Ultra-high energy cosmic-ray spectra measured by the Telescope Array experiment from hybrid observations

D.IKEDA[1], H.SAGAWA[1], Y.TSUNESADA[2], D.C.RODRIGUEZ[3], T.Z.ABUZAYYAD[3], AND C.C.H.JUI[3],
FOR THE TELESCOPE ARRAY COLLABORATION
[1]*Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[2]*Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[3]*University of Utah, High Energy Astrophysics Institute, Salt Lake City, Utah, USA*
ikeda@icrr.u-tokyo.ac.jp
DOI: 10.7529/ICRC2011/V02/1264

Abstract: The three fluorescence detector (FD) stations of the Telescope Array (TA) experiment have been taking data since the end of 2007. In this paper, we report the spectrum from hybrid events recorded from the Black Rock Mesa (BR) and Long Ridge (LR) sites in coincidence with the surface array. The hybrid events from the new FADC-based cameras and 6 m^2 mirrors at BRM and LR sites give the best geometrical and energy resolution as well as the most reliable aperture calculation. The MD site was built exclusively from refurbished telescopes from the HiRes-1 site of the High Resolution Fly's Eye (HiRes) experiment. The latter was the first to observe the Greisen-Zatsepin-K'uzmin (GZK) prediction of suppressed flux above 6×10^{19} eV. An updated MD monocular spectrum is included in this paper, while the hybrid MD analysis will be reported in another paper

Keywords: ultra-high energy cosmic rays, extensive air shower, energy spectrum, Telescope Array

1 Introduction

The Telescope Array (TA) experiment, located in the West Desert of Utah, is the largest ultra-high energy cosmic ray (UHECR) observatory in the Northern Hemisphere [1]. The experiment operates three fluorescence detectors (FDs) in hybrid mode with an array of 507 scintillation surface detectors (SDs). The SD array is deployed on a square grid of 1.2 km spacing and covers a total area of about 700 km^2 [2]. Three FD stations are located on the periphery of the SD array at Middle Drum (MD), Black Rock Mesa (MR) and Long Ridge (LR) [3]. The MD station consists of the 14 refurbished HiRes-I telescopes. The BR and LR stations each comprises 12 newly constructed telescopes that were specifically designed for TA. The FDs began observation in November 2007, and the SD array came on-line in March of 2008.

The data from each of the FD stations have been analyzed in both monocular and in stereo mode. Those events that were seen in coincidence between the FDs and the SD array are referred to as hybrid events. The hybrid data set is particularly suitable for the measurement of the UHECR energy spectrum. The geometry and energy of each extensive air shower (EAS) observed this way are constructed with excellent resolution, using the longitudinal calorimetric measurements from the FD and the additional timing information of the SD. These give much more accurate results than monocular reconstruction alone. Moreover, the exposure is obtained with great precision from the flat (in energy dependence), geometrically determined aperture of the SD array. In this paper, we present the hybrid spectrum from the BR and LR sites, and compare the results to the monocular spectrum from the MD site. The hybrid analysis from the MD site will be presented in another paper [4]

2 Analysis of BR and LR Data

2.1 Analysis method

The hybrid event reconstruction is divided into two steps. First, the trajectory of the shower axis is determined from the pointing direction of FD pixels containing light pulse from the EAS, and from the combined FD and SD timing information. Second, the longitudinal development and total calorimetric energy of the shower are determined amount of light gathered by the FD. In this section, we discuss the geometrical reconstruction of the hybrid events and the spatial and energy resolution obtained.

The geometrical reconstruction is also divided into two parts. The shower-detector plane (SDP), which contains both the line of the shower axis and the point of the FD station, appears as a track in the PMT pixels of the camera (Fig. 1). The normal unit vector $\vec{n}$ of SDP can be found by searching for a least-squares solution, which minimizes

$\sum_i (\vec{n} \cdot \vec{k_i})^2$, where $\vec{k_i}$ is the direction unit vector of the i-th PMT.

