Observation of Ultra High Energy Cosmic Ray at Telescope Array Experiment

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The Telescope Array(TA) experiment, located in the western desert of Utah, USA, at 39.3° north and 112.9° west, is designed for observation of air showers from ultra high energy cosmic rays. The experiment has a Surface Detector (SD) array surrounded by three Fluorescence Detectors (FD) to enable simultaneous detection of shower particles at ground level and fluorescence photons along the shower track. The SD array consists of 507 scintillation detectors (each consisting of 2 layers of scintillator of area 3m^2) deployed with 1.2km of separation. Total coverage of the array is $\sim 700\text{km}^2$. Full hybrid observation was started using the entire array in March,2008. Detailed monitoring of the detector has been dedicated to confirm the stability of detector response and system operation. The variation of detector response due to outdoor environment needs to be monitored carefully. Here the observation status and result are presented.

1 Introduction

The main aim of the Telescope Array (TA) experiment [1] is to explore cosmic ray origin of the extremely high energy cosmic rays (EHECR) using their energy spectrum, composition and anisotropy. There exist two major methods of observation for detecting cosmic rays in this energy region. One is the method which was taken at the High Resolution Fly's Eye (HiRes) [5] experiment that detects air fluorescence light along air shower track using fluorescence detector. The other is the method adopted by the AGASA experiment that detects air shower particles at ground level using surface detectors deployed in wide area ($\sim$100km^2).
The AGASA experiment reported that there are 11 events beyond the GZK cutoff [2,3] in the energy spectrum [4]. However, the High Resolution Fly's Eye (HiRes) experiment reported the existence of the GZK cutoff [5].
The Pierre Auger experiment confirmed a suppression on the cosmic ray flux at energy above 4×10^{19}eV [6]. But still the contradiction between results from fluorescence detectors and surface arrays remains to be investigated by having independent energy scale by both techniques.

2 Telescope Array experiment

The TA site is located in the desert at about 1400 m above sea level at the position (39.3° N, 112.9° W) as the center of the site in Millard County, about 200 km southwest of Salt Lake City in the state of Utah in the United States. An observatory to support construction and operation of the TA instruments is in Delta city located near the northeast side of the array. The experiment is aimed for observation of the cascade shower induced by cosmic rays above 10^{19}eV. The altitude of the experimental site between 1300 and 1500 m above sea level is required for optimal condition to observe particles at nearly maximum development of the cascade. For hybrid observation the site is located in the semi-desert area with less town lights also. The climate enables us to keep higher duty cycle of FD-SD hybrid exposure. It is about 7 % of real time. Fig.1 shows layout of experimental setup. Fig.2 shows telescope and one of the deployed surface detector.

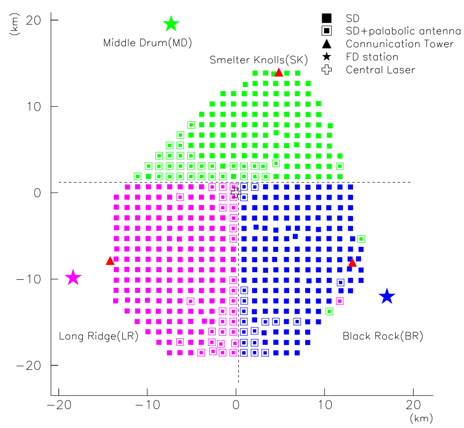

Figure 1: Layout of the Telescope Array in Utah, USA. there are three FD stations,three Commnunication Towers and 507 SD detectors)

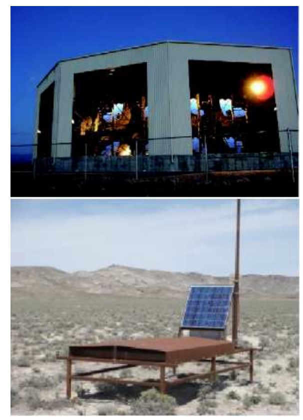

Figure 2: Top: Telescope array Fluorecence Detector (LR,BR)Bottom: Surface Detector deployed in the field.

