Distribution of arrival directions obtained from the first year data of Telescope Array.

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***Abstract*. The Telescope Array (TA) experiment is a detector of ultra-high-energy (UHE) cosmic rays, which is composed of a surface detector (SD) array and air fluorescence telescopes. TA is the only hybrid UHE detector in the northern hemisphere. The SD array of TA is composed of 507 units of plastic scintillator detectors deployed on a 1.2 km grid. The total detection area is about 700 km^2. It has been observing extensive air showers continuously since it started a full operation in spring, 2008. We analyse the data observed over a year. In this paper, the distribution of arrival directions with energy above $10^{18.5}$ eV will be presented. The angular resolution is estimated by Monte Carlo simulation. From this result, we test the autocorrelation between the arrival directions of events, and the energy dependence of the autocorrelation. We also present cluster candidates on the skymap.**

***Keywords*: Ultra high energy cosmic ray, Telescope Array, Arrival direction**

I. INTRODUCTION

The AGASA observed 11 cosmic rays above 10^{20}eV in 12 years operation and shows the extension of the cosmic ray energy spectrum above the GZK cut-off.[1] Although the arrival direction distribution of EHECRs observed by AGASA is almost isotropic, some events shows an indication of point sources, from which 2 or more EHECRs arrived.[2] High energy astronomical objects such as quasar remnants and BL Lac objects have been searched behind these events, but nothing have been found. There have been several hypothesis to explain these super-GZK events and point sources : super-heavy relics[3], Z-burst[4], the violation of Lorentz invariance at extremely high energy[5], and so on. Hires group have also studied the EHECRs and they reported that their energy spectrum is consistent with the existence of the GZK cutoff.[6] From discussions of these two groups, it seems clear that a part of the inconsistency is due to the systematic error of both experiments in the determination of primary cosmic ray energy.

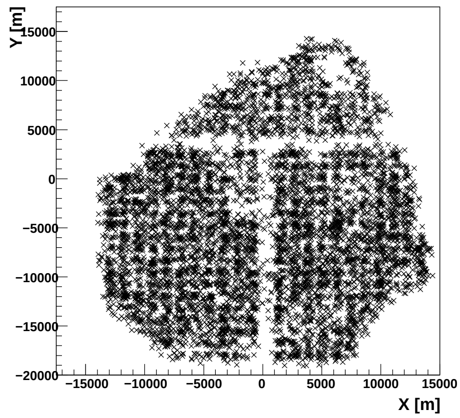

Fig. 1. The reconstructed core position distribution. The large blank region corresponds to the border of 3 part of SD array.[9] A few of unstable SDs also cause the small blank regions.

II. DETECTOR

In order to reconcile the results of AGASA and Hires, we constructed a hybrid detector which has an AGASA type ground array (SD array) and 3 air Fluorescence telescope stations like Hires detector (FD) as the First step of TA experiment.[7] The West Desert in Utah, USA is the experimental site. The Hybrid-TA consists of 507 plastic scintillation counters which cover the ground area of 700 km^2 in 1.2 km grid and 3 telescope stations (FD stations) which surround the array and look inward.

The Field of view (FOV) of each FD station is $3^\circ \sim 34^\circ$ in elevation angle and 120° in azimuthal angle.[8] There are 12 telescopes in each FD station. The FOV of each telescope is 15.5° in elevation and 18° in azimuthal. Each telescope has spherical mirror of 3.3 m in diameter. The shower image is recorded by a camera composed of 2-inch hexagonal PMTs placed on image plane.

Each particle detector of the SD has 2 layers of plastic scintillator. [9] The area is 3m^2 and the thickness is 1.2cm. The scintillation photons are fed into PMT via wave length shifter fibers installed in grooves cut on the surface of the scintillator. The output signal from PMT is digitized by 12bit 50Hz Flash ADC (FADC). When the PMT signals of both layer exceeds the threshold level ($\sim$0.3MIP), data is stored in the memory. The trigger timing information of local SD which has the signal above 3MIP is sent to the central DAQ system via wireless LAN. If the central DAQ find triggers from 3 or more adjacent SDs, the waveform information of triggered SD (>0.3MIP) gathered and stored in the central DAQ system.

III. Geometrical reconstruction of SD data

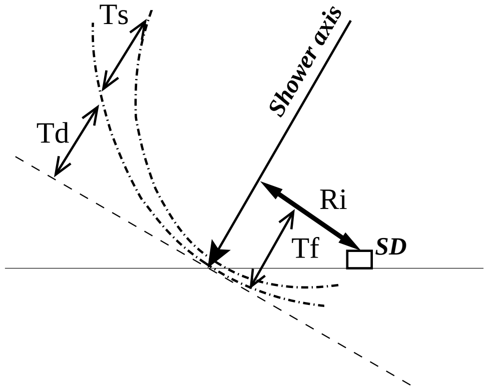

Fig. 2. Diagram of an air shower hitting the ground.

