary Henry Radio [33] unit designed to amplify a very weak signal of order milliwatts to 60 W. The second amplifier is an Acom 1000 [34] modified

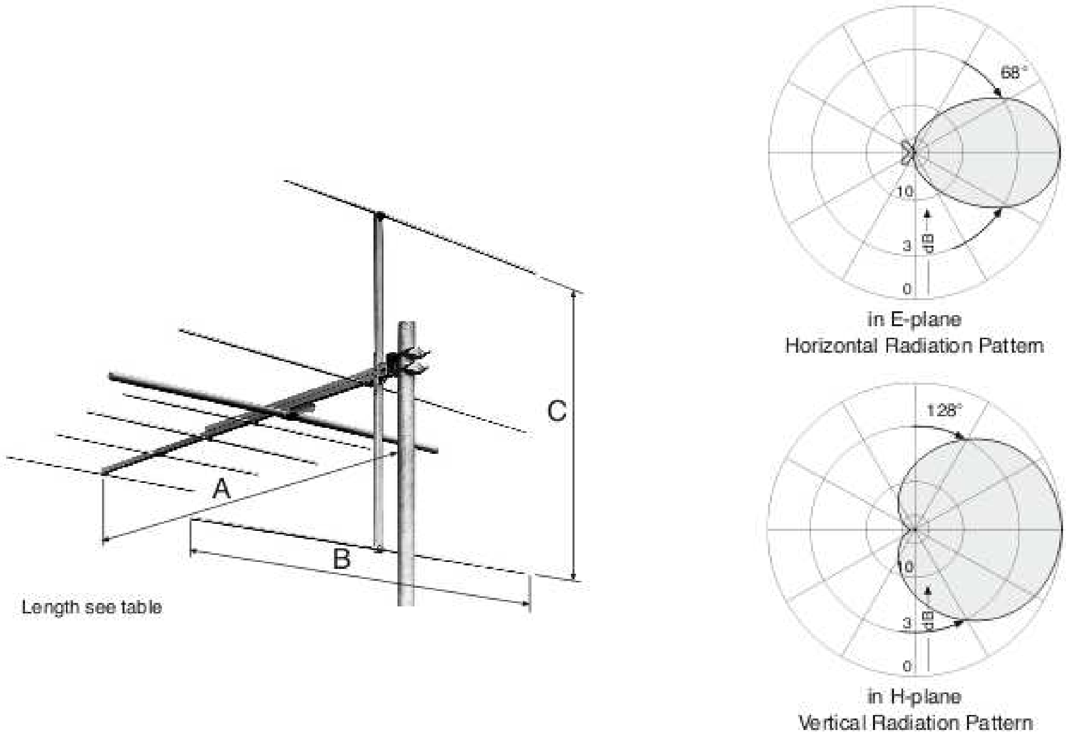

Figure 7: Kathrein 8-element Yagi antenna and mid-band horizontal and vertical radiation patterns. This antenna has a gain G_T = 6.0. Its radiation pattern is similar to the M2 Inc. [36] antenna that will be used in this experiment.

slightly by Acom to amplify in the desired frequency range and below its maximum output of 1 kW.

The frequency mentioned above was chosen to be just outside the amateur radio service 6 m band to avoid interfering with amateur operators. There is still a small contigent of analog channel two broadcast facilities (found via the FCC query page [35]), including standard TV and translators, throughout our country, Canada, and Mexico. Several dozen stations in the US operate in the kilowatt range and Canada and Mexico currently host ten stations that broadcast at 100 kW ERP. Specifically, Utah is host to six 1 kW translator stations. These data are mentioned to point out that our transmission shouldn't substantially interfere with extant broadcasters if these stations can operate successfully simultaneously. Additionally, Delta is located among mountain ranges that isolate it both to incoming and outgoing transmissions. We have created two plots of the topography of the valley filled in at the height of the CRC with a red dot indicating the position of the CRC. The axes are longitude (easting), latitude, and elevation (meters relative to sea level). It is evident that mountains will prevent almost all direct-signal illumination of anything outside the valley and possible interference signals will have been reflected at large angles. The images are large so they have been included as attachments; see `delta_north.png` and `wUtah_perspective.png`.

Our carrier signal will be 0.25 Mhz below the NTSC video carrier, near the bottom of the band, which further reduces the possibility of interference. Please note the cited frequency was chosen based on criteria explained above and the requirement that the carrier signal lie in the range 50-60 MHz. However, it can be adjusted within this range if there is a particular frequency preferred by the FCC. Because we are only interested in the carrier and not transmission content, we will broadcast a simple sine wave.

The RF signal will be piped via Heliax waveguide to the antenna, an M2 Inc. [36] 6m3 3-element Yagi antenna. The radiation pattern will be similar to that shown in Figure 7, and will be attached to a metal mast in the position indicated on the facility schematic (see supporting documents). With the mast and antenna boom height combined, antenna elements will be approximately 30 feet from the ground, 4665 ft MSL or 14 m HAAT (4635 ft MSL at ground [38]). Antenna alignment will be in a west-southwesterly direction, in order to illuminate the sky above the center of the TA surface detector array.