2.1 *Fluorescence Detector*

The three FD stations which is surrounding SD array is observing sky above SD. The FD locates at the North west of site is known as the Middle Drum (MD) station [9]. The FDs locates at West and East of site is known as Long Ridge(LR) and Black Rock (BR) respectively. The MD station is instrumented with 14 refurbished telescopes from the HiRes-I site. The telescopes have a field of view that is 3-31° above horizon and 114° in azimuth centered to Central Laser Facility [10] which locates at center of TA observation site. The electronics system also shifted to MD site from HiRes experiment. The other two station LR and BR sites are each instrumented with 12 new telescopes and have a field of view which is 3-33° above horizon and 108° in azimuth. Three FD sites started standard data collection in Nov.2007.

2.2 *Fluorecence Detector calibrations*

New constructed FD detector(LR and BR telescope) consist of a spherical mirror,a PMT camera, and readout electronics [22,23]. The mirror has 3m of aperture. It is consist of 18 segment of hexagonal mirror. Each telescope has one camera at the prime focus of the mirror. The camera consist of 16x16 PMTs that has hexagonal shape (HAMAMATSU R9501) and UV transparent filter cut light $\lambda \geq 400$nm on its surface. The corresponding field of view is $15^\circ \times 18^\circ$ (elevation×azimuth).

There are several steps of calibration to monitor absolute gain of PMTs. For several number of PMTs,the quantum efficiency (QE) and collection efficiency (CE) are measured by production company. To obtain non uniformity of each PMT, uniformity of photo cathode have been measured by using LEDs on XY scanner [25]. Three PMTs for each camera are calibrated its

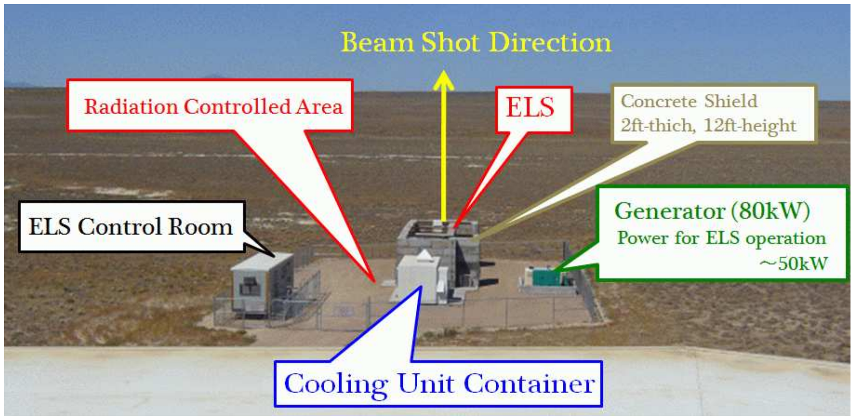

Figure 3: Set Up of ELS facility

absolute gain in Laboratory using Rayleigh scattering light from nitrogen [26]. The gain of those standard PMT are monitored using tiny light source called YAP pulser on its surface. The YAP pulser is an scintillator($YAlO_3$:Ce) contain 50Bq alpha-ray source (Am^{241}). The temperature dependence of the YAP also checked [30]. The relative gain of PMTs in a camera is measured and every hour by using Xe light source. The Xe light source consists of an Xe lanp and a 4mm thick Teflon diffuser is mounted at the center of each telescope.The detailed uniformity of light on the camera surface and its evaluation is summarized in a paper [25]. Since the mirrors are exposed to out side while observation the reflectivity of mirror are monitored. The precise measurement of reflectivity are done regularly with the photometer. It enable us monitor time variations and degradations of mirror reflectance. The reflectance change is ∼3% per half year at a mirror mounted lowest place and less than 1% per half year at a mirror highest place. The mirror is washed periodically the washing make the reflectivity to be recovered. For more the detail of instrument and evaluation of spectral reflectivity,it is summarized in a paper [24].

