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The measurements of the cosmic ray energy spectrum and the depth of maximum shower development of Telescope Array Hybrid trigger events

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The Telescope Array experiment is an ultra-high energy cosmic ray observatory located in Millard County, Utah, USA. The observatory consists of 3 fluorescence detector (FD) stations and 507 surface detectors (SD) that cover an area of 700 km^2. Hybrid trigger is an external trigger system for the SD arrays that prompts the SD to perform data acquisition when an FD detects a shower-like event. In comparison with the SD autonomous trigger, hybrid trigger allows the SD to collect the data of an air shower that has primary energy below $10^{18.5}$ eV, where the efficiency of SD autonomous trigger decreases rapidly. We present the measurements of the cosmic ray energy spectrum and the depth of maximum shower development of hybrid trigger events observed from October 2010 to September 2014.

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1. Introduction

The Telescope Array (TA) experiment is the largest ultra high energy cosmic ray (UHECR) observatory placed in Millard County, Utah, USA that aims to investigate the origin and properties of UHECR[1]. The observatory consists of three fluorescence detector (FD) stations[2] that are surrounding the surface detector (SD) arrays that cover an area of 700 km^2[3]. A satellite photograph of the observatory indicating the positions of each detector and the observatory's location in USA are shown in the Figure 1.

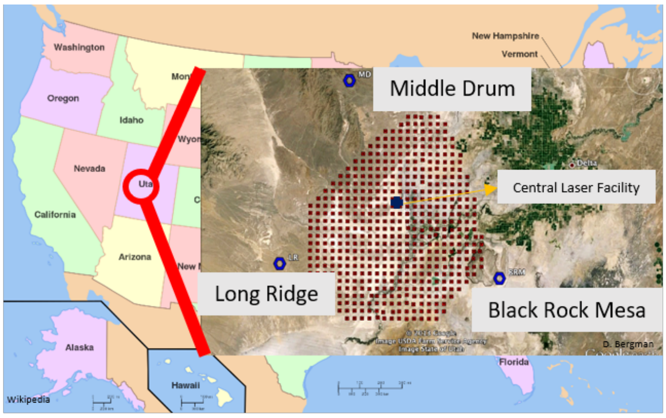


Figure 1: A satellite photograph of the Telescope Array observatory on a map of USA. The blue circles indicate the position of each FD station. From north clockwise, Middle Drum (MD) station, Black Rock Mesa (BRM) station, Long Ridge (LR) station. The red squares indicate the position of each SD of all 507 of them. The blue cross in the middle of the SD array indicates the position of Central Laser Facility (CLF). credit - D. Bergman, Wikipedia

Recent researches suggest that the composition of the cosmic rays with the primary energy of $10^{18.5}$ eV is dominated by lighter nuclei[4], while the composition of the cosmic rays becomes heavier as the primary energy decreases to 10^{17} eV[5]. The transition might be caused by the difference in their origins. In order to investigate this transition further, the precise measurements of the energy spectrum and the depth of maximum shower development, X_{max} is critical. To achieve such precise observation, the hybrid reconstruction technique with the timing information of an SD in proximity of the core of extensive air shower (EAS) is employed. By using the timing information from the SD, it is possible to improve the accuracy in determination of shower geometry[6].
The TA collaboration implemented an external trigger system called "Hybrid trigger" in 2010. The hybrid trigger is issued by an FD station for SD array when an FD detects a shower-like event. This allows an SD subarray to collect the timing information from an extensive air shower with the primary energy below $10^{18.5}$ eV, where the efficiency of SD autonomous trigger decreases rapidly[3].
The energy threshold of the hybrid trigger system implemented in the MD station is different than that of the system implemented in BRM station and LR station. This is mainly due to the different distance between an FD station and a corresponding SD sub-array. Therefore, in this analysis, only hybrid trigger events observed in BRM station and LR station are used.

