Ultra-High Energy Cosmic Ray Spectrum Measured by the Hybrid Analysis in the Telescope Array

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Abstract: We developed a hybrid reconstruction technique using both by Fluorescence Detectors and Surface Detectors in the Telescope Array Experiment, and measured energy spectrum of ultra-high energy cosmic rays with energies above $10^{18.2}$ eV using the data obtained in our first 4-year observation. The hybrid reconstruction technique improves the accuracies in determination of arrival directions and primary energies of cosmic rays compared to that of FD monocular mode. The energy spectrum presented here is in agreement with our previously published spectra and the HiRes results.

Keywords: ultra-high energy cosmic rays, energy spectrum, telescope array, hybrid analysis

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. 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 an area of about 700 km^2. Each of the 3-m^2 SDs includes two layers of plastic scintillators. The SDs measure arrival timings and local densities of shower particles at the ground. The arrival direction and primary energy of an air shower is determined from the relative timing differences of particle arrivals between SDs, and from the lateral distribution of local particle densities around the shower core, respectively. The duty cycles of SD is nearly 100%. The full details of the SDs are found in [1].

Three FD stations are located on the periphery of the SD array at Middle Drum (MD), Black Rock Mesa (MR) and Long Ridge (LR). The BR and LR stations contains 12 telescopes, observing 3° to 31° in elevation and 108° in azimuth. Each telescope consists of a spherical mirror of 6.8 m^2 effective area, a camera of 256 PMTs and a FADC-based electronics. The FDs measure longitudinal development and primary energies of air showers in the atmosphere from the amounts of light emitted by atmospheric molecules excited by charged particles in the showers. The telescopes are operated on clear, moonless nights. The full details of the FDs are given /in [2].

The advantage of FD is that air shower energies can be determined calorimetrically knowing the fluorescence yield, which is the amount of lights emitted by molecules per total energy losses of charged particles in the showers. However there is a rather large uncertainty in arrival directions of cosmic rays determined with FD in monocular mode, in which time differences between signals of the photo-tube pixels with small angular separations are used.

A hybrid reconstruction technique, using the timing information of an SD at which air shower particles hit the ground, solves the problem. Our Monte-Carlo study showed that an inclusion of the SD timing in FD monocular reconstruction significantly improves the accuracy in the determination of shower geometry. Moreover, the fluctuation of the aperture estimation in the energy region above about 10^{19} eV is smaller than that of FD monocular analysis since the aperture of the hybrid events is limited by the SD array edges. Therefore, this method is particularly suitable for the measurement of the UHECR energy spectrum.

In this paper, we present the developed hybrid technique and its performance obtained from the Monte-Carlo study. The energy spectrum measured by using the hybrid events in TA four years observation is also presented.

2 Hybrid Reconstruction

The process of the analysis consists of four steps: PMT selection, shower geometry reconstruction, reconstruction of longitudinal shower profile and quality cuts. The geometry of the air shower is determined with a timing information of one SD in addition to the FD tube timings. This is the key to improve the accuracy of the reconstruction compared to that of FD monocular mode. The energy of the UHECR is measured via the calorimetric technique of the FD.

First the PMTs to used in the reconstruction are chosen from the triggered data. The shower track is identified from the PMT hit pattern in the camera, and PMTs that are spatially and temporally isolated from the track are rejected. Further selection is made by discarding the separated PMTs from the Shower Detector Plane (SDP), which obtained

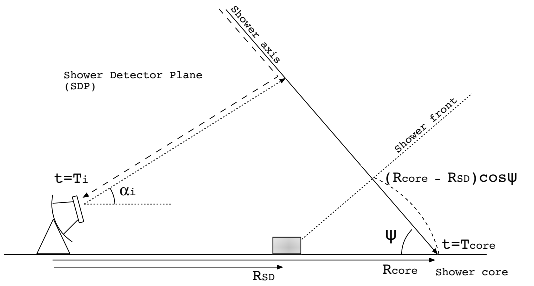

Fig. 1: Diagram indicating the Shower Detector Plane (SDP) for use in the time fit.

from the pointing direction vectors of the selected PMTs. These procedures are iterated until no more PMTs are rejected or reintroduced.

Second the shower geometry is determined from the pointing directions and timings of the those PMTs:

$$T_{\mathrm{exp},i} = T_{\mathrm{core}} + \frac{\sin\psi - \sin\alpha_i}{c\sin(\psi+\alpha_i)} R_{\mathrm{core}}, \qquad (1)$$

where $T_{\mathrm{exp},i}$ and α_i are the expected timing and elevation angle in the SDP for the i-th PMT, respectively, T_{core} is the timing when the air shower reached the ground, R_{core} is the distance from the FD station to the core, and ψ is the elevation angle of the air shower in the SDP (Fig. 1).