2.3 Electron light source

To do an end to end calibration ,electron light source [13] also have started operation. The Electron Light Source (ELS) is an electron linear accelerator. The output beam energy is 40 MeV and the typical out put is 10^9 electrons in 1μsec pulse width. It locates 100m away forward of center of BR telescopes. The light amount observed at FD station is compared with the expectation obtained from calculations based on electron transportation , ray trace and fluorescence yield model using measured out put beam energy and measured current. Currently The instrument also have started it's operation since September of 2010. [11] The system was constructed and assembled in KEK [?] in Japan and shipped to Utah.

2.4 Surface Detector

Fig.2 shows one of the SDs which have deployed at one of the communication towers placed at hill called Smelter Knolls(SK). The SD communication antenna is mounted at the 3m of iron pole and the height is adjustable. There a 1m×1m square solar panel is seen. Front end electronics and a battery are contained in the box made of 1.2mm of thick stainless steel under the solar panel. Each surface detector consists of two layers of plastic scintillators. Each layer of scintillator has 3m^2 of area and 1.2cm thick. Scintillation light is collected through 104 of 5m long Wave-Length Shifting fibers (WLSfiber Y-11 Kuraray make) those are laid for each layer. Both ends of the fiber are bundled and connected to a PMT (Electron tubes : 9124SA) to obtain uniform responce. The SD array is divided into three sub-arrays of 207,190 and 110

SDs. The sub-arrays are named Long Ridge(LR) array , Black Rock(BR) array and Smelter Knolls(SK) array respectively. The LR array covers west side of the entire array.The SK and BR covers north and east side,respectively. Each sub-array is controlled from its trigger judgment electronics installed at communication tower. At energy of $\sim 10^{18.7}eV$, the trigger efficiency of SD array reaches 100%. [16] The more detail of trigger system and calibrations is summarized in paper [17,18,19]

3 Current observation result

In the analysis, we determine total energy of primary cosmic ray , arrival direction and depth of maximum development. Here the depth of maximum development is called Xmax.

In case of event reconstruction using SD data, arrival direction and charge density at 800m from shower core is extracted as S(800) from observed arrival timing and lateral distribution of shower particles.

Here the S(800) is known as a parameter which well represent primary energy as shown in fig4. The 800m is optimized distance under TA detector configuration and altitude. The details of employed Lateral Distribution Function and shower disk structure are based on the lateral distribution [28] and arrival time distribution [27] respectively. And those LDF are made to fit well with the one obtained air shower Monte Carlo simulation (CORSIKA +QGSJETII) [31]. This method gives 1.2° of resolution in arrival direction and 20% of energy resolution at $E \geq 10^{19.0}eV$. Using the relation between observed S(800),zenith angle and primary energy obtained from MC, first estimation of primary energy is obtained. The detailed procedure for reconstructing shower in SD observation is described at [29].

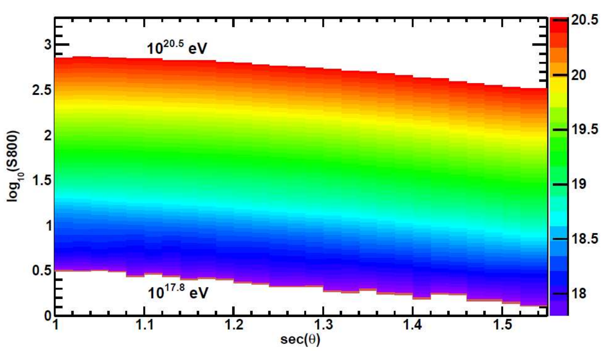

Figure 4: S(800) and primary particle energy at different zenith angale.

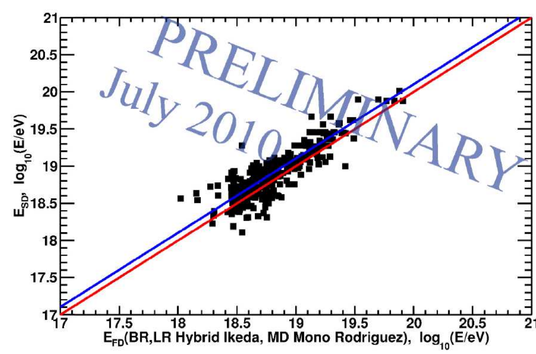

Figure 5: Energy calibration betwenn SD and FD using hybrid event

In case of FD event reconstruction, there are two way of reconstruction of shower geometry. One is using shower track and timing recorded in one FD and timing in SD. Another is using shower track recorded in two FDs. The former is called Hybrid reconstruction, latter is called stereo reconstruction. In case of hybrid reconstruction,the angular resolution is typically 1.1°[32]. In case of stereo reconstruction ,the angular resolution is more precise.

