Updated analysis of the Telescope Array's Middle Drum (MD) fluorescence detector data

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Abstract: The Telescope Array's Middle Drum (MD) fluorescence detector provides a direct link to the HiRes-1 energy scale. The current MD monocular energy spectrum measurement uses the same physics input and the same analysis technique as the HiRes-1 analysis. We have updated the MD data analysis to bring it in step with the analyses based on the other two TA FD stations. In this poster we present a summary of the changes made to the analysis: These changes include updating shower energy deposit calculation and light production modeling. Preliminary results on detector performance simulation and the effect on shower energy determination will be presented.

Keywords: UHECR, fluorescence, shower energy, detector simulation.

1 Introduction

1.1 Detectors

The High Resolution (HiRes) Fly's Eye detector was a UHECR fluorescence detector (FD), which operated from the year 1997 through the middle of 2006. The detector comprised two sites separated by 12.6 km. Each site had full azimuthal coverage but differed in elevation angle extent (HiRes-1 covered $3° - 17°$, HiRes-2 covered $3° - 31°$). The two sites were operated both as separate detectors as well as a single stereo detector. The HiRes-1 detector came online in July 1997 while HiRes-2 started physics data taking in December of 2000. Both sites were shut down in 2006.

The Telescope Array (TA) detector is a hybrid detector comprising three FD's and a large ground array of scintillation counters. One of TA's three FDs, located at Middle Drum (MD), is made up of redeployed HiRes-1 mirrors and electronics. 14 of the HiRes-1 telescopes were moved to the MD site and were deployed in a two ring configuration (112° azimuthal, $3° - 31°$ elevation coverage) that overlooks the ground array. The MD site began operation in late 2007 and is still in operation today.

1.2 Detector Simulation and Data Analysis

One of the major goals of the TA detector is to resolve the discrepancy in the AGASA and HiRes results with respect to the observation of the GZK cutoff in the energy spectrum [3] [4] It was suspected that this discrepancy might be due to a difference in the energy scale of the two experiments and therefore a hybrid observation using detectors and techniques as close as possible to the original experiments was the best way to understand the different results.

Due to HiRes-1 earlier start date, the analysis procedure [8] of the data collected by HiRes-1, operated in monocular mode, including the shower simulation in the detector Monte Carlo had matured by the early 2000's and was therefore "frozen" or unmodified thereafter to maintain consistency with the earliest published results [3]. After the construction of the Telescope Array Middle Drum FD, it was decided that the MD data analysis should use the same simulation and data analysis programs used for HiRes-1. This guarantees that the MD energy scale matches the original HiRes-1 energy scale and could therefore provide continuity in the CR energy spectrum measurement from experiment to experiment.

Newer measurements of the Air fluorescence yield and newer extensive air shower simulation models have come into use since the original HiRes-1 analysis was "frozen". These newer measurements and models are used in the analysis of the other two TA fluorescence detectors. Having served its purpose of transferring the HiRes-1 energy scale to the TA experiment it is time to update the MD analysis to using these models. In particular, we made the following changes to the shower simulation used in the detector Monte Carlo and the energy reconstruction programs:

- The wavelength spectrum of fluorescence light was updated from the Bunner [1] spectrum to the spectrum measured by the FLASH experiment [2].
- The shower energy deposit function was updated from the Hillas [5] model to Nerling *et al.* [7]

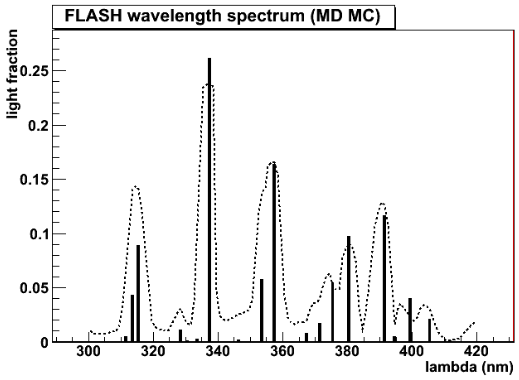

Figure 1: FLASH wavelength spectrum at 155 torr [2]. Also shown is the Bunner spectrum (Arbitrary scale)

- The Cerenkov light production was also updated from Hillas [6] to Nerling [7].