For an event that has the timing information of one SD near the core, T_{core} is expressed by:

$$T_{\mathrm{core}} = T'_{\mathrm{SD}} + \frac{1}{c}(R_{\mathrm{core}} - R_{SD})\cos\psi, \qquad (2)$$

$$T'_{\mathrm{SD}} = T_{\mathrm{SD}} - \frac{1}{c}((P'_{\mathrm{SD}} - P_{\mathrm{SD}})\cdot P), \qquad (3)$$

where P_{SD} is the position of the SD, P'_{SD} is the projection of P_{SD} onto the SDP, P is the direction of the shower axis, T_{SD} is the timing of the leading edge of the SD signal. The quantity to be minimized in the fitting is written as

$$\chi^2 = \sum_i \frac{(T_{\mathrm{exp},i} - T_i)^2}{\sigma^2_{T,i}}, \qquad (4)$$

where σ_{T} is the fluctuation of the signal timing. The SDs with distances greater than 1.2km from the line of intersection of the SDP and the ground are rejected, and those far from the shower core more than 1.5km are also rejected. These procedures are repeated and only one SD that gives the best χ^2 is chosen. The resolution of the arrival direction is about 0.9 degrees which is significantly improved compared to that in FD monocular mode about 5 degrees (see Fig. 2).

The longitudinal profile of the shower development can be reconstructed from the signal vs. shower depth curve obtained from the "known" shower axis. However the components which contribute to the detected signals are not only the fluorescence photons but also Cherenkov light beamed near the direction of an shower axis and those scattered by atmospheric molecules and aerosols. In addition, we should take into account the all of the detector characteristics including the shadowing effect by the telescope structure, gaps between the segment mirrors, the mirror reflectivities, non-uniformities of the PMT cathode sensitivities and so on.

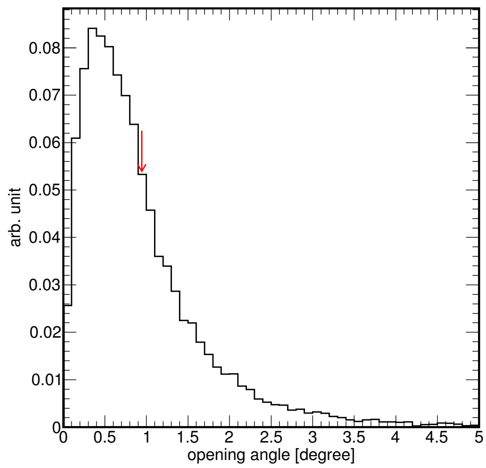

Fig. 2: Opening angle between reconstructed and thrown Monte Carlo events. Below 0.9 degrees (red arrow), 68.3% of the reconstructed showers are contained.

This is straightforward in detector simulation with ray-tracing, however, not in data reconstruction because of the irreversible nature (for example, it is not possible to know the position at which a photon hit the photo-cathode of a PMT). Therefore we employ an "inverse MC method" in shower reconstruction to find an MC shower which best reproduces the data considering all the photon components (fluorescence and Cherenkov photons) and detector responses.

We assume that the profile of the shower development is represented by the Gaisser-Hillas function [3],

$$N(X; X_{max}, X_0, \Lambda) = N_{\mathrm{max}} \left(\frac{X - X_0}{X_{\mathrm{max}} - X_0}\right)^{(X_{\mathrm{max}} - X_0)/\Lambda} e^{(X_{\mathrm{max}} - X)/\Lambda}, \qquad (5)$$

where X is the atmospheric depth, X_{max} is the depth at the shower maximum, Λ is the interaction length of the shower particles, and X_0 is the offset of X. Since Λ and X_0 do not give significant contribution to the bulk of the profile, we only consider the one parameter X_{max} i.e. $N(X; X_{\mathrm{max}})$.

The X_{max} is obtained by maximizing the likelihood L:

$$L = \sum_i n^i_{\mathrm{obs}} \log\left(\frac{n^i_{\mathrm{exp}}(X_{\mathrm{max}})}{\sum_i n^i_{\mathrm{exp}}(X_{\mathrm{max}})}\right), \qquad (6)$$

where n^i_{obs} is the sum of the photo-electrons at each PMT, $n^i_{\mathrm{exp}}(X_{\mathrm{max}})$ is the expected number of photo-electrons in the output of the i-th PMT obtained from the Monte-Carlo simulation including "real" characteristics of the detectors and atmophere with the time-dependent calibration data.

