Direct Comparison of the Telescope Array and the High Resolution Fly's Eye Energy Scales and Spectra

D. C. RODRIGUEZ[1] AND C. C. H. JUI[1] FOR THE TELESCOPE ARRAY COLLABORATION
[1]*University of Utah, Salt Lake City, UT, U.S.A. 84112*
doug@cosmic.utah.edu

Abstract: The Telescope Array's Middle Drum fluorescence detector was built using refurbished telescopes from the High Resolution Fly's Eye's HiRes-1 site and calibrated using the same techniques. As such, a direct comparison can be made between the energy scales and spectrum of the two experiments. Both sets of data represent measurements made via monocular observation and were analyzed using the profile-constrained geometry reconstruction technique developed for HiRes-1. The HiRes-1 data represents almost nine years of exposure and was collected between May 29, 1997 and May 26, 2006. The current Middle Drum spectrum uses data collected over a three-year period, between December 16, 2007 and December 16, 2010. The results of these comparisons are presented.

Keywords: Telescope Array, HiRes, Spectrum

1 Telescope Array Middle Drum

The Telescope Array is a collaboration composed of institutions from the U.S., Japan, Korea, Russia, and Belgium. The experiment consists of three fluorescence telescope detectors overlooking 507 surface detectors arrayed over $\sim 750\ \mathrm{km}^2$. The northernmost fluorescence detector, known as Middle Drum, consists of 14 telescopes refurbished from the High Resolution Fly's Eye (HiRes) experiment. These were arranged to view $\sim 120°$ in azimuthal coverage and between $3°$ and $31°$ in elevation. Each telescope unit uses the HiRes-1 observatory's sample-and-hold electronics with a $5.6\ \mu s$ gate with floating tube-thresholds, allowing each photomultiplier tube to have an individual firing rate of ~ 200 Hz. Each telescope camera consists of 256 photomultiplier tubes covered with an ultra-violet transmissive filter.

1.1 Goals of Middle Drum

Since the Middle Drum detector has been operating for over three years, the primary goal of this analysis is to determine the flux of particles observed using the same Profile-Constrained Geometry Fit (PCGF) analysis technique used to produce the HiRes-1 monocular spectrum [1]. Secondly, since the telescope units are composed of the same equipment used at HiRes, a direct comparison between Middle Drum and HiRes can be performed. This results in a direct link in the energy scale between these two experiments. Future studies can transfer the energy scale of HiRes to the entire Telescope Array experiment by comparing events observed by Middle Drum and any of the other detectors.

2 Exposure

The Telescope Array Middle Drum detector was refurbished and deployed between November, 2006 and October, 2007 [2]. The first year of data was collected between December 16, 2007 and December 8, 2008. This data was analyzed and compared to HiRes, but statistics limited a comparison between the experiments [3]. The current spectrum now contains data collected through December 16, 2010, collected only on nights that had at least three hours of full-dark: no sunlight and no moonlight. The final collected time (see figure 1) consisted of ~ 2900 hours ($\sim 68\%$ of available dark time) of which ~ 2400 hours ($\sim 82\%$ of collected time) were considered good, i.e. minimal cloud cover in the view of the detector. This correlates to a $\sim 9\%$ duty cycle with $\sim 1/4$ the ontime of HiRes-1.

The aperture of the Middle Drum detector was determined using Monte Carlo simulations. The potential aperture is defined as the effective area times the solid angle of acceptance. The detector aperture is then determined by multiplying the potential aperture by the ratio of the number of simulated events that were reconstructed in a given energy bin divided by the number of events thrown in the same bin. The aperture of the Middle Drum detector has been calculated to be roughly half that of the HiRes-1 detector for energies above $10^{19.0}$ eV (see figure 2). The exposure of the detector is defined as the multiplication of running

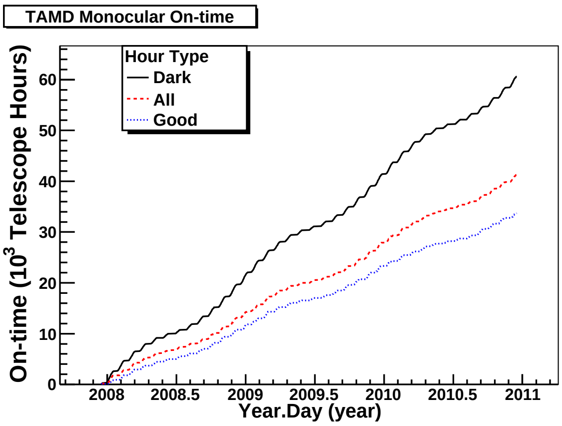

Figure 1: On-time of Middle Drum data collection over three years.