The primary energy and Xmax depth is determined from observed shower development after deter ming shower axis. The observed photon is basically proportional to energy deposition of shower particles and Cerenkov photons directed to telescope. The shower development fit with Gaisser-Hillas (GH) function. Here a method called Inverse Monte Carlo are employed. It determines the longitudinal shower development by comparison with the observed charge of each PMT between data and MC generated by using GH function. In the MC we consider Cherenkov and non-uniformity of detector response with applying calibration factor. Currently the fluorescence yield used in this analysis consists of differential spectrum taken from FLASH model[33] and total yield from Kakimoto model[34]. Missing energy which is a energy taken by neutral particles in shower is also considered by comparing standard air shower Monte Carlo codes. The estimated amount of missing energy is about 8%. The more detail of calculation is described in [32]. Fig5 shows correlation of reconstructed energy reconstructed with SD and FD(Hybrid analysis).

3.1 *Energy spectrum*

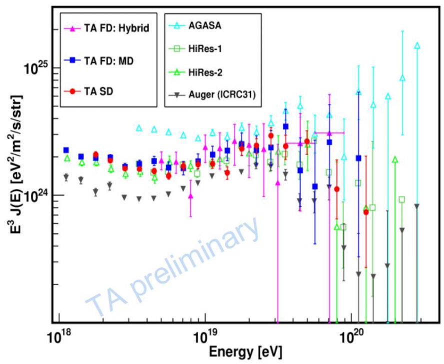

Figure 6: Observed energy spectrum at TA with different method.

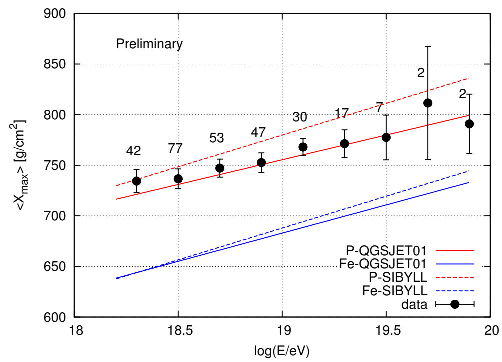

Figure 7: Observed Xmax elongation compared with the one expected from Proton and Iron primary.

Spectrum from MD station from data collected over a three year period December 2007-September 2010 shows very good agree ment with HiRes spectra. The detail of the analysis of the MD telescope is described in [35]. At Hybrid event reconstruction performed using LR and BR FD. The effective aperture after the quality cuts in obtained using Monte Carlo simulation code COSMOS [36]. Systematic uncertainty in the fluorescence yield(12%), atmospheric attenuation (11%) and the absolute detector calibration (10%). Total systematics are $\sim$19% in energy measurement from Hybrid observation. The Hybrid spectrum was obtained data set from May 2008 to Septamber 2009. There was 1978 of hybrid event. After reconstruction , 124 event remain above $10^{18.65}$eV. The quality cut applied is mainly consist of Xmax is ovserved and zenith angle is less than 45°. The energy resolution is 8%. The preliminary spectrum is shown in fig.6, together with MD FD and SD spectrum [29] calibrated using FD Hybrid energy scale. The SD spectrum shown in Fig.6 is obtained from data from May 2008 to February 2010. Its energy is calibrated using the hybrid event. The exposure at SD observation is approximately 1500 km^2 sr yr. Which is equivalent the total exposure of the AGASA experiment. The spectrum from SD shows feature that there is two breaks at logE of 19.75 and 18.71 which is correspond to the GZK suppression and the ankle respectively. Observed event above $10^{19.75}$eV are five event. Expected number of event from continuous spectrum is 18.4 event. The suppression of flux is seen with significance of about 3.5σ.