After fitting for the X_{max}, the N_{max} is obtained by the scaling as,

$$N_{\mathrm{max}} = \frac{\sum_i n^i_{\mathrm{obs}}}{\sum_i n^i_{\mathrm{exp}}(X_{\mathrm{max}})}. \qquad (7)$$

The primary energy is obtained by integration of the Gaisser-Hillas function (Eq. 5) with a correction of the missing energy that are carries away by neutral particles.

To ensure the quality of the reconstruction, we accept only events which satisfy the following quality criteria;

(1) The number of PMTs used in the reconstruction is greater than 20, (2) the zenith angle of the reconstructed shower axis is less than 55 degrees, (3) the shower core is inside the edges of the SD array, (4) the angle between the reconstructed shower axis and the telescope is greater than 20 degrees , (5) the $X_{\max}$ has to be observed.

If the events pass the cuts for both the BR and LR stations, we adopt the reconstruction result of the station in which the larger number of PMTs are involved. For all energy ranges, the resolution of the energy is on the order of 7%.

3 Hybrid Aperture and Exposure from MC

The performance of our detectors, the reconstruction programs, and the aperture are evaluated using our Monte-Carlo (MC) program. The TA MC package consists of two parts, those are the air shower generation part and the detector simulation part.

We generate cosmic-ray showers using the CORSIKA [4] based MC simulation code developed for TA [5]. We use proton primary particles with QGSJET-II-03 [6] hadronic interaction model. For data and MC comparison, the MC events are sampled with the energy spectrum measured by the HiRes experiment [7, 8], excluding the GZK suppression effect [9, 10].

The SD simulation, which based on the GEANT4 [11], includes the response of the SD electronics and trigger scheme of the SD array, a three-fold coincidence of adjacent SDs with signals greater than three particle-equivalent [1]. The energy deposit in each SD is calculated the particle information at the ground in the air shower MC.

The FD simulation includes fluorescence and Cherenkov photon generations, telescope optics, detector calibration, and the response of the electronics [2, 12]. The radiosonde data and the distribution of aerosols measured with a LIDAR system at BRM are used for the atmosphere [13]. For the fluorescence yield, as the number of photons per energy deposit, we use the absolute value reported by Kakimoto *et al.* [14] and the temperature and pressure dependence reported by FLASH [15]. The Cherenkov light emission is also implemented from the energy spectrum of charged particles and angular distribution of produced photons based on CORSIKA [16].

The quality of the generated MC events is examined by comparing the real data to validate the aperture calculation. We use the shower events detected with the SDs and FDs at the BR and LR sites collected from May 2008 to February 2012. In total 3449 events remained after hybrid reconstruction and quality cuts. Among the 3449 events, 1953 are from BR and 1692 are from LR, and we found 196 "stereo" events that are detected at both BR and LR. The difference in the number of events from the two sites is consistent with the difference in the telescope on-time and a slight different aperture due to the elevations of the sites and the distance to the closed SDs. Here we show the comparison of MC and the real data in terms of several quantities that are sensitive to the aperture, the shower impact parameter R_P, the shower arrival direction angle on SDP ψ (Fig. 3). For all the parameters, the data and MC events are in excellent agreement.

The effective area and aperture for the hybrid events increase with energy in lower energies, and limited by the area of the SD array above 10^{19} eV. Therefore the aperture in the hybrid mode is well defined than in case of FD monocular analysis.

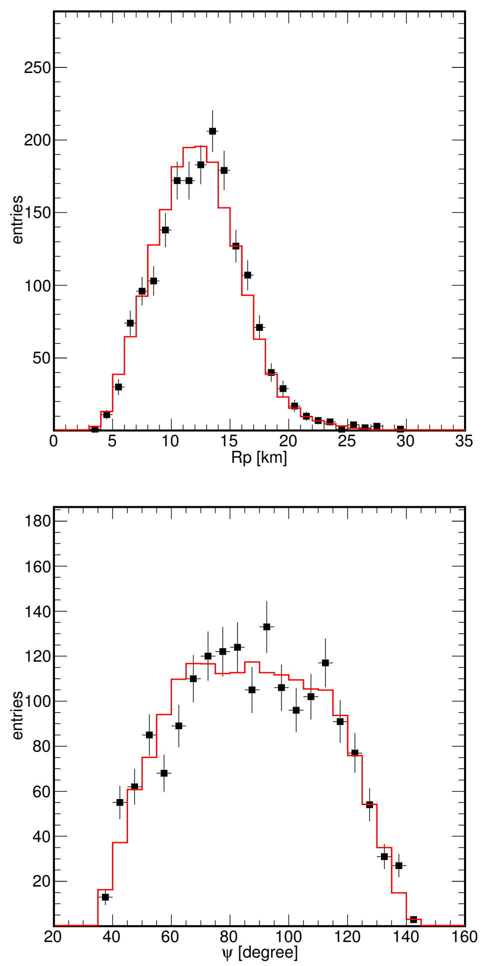

Fig. 3: Comparison of the data and Monte Carlo distributions of the impact parameter R_P (upper figure) and ψ (lower figure). The data is shown by points with error bars and the Monte Carlo simulation is shown by the histogram.