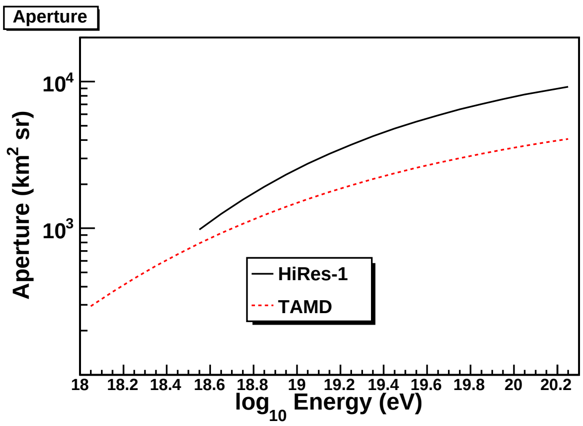

Figure 2: Middle Drum aperture compared to HiRes-1 aperture.

time and aperture. The exposure of Middle Drum is then $\sim 1/3$ the exposure of HiRes-1.

3 Monte Carlo

The Monte Carlo was thrown with an isotropic distribution and sent through the same processing cuts and PCGF reconstruction that was performed on the data. The Monte Carlo was thrown with a HiRes spectrum between $10^{17.5}$ eV and $10^{21.0}$ eV: using a spectral index of 3.25 below $10^{18.65}$ eV and 2.81 above that energy. The Monte Carlo spectral set was thrown without the GZK cutoff [4, 5]. The HiRes-1/Middle Drum Monte Carlo uses the Gaisser-Hillas parameterization to determine the number of charged particles at each slant depth into the atmosphere. The amount of energy deposited into the atmosphere is estimated using the Hillas dE/dx parameterization.

3.1 Resolution

Resolution plots show how well the reconstruction programs perform by determining the difference between the

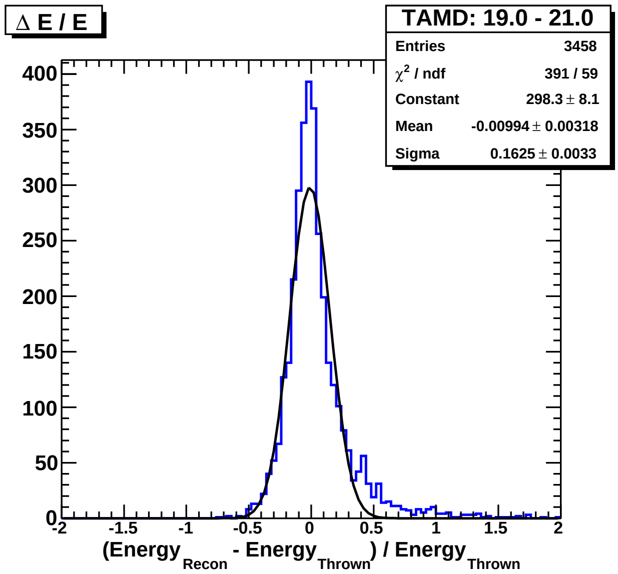

Figure 3: Middle Drum energy resolution for events with energy between $10^{19.0}$ and $10^{21.0}$ eV.

thrown and the reconstructed energy and geometry in Monte Carlo simulations. The three primary parameters that show the quality of the reconstruction are the energy, the impact parameter, R_P, and the in-plane angle, Ψ. These are determined for three energy ranges to show trends in the reconstruction: $10^{18.0-18.5}$ eV, $10^{18.5-19.0}$ eV, and $> 10^{19.0}$ eV. The upper range shows to have a good resolution for these reconstructed events (see figures 3, 4, and 5).

3.2 Data-MC Comparison

The aperture is solely based on the Monte Carlo simulation of real events and how they are observed by our detector. In order to show how well we can rely upon our aperture, data-Monte Carlo comparisons are made. The same three energy ranges used in the resolution are again compared with the upper range showing the most important events observed by the detector. The two reconstructed parameters compared here are the impact parameter, R_P, and the zenith angle, θ (see figures 6 and 7). Due to the small statistics in the actual data the error bars on the data points are quite large. Nevertheless, it can be seen that the Monte Carlo histogram is in excellent agreement with the data.

