The Telescope Array Experiment

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Abstract: The Telescope Array (TA) Experiment is the largest ultra-high energy cosmic ray detector in the northern hemisphere. The Telescope Array is a follow up to the High Resolution Fly's Eye and AGASA experiments. It is located near Delta, Utah, about 200 kilometers southwest of Salt Lake City, Utah, USA. The detector consists of 507 three square meter scintillator counters distributed in a square grid with 1.2 km spacing. Three fluorescence detector stations (12, 12, and 14 telescopes) sit on the corners of a 30 km equilateral triangle overlooking the array of surface detectors. The stations view 108, 108, and 114 degrees in azimuth and 3-31 degrees in elevation. They provide full hybrid coverage with the scintillator array above 10 EeV. The Telescope Array underwent commissioning in 2007 and began routine data collection operations at the beginning of 2008. A low energy extension to TA (TALE) will add new telescopes to the Middle Drum site and increase the elevation angle view up to about 60 degrees, providing for cosmic ray observation down to about 10^{17} eV. In conjunction with the new telescopes, a graded array of infill scintillator counters will be added. An overview of the experiment and its measurements will be presented.

Keywords: Telescope Array, High Resolution Flys Eye, AGASA, UHECR, Spectrum, Composition, Anisotropy

1 General Requirement

The Telescope Array Collaboration was forged by members of the High Resolution Fly's Eye (HiRes) and the Akeno Giant Air Shower Array (AGASA) to study Ultra High Energy Cosmic Rays (UHECR). The purpose of Telescope Array is to a) understand the differences between the results of HiRes and AGASA, b) to study the spectrum, composition, and anisotropy of ultra high energy cosmic rays, and c) to study the galactic to extra-galactic transition of cosmic rays. The collaboration has grown to include groups from the US, Japan, South Korea, Russia, and Belgium.

The Telescope Array Observatory is located about 2.5 hours south of Salt Lake City, just west of Delta, Utah USA. The Central Laser Facility (center of the observatory) is located at 39.297° N, 112.909° W and is 1370 meters above sea level. The high energy component of the Telescope Array consists of 38

fluorescence telescopes (9728 PMTs) located in three stations at the corners of a triangle which is approximately 30 km on each leg. The telescopes overlook an array of 507 scintillator surface detectors. The Telescope Array is complete and has been operational since about 1/2008.

The northern telescope station is composed of 14 telescopes from the HiRes-I observatory previously located at Dugway Proving Ground, Utah. The spherical mirrors are 5.2 m^2 in area and the cameras each have 256 pixels which are 40mm hexagonal Philips/Photonis XP3062-FL PMTs. Each pixel subtends about 1° of sky. The PMTs are in a 16x16 hexagonal close pack array, so that the site has a view which subtends about 120° in azimuth and 3 to 31° in elevation. The telescopes are running the same Sample and Hold data acquisition system that they were running for HiRes-I. The site has been making routine observations since 10/2007.

The two southern telescope stations are each instrumented with 12 new telescopes. These have 6.8 m^2 spherical mirrors and cameras with 256 hexagonal Hamamatsu R9508 PMTs. These also subtend about 1° of sky. Each of these sites has a view which subtends about 112° in azimuth and from 3 to 33° in elevation. The data acquisition electronics of these new telescopes stations is similar in concept to those of the HiRes systems. However, each PMT channel is digitized by a 14 bit FADC system operating at 10 MHz. The eastern site saw first light in 6/2007 and the western site followed in 11/2007.

Each Scintillator Detector (SD) is composed of two layers of half inch scintillator and has an area of 3 m^2. Light collection is accomplished using wavelength-shifting fibers that are embedded in grooves made on the surface of the plastic when it is extruded. The fibers guide the light to two Electron Tube Ltd. 9124SA PMTs (one per layer). This arrangement gives pulse height uniformity within about 7% across the scintillator surface. Each scintillator detector has a solar power panel with a deep-cycle battery for power, a GPS timing system, and a radio system to communicate with a control tower. There are three radio control towers, each located near one of the fluorescence stations and computers at each tower forms triggers and reads out data for about one third of the SD array.