2. Monte Carlo study

To simulate the EAS events, and the detector response for the hybrid trigger system, the Telescope Array collaboration has developed a dedicated Monte Carlo (MC) simulation framework. This MC study is important to evaluate the performance of the hybrid trigger system. The conditions and parameters used in the generation of the MC simulation set are summarized in the Table 1.

Hybrid trigger MC generation conditions	Parameters
Chemical composition	Proton, Iron
Energy step	logE = 0.1
Energy range	$10^{17.5}$ eV to $10^{19.2}$ eV
Zenith angle	0 degree to 60 degree
EAS core position	Inner 25 km radius from CLF
Atmospheric model	GDAS[7]
Simulation period	October 2010 to September 2014
Hadronic interaction model	QGSJET-II-03
Missing energy estimation	QGSJET-II-03 Proton

Table 1: Conditions and parameters used in the generation of the hybrid trigger MC.

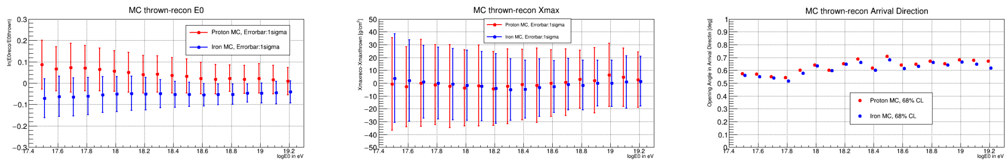
In order to perform the reconstruction of hybrid trigger events, one SD is selected as the "anchor SD" that provides the least χ^2 in the geometric reconstruction of the shower. In this analysis, we set the threshold for an "anchor SD" to be 3 MIPs. This is to prevent the contamination in geometric reconstruction caused by the chance particles.
Reconstruction results are filtered with the following criteria to obtain the results with high precision. This procedure is called "Quality cut" and the criteria used in this procedure are summarized in the Table 2.

Quality cut items	Conditions
Number of PMT with signal	> 20
Length of track	> 15 degree
Zenith angle	< 57 degree
Minimum viewing angle	> 20 degree
$X_{\max}$ Bracketing	$X_{start} < X_{\max} < X_{end}$
Additional volume cut	X_{start} < 550 g/cm^2 , X_{end} > 850g/ cm^2

Table 2: Quality cut items and criteria used in the reconstruction of the hybrid trigger events. Minimum viewing angle means the angle between the reconstructed shower axis and the FD.

One of the Quality cut criteria, Additional volume cut rejects the events with too deep observation start points (X_{start}) and the events with too shallow observation end points (X_{end}). Since those events have too little observed longitudinal development to reconstruct them precisely.
By comparing this filtered reconstruction results with the MC thrown parameters, it is possible to

estimate the reconstruction accuracy for the hybrid trigger events. The primary energy reconstruction accuracy, the depth of maximum shower development ($X_{\max}$) reconstruction accuracy, and the arrival direction reconstruction accuracy are shown in the Figure 2.



(a) E0 bias and resolution (b) $X_{\max}$ bias and resolution (c) Arrival direction accuracy

Figure 2: (a) The hybrid trigger reconstruction bias and resolution in primary energy E0 calculated by $\ln(\mathrm{E0}_{rec}/\mathrm{E0}_{sim})$. Each distribution is fitted by a Gaussian distribution and σ of the Gaussian distribution is indicated as the error bars. (b) The hybrid trigger reconstruction bias and resolution in $\mathrm{X}_{\max}$ calculated by $\mathrm{X}_{\max\,rec} - \mathrm{X}_{\max\,sim}$ Each distribution is fitted by a Gaussian distribution and σ of the Gaussian distribution is indicated as the error bars. (c) The hybrid trigger reconstruction accuracy in Arrival direction indicated by the data points in opening angle distributions that are placed at the 68% of the distributions from 0 degree. All data points in the three sub-figures are shifted by -0.05 for proton and +0.05 for iron from the actual primary energies for visibility.