4 The Middle Drum Three-Year Spectrum

After three years of collecting data, 3859 events were observed with energy above $10^{18.0}$ eV. Only one event has been observed with energy above $10^{20.0}$ eV and three events have been observed above the HiRes measured GZK value of 5.6×10^{19} eV [6, 1]. Dividing the number of events by the exposure the flux is determined for each tenth-decade energy bin. The Middle Drum flux spectrum

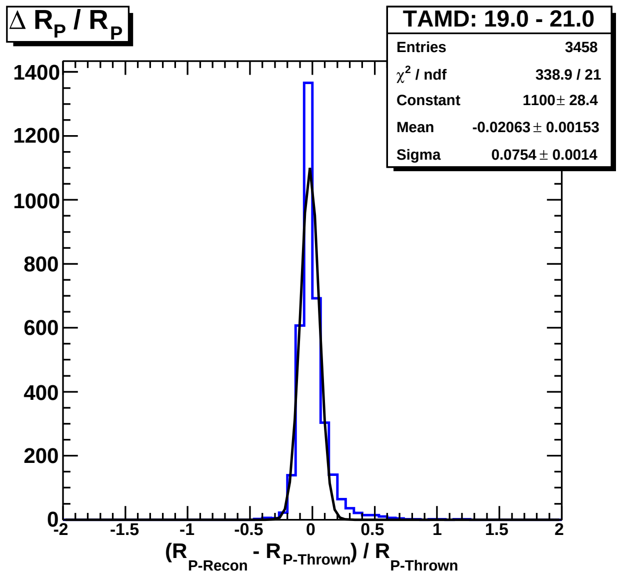

Figure 4: Middle Drum R_P resolution for events with energy between $10^{19.0}$ and $10^{21.0}$ eV.

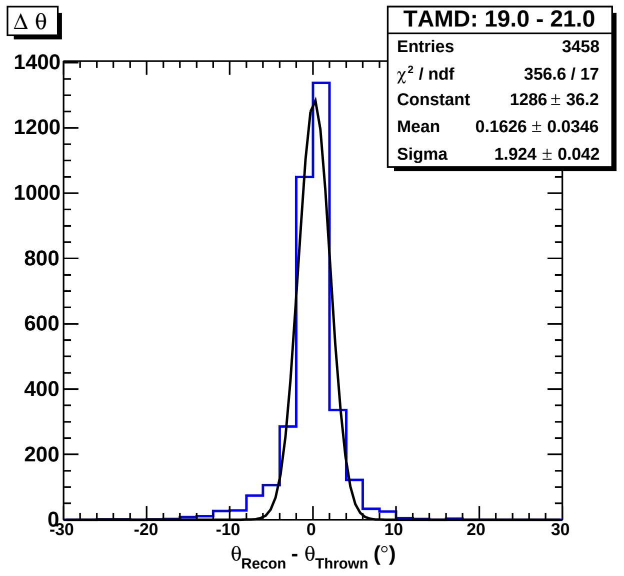

Figure 5: Middle Drum Ψ resolution for events with energy between $10^{19.0}$ and $10^{21.0}$ eV.

appears consistent with that of the HiRes monocular spectrum (see figure 8) [6].

5 Middle Drum Comparisons

Observing the individual bin differences between the HiRes-1 and Middle Drum spectra in the overlapping energy range, a calculation can be made of an overall χ^2 difference between the two spectra. Using only those bins with more than seven observed events, the χ^2 is calculated by

$$\chi^2 = \sum \left[\frac{\left(AE^3 J_{TAMD} - AE^3 J_{HiRes-1}\right)^2}{\sigma^2_{Internal}} \right] \quad (1)$$

where $E^3 J$ is the measured flux for Middle Drum and HiRes-1, respectively, multiplied by a reduction factor, $A = 10^{-24}$, and

$$\sigma_{Internal} = \sqrt{(A\sigma_{GL})^2 + (A\sigma_{SU})^2} \quad (2)$$

where σ_{GL} is the lower (L) error of the flux in the spectrum with a greater (G) flux, and σ_{SU} is the upper (U) error of the flux in the spectrum with a smaller (S) flux for individual bins. This caluclation results in a $\chi^2/N.D.F. = 12.21/10$ for all of the overlying bins and $\chi^2/N.D.F. = 4.47/5$ for bins $\geq 10^{19.0}$ eV. Creating this bridge between the two detectors now allows any future corrections to the Middle Drum spectrum to be translated back to the HiRes spectrum.

6 Acknowledgements

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (21000002) “Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays”, basic research awards 18204020(A), 18403004(B) and 20340057(B); by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006-0050031, 2007-0056005, 2007-0093860); by the Russian Academy of Sciences, RFBR grants 10-02-01406a and 11-02-01528a (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions and the University of Utah Center for High Performance Computing (CHPC).

