TALE Hybrid Simulation and Analysis

T. ABUZAYYAD[1], B. T. STOKES[1], D. IVANOV[1] FOR THE TELESCOPE ARRAY COLLABORATION.

[1]*University of Utah, Dept. of Physics & Astronomy & High Energy Astrophysics Institute, Salt Lake City, Utah, USA*

ivanov@cosmic.utah.edu

Abstract: The Telescope Array (TA) is the largest cosmic ray detector in the Northern hemisphere for the study of ultra high energy cosmic ray anisotropy, energy spectrum, and mass composition at primary energies above 10^{18} eV. The Telescope Array Low-energy Extension (TALE) is expected to provide additional observational capability for primary energies between 3×10^{16} eV and 10^{18} eV. TALE is a hybrid detector which consists of ten additional fluorescence telescopes situated at the TA Middle Drum (TAMD) fluorescence detector site. These telescopes add to the sky view of the site between 30-57 degrees in elevation. In addition, a graded infill surface array of 101 plastic scintillation counters with variable 400 to 600-meter spacing allows for hybrid observation. Together with the original TAMD detector, this yields a combined sky coverage of 114 degrees in azimuth and 3-57 degrees in elevation for the Middle Drum telescope site. In this poster, techniques for the simulation and reconstruction of TALE data are described with emphases on comparisons between data and simulation and estimates of detector resolutions.

Keywords: TALE, hybrid, cosmic, ray, energy, composition

1 Introduction

The Telescope Array (TA) experiment is a hybrid cosmic ray detector located in the Millard County, UT, USA. It is designed to measure ultra high energy cosmic ray events of energies 10^{18} eV and above. The detector is in operation since March of 2007 and it consists of three fluorescence detector (FD) sites overlooking an array of 507 surface counters. Each surface detector counter contains 2 layers of $3m^2 \times 1.2$cm scintillators. The main TA surface array counters are positioned on a 1200m grid and span a 730m^2 area. The main results of the TA are the measurements of cosmic ray energy spectrum, mass composition, and anisotropy.

The TA Low Energy Extension (TALE) consists of an additional fluorescence detector looking higher in elevation and an infill array, with a goal of increasing the TA hybrid observation sensitivity range down to 3×10^{16} eV. Construction of the TALE fluorescence telescopes has been completed at the end of 2012 and the construction of the TALE low energy infill array is under way.

Figure 1 shows the configuration of the TA and TALE detectors. The TALE infill array consists of the same counters as those used by the main TA surface array (including the 50 MHz FADC readout) except spaced more densely, at 400 to 600 m (open circles in Figure 1). The TALE fluorescence detector has been built at the TA Middle Drum site. As Figure 2 shows, the TALE FD provides an additional coverage of 30 to 57 ° in elevation, so that the combined MD-TALE fluorescence detector covers 114° in azimuth and 3 to 57° in elevation. The TA MD uses sample and hold system [2], and the TALE FD mirrors use HiRes-II [3] electronics, including 10 MHz FADC boards.

2 Monte-Carlo Simulation

The trigger efficiency of the TALE hybrid detector is energy dependent, because low energy events produce less light in the atmosphere and so they are effectively seen in
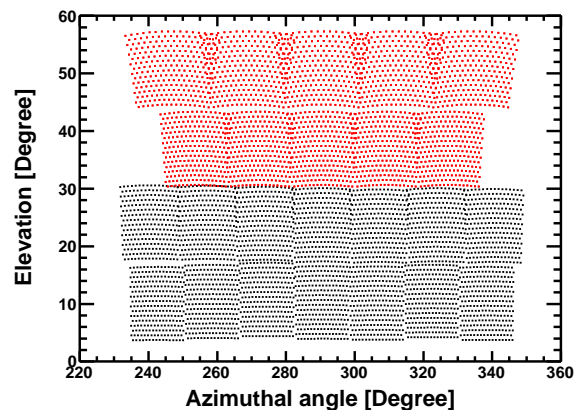

Fig. 2: The field of view of the combined TA MD and TALE fluorescence detector. Points indicate each photomultiplier tube pointing direction on the sky, bottom two rings of mirrors correspond to the TA MD and the top two rings correspond to the TALE. Dotted arrows show the azimuthal fields of view of the TA fluorescence detectors.

a smaller geometrical volume around the fluorescence detector. The trigger of the infill array is driven by the TALE fluorescence detector. Furthermore, a realistic event reconstruction applies quality cuts to remove events with poor resolution. Consequently, aperture and model prediction values of $< X_{\text{Max}} >$ for different primaries should be estimated by a detailed Monte-Carlo that is based on characteristics of real data.