2 Physics Models

The FLASH experiment measured the air florescence efficiency and the wavelength spectrum of emitted light. We have incorporated the measurement of the wavelength spectrum, figure 1, into the simulation but retained the absolute yield measurements done by Kakimoto *et al.* [9].

The energy deposit formula used in the HiRes-1 analysis and the first analysis of TA MD data is based on shower simulations done by Hillas in the early 80's [5]. Hillas also provided a formula for calculating the Cerenkov light production in extensive air showers [6]. More recently, Nerling *et al.* used Corsika simulations to produce formula for the same quantities as Hillas. These formula are now used by AUGER as well as TA FD analyses. Figure 2 shows the difference between the shower energy deposit function calculated based on Hillas simulations and the effective energy deposit from the Nerling paper. Note that the Hillas formula was scaled up by 20%; this is because we use a Corsika shower library for the detector simulation. These Corsika shower simulations produced roughly 20% fewer particles than the Hillas Monte Carlo and therefore the scaling was required to conserve shower energy. In going from Hillas to Nerling parametrizations we also had to update the missing energy correction in order to have a self consistent shower simulation. Specifically this means that the missing energy fraction was adjusted such that the primary CR particle energy equals the sum of the shower colorimetric energy, given by the shower integral of the dE/dx curve, and the shower missing energy carried by neutrinos and other penetrating particles that do not deposit their energies in the atmosphere.

The electron energy distribution found by Corsika simulations differs from the Hillas simulations. This results in a small change in the total amount of produced Cerenkov light. Hillas' calculation accounted for the altitude dependence of the Cerenkov light. Nerling *et al.* provide a refined procedure which accounts for the shower development stage (shower age) in addition to the altitude. They also update the calculation of the angular distribution of the emitted light. A comparison of the two calculations shows some minor differences, see figure 3 for an example.

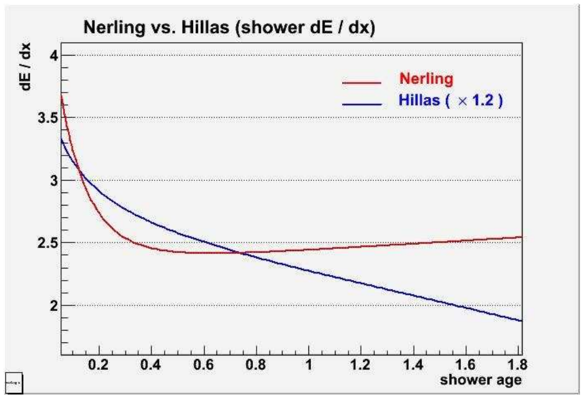

Figure 2: Shower energy deposit functions. Shown are Nerling's "effective α", and the dE/dx function based on Hillas' paramaterization.

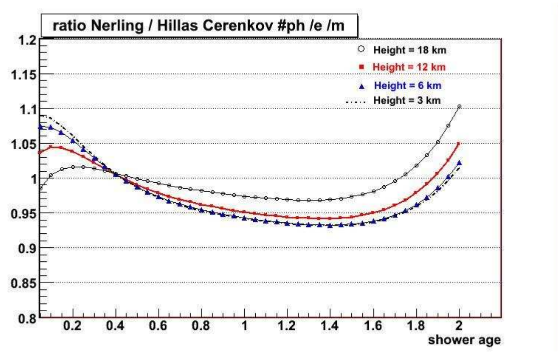

Figure 3: Ratio of total Cerenkov light production from an air shower as a function of shower age at different altitudes.

In practice the Cerenkov light calculation is not a signifacnt factor in energy determination because we typically implement quality cuts that eliminate events with large Cerenkov signals from the final data sample used for spectrum or composition.

3 Detector Aperture

Table 1 showes the Middle Drum trigger aperture calculated with the old and new shower models. As the energy increases the effect on the trigger aperture gets smaller, resulting in a slight change in the shape of the aperture function.

Energy(EeV)	Hillas	Nerling	Ratio
0.3	173.1	191.7	1.11
1.0	654.3	715.0	1.09
3.0	1683.0	1813.2	1.08
10.0	3496.5	3599.8	1.03
30.0	6243.3	6258.3	1.00

Table 1: Middle Drum trigger aperture calculated for proton primaries.

