Journal of Physics: Conference Series

# MC study for TALE Hybrid detector

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Abstract. The Telescope Array Low-energy Extension (TALE) Experiment is a hybrid air shower detector for observation of air showers induced by very high energy cosmic rays above  $10^{16}$  eV. The TALE detector consists of a Fluorescence Detector (FD) station with ten FD telescopes and a surface detector (SD) array made up of 80 scintillation detectors. The TALE-FD and the TALE-SD array have been operational since 2013 and 2017 respectively. A triggering system of the TALE-SD using external triggering signals from the TALE-FD that is of a lower energy threshold, so called the hybrid trigger system, has been working since 2018. We evaluated the performance of hybrid mode of the TALE detector by using Monte Carlo simulation. Here we show analysis method for air shower events observed by the TALE hybrid detector and report the accuracies of air shower parameters.

## 1. Introduction

The TALE, located at the north part of the Telescope Array (TA) Experiment site in the western desert of the Utah State, is aimed at measuring energy spectrum and mass composition of very high energy cosmic rays above 10<sup>16</sup> eV. The experiment consists of one FD station with ten fluorescence telescopes and an array of 80 scintillation surface detectors, which were deployed to cover a total area of approximately  $40 \text{ km}^2$ . The full details of the detectors are found in [1] [2] .

The advantage of FD is its direct measurement of the longitudinal development of an air shower and calorimetric determination of the energy. On the other hand, there is a large uncertainty in calculation of the arrival direction of an air shower because the time difference between signals of the phototube pixels can be small. The 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 the inclusion of the SD timing in FD monocular reconstruction significantly improves the accuracy in determination of the shower geometry. In this paper, we present the developed hybrid technique and its performance obtained from the Monte Carlo study.

## 2. Hybrid Reconstruction

The reconstruction process consists of 3 steps: the PMT selection, the shower geometry reconstruction and the shower profile reconstruction. The geometry of an air shower is determined using the 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.

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#### TAUP 2019

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First PMTs to be used in the reconstruction are chosen with criteria optimized by our Monte Carlo. The shower track is identified from the PMT hit pattern in the cameras, and PMTs that are spatially and temporally isolated from the track are rejected. Once the shower detector plane (SDP) is determined from the pointing direction vectors of the PMTs, further selection is made by discarding the PMTs far from the SDP. These procedures are iterated until no more PMTs are rejected or reintroduced.



Figure 1. The schematics of the monocular and the hybrid shower geometry reconstruction. The relations between the measured values, which are  $t_{exp,i}$ ,  $\alpha_i$  and the fitting parameters, which are  $t_{core}$ ,  $r_{core}$  and  $\psi$ . In the hybrid analysis the two observable,  $t_{SD}$  and  $r_{SD}$ , are added to the relation of the monocular analysis, and as a result the number of the fitting parameter is reduced to two and the geometry determination accuracy is improved.

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

$$t_{\exp,i} = t_{\rm core} + \frac{1}{c} \frac{\sin\psi - \sin\alpha_i}{\sin(\psi + \alpha_i)} r_{\rm core} \tag{1}$$

where  $t_{\exp,i}$  and  $\alpha_i$  are the expected timing and elevation angle in the SDP for the *i*-th PMT, respectively,  $t_{\text{core}}$  is the timing when the air shower reached the ground,  $r_{\text{core}}$  is the distance from the FD station to the core, and  $\psi$  is at an shower inclination angle in the SDP (Figure 1).

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

$$t_{\rm core} = t_{\rm SD} + \frac{1}{c} (r_{\rm core} - r_{\rm SD}) \cos\psi \tag{2}$$

where  $t_{SD}$  is the timing of the leading edge of the SD signal. The quantity to be minimized in the fitting is written as

$$\chi^{2} = \sum_{i} \frac{(t_{\exp,i} - t_{i})^{2}}{\sigma_{t,i}^{2}}$$
(3)

where  $\sigma_{t,i}$  is the fluctuation of the signal timing. The resolution of the arrival direction is about 1.2 degrees, which is significantly improved compared to that in FD monocular mode about 6 degrees.

Once the shower geometry is determined, the longitudinal profile of the shower is fitted using the Gaisser-Hillas parameterization formula [3]

$$N(x) = N_{\max} \left(\frac{x - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max} - X_0}{\lambda}} \exp\left(\frac{X_{\max} - x}{\lambda}\right)$$
(4)

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where N(x) is the number of charged particles at a given slant depth, x,  $X_{\text{max}}$  is the depth of shower maximum,  $N_{\text{max}}$  is the maximum number of particles at  $X_{\text{max}}$ ,  $X_0$  is the depth of the first interaction, and  $\bullet$   $\bullet$  is interaction length of shower particles.

## 3. Accuracy

The performance of our detectors and the reconstruction programs are evaluated using our Monte Carlo program. The TALE 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-based MC simulation code developed for TA [4]. Here we use proton primary particles with QGSJET-II-04 [5] hadronic interaction model. The MC events are generated with fixed energy at 10<sup>17.5</sup> eV in this work. All of the calibration factors with time dependence are applied to SD and FD detector simulations.

Figure 2 shows the resolution of important air shower parameters from reconstruction. We evaluate the resolutions of 1.2° in  $\psi$  angle, 1.1 % in  $R_p$ , 15 % in energy, and 33  $g/cm^2$  in  $X_{\text{max}}$  at  $10^{17.5}$  eV.



Figure 2. Resolution studies using Monte Carlo events. Upper-Left: the in SDP angle,  $\psi$ . Upper-Right: the impact parameter,  $R_p$ . Lower-Left: the depth of shower maximum,  $X_{\text{max}}$ . Lower-Right: primary cosmic ray energy. The Gaussian fit is used to determine the detector bias and resolution.

## 4. Summary

The total of 80 SDs were deployed by the end of February 2018 and the TALE SD array started operation in March 2018. Also the observation with hybrid triggering system started in November 2018. Currently, we are developing the hybrid Monte Carlo/reconstruction programs. The hybrid geometry reconstruction method improved the determination accuracy of the shower geometry, as shown in Figure 2.

### References

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