The analog signal from each SD PMT is digitized by a 50 MHz, 12-bit flash analog-to-digital converter (FADC). Each counter is set to trigger at a signal equivalent to 1/3 of a Minimum Ionizing Particle (MIP), and when a coincidence occurs between the two scintillator layers. Every second the radio control towers poll the ground array stations to enquire if they have any signals above 3 MIPs. An array trigger is formed when, within 8 μsec, three neighboring counters each have 3 MIP signals in both of their scintillator layers. For each detector level trigger, the sum of 20 FADC bins is saved for self-calibration purposes. A histogram of such sums is read out and saved every 10 minutes for later use during analysis. Signals are shared among the three radio communication towers to ensure that there are no cracks in the array efficiency along boundaries between the radio tower catchment areas. The scintillator surface detector array occupies a total of about 750 square km and has been operational since 3/2008

Each of the detector systems is independently operated, however a hybrid trigger system was installed in the fall of 2010, which allows the fluorescence telescope stations to trigger the SD array. Even before this trigger, however, many events were observed by multiple detector systems. Events observed in monocular by a telescope station have an average of 5° resolution in ψ, the angle of the shower within the shower-detector plane. By adding SD information, or information from multiple fluorescence stations (stereo) improves the resolution to about 0.5°.

In comparing with the High Resolution Fly's Eye (HiRes) experiment with the Telescope Array, the spectrum from the northern fluorescence site (Middle Drum) is a natural place to start. The 14 telescopes at the site used to be part of the HiRes-I detector. They have simply been refurbished and tuned up. We can use the same average atmosphere (VAOD = 0.04), same cuts and (almost) the same analysis programs. There are, however, some differences. The telescopes are now pointing in different directions. In particular, they observe over a broader range of elevation angles, making longer tracks in the cameras. Another difference is that the night sky in Delta is darker than that in Dugway, resulting in thresholds which are about 20% lower.

We use the Monte Carlo method to test our understanding of the physics and detector. We start with the previously measured spectrum and composition and use Corsika/QGSjet to generate events with an isotropic distribution. Atmospheric scattering is taken into account and these events are then fed into detector simulations which include the front end electronics, trigger, and DAQ. We write the events out in the same format as the real data and analyze the MC simulated data with the same programs as are used for the real data. We then validate the Monte Carlo by comparing data and Monte Carlo distributions of various physical measurables.

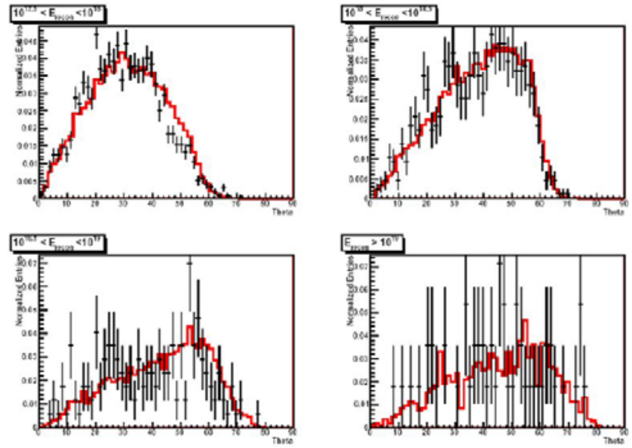


Figure 1: Zenith Angle Distributions for the Middle Drum Fluorescence Site. Data (Black Points) and Monte Carlo (Red Histogram) zenith angle distributions for four energy ranges - from top left - a) $10^{17.5}$ to 10^{18} eV, b) 10^{18} to $10^{18.5}$ eV, c) $10^{18.5}$ to 10^{19} eV, and d) $>10^{19}$ eV. There is good agreement between the data and the Monte Carlo. Note that the lowest energy range, $<10^{17.5}$eV, is NOT used in the spectrum.

Figure 1 compares data and Monte Carlo distributions for the zenith angle of cosmic ray events. The distributions are shown for four energy different energy ranges. The lowest energy range is not used in making a cosmic ray energy spectrum. There is excellent agreement between the data and the Monte Carlo simulations. These plots are indicative of many such comparisons and give us confidence that the Monte Carlo is doing a good job of simulating the data as well as giving us confidence in the aperture calculation.

Figure 2 shows our preliminary energy spectrum using the first three years of data from the Middle Drum station. This spectrum is overlaid with the monocular spectra from the HiRes-I and HiRes-II sites. The Middle Drum exposure in this three years is larger than the AGASA exposure. There is excellent agreement between the Telescope Array and HiRes spectra. Similar analyses are ongoing with the other two fluorescence telescope sites and they are making good progress.