4 Reconstructed energy and profile

Hybrid reconstruction of showers observed by Middle Drum FD makes use of the ground array in the geometrical reconstruction of the shower track. The resulting geometry is very well determined with the impact parameter, Rp, resolution on the order of 1% and angular resolution of better than a degree. The hybrid geometry is used by the energy and x_{max} (profile) reconstruction program without modification. On the other hand, the monocular reconstruction relies on the profile constrained fit method in which the shower geometry and profile are reconstructed in one step. Here we impose a predefined set of Gaisser-Hillas (GH) profile parameters and calculate the shower geometry that, a shower with the preset profile produces the best fit to the data. In the monocular case, changing the physics models changes not only the reconstructed energy and x_{max} but the track geometry as well.

The following plots show the results of a comparison of the reconstructed paramaters for a set of hybrid observed events. Figure 4 shows that the shower energy reconstructs 7-8$\%$ lower with the new models than with old. The x_{max} values also came out 16 gm's smaller, figure 5. Figure 6 shows the change in monocular energies to be on the order of -6%. With a much larger set of events it was found that the new energies were lower by 8.9%.

5 Summary

The Middle Drum Monte Carlo and energy reconstruction programs were updated to the currently accepted models of shower energy deposit and light production. Overall we find that the updated estimated shower energies for events observed with MD is 8% lower than in the first analysis which matched the HiRes-1 energy scale.

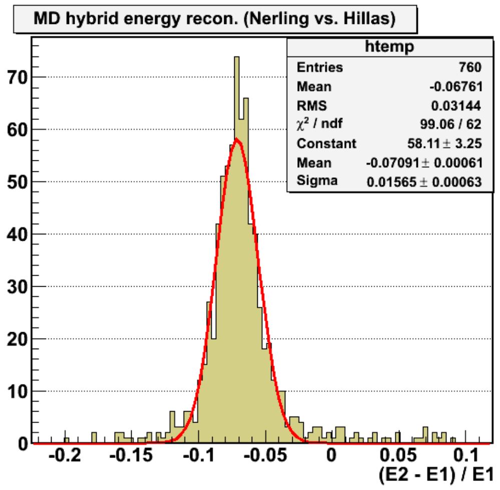

Figure 4: Hybrid energy reconstruction. Change in energy in going from the old models (Hillas) to the new models (Nerling)

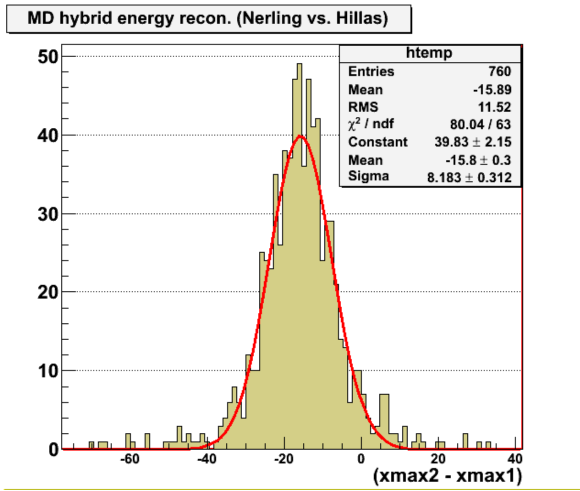

Figure 5: Hybrid energy reconstruction. Change in x_{max} in going from the old models (Hillas) to the new models (Nerling)

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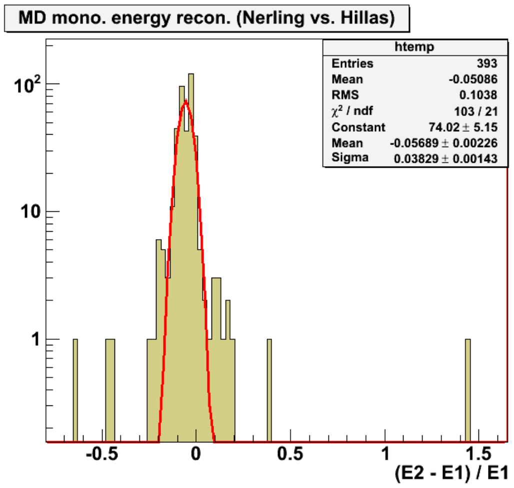

Figure 6: Monocular energy reconstruction (energy) in going from the old models (Hillas) to the new models (Nerling)

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