To measure the spectrum, we use the data collected on clear and moonless nights with minimal cloud cover in the view of the detector for reliable reconstruction. In this analysis, we uses about 70% period which corresponds to the half or less cloud coverage. The total observation time after subtracting the dead time of the detector is 2350 hours for BR and LR, which consists of 1551 hours for stereo observation, 548 hours for BR and 251 hours for LR.

The aperture of the hybrid events with E $> 10^{19}$ eV is about 1.2×10^{9}m^{2} sr, which is mainly determined by SD.

Combining the on-time hours we obtained the exposure for the hybrid events 8×10^{15} m^{2} sr s (Fig. 4).

4 Energy Spectrum

Figure 5 shows the energy spectrum above $10^{18.2}$ eV. The TA hybrid spectrum and our previously published spectra are in agreement with the HiRes results.

Systematic uncertainties in energy determination are estimated by the uncertainties in the fluorescence yield (11%), atmosphere attenuation (11%)[13], the absolute detector calibration (10%) [12][17], and reconstruction (10%). The total systematic uncertainties is 21% by adding

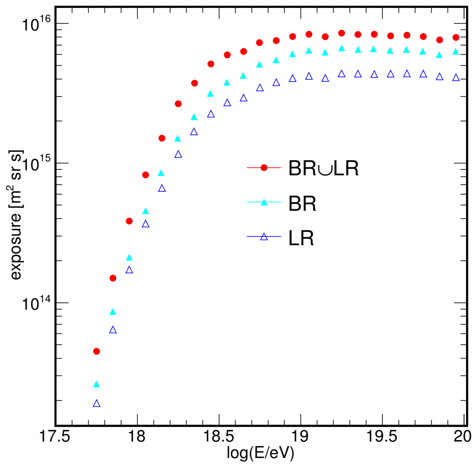

Fig. 4: The calculated hybrid exposure as a function of the energy of the cosmic ray primary.

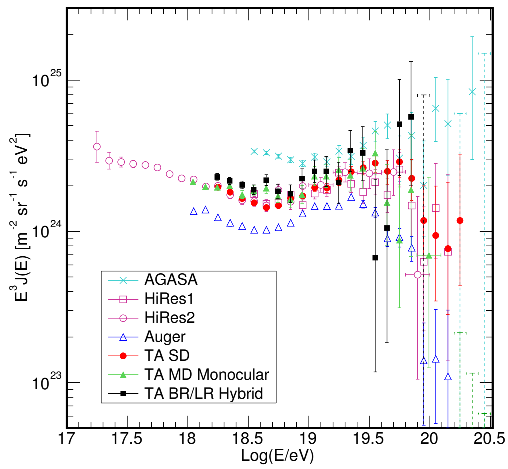

Fig. 5: The energy spectra multiplied by E^3. The spectrum determined from the hybrid data is shown by the black boxes. The spectra of AGASA [18], HiRes-1/HiRes-2 [7], Auger [19],TA SD [20] and TA MD [21] are also shown for comparison.

all the uncertainties in quadrature.

5 Conclusion

The Telescope Array was operated in hybrid mode since May 2008. We developed a hybrid reconstruction technique for air showers using the longitudinal shower profile from FD and the particle arrival timing at the position of SD. The arrival direction and energy of an air shower can be determined in accuracies of 0.9° and 7%, which are significantly improved compared to those in FD monocular mode. The systematic uncertainty in determination of energies is evaluated as 21%.

We determined the energy spectrum of cosmic rays with energies above $10^{18.2}$ using the hybrid reconstruction technique using both FD and SD data. The aperture of the detectors is evaluated by taken into account the details of detector performances and atmospheric conditions at the site. The result in this work is in agreement with our previously published spectra obtained from the SD and FD monocular analyses.

Acknowledgment: 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", and the Inter-University Research Program of the Institute for Cosmic Ray Research; by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, PHY-0848320, PHY-1069280, and PHY-1069286 (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 as well as the University of Utah Center for High Performance Computing (CHPC).

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