The accuracy of the hybrid trigger reconstruction in arrival direction is better than 0.8 degree with 68% of C.L. in the all simulated energy bins for both proton and iron.
The reconstruction biases in primary energy E0 differ with the composition and primary energy. For the lower primary energy of $10^{17.5}$ eV, the bias is around $\ln(\mathrm{E0}_{rec}/\mathrm{E0}_{sim}) = 0.08$ for Proton, and $\ln(\mathrm{E0}_{rec}/\mathrm{E0}_{sim}) = -0.07$ for Iron. The reconstruction bias in primary energy decreases as primary energy increases. For the higher energy of $10^{19.2}$ eV, the bias is around $\ln(\mathrm{E0}_{rec}/\mathrm{E0}_{sim}) = 0.02$ for proton, and $\ln(\mathrm{E0}_{rec}/\mathrm{E0}_{sim}) = -0.04$ for iron. The positive bias means the primary energy is overestimated in reconstruction and the negative bias means the primary energy is underestimated in reconstruction.
The reconstruction biases in $X_{\max}$ are within -5 g/cm^2 to 7 g/cm^2 for all primary energy bins and compositions. The resolutions have the small energy dependence of 35 g/cm^2 at the primary energy of $10^{17.5}$ eV and 20 g/cm^2 at the primary energy of $10^{19.2}$ eV.

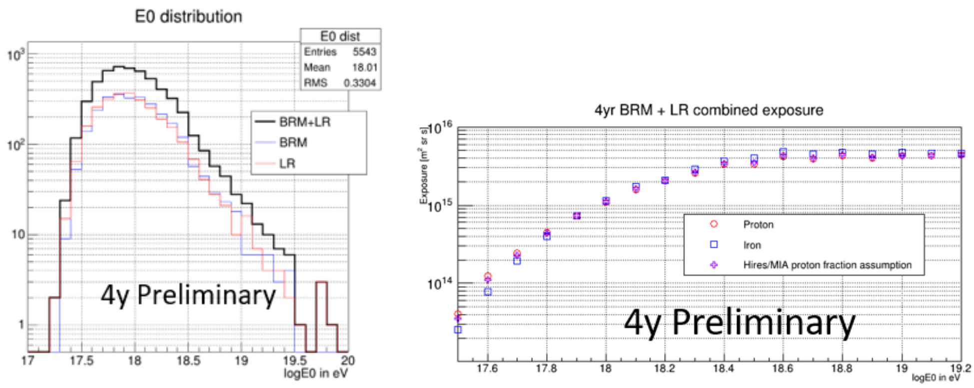
3. Results

The hybrid trigger mode of FD operation started from October 8th 2010. Since the nature of fluorescence detection method, it is important to choose the data acquired in only clear nights. In this analysis, the method of visual confirmation of the cloud in the sky, called "WEAT code" is employed. From October 2010 to June 2019, BRM station recorded 3,297 hours and LR station recorded 2,900 hours of analyzable live time that makes total 6,197 hours of hybrid trigger observation.
For the first 4 years of observation, the total number of the hybrid trigger events after applying the quality cuts shown in the Table 2 and the aforementioned WEAT code is 2,774 events and 2,769 events for the BRM station and the LR station respectively that makes total 5,543 events. The

energy distribution of the 5,543 hybrid trigger events is shown in the Figure 3-(a).
The hybrid trigger observation's BRM+LR total exposure for the proton and iron primary is calculated from the aperture, and the integrated observation time. The aperture of hybrid trigger for a certain energy bin $\mathrm{A}\Omega(E)$ can be written as,

$$\mathrm{A}\Omega(E) = \frac{N_{rec}(E)}{N_{sim}(E)} \times \mathrm{A}_0\Omega_0 \tag{1}$$

where $N_{rec}(E)$ is the number of reconstructed MC events in the energy bin after quality cut, $N_{sim}(E)$ is the number of simulated MC events in the energy bin. A_0 represents the effective area that is determined by the maximum impact parameter, and Ω_0 represents the solid angle that is determined by the maximum zenith angle. Therefore the total exposure for a certain energy bin is $\mathrm{A}\Omega(E)\mathrm{T}$, where T is the detector live time.
The first 4 years of hybrid trigger observation's BRM+LR total exposure for proton and iron primary is calculated and shown in the Figure 3-(b).



