The hybrid trigger system in the Telescope Array experiment

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Abstract. We report the development of a "hybrid trigger" system for the fluorescence detectors (FDs) and the surface detectors (SDs) in the Telescope Array (TA) experiment. It is shown from our Monte-Carlo studies that geometry determination accuracies of monocular FD events are significantly improved using SD information (position at the ground level, timing of arrival, etc...). On the other hand, in a lower energy event, the trigger efficiency of SD for lower energy showers is smaller than that of FD. Therefore no SD information is available for events with energies below $10^{18.5}$ eV taken with the TA original data acquisition system. In order to collect the small SD signals, we developed an FD-driven SD triggering system: this introduces an external triggering scheme to the TA-SD using triggering signals from FD. We present the design of the system, installation and the operational stabilities in TA observation from October 2010.

Keywords: ultra-high energy cosmic rays, data acquisition system, Telescope Array

INTRODUCTION

The Telescope Array(TA) is the largest stereo-hybrid detector in the northern hemisphere[1] for ultra high energy cosmic ray (UHECR)observation. The TA experiment utilizes the two types of detectors, the one is an array of surface particle detectors as used in the AGASA experiment [2] , and the other is fluorescence telescopes in three sites as in Fly's Eye and HiRes [3].

The FIGURE 1 shows the positions of SDs and FDs. The SD array covers about 700 km^2 and operated by three control branches ("BR", "LR" and "SK" branches in FIGURE 1). The trigger criterion of SD is a coincidence of particle incidents to at least 3 neighboring detectors with signals greater than 3 MIPs (minimum ionizing particles) equivalent. Three FD stations (BR, LR and MD sites) are installed around the SD array. The FD data acquisition is carried out independently of the SD operation, and the system trigger is brought by a shower "track" recognition in a camera with ≥ 5 photomultiplier tubes (PMTs) [4].

In the TA original design, FDs and SD array have been operated independently with their own triggering conditions. Both FDs and the SD array are triggered in case of a high energy shower event more than 10^{19} eV. In this case, a "hybrid reconstruction method" [5] can be used, with a signal timing of an SD and information from FDs, which gives a good accuracy in geometry reconstruction, even in case of FD monocular event. The angular resolution is < 1 degree for hybrid reconstruction. The distributions of angular distances of between simulated and reconstructed showers are shown in FIGURE 2.

On the other hand, in cases of lower energy showers below 10^{19} eV, many events are detected only by FDs, because of the difference in the trigger efficiencies of FD

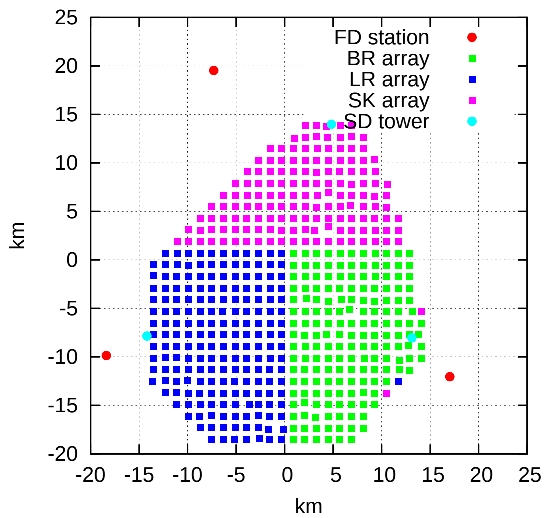

FIGURE 1. Area of hybrid trigger for each FD station. FD send the trigger to the nearest SD tower and collect data from each area.

and SD. These events are analyzed with the method of FD monocular reconstruction. The accuracies of shower parameter determination monocular reconstruction, in particular for shower geometries, is poor in this energy region: the upper panel of FIGURE 2 shows the angular resolution of our monocular reconstruction, which is 5 degrees (68%). This angular resolution is not good enough for detailed studies on longitudinal profile of air showers, or cosmic ray arrival directions.