Next, the shower axis in the SDP is determined by timing and direction of the triggered PMTs, combined with the arrival time recorded by an SD counter near the SDP. The following equations are used to fit for r, the distance of the shower core on the ground from the FD station, where ψ is the elevation angle of the shower axis in the SDP.

$$t_i = t^* + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r, \quad (1)$$

$$t^* = T'_{SD} + \frac{1}{c}(r - r_{SD})\cos\psi, \quad (2)$$

$$T'_{SD} = T_{SD} - \frac{1}{c}\left\{(\vec{r}'_{SD} - \vec{r}_{SD}) \cdot \vec{S}\right\}. \quad (3)$$

Here t_i and α_i are the time and the elevation angle in the SDP for the i-th PMT, t^* is the time at which the air shower reaches the ground, $\vec{r}_{SD}$ is the position vector of the SD from the FD station, $\vec{r}'_{SD}$ is the SD position projected onto the SDP, and $\vec{S}$ is the direction vector of the shower axis at the shower core. Note that the time of the SD counter, T_{SD}, is included in the fit to improve the precision.

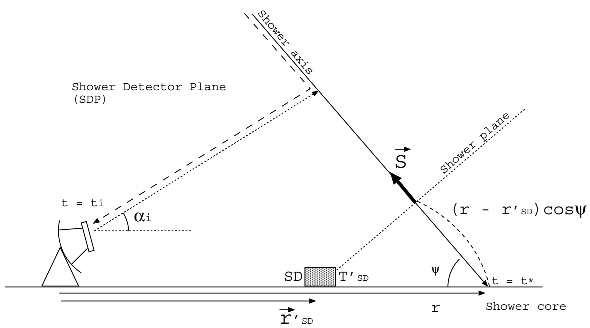

Figure 1: Shower detector plane and the time fit. In this analysis, we assume the shower front to be a flat plane.

From the shower trajectory determined above, the pulse information from the time bins of PMTs involved in the event are projected on to the shower axis. From this we obtain a signal vs. shower depth curve. The shower profile (number of charged particles vs. shower slant depth) is obtained by an Inverse Monte Carlo (IMC) method. The total energy deposit along the shower axis is determined by the comparison between data and MC events generated by the Gaisser-Hillas (GH) function. The details of the MC and IMC are discussed in other papers [5] [6] [7].

The calibration parameters are applied to MC in the IMC procedure. In this analysis, the differential fluorescence yield spectrum used to convert number of photons to energy deposit is taken from the published result of the FLASH experiment [8], normalized to the total yield from the Kakimoto model [9].

The calorimetric energy determined from the IMC procedure is corrected for missing energy carried off by neutral particles that do not emit fluorescence light. This "missing" energy is calculated using the air shower Monte Carlo (MC) simulations code CORSIKA [10]. This difference between primary energy and energy measured by the integration of the fitted GH function, is found to be $\sim$8%. The energy of the primary particle is determined by integration of the fitted GH function with the correction of missing energy.

To ensure the quality of the reconstruction, we accept only events which satisfy the following quality criteria; (1) the number of PMTs used in reconstruction is more than 20, (2) the reconstructed zenith angle is smaller than 55 degrees, (3) shower core is inside the edge of SD array, (4) angle between reconstructed shower axis and telescope is more than 20 degrees, and (5) the maximum of the shower development (X_{max}) has to be observed.

In the case of stereo event, if the events from both of BR and LR are accepted, the event with more PMTs is selected. For all energy ranges, the resolution of the arrival direction is about 0.9 degrees, and the resolution of the energy is on the order of 7% (see Figure 2).

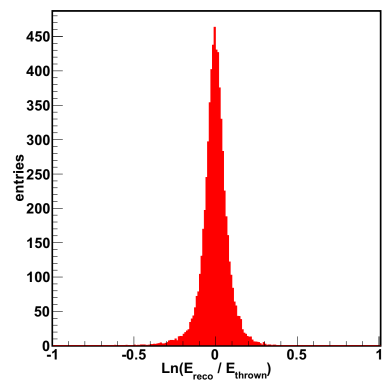

Figure 2: The energy resolution by the hybrid technique. The horizontal axis is natural logarithm of the reconstructed energy over true simulation energy. The vertical axis is the number of events. The standard deviation is 7%.

2.2 Data and MC

Hybrid events were identified by matching FD and SD events whose trigger times fall within a coincidence window of 200 μs. Only good weather data collected between May 2008 and September 2010 were used. After the reconstruction for the time-matching events, a total of 2242 events were found: 1306 recorded by the BR station, and 1051 by LR. This data set also contained 115 stereo hybrid events recorded by both the BR and LR sites.

