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# The Status of the Track Imaging Cerenkov Experiment

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**Abstract:** In distinguishing between the atmospheric Cerenkov light initiated by the primary cosmic ray and its associated air shower, the Track Imaging Cerenkov Experiment (TrICE) is devised to measure the composition of cosmic rays at TeV-PeV energies. The instrument is a fixed-mount zenith telescope that uses a Fresnel lens as a early trigger and 4-m spherical mirrors to produce the image on the focal plane over a 1.5° field-of-view. The TrICE camera, composed of multi-anode photomultiplier tubes with 0.086 degree angular spacing, is digitized continuously by a custom ASIC at 53 MHz with a dynamic range of 16 bits. Here we describe the commissioning and calibration of TrICE.

## Introduction

The Track Imaging Cerenkov Experiment (TrICE) utilizes the Direct Cerenkov technique (DC) to make a ground-based composition measurement of cosmic rays at TeV-PeV energies. The DC technique determines the charge by separating Cerenkov light generated by the primary particle from that of the secondaries in the extensive air shower (EAS). The primary initiates Cerenkov radiation upon entering the atmosphere, microseconds before the EAS begins. Due to the index of refraction of an atmosphere with a non-uniform density, the arrival of the DC photons at ground level is delayed by a few nanoseconds. There is an inherent separation in the arrival angle of the two signals, because the DC light is emitted at a narrow angle, and the air shower light scatters due to the interactions of the secondary particles,

Cerenkov light production scales with the square of the primary charge and is a strictly electromagnetic effect. Thus, by determining the intensity of the DC light, one can measure the composition independently of poorly understood air shower hadronic interaction models [1]. The imaging atmospheric Cerenkov telescope array, H.E.S.S., has already seen evidence of this effect [2].

## High Resolution Camera Studies

Air shower simulation studies indicate that sufficient timing and angular resolution permit the discrimination of the DC light from the EAS. The separation efficiency depends on the geometry of the cosmic-ray shower and the energy and charge of the cosmic ray [1]. The direct emission is confined to a narrow angular region and late arrival time on the ground relative to that of a non-interacting particle, as shown by the simulated time and angle properties for a 100 TeV $^{56}$Fe cosmic ray in Figure 1.

After assuming an angular resolution of $0.01^\circ$ and a 1ns time resolution, the DC peak remains visible, suggesting that an imaging Cerenkov telescope could distinguish the peak (Figure 1). An ideal detector would see first the elliptical development the EAS on the camera plane, followed by the sharp peak of the DC pulse. Since TrICE, in its current prototypical phase, has a time resolution of 18.8ns, it is limited to detecting DC light using the angular properties of the shower development. Therefore, the best candidates for TrICE observations of DC emission are high charge primaries that interact relatively deeply in the atmosphere.

Modern Imaging Atmospheric Cerenkov Telescopes (IACTs), such as VERITAS and H.E.S.S. [2, 3], see evidence for the DC effect, however, their charge resolution is limited by their angular pixel size and time resolution. In a detector like VERITAS, light from the primary is concentrated into 1-3 pixels at best, which permits contamination of the pertinent phototube signal by fluctuations in the EAS. This motivates the development of a pixelated camera such as the one achieved with the TrICE multi-anode photomultiplier camera [4].

## The TrICE Detector

TrICE is a prototypical fixed-mount Cerenkov telescope (shown in Figure 2) designed to look for DC light from cosmic-ray nuclei. It aims to achieve high resolution shower imaging and employs a specialized design to provide an optical trigger. A Fresnel lens mounted directly above the camera plane enables a trigger signal preceding for a delayed and magnified image of the shower, which is focused onto the camera by mirrors. Eight spherical mirrors are arranged on a square perimeter around the base of the telescope. These are focused onto the camera via a secondary planar mirror that also serves as a frame for the Fresnel lens. The TrICE camera consists of 16-channel Hamamatsu R8900 multi-anode photomultiplier tubes (MAPMTs). For more details on the performance of the camera see K. Byrum's review in these proceedings [4].

