Search for small clusters by auto-correlation analysis from Telescope Array

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Abstract. The Telescope Array (TA) experiment detects air showers induced by extremely high energy cosmic rays in the middle west of Utah, USA. The TA experiment consists of two different types of detector such as atmospheric fluorescence detectors (FDs) and surface array particle detectors (SDs). The SD observation started in March 2008. This paper describes the search for the small scale clusters from 850-days TA SD data by auto-correlation method for several energy thresholds. As a result, there is no indication of small scale clusters by TA SD.

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INTRODUCTION

The small scale clusters of arrival direction of ultra high energy cosmic rays are reported from the AGASA experiment [1]. However, the result of small scale anisotropy from the HiRes experiment is consistent with isotropic arrival direction [2]. The Telescope Array experiment takes place almost at the same latitude of above two experiments in northern hemisphere. Therefore, the result of small scale clusters can be compared with previous two experiments directly. The galactic and intergalactic magnetic field cannot be neglected for charged cosmic rays. If magnetic field is strong or composition of cosmic ray is heavy, the arrival direction of cosmic ray is far from its source by deflection. However, the charged particles travel along straighter line as their energies increase. So, if there are small clusters of arrival direction of ultra high energy cosmic rays, it can limit the strength of magnetic field, source candidates or composition.

TELESCOPE ARRAY

The Telescope Array experiment takes place in the middle west of Utah, United States (39.3°N, 112.9°W, alt 1400 m). The TA consists of three atmospheric fluorescence detector stations, 507 surface array particle detectors, the central laser facility, the electron light source and three telecommunication towers. One of three FD stations is moved from HiRes. Therefore, the direct comparison with HiRes and TA is possible. In addition, the LIDAR and IR camera are installed for the calibration of atmospheric transparancy for fluorescense detector. The SDs are deployed in a square grid of 1.2 km spacing. The effective area of TA SD is about 680 km^2.

Surface Detector

The particle detection part is plastic scintillator with an area of 3 m^2. It consists of two layers of scintillator each with wavelength shifting fibers (WLSF) to one PMT separately. The overview of the particle detection part of SD is shown in Figure 1. The thickness of each layer of plastic scintillator is 1.2 cm Each SD is powered by solar panel and battery system and controlled by WLAN. The signal from PMT is read out by 12-bit FADC with sample rates of 50 MHz. The signal is stored as 128-bin waveform ($\sim$2.6 μs), when the signal size is over $\sim$0.3 Muon Peak. The timing information of the signal of which size is over $\sim$3 Muon Peak is collected by the telecommunication tower through WLAN. When there are three adjacent SDs for collected timing within 8 μs, the tower system generates the shower trigger and collects waveforms from all SDs within 32 μs for shower triggered timing. The surface detector array is divided into three areas to collect information via three towers.

Major construction of the Telescope Array experiment started in 2005. The particle detection part of SD was assembled in the Institute for Cosmic Ray Research in

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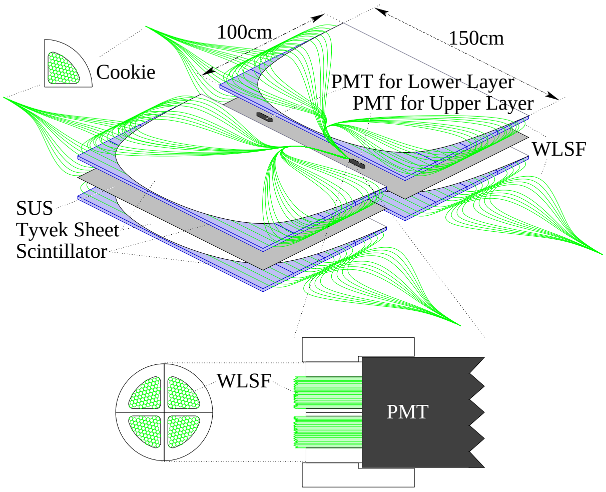

FIGURE 1. Overview of particle detection part of SD.

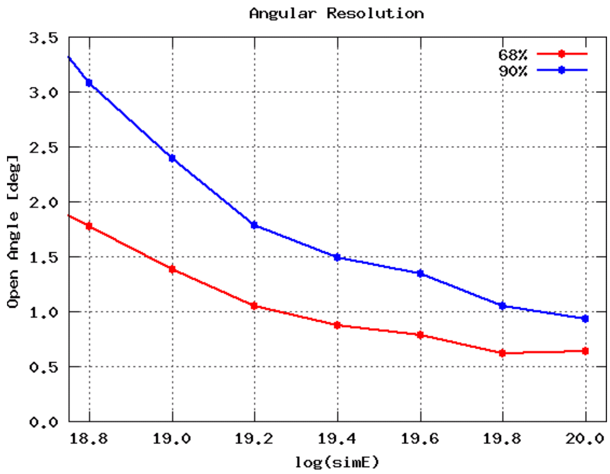

FIGURE 2. Energy dependency of angular resolution. The red and blue points show the opening angle encompassing 68% and 90% of simulated direction for several simulated primary energy, respectively.