5.2 Receiver Stations

The Long Ridge fluorescence detector facility (Figure 8) is one of three such facilities maintained and operated by the collaboration. Before analog TV stations made the switch-over, the Long Ridge site was outfitted as a reciever station.

The bistatic radar receiver stations which we will construct are straightforward, and will be similar in design to those used in preliminary studies in Long Island, New York and Millard County, Utah. Each consists of an antenna, receiver and signal processing electronics, a GPS timing system and a personal computer.

We will continue to use both crossed dipole antennas (made in-house) and off-the-shelf directional Yagi antennas. The crossed dipole receiver antenna (Figure 6) is tuned to the frequency of interest by trimming the lengths of the crosspieces. The two dipoles provide directional information, with a fourfold ambiguity, by comparing amplitudes in the North-South and East-West arms. A minimum of three of these antennas at some distance apart is required to obtain an unambiguous shower position.

During preliminary studies we made use of two receiver schemes. The simplest to get up and running uses two ICOM PCR1500 receivers [37] and an external Sound Blaster to digitize the signal in the form of .wav files. These files are then written to disk for offline processing. A more sophisticated system utilizes an Ettus Research [21] Universal Software Radio Peripheral (USRP) device along with two TVRX 50 to 870 MHz receiver daughterboards. The USRP works with GNU Radio [25], an open source framework for the creation of software-defined radios. As the software-defined radio ultimately gives us greater flexibility in the processing of our signals, our long term plan is implementation of an array of GNU-radio controlled receivers.

As we are searching for coincidences with the Telescope Array surface detectors, it is desirable to be able to attach a precise (sub-millisecond) Global Positioning System (GPS) time stamp to the receiver output stream. In preliminary work conducted in Utah, we have developed techniques based on the GPSY-II [26] timing module. The GPSY-II is programmable to produce a TTL pulse at regular GPS intervals. This pulse is then used to either drive a spark gap to generate RF pickup which can be seen by the antennas, or to close a switch and briefly interrupt the data stream.

Figure 8: Long Ridge fluorescence detector facility as seen from the air. The command center was not built at the time this photo was taken. Note the green five feet tall diesel generators on the right.

5.3 Plan of Analysis

The first analysis goal of the proposed project will be to identify a set of events in which a radar transient of the appropriate frequency is coincident in time, and has a pointing direction consistent with a reconstructed TA Surface Detector (SD) event. We will start by generating a list of SD event times, then hand-scan the radar data stream. This will enable us to establish criteria for a pattern recognition program (preliminary versions of which have already been written based on data obtained during passive-radar observation periods), both for the automatic matching of radar and SD events and for online filtering. Online filtering of the radar data stream will be required in order to reduce the output to manageable levels over the long term.

Once a sample of coincidences is obtained, we will want to compare the received power with predictions, as a function of energy and airshower geometry. We will quantify and fine-tune angular and timing resolutions, and finally work to understand airshower energy estimation within the radar technique.

6 Outreach and Broader Impacts

The MARIACHI [19] project in Long Island, New York, which was created by one of the Co-Investigators of this proposal (Helio Takai) and through which we have obtained most of our knowledge of radar receiver technology, has long been involving New York high schools and community colleges in cosmic ray and bistatic radar studies. Students and teachers built the cosmic ray detectors described in Section 4.1 in workshops led by MARIACHI physicists. Students are also given access to live data through the MARIACHI webpage, and participate directly in data analysis. The program also encourages students to develop original research projects, maintains a database of classroom activities, and offers short courses in physics and cosmic rays. MARIACHI has been mentioned in Science Magazine [27] and has attracted the attention of national teachers organizations.

In Utah, the outreach efforts of the Telescope Array — and formerly of HiRes — have been coordinated under the rubric of the ASPIRE [28] project. ASPIRE is responsible for producing a set of web-based lessons and lab activities with an astrophysical bent, in accordance with Utah State and national science core standards. ASPIRE provides direct outreach to local teachers and students in the form of presentations and workshops for groups underrepresented in the sciences and rural schools in Utah and Montana. Also, ASPIRE has involved Utah students and teachers in atmospheric monitoring and prototype detector testing in the past, and plans to involve them in radiosonde balloon flights which are being planned to survey atmospheric conditions over the Telescope Array site.

The radar project which is the subject of the present proposal has already begun cooperating with ASPIRE in its efforts to connect to the local community to particle astrophysics research. In August, we jointly hosted a Perseid “meteor party” in which members of the Salt Lake Astronomical Society and teachers and students from Long Island, NY toured the Telescope Array site and then “listened” to the meteor shower using the audio output of the radar receiver system. We will continue to develop this connection with displays at the Cosmic Ray Center, which will both serve as a home for the bistatic radar transmitter and as the outreach center for the Telescope Array project.