The TALE hybrid event simulation is based on CORSIKA QGSJET2 [1] air shower simulation code and consists of two major parts. First part is the longitudinal profile, measured by the FD, and the second part is the particle distribution on the ground, sampled by the infill array. The parameters of the longitudinal distribution are passed
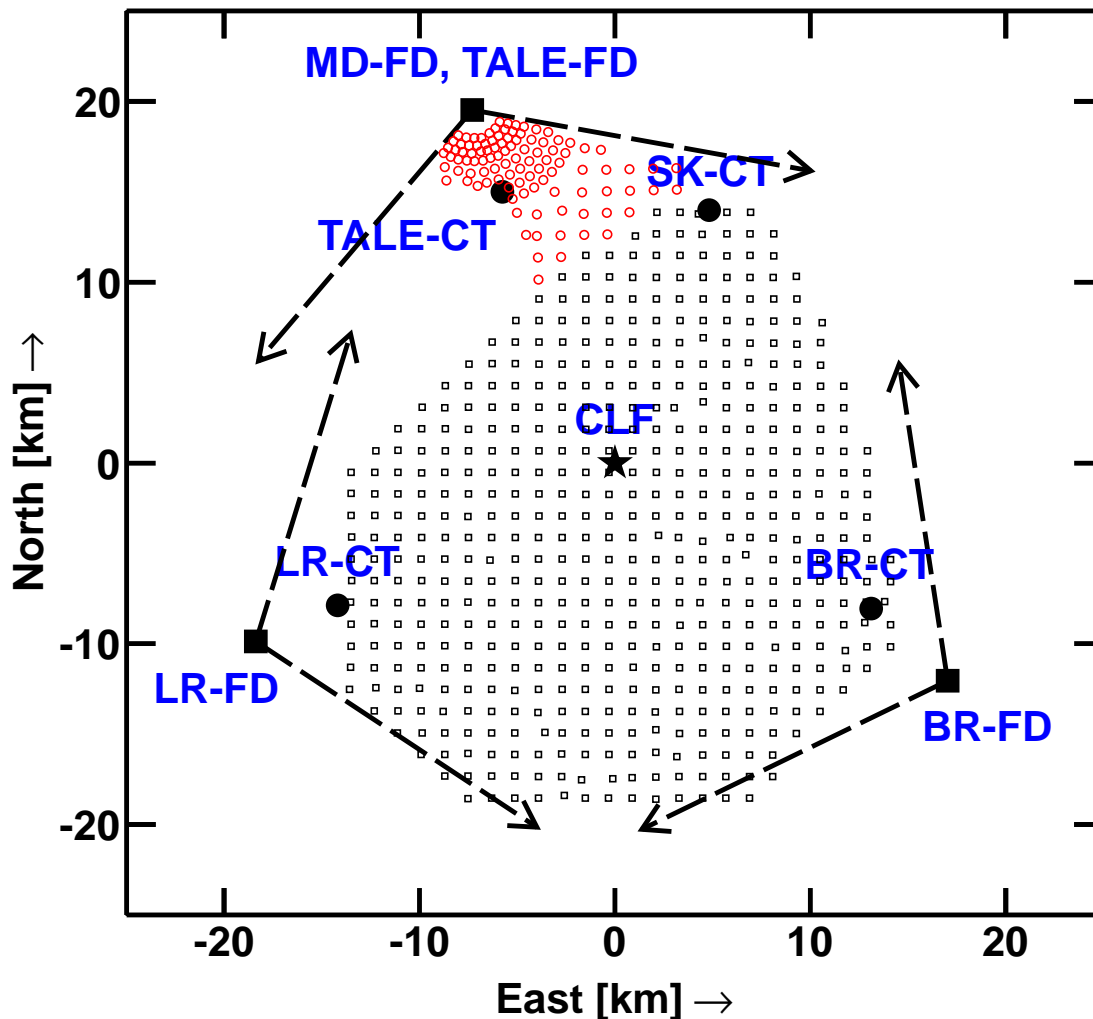
Fig. 1: The TA and TALE experiment layout in the coordinate system of the TA Central Laser Facility (CLF), indicated by a filled star. Open squares represent the positions of the TA main surface array counters and open circles show the positions of the TALE infill array counters. Filled squares represent the locations of the fluorescence detectors (FD): Black Rock Mesa (BR), Long Ridge (LR), Middle Drum(MD), and TALE (a higher elevation looking FD built at the MD site). Filled circles represent the locations of the communications towers (CT) needed by the TA/TALE surface arrays: Black Rock Mesa (BR), Long Ridge (LR), Smelter Knolls (SK), and TALE.

to the same detector response simulation codes as those used by the TA MD [2] and HiRes-II [3] (the electronics of TALE mirrors is identical to that of HiRes-II). The simulation of the lateral distribution of particles on the ground is done in the same way as for the main Telescope Array surface detector [4], except using smaller spacing between the counters appropriate for the TALE infill array. Currently, the simulation is done for the event energies starting at $10^{16.5}$ eV and up, and for zenith angle in 0 to 60° range.