References

[1] D. C. Rodriguez, 2011, Ph.D. Dissertation, University of Utah

[2] S. A. Blake *et al.* , Proc. 30^{th} ICRC, 2008, **5**: page 1157-1158

[3] C. C. H. Jui et. al., Proc. 31^{st} ICRC, 2009

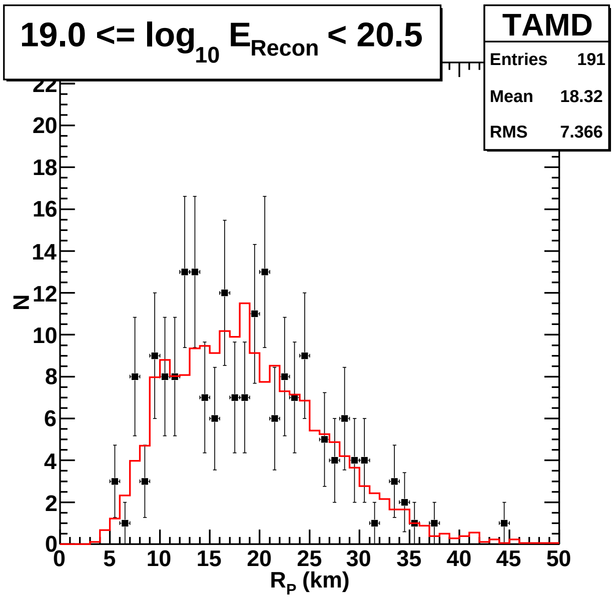

Figure 6: Middle Drum R_P Data-Monte Carlo comparison for events with energy between $10^{19.0}$ and $10^{20.5}$ eV.

[4] K. Greisen, Phys. Rev. Lett., 1966, **16**(17): page 748-750

[5] G. T. Zatsepin and V. A. Kuz'min, Sov. Phys. JETP Lett., 1966, **4**: page 78

[6] R. U. Abbasi et. al., Phys. Rev. Lett., 2008, **100**: 101101

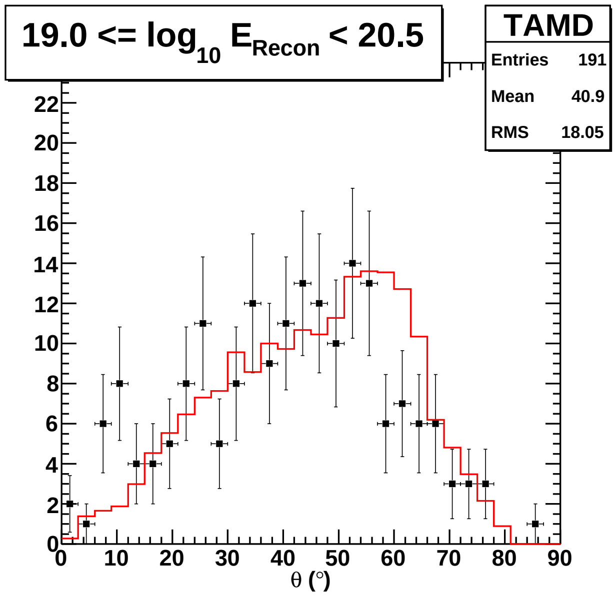

Figure 7: Middle Drum θ Data-Monte Carlo comparison for events with energy between $10^{19.0}$ and $10^{20.5}$ eV.

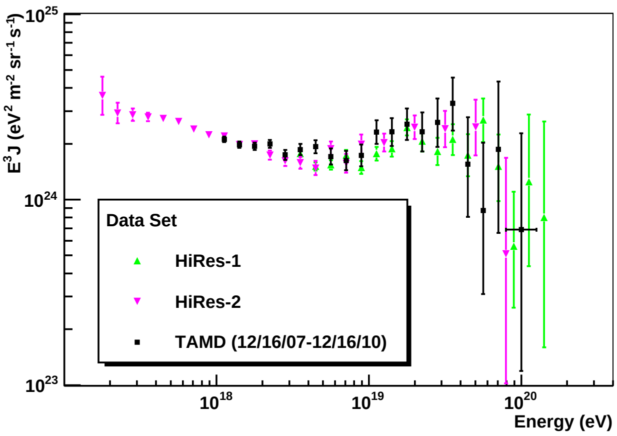

Figure 8: Middle Drum energy spectrum compared to HiRes.