Cross-calibration of Telescope Array Fluorescence Detectors with Static and Roving Standard Candles

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Abstract: The Telescope Array ultra-high-energy cosmic-ray detector experiment in central Utah includes a heterogeneous set of detectors for atmospheric fluorescence, with independent internal calibration procedures, data acquisition, and analysis chains. A unified photometric scale among the different detectors is essential to an accurate stereo energy spectrum. To attain this agreement, we employ numerous standard candles for cross-calibration. A central laser facility provides a signal simultaneously visible to a pair of telescopes in each detector. Two separate portable lasers are transported to at least nineteen sites, each visible to one of the experiment's telescope pairs. Additionally, an assortment of mirror-mounted portable flashers illuminate the telescopes' photomultiplier tube clusters directly. Intrinsic differences between detector sites, telescopes, and pixels can then be accounted for in the analysis of cosmic-ray data. We present a synopsis of the various cross-calibration techniques to be employed and the expected improvements to the fluorescence detector energy scale accuracy.

Keywords: Ultra-high-energy cosmic rays, Atmospheric fluorescence, Calibration, Telescope Array Experiment.

1 Introduction

The Telescope Array (TA) cosmic-ray detector, sensitive to cosmic rays with energies above $\sim 10^{18}$ eV, has been operating in Millard County, Utah, since late 2007. Two detection mechanisms are employed at TA: three atmospheric fluorescence detectors (FDs) record the ultraviolet light emitted from the extensive air shower (EAS) produced when a cosmic ray enters the atmosphere, and a grid of 507 scintillation detectors (SDs) measures the flux of secondary charged particles arriving at the surface. It is possible to measure the cosmic-ray spectrum using the air-shower geometry and and energy reconstruction from data taken by any single FD ("monocular"), or the "stereo" operation of multiple FD sites, the SD array alone, or the "hybrid" operation of the SDs with one or more FDs.

The analysis of FD measurements depends on the accurate photometric calibration of the detectors. Ultraviolet light from an EAS reflects from a spherical mirror into a close-packed cluster of photomultiplier tubes (PMTs), and it is essential to understand the relationship between the incident photon flux and the signal measured in the detector electronics. Each FD has an internal photometric calibration mechanism, but an important constraint on this calibration is the requirement that a source of fixed intensity appear equally bright to each detector that measures it. To confirm that the detectors are calibrated correctly, multiple "standard candles" may be observed and the results checked for consistency. The available sources comprise two categories: flashers, which illuminate the PMTs directly, and vertical lasers, located some distance from the FD site. After describing the internal calibration and other characteristics of each FD site briefly in Section 2, we will present details of the expected operation of each standard candle in Section 3, followed by results of a preliminary analysis of selected sites and sources and a discussion of the role of cross-calibration in the broader context of the experiment in Section 4.

2 TA fluorescence detectors

Three fluorescence detectors (FDs) are situated on the perimeter of the Telescope Array site in the desert of central Utah, facing inward; their combined field of view includes nearly full coverage in azimuth, between three and thirty-one degrees above the horizon. Middle Drum (MD), the northern site, contains fourteen telescopes refurbished from the High-Resolution Fly's Eye (HiRes) experiment, while the two southern sites, Black Rock Mesa (BR) and Long Ridge (LR), each contain twelve new telescopes designed for TA, for a total of 38 telescopes.

The camera of each telescope in TA contains 256 hexagonal PMTs. The electronic readout system for each PMT at the two southern sites is based on a 14-bit FADC operating at 10 MHz, while the corresponding system at the northern Middle Drum site is based on a sample-and-hold circuit.

The photometric calibration of the FADC-based southern detectors is founded on the absolute calibration of a subset of PMTs via the CRAYS mechanism [1], with the remaining PMTs adjusted relative to the absolutely calibrated tubes in the presence of a source with known emission geometry [2]. The absolutely calibrated PMTs are outfitted with a small stable emitter in the center of the photocathode to track long-term aging effects, and hourly variations in the PMT gains are monitored via the regular operation of fixed xenon flashers.

Middle Drum PMTs are calibrated using a high-stability roving xenon flasher (RXF), a source of known intensity and geometry. Approximately once per month, the RXF is installed in each telescope assembly and the response of the PMTs is recorded. During normal operation of the detector, a stable ultraviolet light-emitting diode (UVLED) in temperature-controlled housing illuminates the PMTs once per second, which permits the tracking of gain variations between RXF calibrations.

3 Standard candles for calibration

Two classes of source, flashers and lasers, enable the thorough testing of fluorescence-detector photometric calibration and the isolation of discrepancies. Flashers consist of modules that insert into a multi-purpose socket in the center of each telescope's mirror. This position enables them to illuminate the entire face of the camera associated with that mirror. The geometry of the flasher configuration permits light that reflects from the camera to strike the mirror at nearly normal incidence and possibly return to the camera. To prevent reflected-photon contamination of the measurement, the mirrors must be covered with sheets during cross-calibration flasher measurements. Because flasher sources are located within the buildings that house the FD telescopes, this type of cross-calibration is possible during moonlight or inclement weather when the detectors would not otherwise be operating.

Laser sources are situated at a distance and oriented vertically, so that their beams traverse the field of view of one pair of FD telescopes. This configuration does not illuminate the entire camera face, but only (at most) a few columns of PMTs. Rayleigh and Mie scattering of the beam into the line of sight, and by the same mechanisms attenuation of light en route to the detector, introduce into the observed flux a dependence on atmospheric details, and the amount of light reaching the PMT photocathodes is sensitive to shadowing caused by the camera support structures, the reflectance of the mirror, and the transparency of the protective barriers present in the camera assembly. Their position in the field requires that laser sources be measured during normal FD dark-sky operation.