7 Results of Prior NSF Support

7.1 SUNY Stony Brook

The MARIACHI [19] project, of which the major results were previously described in Section 4.1, was funded by a grant from NSF-CI TEAM. This grant was a Cyberinfrastructure E&O grant. With the grant we were able to set up a system of shower array detectors in 12 Long Island high schools, in order to detect shower arrival time. Three radar stations were also installed, but with only one of them yielding low noise data. The experiment collected data to search for coincidences, and we have analyzed data covering a period of two weeks. Data from other run periods are “on disk” and available for further analysis. MARIACHI has also detected meteors and lightning.

7.2 University of Utah

Work by the PI (JB) and Co-I (GBT) currently at The University of Utah has focussed on studies of the highest energy cosmic rays with the High-Resolution Fly’s Eye (HiRes) and Telescope Array observatories.

HiRes was a stereo fluorescence observatory which operated from 1997 to 2006 on the U.S. Army’s Dugway Proving Ground. Among HiRes major scientific achievements are the first observation [29] of the high-energy cutoff in the cosmic ray energy spectrum predicted in 1966 by

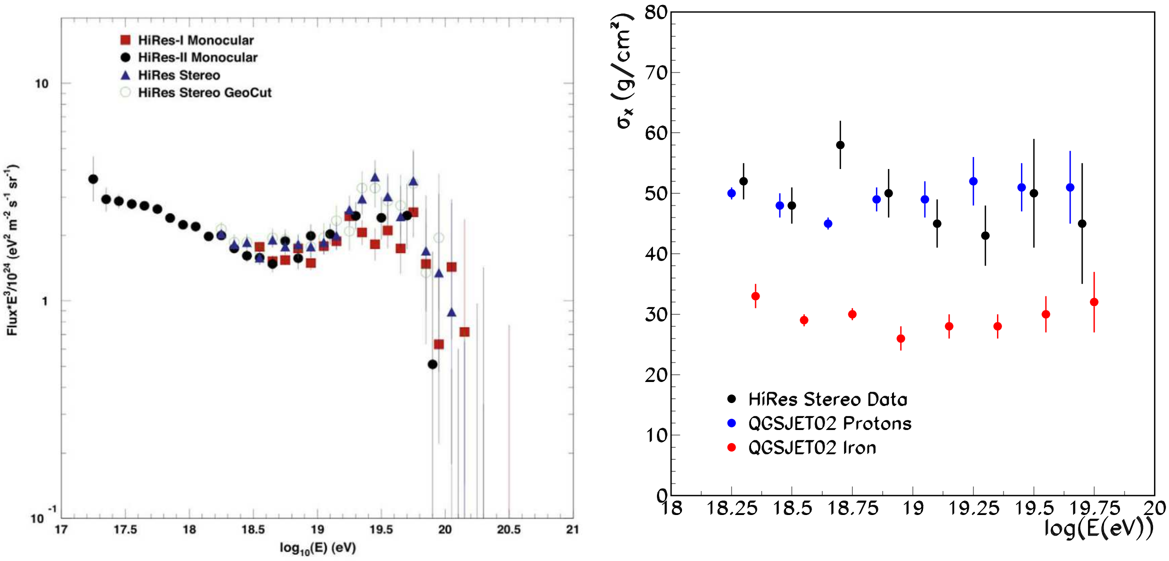

Figure 9: *Left:* Compilation of final HiRes spectrum results, including HiRes-I and HiRes-II monocular, HiRes stereoscopic and HiRes stereoscopic with geometrical constraints as a systematic check [32]. The GZK [30, 31] flux suppression starting at $\log E = 19.5$ is observed with a significance of over five standard deviations. *Right:* Recent HiRes results on the width of shower maximum distribution as a function of $\log(\text{energy})$ [3], compared with CORSIKA [6] predictions using the QGSJET02 high energy hadronic model. Together with the $<X_{max}>$ results (Figure 1), these data constitute strong evidence that the highest energy cosmic rays have a predominantly protonic composition.

Greisen [30], Zatsepin and Kuz'min [31]. This discovery, in an analysis of monocular data led by HiRes co-spokesperson GBT and Utah Professor C.C.H. Jui, provides strong evidence that the highest energy cosmic rays both originate far outside the Milky Way galaxy and are of light composition. Recently, the monocular observations have received confirmation in the stereo spectrum results (Reference [32] and Figure 9) with which they are in excellent agreement.

Principal Investigator JB conducted an analysis of cosmic ray composition with HiRes stereo data, using the depth of shower maximum X_{max} as a composition discriminant. These results, focusing on both mean X_{max} as a function of energy (Figure 1) and the width of the X_{max} distribution (Figure 9) provide additional evidence for the protonic composition of nature's most energetic particles. A paper describing this work is under collaboration review [3], and this work will be presented by JB as an invited talk at the Spring 2010 Meeting of the American Physical Society.

Recently, both Utah investigators have been working on the Telescope Array project. In addition to carrying out analysis of the "standard" TA surface and fluorescence detector data, both have been involved in detector design and prototyping studies for the proposed TA Low Energy extension TALE. TALE will measure the spectrum and composition of cosmic rays in the galactic-to-extragalactic transition region with unprecedented sensitivity.

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