Japan. The whole SD was finally assembled in the Cosmic Ray Center in Delta, Utah, near the observation site, and deployed by helicopter. In 2007, WLAN antenna adjustment, basic calibration, development of the firmware of electronics and DAQ program were performed. The stable SD observation started in May 2008. The cross boundary trigger for three tower sub-arrays was installed at the end of 2008. The SD status is monitored every day and maintained quickly for individual troubles.

DATA RECONSTRUCTION

The data of each SD is FADC waveform. To get particle arrival timing and energy deposit, the signal FADC counts are integrated as a Vertical Equivalent Muon (VEM) unit and the leading edge of FADC integration is taken as the timing.

After the integration, there are pre-selections by requiring a SD with maximum signal beyond 50 VEMs, adjacent six or more hit SD and simple hit pattern of SD to ensure that the core location is inside active array. By shower simulation whose zenith angle is up to 45°, 99% events of primary energy at 10 EeV pass this pre-selection and more events pass for higher primary energy.

Direction search is done by minimization of chi-square of asymmetric Gaussian distribution for timing. Core search is done by maximum likelihood. The fit function contains rotational effect of detectors for shower axis. These processes take place with iteration. The energy is determined by zenith angle and scale parameter (related shower size). For evaluating the reconstruction resolution, COSMOS [3] shower simulator with QGSJET-II proton model is used. The resolution of energy is about 15% and 12% for simulated energy 10 EeV and 40 EeV. The resolution of arrival direction which is defined as the opening angle encompassing 68% of simulated direction of events is about 1.4° and 0.8° for simulated energy 10 EeV and 40 EeV, respectively. The energy dependence of angular resolution is shown in Figure 2.

We used the TA SD data from May 11, 2008 to September 07, 2010 for this paper. The number of triggered events is 393509. And then, 16902 events are reconstructed. Among them, there are 12578 events whose zenith angle is equal or less than 45° and core is located inside active array. For this paper, we used the event with energies above 10 EeV in above 12578 events.

ARRIVAL DIRECTION DISTRIBUTION AND SKY MAP

For the event whose energy is higher than 10 EeV and zenith angle is equal or less than 45°, the reconstruction efficiency is over 99%. In addition, the surface detectors are arrayed on quite flat ground. Therefore, if the arrival direction is isotropic, the uniform exposure of each direction follows $\sin\theta\cos\theta$. Here, θ is zenith angle. The arrival direction distribution in the equatorial coordinate for the events with energies above 10 EeV is shown in Figure 3. It is compatible with the expectation from isotropic model. The sky maps for the events above 10 EeV and 40 EeV are shown in Figure 4, respectively.

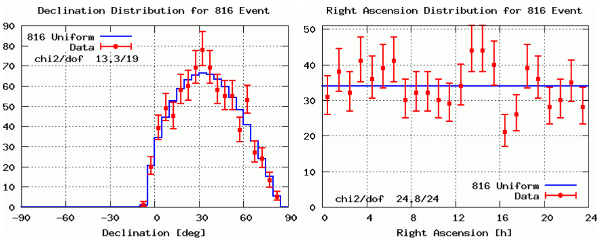

FIGURE 3. Arrival direction distribution in the equatorial coordinate for the events with energies above 10 EeV. Blue histogram shows expectation from isotropic model. Red points show observed data. The error bars and the chi-square are obtained using binomial distribution. Left: Declination distribution, Right: Right Ascension distribution.

TABLE 1. Doublet counts of observed data and expectation from isotropic model. Top: doublet in 2.5°, Bottom: doublet in 5.0°

Energy Threshold	Events	Average	Deviation	Observed
10 EeV	816	323.5	18.9	311
20 EeV	224	24.31	5.01	20
30 EeV	83	3.32	1.82	2
40 EeV	42	0.838	0.919	1
50 EeV	22	0.225	0.474	0

Energy Threshold	Events	Average	Deviation	Observed
10 EeV	816	1291.0	42.2	1300
20 EeV	224	97.1	10.4	96
30 EeV	83	13.22	3.69	17
40 EeV	42	3.33	1.83	5
50 EeV	22	0.896	0.947	1

AUTO-CORRELATION

A separation angle is defined as an open angle of any two events. The auto-correlation analysis procedure is following. First, separation angle is calculated for all pairs. Second, the number of pairs in certain range of separation angle is counted. Third, the counted number of pairs is compared with the number of pairs in the same procedure from model calculation whose event statistics is the same. The separation angle distribution of observed data and isotropic model, normalized by solid angle to the first bin, is shown in Figure 5. This is same style of AGASA plot [1].

The number of pairs with separation angle less than a certain angle is called doublet count. The doublet counting in 2.5° and 5.0° for several energy threshold are shown in Table 1. The doublet counting in 2.5° was done by AGASA for the events with energies above 40 EeV with isotropic model, and the result of small scale clusters from the AGASA experiment is inconsistent with isotropic model [1]. From Table 1, the result of doublet counting from the TA experiment is very consistent with isotropic model.