Our Monte-Calro study showed that even in a lower energy case, the accuracy in shower geometry recon-

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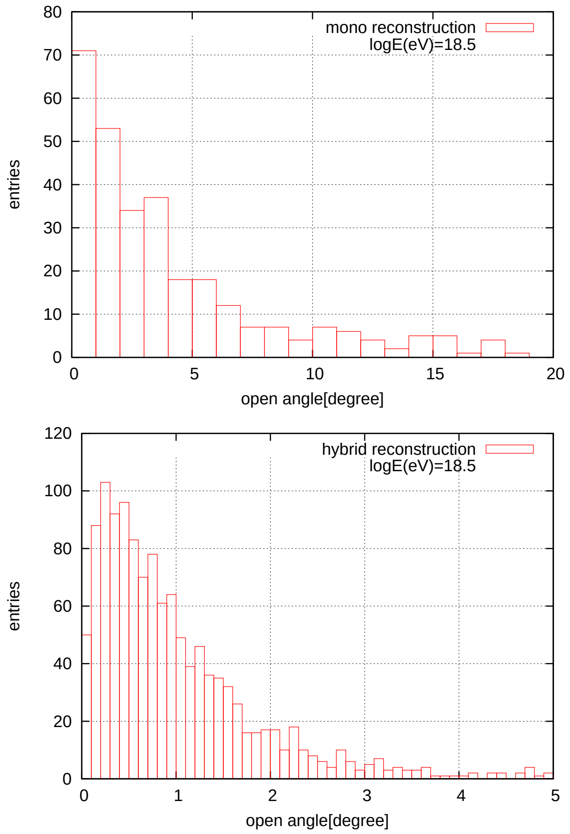

FIGURE 2. Top: angular distances of shower arrival directions of thrown showers and reconstructed ones in the FD monocular mode. Bottom: angular distances in case of FD+1SD analysis (hybrid reconstruction[5]).

struction is significantly improved if a timing information of an SD is available. Therefore we developed another SD triggering system to improve the accuracies in shower reconstruction of monocular FD events.

HYBRID TRIGGER

For FD analysis of lower energy showers (below $10^{18.5}$ eV), additional SD information is essential to obtain reconstruction results with high accuracies in shower parameter determination. In the lower energies, the SD efficiency of its original triggering criteria (3-fold coincidence of neighboring detectors with signals greater than 3 MIPs equivalent) becomes smaller with decreasing primary energies. From the gray data points in FIGURE 3, the SD efficiency is lower than 80% at $10^{18.5}$ eV, and 20% at 10^{18} eV. In order to collect SD data in the lower energies efficiently, we employ a new data taking scheme of SD by using external trigger signals from FD, called the "hybrid trigger". When the FD detects an air shower

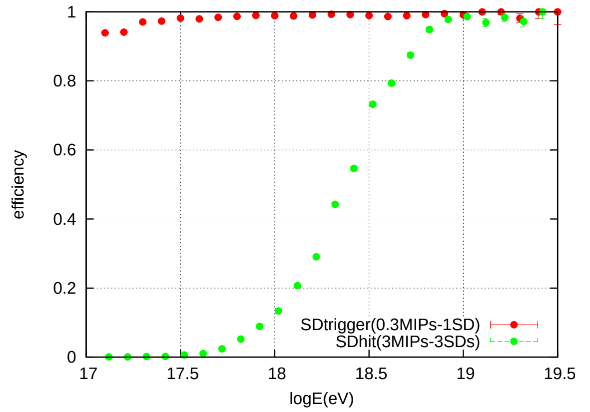

FIGURE 3. Gray: SD self-trigger (3MIPs 3SDs) efficiency. Solid: the 1SD hit (0.3MIP) probability.

event, a trigger signal is sent to the nearest SD control tower, and the SD control tower collects data of SDs in the branch which detect signals greater than 0.3MIPs. The probability that at least one SD has a signal ≥ 0.3 MIPs associated with an air shower event triggered by FD is higher than 90% for energies above 10^{17} eV as shown by the solid data points in FIGURE 3. The statistics increases by about 10 times at 10^{18} eV.