(a) E0 distribution for reconstructed events in 4 years observation.

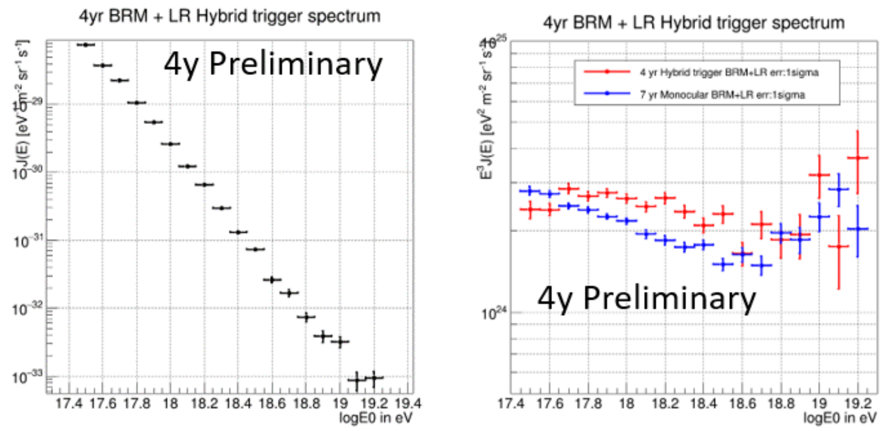
(b) Combined exposure for proton and iron in 4 years observation.

Figure 3: (a) The distribution of the number of reconstructed events for the first 4 years of hybrid trigger operation. Quality cuts and weather cuts are applied. The blue line indicates the events from BRM station, the red line indicates the events from LR station, the black line indicates the sum of both stations. (b) The combined exposure of BRM and LR stations for the first 4 years of observation as a function of energy. The red circles indicate the exposure for proton primary, and the blue squares indicate the exposure for iron primary. The purple crosses indicate the combined exposure where the HiRes and HiRes/MIA composition[8] is considered.

The spectrum of hybrid trigger observation is estimated by calculating the fluxes of cosmic rays for each energy bin. This can be written as,

$$\mathrm{J(E)} = \frac{\mathrm{N(E)}}{\mathrm{A}\Omega\mathrm{(E)T}\Delta\mathrm{E}} \tag{2}$$

where N(E) is the number of observed cosmic rays, and ΔE is the size of energy bin. The calculated spectrum of hybrid trigger observation for the first 4 years with the pure proton assumption is shown in the Figure 4-(a). In order to see the fine structure of the spectrum better, $\mathrm{E}^3\mathrm{J(E)}$ flux is also shown with the spectrum measurement result by FD monocular observation in the Figure 4-(b).