## Optical Design

TrICE has a primary mirror area of 6.4m$^2$, which is achieved by eight 1-m spherical mirrors with focal lengths of 4m. The 3.7° wide field-of-view of the Fresnel lens is larger than the 1.5° mirror acceptance angle, and the difference in magnification between these two systems is $\sim$ 4x. Furthermore, the light falling on the spherical mirrors will arrive $\sim$ 10ns after the light from the Fresnel. The light from the air shower imaged by the coarse-grained optics of the Fresnel will trigger the system, while the light from the mirrors, which will come from both the air shower and the primary, will arrive nanoseconds later (Figure 3). Using the Fresnel lens as an early trigger allows TrICE to first get a wide-field view of the air shower and later get a focused image of the shower and the DC light. Since the difference between the optical path length of the imaged light and the triggering light is 10ns and the digitization time is 18.8ns, the best candidate events to evaluate the performance of the Frensel lens as a trigger include an early diffuse

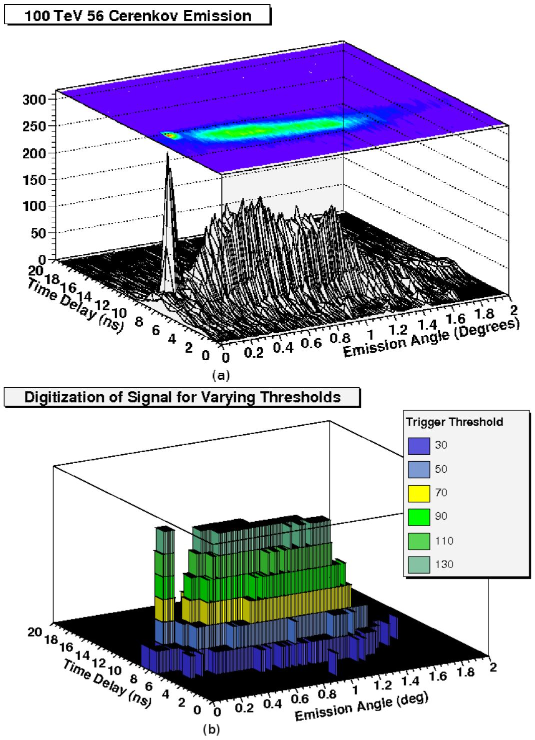

Figure 1: Simulated Cerenkov emission due to a 100 TeV $^{56}$Fe nucleus collected in bins of 1ns resolution in time delay and 0.01° resolution in emission angle. (a) Photons falling in a radius between 67 and 94m from the shower core reveal a well-defined peak at small angles from the DC light. (shown here in arbitrary units) (b) If this signal is digitized at several thresholds, the DC peak remains visible.

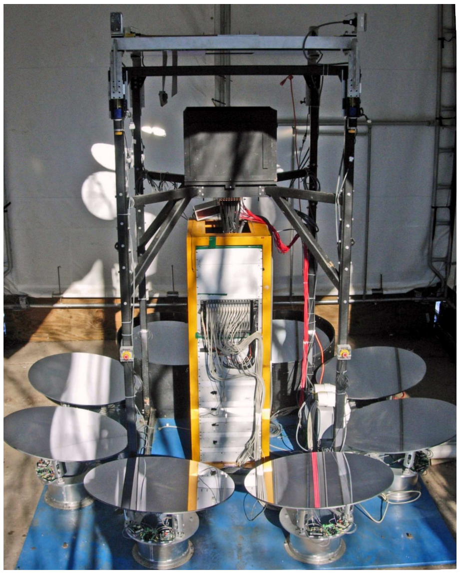

Figure 2: The completed TrICE telescope, shown here with the baffle and electronics rack in the center of the telescope. The planar mirror and Fresnel lens are placed 3m above the optical axis of the 4-m focal length spherical mirrors, on top of motor mounts allowing for precision focusing of the secondary mirror.

shower image from the Fresnel lens followed by a high-resolution air shower image with a DC peak.