3 Reconstruction

When cosmic rays trigger the MD/TALE fluorescence detector, a request (hybrid trigger) is sent out to the infill array to read out the information on the ground. FADC waveforms and signal time and pulse heights are then saved for the TALE and MD fluorescence detectors and the ground array counters.

The measurements relevant in the event reconstruction are the times and pulse heights of the FD photomultiplier tubes (PMT) and the surface detector counters, which are available after the calibration and signal processing. The PMT pulse heights are measured in the photoelectron units, while the infill counter pulse heights are calibrated using the the vertical equivalent muon units (VEM). Figure 3 shows a ground footprint of a typical Monte-Carlo event of energy around $10^{17.5}$ eV. Figure 4 shows the appearance of the same event in the fields of view of the MD and TALE FDs.

The event reconstruction consists of two parts. First, the arrival direction is determined from the shower detector plane and a hybrid time fit, shown in Figures 4 and 5, and second, the event longitudinal profile is fitted using the
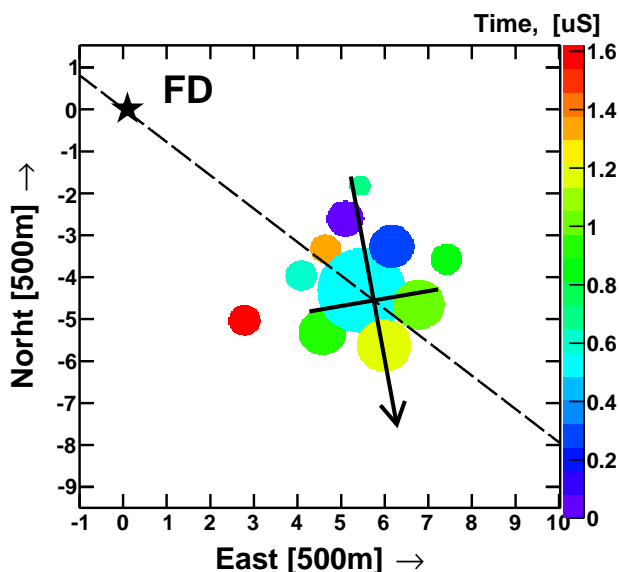
Fig. 3: Footprint of a Monte-Carlo event. Each circle represents an infill array counter. Circle area is proportional to the logarithm of the counter pulse height in VEM, circle color represents the counter time in μS, black arrow shows the reconstructed event direction, and the dashed line is the intersection of the reconstructed shower-detector (MD/TALE FD) plane and ground. Star represents the location of the MD/TALE FD.

HiRes inverse Monte-Carlo technique [2] to determine the event energy and Xmax, as shown in Figure 6.
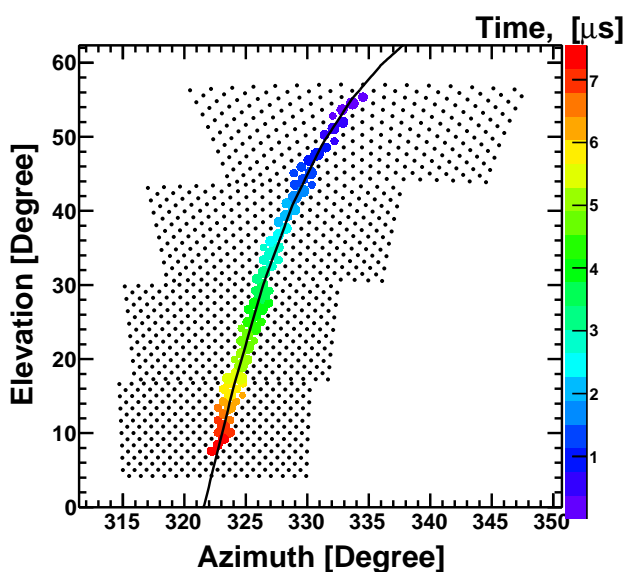

Fig. 4: Appearance of the simulated event in the field of view of the TALE and MD fluorescence detectors. Circles represent the PMTs that were hit, circle area is related to the logarithm of the tube pulse height in photo electrons (PE), and color represents the time. PTMs that belong to the triggered mirrors but which were not hit are represented by points. Solid line shows the reconstructed shower-detector plane that contains the shower and the MD/TALE FD.

