Measuring the Spectrum of Ultrahigh Energy Cosmic Rays using the Monte Carlo Technique

L.M. Scott*, D.R. Bergman*, S.R. Stratton*, Y. Tsunesada†, for the Telescope Array Collaboration

*Rutgers, the State University of New Jersey, Piscataway, NJ, USA 08854
†Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo 152-8550, Japan

***Abstract*. The technique for measuring the spectrum of the highest energy cosmic rays using the air-fluorescence technique has been well-developed over the last few decades. Due to the complexity of the phenomena that occur during an extensive air shower (the production of fluorescence and Cerenkov light including scattering and attenuation), correctly determining the energy-dependence of the aperture requires the creation of a good full-detector Monte Carlo which accurately reproduces measurable quantities of the air shower. The Telescope Array Monte Carlo simulation will be explained and plots comparing data and Monte Carlo will be shown.**

***Keywords*: UHECR, fluorescence, Telescope Array**

I. Introduction

The Telescope Array Experiment (TA) is an experiment designed to measure the energies, composition and arrival directions of ultrahigh energy cosmic rays (UHECRs). Located in Millard County, Utah, this “hybrid” detector is composed of 3 nitrogen fluorescence detectors (FD) overlooking 507 surface detectors (SD). Detection in “hybrid” mode (using these two techniques together) provides independent measurements of the development of a cosmic-ray induced shower in air, in addition to its footprint on the ground. In this way, measurements taken using both techniques can be cross-checked and cross-calibrated, thereby greatly improving measurements of geometry and energy as compared to either technique alone. The FD have been online and taking data since November 2007; the SD since April 2008.

In this paper, we report on the results of our work with the two southern FD sites of the array. We present the data and the techniques used to calculate the energies of UHECRs, and a preliminary detector aperture, emphasizing the importance of a full-detector Monte Carlo simulation in the determination of the UHECR aperture of the detectors.

II. TA Fluorescence Detectors

The three FD stations, known as Middle Drum (MD) to the northeast, Black Rock Mesa (BR) to the southeast and Long Ridge (LR) to the southwest, consist of two-rings of mirrors that view the sky from 3 to 31° in altitude and $\sim 100°$ in azimuth. Middle Drum consists of 14 mirrors and cameras containing 256 photomultiplier tubes (PMT) each and electronics taken and from the High Resolution Fly’s Eye I site. The acquisition and analysis of data from this site is identical to that used in HiRes [1]. The sites at BR and LR were designed specifically for the TA experiment. Each site contains 12 mirrors and cameras containing 256 PMTs with a data acquisition system consisting of a flash ADC operating at 10 MHz (100 ns period). A waveform of duration 51.2 μs is recorded for every PMT each time a given camera is triggered. In this paper, we report on our work with the FD sites at BR and LR.

III. The FD “Monte Carlo” technique

A. Motivation

When an ultrahigh energy cosmic ray undergoes an extensive air shower, the number of charged particles created as a function of depth along the track of the shower (known as the “longitudinal profile”) can be fit to a four-parameter function first developed by Gaisser and Hillas [2]. Known as the Gaisser-Hillas function, the parameters are N_{max}, the number of charged particles at the shower maximum, X_{max}, the position of the shower maximum in g/cm^2, X_0, the depth of the first interaction and λ, which is related to the longitudinal width of the shower.

In addition to the production of isotropic fluorescence light by excitation of molecular nitrogen in the atmosphere, charged particles at high energies also produce Cerenkov radiation that can be beamed or scattered into the mirrors. Since the higher the energy of the incident cosmic ray, the brighter the event, the aperture of the FD can change quite rapidly with increasing cosmic-ray energy. Integral to the calculation of an FD aperture is the development of a good full-detector Monte Carlo program which accurately predicts the light produced by extensive airshowers, simulates the detector response to this light and, when analyzed, reproduces all aspects of the data.

B. The Monte Carlo

Using the energy spectrum as measured by the HiRes experiment, we “throw” events isotropically according to actual detector on-times from a library of Gaisser-Hillas parameters taken from Corsika simulations of ultrahigh energy cosmic ray extensive airshowers. We follow the development of the shower in 1 g/cm^2 steps calculating the appropriate amounts of fluorescence and Cerenkov light using actual radiosonde measurements of atmospheric temperature and pressure. Fluorescence light is scattered isotropically to the detector; Cerenkov light builds along the track and is scattered using the appropriate Rayleigh and aerosol scattering functions. All attenuations due to Rayleigh, aerosol and ozone scattering are taken into account.

Using actual measurements of mirror reflectivity and PMT response and quantum efficiency, we raytrace light that reaches the detector to determine the appropriate acceptance in the PMTs. We then simulate the actual trigger conditions of the detector and the electronic response, and store the simulated signal in the same format as the raw data.