Next, we consider the scintillator surface detector array. Events with bad resolution must be cut and this will affect the aperture, therefore we calculate the aperture via Monte Carlo. We use the same techniques as for the fluorescence detectors, folding in all that we know about the showers and the detectors before writing the data out in the same

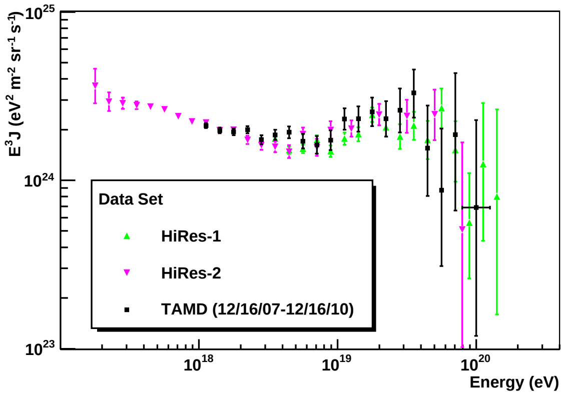


Figure 2: Energy Spectrum the Middle Drum Fluorescence Site. The energy spectrum from the first three years of data from Middle Drum fluorescence site (black) is overlaid with the HiRes-I (green) and HiRes-II (magenta) monocular spectra. There is good agreement between the Middle Drum and HiRes spectra.

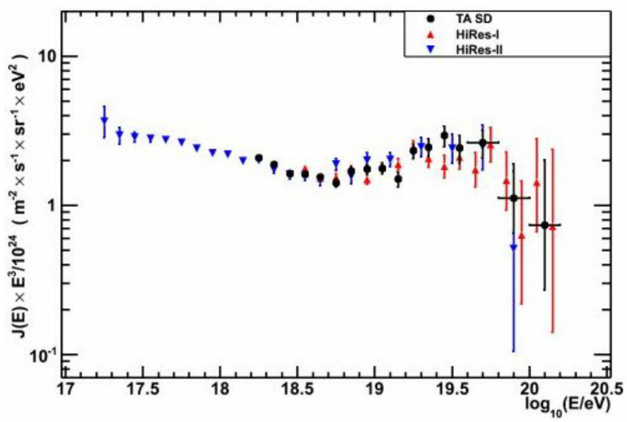


Figure 3: Energy Spectrum the Scintillator Surface Array. The energy spectrum from 1.75 years of scintillator array data (black) is overlaid with the HiRes-I (red) and HiRes-II (blue) monocular spectra. There is excellent agreement between the Scintillator Array and HiRes spectra.

format as the real data. The Monte Carlo simulated data is then analyzed using the same programs as for the real data and again we validate the Monte Carlo by comparing with the data distributions.

In reconstructing the SD events, we use two fits. The first is the timing fit which compares the time vs. the distance along the shower axis on the ground to determine the event geometry. For this fit, we use a modified Linsley function. The second fit is the Lateral Distribution fit. It compares the charge density in a detector to the perpendicular distance from the shower axis. This is fit, using the AGASA fitting function, to determine the signal size at a distance of 800 m from the shower core (S800).

Next we use the CORSIKA based Monte Carlo to construct a table of S800 and sec(θ), where θ is the zenith angle, for each energy. The first estimation of an event's energy is made using this table, interpolating between S800 and sec(θ) lines. After data quality cuts, we have resolutions of 20% in energy and about 1° each in zenith and azimuth for events with energy greater than 10^{19}eV.

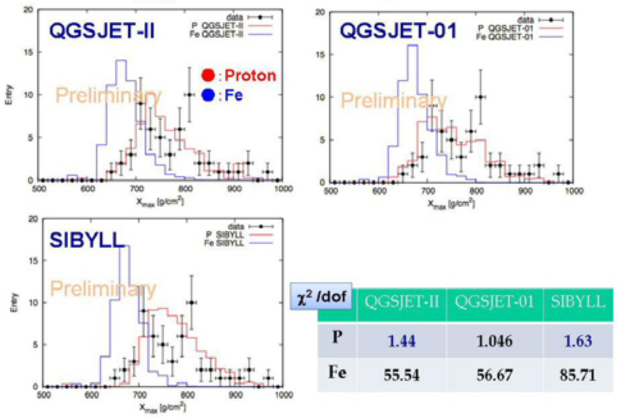
The final energy scale of the scintillator array data is determined experimentally by using the fluorescence telescopes. We use events that are well reconstructed by both detector systems (fluorescence telescopes and scintillator array) to do this. The scatter plot of SD vs. FD energy is well represented by a straight line with a slope of one, however there is an off-set of 1.27 in the energy scales. Hence, we renormalize the scintillator array energy measurements by this. Without this renormalization, the energy scale of the scintillator array is similar to that of AGASA. However, the Telescope Array scintillator spectrum differs from that of AGASA in that we have fit the TA scintillator spectrum to a broken line fit and it observes the GZK suppression at the 3.5σ level. (Using a broken line fit we observe 5 events above the cutoff where we would have expected 18.4 events.)