Developments

Two requirements are considered for the hybrid trigger system. The first comes from an SD data collection rate limit, 0.17 Hz. Since the normal FD trigger rate is ~ 2 Hz, whereas the air shower event rate is $\sim 10^{-3}$ Hz, we developed an on-line FD event filtering program to reduce FD noise events and the hybrid trigger rate below the SD data collection limit. An "off-line filtering" test using the FD data taken by our original system shows that the event reduction power of the filtering program is $\sim 10^{-3}$, which gives an expected hybrid trigger rate $\sim 10^{-3}$ Hz, near the actual event rate and well below the SD limit. The second requirement is a wide signal collection window for SD. In the SD self trigger data acquisition, particle data within a time window of $\pm 32\mu$s around a trigger signal are collected. On the other hand, because of a triggering timing difference between FD and SD, a wider time window of SD data collection is required for the hybrid event detection. The event trigger time difference between FD and SD ranges about $\sim 100\,\mu$s as shown in FIGURE 4. From this result, we determined the window size for hybrid data collection as $\pm 64\,\mu$s, keeping the $\pm 32\mu$s window for the SD self triggers, and the firmwares of the SD electronics and control towers have been updated for this purpose.

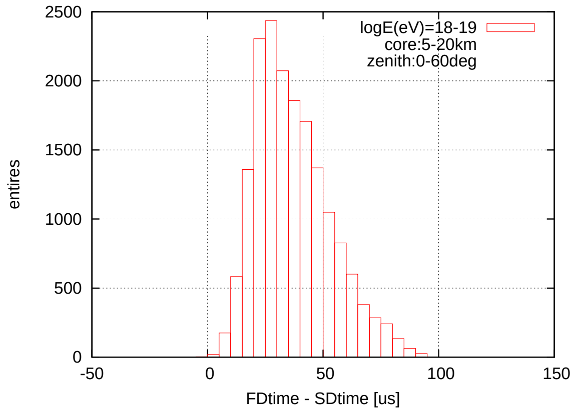

FIGURE 4. The distribution of FD-SD time differences calculated by MC simulation. logE(eV)=18-19, zenith:0-60deg, core:5-20km from FD.

INSTALLATION AND OPERATION

We developed the firmware and DAQ program for SD, and an event filtering program and a trigger generator for FD. The hybrid trigger system was installed from September 2010, and is in stable operation from 08 October 2010. The operational status in the first week observation is summarized in Table 1. For example, the number of trigger signals sent from FD to SD is 76 in the observation Oct/08. Among the 76 trigger requests, 75 SD events are recorded as hybrid trigger events using external triggers by FD. In one event out of the 76 trigger requests, an SD self trigger also occurred: in such a "collision" case, a trigger request from FD is ignored, and the event is recorded as an SD normal event with a "hybrid trigger canceled" flag. All the trigger requests from FD are correctly accepted by SD, and there is no timeout case that a trigger request is not delivered or not received by SD within16 seconds from the FD trigger, which corresponds to the SD data buffer size.

The hybrid trigger rates in observation Oct 08 2010 are shown in FIGURE 5. After the event filtering, the rate is reduced from ~ 2 Hz (FD trigger rate) to $\sim 10^{-3}$ Hz, which is well below the SD data collection rate limit 0.17 Hz. We confirmed the stable operation and trigger rates in other observation days. An increase of data collection time (dead time) due to FD event filtering is negligible.

Data Analysis

We analyzed the hybrid trigger events obtained in the operation from 2010/Oct/08 to Dec/14. The arrival direction distribution of the showers in this period after data cuts ($\theta < 55°$, and Xmax (the shower maximum) seen by the detector) is shown in FIGURE 6, and the number of shower events is listed in Table 2. After installation of the hybrid trigger system, the number of events to which the hybrid reconstruction method (FD monocular reconstruction with timing information from SD) can be applied increases from 58 to 526 in the BR branch, which gives 10 times statistics of shower events with good reconstruction accuracies. A detailed analysis to obtain cosmic ray energy spectrum for energies above 10^{17} eV is on going.

TABLE 1. Number of hybrid triggers generated by FD and SD responses in operation from 2010/Oct/09 to Oct/16. See text for details.