The air shower simulation code CORSIKA with the QGSJET-II hadronic model [11] was used to generate the MC events. For the detector response simulation for these MC events, all of the time-dependent calibration parameters were applied according to the relative exposure for the applicable periods. The MC event data were subjected to the same IMC reconstruction procedure and event selection cuts. For the purpose of validating our MC events, the reconstructed shower geometry is compared between observed data and MC events (see Figure 3). The MC events are in good agreement with the observed data. From the simulation, the effective exposure was calculated to be $\sim 6\times 10^{15}$ m^2 sr s for UHECR above 10^{19} eV. This value is consistent with a purely geometrical acceptance for the SD, taking into consideration the boundary inefficiencies of the initial three-sub array configuration during the first year of observations.

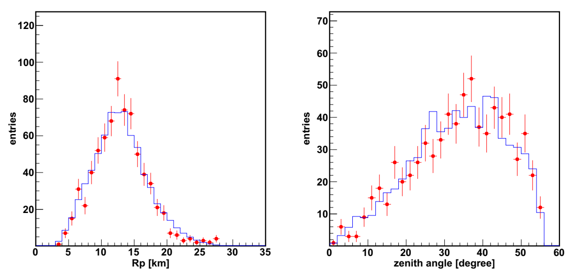

Figure 3: The comparison between real data and MC events, which observed in BR station and the reconstructed energy is above $10^{18.2}$ eV. The left figure is the comparison with the distance between shower axis and FD station (Rp), and the right figure is the comparison with the zenith angle. In each case, the real data is represented by the red circles and MC data is represented by the blue solid histogram.

2.3 Systematic Uncertainty

The systematic uncertainties in energy determination are discussed in another paper [7]. They are dominated by the uncertainties in the fluorescence yield (11%), atmosphere attenuation (11%) [12], the absolute detector calibration (10%) [13][14][15], and the reconstruction procedure itself (10%). The total systematic errors are estimated at 21% for the energy scale, and 12% for the aperture uncertainties related to the cloud monitoring [16].

3 Analysis of MD Data

The Middle Drum(MD) FD site, located at the northern end of TA, is instrumented with refurbished telescopes from the HiRes-1 site. Monocular observations from the HiRes-1 detector site also contributed most of the statistical power for the first observation of the Greisen-Zatsepin-K'uzmin (GZK) cut-off [17][18][19]. Each telescope consists of 2 m diameter mirror of 3.7 m^2 unobstructed light collection area. Each camera uses 256 two-inch photo-multiplier tubes (PMT) arranged in a row-wise hexagonal close-pack configuration. Each PMT pixel views a one-degree cone in the sky, and each camera has a $16°$(azimuth) $\times 14°$ (elevation) field-of-view (FOV). Unlike the BR and LR sites, the read-out electronics are based on TDCs for time measurements of the light pulse, and on sample-and-hold charge integrators for pulse area determination.

The performance of these 14 telescopes are well understood. For direct comparison to the HiRes results, the same profile-constrained fit from the Hires-1 monocular reconstruction was used for MD analysis. Details can be found in reference [20]. There are two main differences between the MD and HiRes-1 detectors. First, the MD station views up to $31°$ in elevation, twice as high as HiRes-1, and covers only about $110°$ in azimuth (full azimuth for HiRes). Second, the MD site is about 20% darker in ambient background light, which permitted the detectors to run at a lower threshold, improving the aperture of the MD detector to about 1/2 that of HiRes-1, even though MD has less than 1/3 the azimuthal coverage.

An initial monocular MD spectrum based on one year of data was shown at the ICRC in 2009 [21]. The most current monocular spectrum from the MD site is based on three years of data collected between December 2007 and December 2010. Both the ankle and the GZK cut-off are clearly seen in the TAMD spectrum, which is in excellent agreement both in shape and normalization with the one year spectrum [21], and with the HiRes results [19] (see Section 4).

A hybrid analysis based on MD data is being carried out in parallel. The FD reconstruction follows closely the technique used for the MD monocular spectrum, but without the profile constrain developed for the original HiRes-1 analysis [20]. The addition of the timing from the SD incorporates the method described earlier in this paper. This study will be presented in another paper [4]. In addition, an FD-initiated hybrid trigger that lowers the physics threshold to below $10^{17.5}$ eV for coincident FD-SD events has been in operation since October of 2010 [22] at BR and LR. A similar hybrid trigger is now being commissioned at the MD site. The hybrid spectra from TA will be extended to much lower energies in the near future.