4 Acknowledgments

References

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[3] R. U. .Abbasi et al. [High Resolution Fly's Eye Collaboration], Cosmic Rays by the FADC Detector of the HiRes Experiment," Astropart. Phys. **23**, 157 (2005) [astro-ph/0208301]. as of 19 May 2013

[4] T. Abu-Zayyad, R. Aida, M. Allen, R. Anderson, R. Azuma, E. Barcikowski, J. W. Belz and D. R. Bergman et al., Astrophys. J. **768**, L1 (2013) [arXiv:1205.5067 [astro-ph.HE]].

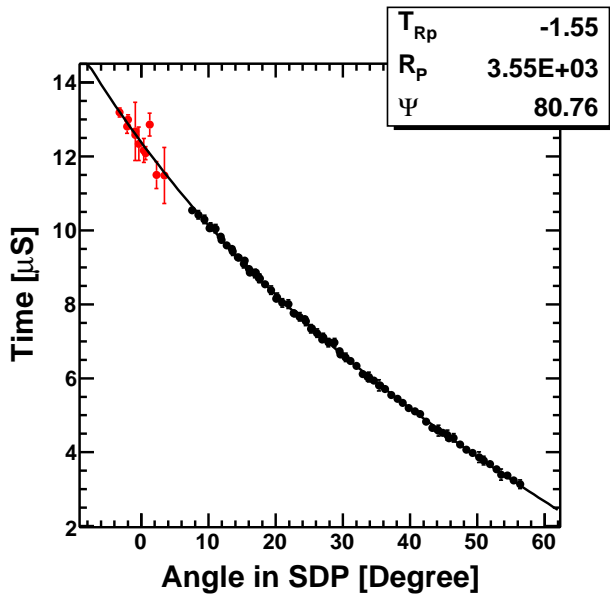| T_{Rp}	-1.55
R_P	3.55E+03
Ψ	80.76

Fig. 5: Hybrid time fit. Horizontal axis is the PMT viewing angle in the FD shower-detector plane and vertical axis is the time. MD/TALE PMTs are represented by black points. Red points correspond to the infill array counters: each counter corresponds to a certain point on the shower axis, which translates to the corresponding point on the time vs angle plot. The fit parameters are the distance of closest approach, R_p, time of the shower front at the closest approach, T_{RP}, and the angle in the shower-detector plane, Ψ.

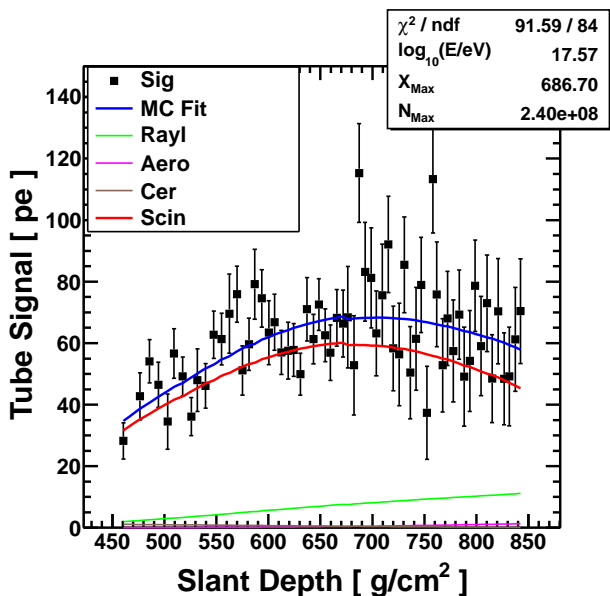| χ^2 / ndf	91.59 / 84
$\log_{10}(E/eV)$	17.57
X_{Max}	686.70
N_{Max}	2.40e+08

Fig. 6: Longitudinal profile fit using the inverse Monte-Carlo technique. Black points show the PMT signal, blue line shows the overall fit expectation values, while the red line shows the direct and Rayleigh-scattered fluorescence light. All other light contributions, such as direct Cherenkov and Aerosol scattered are negligible for this event. Fit parameters are the event energy, position of the shower maximum, Xmax, and the number of charged particles at the shower maximum, Nmax.