	BR station			
Date	hybrid trigger	SD response		
		TO	SD self	Data collected
10/08	76	0	1	75
10/09	84	0	2	82
10/10	72	0	3	69
10/11	93	0	5	88
10/12	83	0	2	81
10/13	61	0	2	59
10/14	75	0	1	74
10/15	43	0	1	42
10/16	27	0	0	27

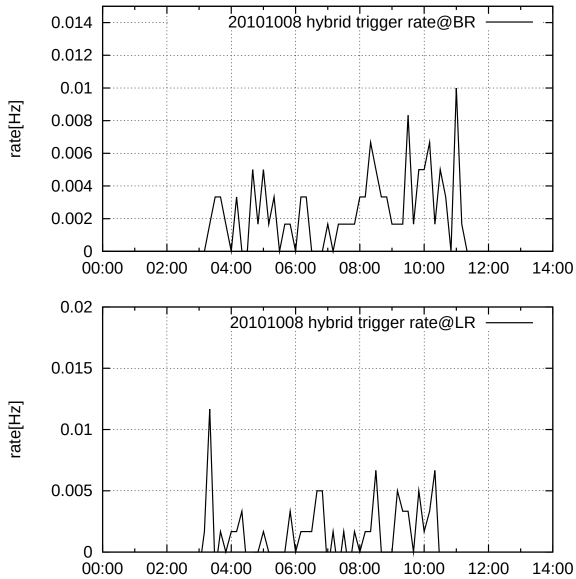

FIGURE 5. Hybrid trigger rate of the BR branch (top, 10 minutes average) and the LR branch (bottom).

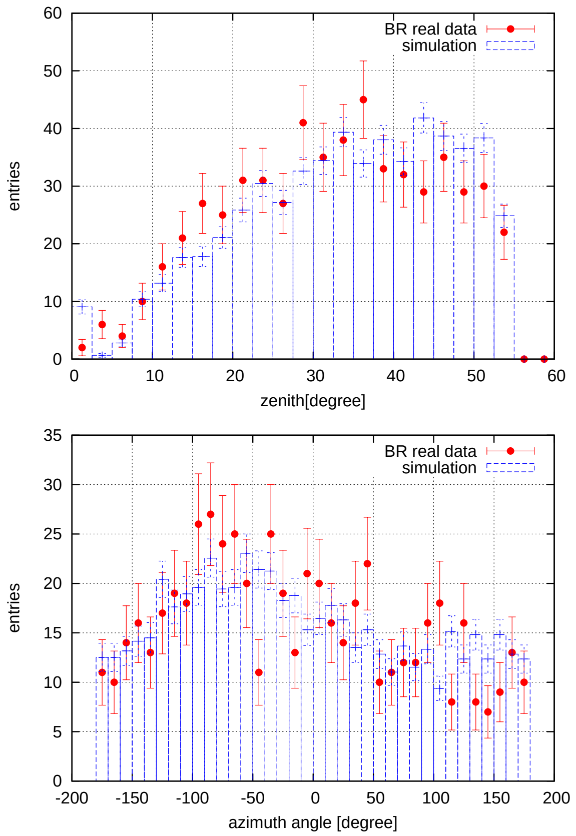

FIGURE 6. Distribution of arrival directions of the hybrid trigger events obtained in the first three months observation. The histograms shows an expectation from Monte-Carlo by assuming uniform cosmic ray arrivals and energy spectrum $\propto E^{-3.1}$.

TABLE 2. The number of reconstructed shower events after data cuts ($\theta < 55°$, and Xmax (the shower maximum) is seen by the detector).

month	BR branch		LR branch	
	SD self	Hybrid	SD self	Hybrid
October	18	136	15	124
November	18	141	22	146
December	22	249	29	342
	58	526	66	612

SUMMARY

We have developed a hybrid trigger system in the Telescope Array experiment to obtain lower energy FD events with SD information with an improved detection efficiency. The SD firmware was upgraded to accept external triggering signals and collect data with a wider signal search window. An online FD event filtering program works well to reject spurious FD triggers and keep hybrid trigger rate well below the SD limit. The hybrid trigger system is in stable operation since October 2010. We analyzed the hybrid events obtained in the first three months observation. The event rate and the distribution of shower parameters such as arrival directions and primary energies are consistent with our expectation from Monte-Carlo studies, and the statistics of low energy shower events of well-determined geometry using SD information increases by a factor of 10 compared to the case of FD-SD independent triggers. Further studies are now ongoing to obtain cosmic ray energy spectrum and composition of energies above 10^{17} eV.

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