Through the application of these distinct sources, it becomes possible to disentangle variations caused by differences in the electronics (which affect flashers and lasers equally) from those caused by differences in the atmosphere or detector acceptances (which affect lasers only).

3.1 Roving xenon flasher

The RXF is a high-stability, nearly monochromatic emitter with a wavelength of 355 nm. It flashes at a rate of 1.45 Hz, which makes one of the slower sources under consideration. The precise combination of xenon flashlamp, filters, and diffusers has been fixed for several years, and its use as a calibration source for both Middle Drum and its predecessor, HiRes, provides a bridge between the two experiments. A cross-calibration campaign involving the RXF must be kept separate from the standard monthly MD calibration, which is performed with mirrors uncovered. Because collecting RXF data is time-consuming, it is not possible to measure its output with all 38 telescopes at three widely separated FD sites in a single night. Three or more successive moonlit nights with low humidity (for optimal performance of the detector electronics) will provide the best conditions for a cross-calibration campaign.

3.2 Ultraviolet LED flasher

Each mirror at Middle Drum holds an ultraviolet light-emitting diode (UVLED), which produces 355 nm light in a square pulse of programmable amplitude and duration. The UVLED housing includes circuitry to maintain a stable $45°$ C temperature of the electronics. When the flash rate is 20 Hz as during dedicated UVLED data collection at the beginning and end of the night, it is the fastest of our sources. Any UVLED can be released to become a portable source; the unit designated for cross-calibration purposes is the module from MD mirror 1. As with the RXF, it is not feasible to transport the UVLED to all 38 telescopes in one night, so the same conditions for an RXF campaign apply to the UVLED. However, because of the programmable nature of the pulses (and the speed of the source), several combinations of amplitude and duration can be measured during a single telescope installation, providing a test of telescope response linearity.

3.3 Central laser facility

Each FD site is located ~ 20.85 km from the central laser facility (CLF), where a Nd:YAG laser produces 355 nm emission in pulses of typically a few mJ energy. Every thirty minutes throughout the night, the CLF fires a 30-second burst of 300 flashes. Its vertical, depolarized beam produces approximately equal intensity at all three FD sites. Only one pair of telescopes at each site can view the CLF, but because this is the one source that is simultaneously visible at all sites, it offers the best measurement of the agreement of inter-site calibrations. The timing of the CLF operation is determined by GPS, which simplifies the isolation of CLF triggers embedded in the night-sky data. In addition to providing equal flux to each FD site, the CLF provides a means of measuring atmospheric properties such as the distribution of aerosols.

3.4 Roving nitrogen laser

A truck-mounted roving nitrogen laser (RN_2) produces $\sim 70\ \mu$J pulses of 337 nm light. Its operating positions are restricted to paths designated for vehicular transport; consequently, its distance from the detectors varies between 3 and 10 km depending on which two telescopes are viewing it. The corresponding variation in atmospheric attenuation makes the RN_2 more valuable as a test of atmospheric model accuracy than as a true photometric standard candle. With a firing rate of 1 Hz, the RN_2 is our slowest source. Measurement by all nineteen telescope pairs requires three clear nights without strong winds, which have been observed to broaden significantly the measured pulse energy distribution relative to that recorded in calm conditions. As with the CLF, the use of a GPS trigger for firing assists in the isolation of RN_2 events in the night-sky data.

3.5 Portable YAG laser

A second portable laser is presently being developed and tested, for use in conjunction with the electron light source (ELS), a fixed linear accelerator that produces an atmospheric beam of 40 MeV electrons near the FD site at Black Rock Mesa [3], which has not yet begun regular operation. The laser will tuned to produce scattered light of the same intensity as the fluorescence from the ELS electron beam when at the same distance, and then transported to positions at each site. Because the distance from the detector is small (~ 0.1 km), it may ultimately be possible to visit all nineteen telescope pairs in one night. Knowing the energy of the electron beam enables full end-to-end calibration of the entire TA fluorescence detector system via this portable laser.

4 Preliminary cross-calibration efforts and outlook

The full effort of FD cross-calibration has begun and is progressing in stages, and has already yielded modest improvements in the accuracy of the detectors. The CLF has been in operation since 2008, with most nights contributing hundreds or thousands of events seen simultaneously by all three detectors. In late June 2010, the RXF and the UVLED from MD mirror 1 were taken to Black Rock Mesa and Long Ridge for observation by several telescope cameras, but time did not permit the inclusion of all telescopes. In early July 2010, the RXF was also measured at all fourteen Middle Drum telescopes apart from the regular calibration procedure. The following September, the portable YAG laser fired its first test shots, and the roving nitrogen laser was fired from positions in front of all nineteen pairs of telescopes. A thorough campaign with the RXF and UVLED is scheduled for July 2011.

Preliminary inspection of the results has indicated that there is generally good agreement among the telescopes within one site, and between the two newer FD sites; between these and the fundamentally different Middle Drum detector, the agreement is acceptable but also steadily improving with each effort to understand any observed difference. Ongoing efforts at reviewing and correctly interpreting the existing calibration measurements will soon be complete, but further comments would be premature at this time.

Tests of the agreement in photometric calibration between telescopes and FD sites are crucial in determining the uncertainty associated with the cosmic-ray spectrum measured by the Telescope Array experiment. As the cross-calibration campaign enters its final phases and analysis begins in earnest, it will become possible to calculate the detector aperture and consequently the spectrum with unprecedented accuracy.

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