Figure 3 shows the spectrum from the Telescope Array scintillator array overlayed with the monocular spectra from HiRes-I and HiRes-II. There is excellent agreement between the Telescope Array scintillator and HiRes spectra.

As previously noted, many events are observed by multiple detector systems. We have examined some of the stereo data from the two southern fluorescence sites. The reconstructed geometrical parameters (such as zenith angle, azimuthal angle, and impact parameter) of the data are all well modeled by QGSjet-II protons. Next we compared the Xmax distribution of the data to those of iron and protons of various models including QGSjet-I, QGSjet-II, and SIBYLL. In all cases, the data looks much more like protons than iron. The best fit is to QGSjet-I protons. These comparisons are shown in Figure 4. The data is shown as a function of energy (elongation rate) in comparison to the models in Figure 5.

Other analyses underway within the collaboration include searches for sources of anisotropy, for example testing the Auger AGN result, seeking correlation with large scale structure, and looking for photons or exotics within the data. These will be discussed in other TA papers.

Meanwhile, other activities are underway at the Telescope Array. One of these is the installation of a small linear accelerator. The 40 MeV accelerator was built at KEK (the Japanese accelerator laboratory) and transported to Utah. It has been installed 100 m in front of the central telescopes at the south east (Black Rock Mesa) fluorescence telescope site. The accelerator fires pulses of 10^9 electrons at 0.5 Hz. In doing so, it excites the nitrogen in the atmosphere via the same processes as an air shower. It has the same wavelength dependant fluorescence yield and this goes through the air, is reflected off of the mirrors, goes through the op-



χ^2 /dof	QGSJET-II	QGSJET-01	SIBYLL
P	1.44	1.046	1.63
Fe	55.54	56.67	85.71

Figure 4: Xmax Data/Monte Carlo Comparison. The stereo Xmax distribution (black points) is compared to the iron/Fe (blue) and proton (red) distribution for QGSjet-II (top left), QGSjet-I (top right) and SIBYLL (bottom left). In all cases the data looks much more like protons than iron. Bottom right is a table of the χ^2/dof for each of the comparisons, quantifying the comparisons. The data looks most like QGSjet-I protons.

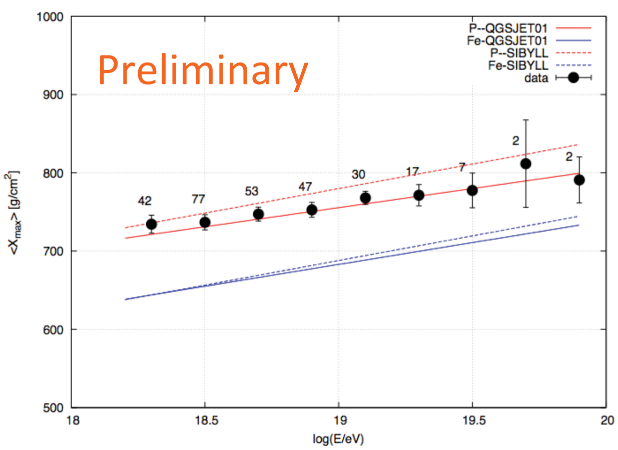


Figure 5: Xmax Data/Monte Carlo Elongation Rate Comparison. The stereo Xmax distribution as a function of energy (black points) is compared to the iron/Fe (blue) and proton (red) distribution for QGSjet-I and SIBYLL. The data favors QGSjet-I and looks much more like protons than iron.

tical filters, and has the PMT quantum efficiency taken into account just like an air shower. In this way, the accelerator provides an end-to-end calibration of the telescopes including the effects of the fluorescence technique. The accelerator fired its first pulses of electrons into the Utah sky in September 2010.

The Telescope Array Collaboration is also in the process of extending its reach to lower energies. As noted above, the Middle Drum Fluorescence site currently views from 3-31° in elevation. The site is being enlarged to host additional HiRes telescopes which will observe 31-59° elevation above the existing telescopes. A graded scintillator array will also be added underneath this field of view to allow hybrid detection down to 10^{17}eV where we will make measurements which overlap with the LHC.

We are also exploring measurements of UHECRs via radar. We have installed a 54MHz transmitter at the Cosmic Ray Center in Delta, Utah and are looking for signals reflected from this beam as cosmic ray induced air showers pass through it.

In conclusion, the Telescope Array has picked up where HiRes left off. It is the largest ultra high energy cosmic ray observatory in the northern hemisphere and is actively collecting data. Though the statistics are limited and the analyses are still preliminary, the task of analyzing the Telescope Array data in a variety of ways is well underway. The results above are meant to give a flavor of the on-going work and its status. Data collection and analysis will continue for the next several years. More details will be presented in other Telescope Array papers/talks.

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