(a) Hybrid trigger spectrum J(E) in 4 years observation

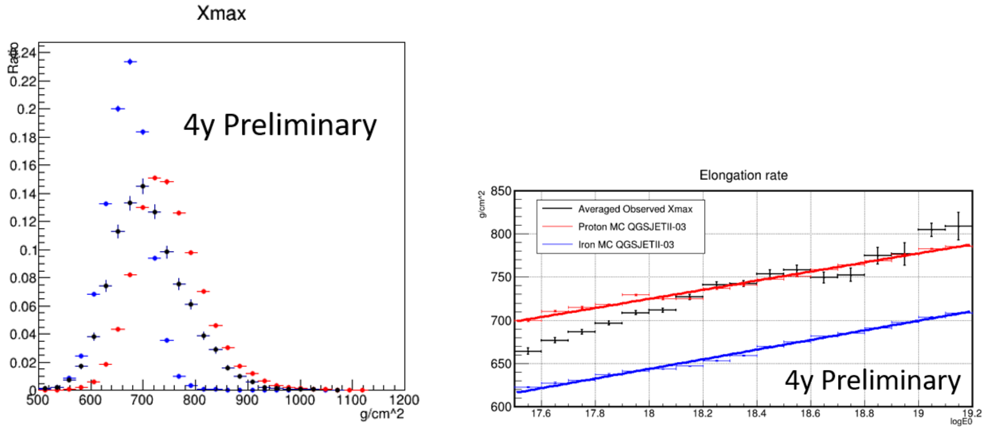
(b) Hybrid trigger spectrum $E^3J(E)$ in 4 years observation with the spectrum measured by TA monocular in 7 years observation[9].

Figure 4: (a) The combined 4 years J(E) spectrum measured by the hybrid trigger. HiRes and HiRes/MIA composition was assumed. Error bars indicate the $\sqrt{N}$ statistical error. (b) The combined 4 years $E^3J(E)$ spectrum measured by the hybrid trigger with the combined 7 years $E^3J(E)$ spectrum measured by the TA monocular. Hybrid trigger spectrum measurement in red dots. TA monocular spectrum measurement in blue dots. Error bars indicate indicate the $\sqrt{N}$ statistical error. The same HiRes and HiRes/MIA composition was assumed for both.

The depth of maximum shower development, $X_{\rm max}$ is an important observable for studying the composition of UHECR. The distributions of reconstructed $X_{\rm max}$ of the proton and iron MC sets generated in the Section 2 were compared with the distribution of reconstructed $X_{\rm max}$ of the 4 years of observation data. Elongation rate of the observation data set and reconstructed MC set are also compared and shown in the Figure 5. As can be seen from the distributions shown in the Figure 5-(a), it is shown that the $X_{\rm max}$ distribution of 4 years observation data set is placed in between that of proton MC distribution and iron MC distribution. The elongation rate shown in the Figure 5-(b) indicates the existence of composition shift in the energy range from $10^{17.5}$ eV to $10^{19.2}$ eV.

4. Conclusion

The TA hybrid trigger has been operating since October 2010 and recorded total 6,200 hours of observation with the BRM station and the LR station. The MC study shows that the primary energy resolutions $\ln(E0_{rec}/E0_{sim})$ are estimated around 0.1 to 0.2 in the energy range from $10^{17.5}$ eV to $10^{19.2}$ eV. The $X_{\rm max}$ resolutions are estimated around 20 g/cm^2 to 35 g/cm^2 in the above energy range. The preliminary hybrid trigger aperture has been estimated as well as the preliminary hybrid trigger spectrum. The preliminary result of measurement of the depth of maximum shower development indicates that the observed $X_{\rm max}$ is between the $X_{\rm max}$ of Proton MC and the Iron MC at the lower energy region. Then the observed $X_{\rm max}$ result gradually shifts to the $X_{\rm max}$ of Proton MC as the primary energy increases.



(a) $X_{\max}$ distributions of the reconstructed MC sets and the 4 years observation data set.

(b) Elongation rate plot of the reconstructed MC sets and the 4 years observation data set.

Figure 5: (a) The distributions of reconstructed $X_{\max}$ for proton MC, iron MC, and observation data. The red dots indicate the proton MC reconstruction. The blue dots indicate the iron MC reconstruction. The black dots indicate the observation data reconstruction. Error bars represent the statistical error. (b) The elongation rate plot of the same data. The red line indicates a linear fit for the proton MC reconstruction data points that are indicated as red dots. The blue line indicates a linear fit for the iron MC reconstruction data points that are indicated as blue dots. Error bars represent the statistical error.

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