The timing information and charge information from hit PMT are used to reconstruct the shower geometry. Prior to the reconstruction, the PMT information from the isolated hit detector is cut to remove the hit caused by random hit. If PMTs do not have the proper calibration constants, they are not used in the reconstruction.

The core location and the arrival direction of the event is obtained by minimizing the chi square defined by the following function.

$$\chi^2 = \frac{1}{n-3} \times \sum_{i=1}^{n} \frac{(T_i - T_f(\overrightarrow{r}_i, \theta, \phi) - T_d(\rho_i, R_i) - T_0)^2}{T_s(\rho_i, R_i)^2 + \sigma_{det}^2} \quad (1)$$

n is the number of hit SDs after the reduction of the isolated SDs. T_i is the arrival time of shower particle observed by i-th SD. T_f is the propagation time of tangential plane of the shower front. T_d is the average delay time of the shower particle from the tangential shower plane. R_i is the distance from the shower axis. θ, ϕ is the arrival direction of primary cosmic ray. T_0 is the time when the shower core hit the ground. T_s is the thickness of shower front. σ_{det} is the uncertainty of the detection timing, which is mainly due to uncertainty of the GPS time.

Here, T_d and T_s are calculatd by the follwing functions.

$$T_d = 1.373 \times \left(1.0 + \frac{R_i}{3000.0}\right)^{1.601} \times \rho_i{}^{-0.1306} \quad (2)$$

$$T_s = 0.1966 \times \left(1.0 + \frac{R_i}{3000.0}\right)^{1.743} \times \rho_i{}^{-0.1743} \quad (3)$$

T_d and T_s were obtained experimentaly by AGASA.[10] We modified the AGASA functions by using of our MC and obtained Eq.(2) and Eq.(3).

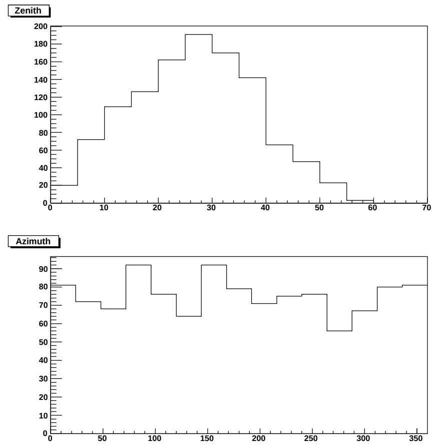

Fig. 3. The upper figure shows the zenith angle distribution of all reconstructed events. The lower figure is azimuth angle ditribution.

The angular resolution of air shower in SD is estimated with our Monte Carlo simulation. It is defined as the angle with respect to the arrival direction of shower that includes 68% of the reconstructed direction. Resolution for the arrival direction is $\sim 2^\circ$ for the air shower with $E > 1 \times 10^{19}$eV.

IV. Angular distribution

The data set used in this proceeding paper covered the period from May 15, 2008 to Nov 28, 2008. It will be updated soon.

To obtain the distributions of Fig.1 and Fig.3, the following cuts are applied.

- The number of PMTs above 3MIP in a event is larger than 10.
- χ^2 defined in Eq.(1) is less than 2.

The efficiancy of these cuts is $> 97\%$ above 1×10^{19}eV, which is estimated by our MC. Reduction ratio for all triggered events in real data is 90%.

From these results, we focus on the small angle anisotropy of the UHE cosmic rays. Because their arrival directions are very useful to point back toward the sources. In order to search for the clustering among the UHE cosmic rays, we must choice the the minimum energy E_c of the data set and the angular separation θ_c of the pairs. In this report we will scan over a range of values of E_c and θ_c and identify the value which maximize the clustering signal. The result of this study will be presented in the ICRC2009.

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REFERENCES

[1] M.Takeda et al.,Astropart. Phys. 19 (2003) 447-462
[2] N. Hayashida et al., Astrophys. J. 522 (1999) 225
[3] G. Gelmini et al, Phys. Rev. Lett. 84, 1378 (2000)
[4] D. Fargion et al., Nucl. Phys. B (Proc. Suppl.) 136 2004 256-262
[5] H. Sato and T. Tati, Prog. Theor. Phys. 47 (1972), p.1788
[6] D. Burgman et al., Nucl. Phys. B (Proc. Suppl.) 165 2007 19-26
[7] H. Kawai et al., Proceedings of 29th ICRC (2005) 181
[8] H. Tokuno et al., Proceedings of 30th ICRC (2007) 1009
[9] S. Ozawa et al., Proceedings of 30th ICRC (2007) 1109
[10] T.Hara et al., Proceedings of 18th ICRC 11 (1983) 276-279