CONCLUSION

The arrival direction distribution of detected events whose energy is higher than 10 EeV is consistent with isotropic model. Therefore, we searched for small scale clusters from 850-day TA SD data by auto-correlation method, which is evaluated with isotropic model. The result is that there were no small scale clusters which are significantly more than isotropic model expectation.

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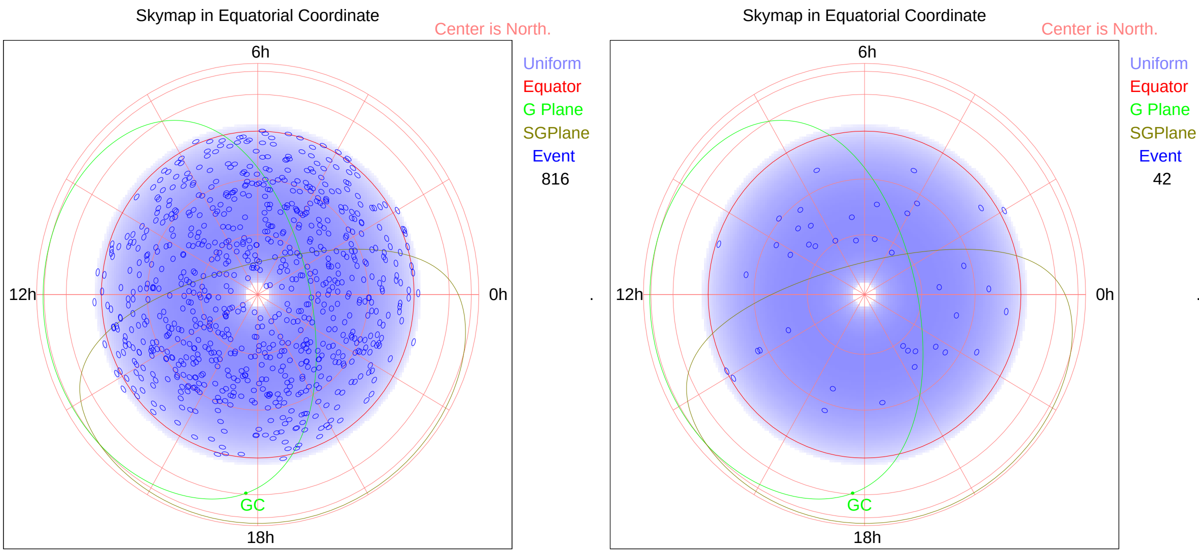

FIGURE 4. The sky maps of cosmic rays observed by the TA SD in the equatorial coordinate. The radius of point is 1.25°. Left: Energy threshold is 10 EeV, Right: Energy threshold is 40 EeV.

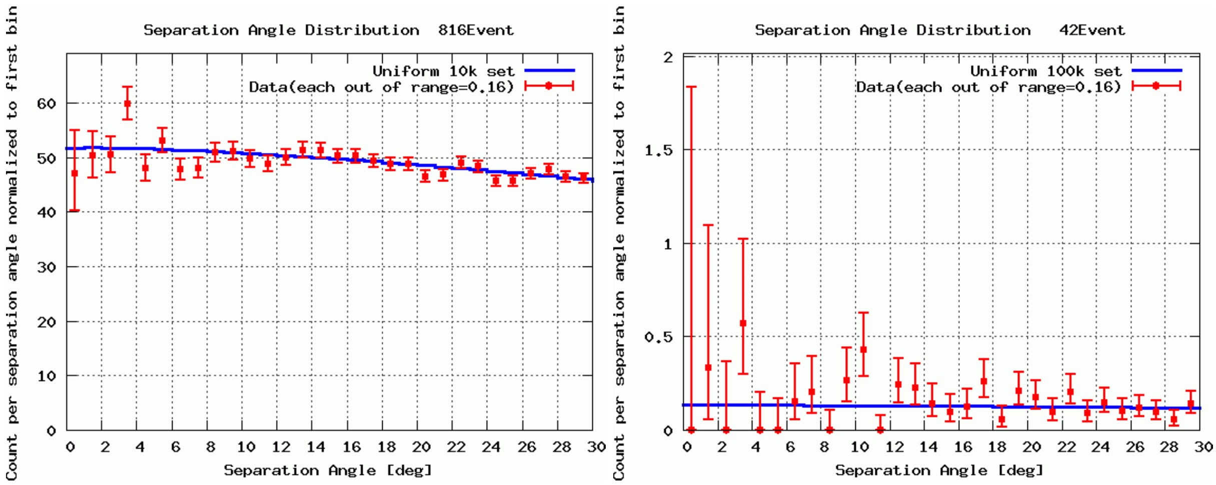

FIGURE 5. Separation angle distribution normalized by solid angle. Left: Energy threshold is 10 EeV, Right: Energy threshold is 40 EeV. The blue line shows expectation from isotropic model. The red points show observed data. The outside of error bar contains 16% from a Poisson distribution for each side. Therefore, the error bars represent 68% by Poisson statistics, and 84% for zero count.