C. The "Inverse Monte Carlo" technique

The FD measure only the light emitted by high-energy particles interacting in the atmosphere. As described above, relating the amount of light detected at the mirrors as a function of time to the number of charged particles at a given depth along the track is therefore a non-trivial task.

For a given event geometry, we find the corresponding slant depth (in g/cm^2) for each time slice in the PMT waveform. Then, using the same raytracing routine mentioned in the previous section, we calculate the PMT acceptance for light coming from the specific location on the shower track, finally calculating the flux of light incident on the mirror at the site.

Since the best-fit Gaisser-Hillas profile for a shower is only weakly dependent on X_0 and λ, average values of -60 and 70 g/cm^2 are considered. Using a fitting routine, we then allow N_{max} and X_{max} to float and generate and propagate light to the mirror using the same routines mentioned in the previous section for throwing simulated showers. The best-fit N_{max} and X_{max} are found by χ^2 minimization, comparing the flux of light in the data and the simulated flux in each time slice. Figure 1 shows the flux of light from a typical good event overlaid with the simulated contributions from fluorescence, direct, Rayleigh-scattered and aerosol-scattered Cerenkov light.

D. Analysis of data and Monte Carlo

The real data and simulated events are passed through the same routines to determine the geometry of the event. As discussed in the previous section, the "inverse Monte Carlo" technique is then applied to both the data and the simulated events to calculate N_{max} and X_{max}. The same quality cuts are then applied to both the data and simulated events. An accurate calculation of the detector aperture is only possible when good agreement is reached in comparisons between the data and Monte Carlo. Figures 2 and 3 show histograms of the cosmic-ray impact parameter, R_p and the total length of the measured shower track, for both data and Monte Carlo.

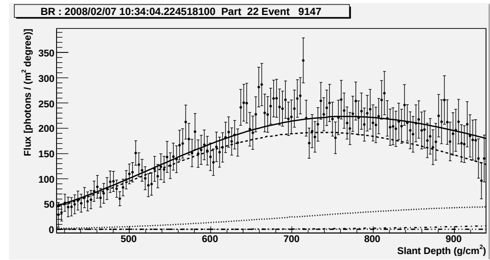

Fig. 1. Flux vs. slant depth for a typical good event. Lines from top to bottom : *Solid Line*: total flux of simulated light, *Dashed Line*: flux of fluorescence light, *Dotted Line*: flux of Rayleigh-scattered Cerenkov light, *Dash-dotted line*: flux of Aerosol-scattered Cerenkov light, *Dash-dot-dotted line*: flux of direct Cerenkov light.

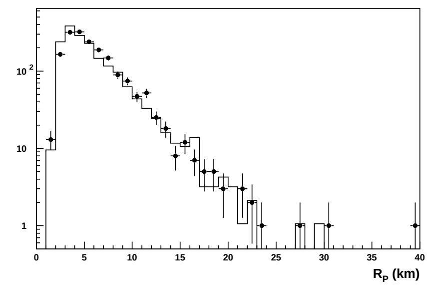

Fig. 2. Data / MC comparison of shower impact parameter, R_p.

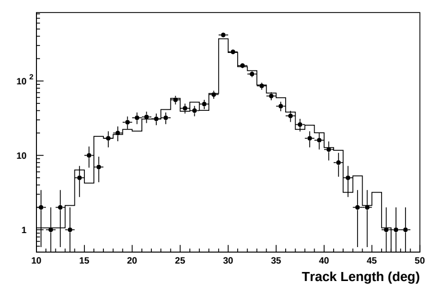

Fig. 3. Data / MC comparison of shower track-length.

Throwing events over a known area, A_0 and solid angle Ω_0, the aperture of the detector as a function of energy, $A\Omega(E)$, can simply be found

$$A\Omega(E) = A_0\Omega_0\frac{N_A(E)}{N_T(E)} \quad (1)$$

where N_T and N_A are the total number of thrown and "detected" events in a given energy bin, respectively. A preliminary aperture for the FD at Black-Rock and Long-Ridge will be shown at the conference.

IV. Acknowledgements

The Telescope Array experiment is supported by the Ministry of Education, Culture, Sports, Science and Technology-Japan through Kakenhi grants on priority area (431) "Highest Energy Cosmic Rays", basic research awards 18204020(A), 18403004(B) and

20340057(B); by the U.S. National Science Foundation awards PHY-0601915, PHY-0703893, PHY-0758342, and PHY-0848320 (Utah) and PHY-0649681 (Rutgers); by the Korean Science and Engineering Foundation (KOSEF, Grant No. R01-2007-000-21088-0); by the Russian Academy of Sciences, RFBR grants 07-02-00820a and 09-07-00388a (INR), the FNRS contract 1.5.335.08, IISN 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.

REFERENCES

[1] R.U. Abbasi et al., Phys. Rev. Lett. **100**, 101101 (2008).
[2] T. Gaisser and A.M. Hillas Proc. 15th ICRC (1971).