3.2 *Chemical composition*

In case of hevier nuclei primary,air shower cascade develop shallower depth. Since the cascade develop until energy is distributed to electro-magnetic component which have energy of critical energy, primary cosmic ray which have higher mass number give shallower Xmax as compared to proton which have same total energy. As an indicator of the primary chemical composition, the Xmax was measured by using data set from November 2007 to September 2010. There stereo reconstruction method is employed to obtain accurate geometry reconstruction and the obtained Xmax distribution are compared with the one obtained from events generated from

CORSIKA code using two interaction model QGSJET-01 and SIBYLL. In this analysis method, the resolution of Energy is $\sim$8% and the one of Xmax is 23g/cm^2 at energy of $10^{19.0}eV$.

Since there is a bias due to a limited elevation range of field of view, the observed Xmax distribution is compared with MC event analyzed in same way with real data. The result shown in fig.7 is the observed Xmax average including observation bias. The result is in good agreement with pure proton predicted using the QGSJET-01 model under same bias effect with real data. Comparison of observed Xmax distribution at several energy bins with Monte Carlo also performed and result is surmised in [37].

3.3 Arrival direction anisotropy

Since the exposure observed by SD array is largest in northern hemisphere and quite uniform along right ascension due to stable operation of array. It is an advantage to see anisotropy of arrival direction .Fig.8 is a skymap from observed events has energy of 4×10^{19}eV. The deflection in our galaxy become smaller int this energy range. If a strong cosmic ray source exist, there is possibility to see such object as a clustering of the observed arrival direction [38,39].

Fig.9 shows number of pair of event per solid angle observed as a function of opening angle between two event. From data set May.2008 to September 2010,Total 42 events are observed

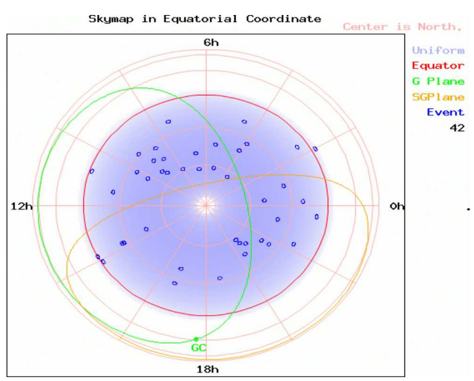

Figure 8: Distribution of arrival direction in equetrial coordinate.

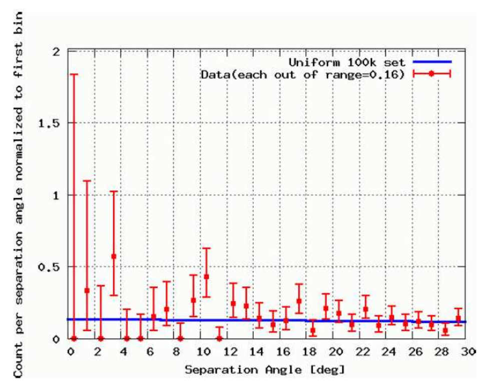

Figure 9: Comparison of number of pair events in unit solid angle with the expected uniform event distribution.

above 4×10^{19}eV. From observed number of event, 0.84 of cluser are expected from uniform distribution in 2.5° of angle distance. Observed number of cluster is 1. Till now there no significant excess of clustering is seen. The detailed analysis method is summarized in a paper [40].

4 Discussion and Summary

We presented current status of observation of Telescope Array experiment. The exposure for UHECR will reach equivarant to AGASA experiment. The spectrum from MD detector obtained monocular observation is consistent with previous observation (HiRes) experiment. The spectrum from Hybrid (BR,LR+SDs) also consistent with MD and HiRes experiment. The spectrum from SD is showing 3.5σ level of flux cutoff at the energy which is consistent with GZK cutoff and HiRes spectrum. The Xmax distribution is compatible with proton in this energy range. Now more detailed study for anisotropy using SD data and more analysis of the recorded data is on going.

Acknowledgments

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