4 Energy Spectra

The preliminary energy spectra from the hybrid events (BR and LR) in TA is shown in Fig. 4. The updated MD monocular spectrum is also shown. These results from TA are consistent with the HiRes result. This indicates that the energy scale of TA is compatible with that of HiRes.

5 Conclusion

The hybrid spectrum using the FD data from BR and LR was presented in this paper. A dedicated reconstruction procedure was developed that included the timing information from the SD in the trajectory fit for the shower axis. The resulting angular resolution is better than $0.9°$ and the energy resolution is about than 7% above $10^{18.2}$ eV. These resolutions represent a substantial improvement over FD monocular analysis, where the angular resolution is of the

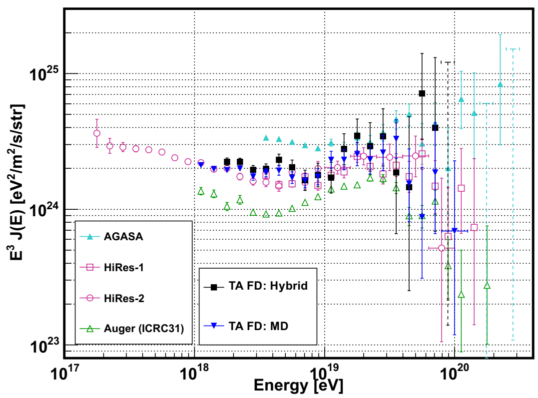

Figure 4: The energy spectra measured by the hybrid analysis in the BR/LR station and monocular analysis in the MD station with other recent experimental data. The dotted line shows the upper limit at 90% C.L.

order of $5°$ and energy resolution about $15-20\%$ for events with the energy above $10^{18.2}$ eV.

For this hybrid analysis, the main contributions for the systematic uncertainty of energy scale are the detector calibration (10%), atmospheric attenuation (11%), fluorescence yield (11%) and the reconstruction procedure itself (10%). The total systematic error of the energy scale is estimated to be 21% by a quadratic sum of these factors.

The measured hybrid energy spectrum above $10^{18.2}$ eV is consistent with the monocular spectrum from the MD site, and with the previously published results of the HiRes experiment.

Acknowledgements

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (21000002) "Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays", basic research awards 18204020(A), 18403004(B) and 20340057(B); by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006-0050031, 2007-0056005, 2007-0093860, 2010-0011378, 2010-0028071, R32-10130); by the Russian Academy of Sciences, RFBR grants 10-02-01406a and 11-02-01528a (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions and the University of Utah Center for High Performance Computing (CHPC).

References

[1] J.N.Matthews *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[2] T.Nonaka *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[3] S.Ogio *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[4] M.Allen *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[5] S.R.Stratton *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[6] B.Stokes *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[7] Y.Tsunesada *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[8] R.U.Abbasi *et al.* , AstroPart.Phys, 29, 77-86, 2007.
[9] F.Kakimoto *et al.* , Nucl.Instr.and Meth.A, 372, 527-533, 1996.
[10] D.Heck *et al.* , Report FZKA, 6019, 1998.
[11] S. Ostapchenko, Nucl. Phys. B, Proc. Suppl. **151**, 143 (2006).
[12] T.Tomida *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[13] H.Tokuno *et al.* , Nucl.Instr.and Meth.A, 601, 364-371, 2009.
[14] D.Ikeda *et al.* , 31st International Cosmic Ray Conference, Lodz, Poland, 2009.
[15] S.Kawana *et al.* , 31st International Cosmic Ray Conference, Lodz, Poland, 2009.
[16] F.Shibata *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings
[17] K. Greisen, Phys. Rev. Lett. **16** (1966) 748.
[18] T. Zatsepin and V.A. K'uzmin, JETP Lett. **4** (1966) 178.
[19] R.U. Abbasi *et al.* , Phys. Rev. Lett. **100** (2008) 101101.
[20] R.U. Abbasi *et al.* , AstroPart. Phys. **23** (2005) 157.
[21] C.C.H.Jui *et al.* , 31st International Cosmic Ray Conference, Lodz, Poland, 2009.
[22] H.Tokuno *et al.* , 32nd International Cosmic Ray Conference, Beijing, China, 2011, in these Proceedings