Relative alignment of the spherical mirrors has been achieved by fixing a white LED, of diameter $0.56$cm, ∼11m above the ground, such that the light would be focused ∼40cm above the ground. The LED was first aligned with a laser placed in the center of the optical system on the ground and next with the light collected by the Fresnel lens. Then using a Starlight Xpress SXV-M7 CCD camera, the images from the mirrors were aligned to one another with a custom motor-controlled alignment system. The intensity of light at the focal plane had a 90% enclosure region of diameter $0.6$cm, as shown in Figure 4. Deconvolution of the intensity function with the inherent width of the LED suggests a point-spread function of 2.2mm which is smaller than the MAPMT camera pixel width of 6mm.

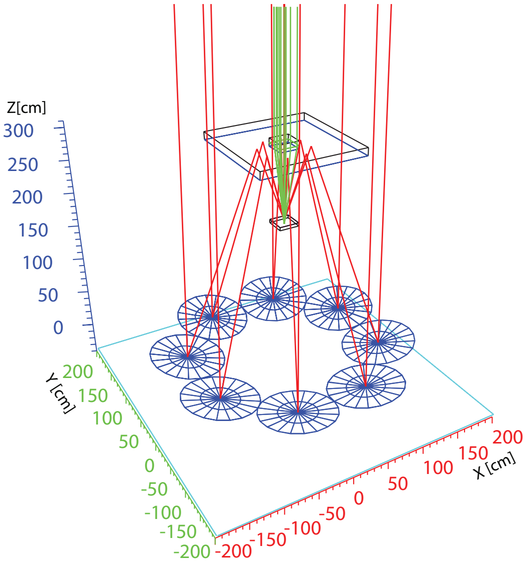

Figure 3: A schematic of the optical design of TrICE. Collimated light impacting the spherical mirrors, shown in red, are reflected onto the camera plane by the planar mirror, while those impacting the Fresnel lens, shown in green, are focused directly onto the camera plane.

## Electronics and Data Acquisition

TrICE records PMT signals using two VME crates of modules designed for the digitization of MAPMT signals and the buffering of data[5]. The analog signals from a 16-channel MAPMT are sent directly to a corresponding 16-channel module housed in the “front-end” VME crate. The integration and digitization of current signals are performed using 53 Msps charge integrating encoders, or QIE’s [5]. The digitized data are transferred to a separate “back-end” VME crate on receiving a trigger.

The dynode signals from the 4 central MAPMTs of the camera are used to trigger the front-end electronics. A trigger is generated by the coincidence of at least two MAPMT dynode signals above a programmable threshold. An approximate analysis threshold requires that $\sim 15$ photoelectrons summed over an MAPMT. In addition to the dynode-based trigger, the front-end electronics also accepts an external trigger signal. This mode is run separately from normal observations and

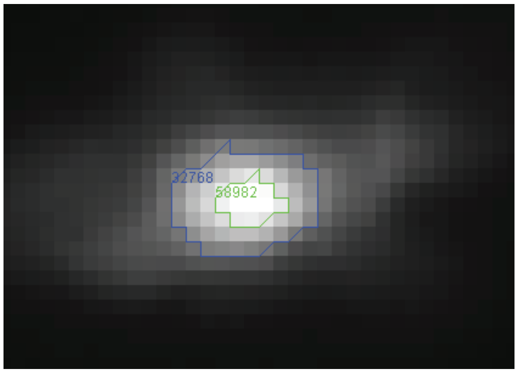

Figure 4: The image of a white LED, of diameter 0.56cm, reflected from the TrICE mirrors placed 11m above the ground. The blue contour outlines the region in which pixels of the image are at 90% of their maximum value, while the green contour labels the region in which pixels are at 50% of their maximum value.

is primarily used for measuring the effects of the night sky photon background on integrated charge values.

The back-end VME data acquisition consists of 9U VME modules designed to receive and buffer the digitized signals until they can be transferred to disk. A VMIVME 7766 single board computer running Linux controls the programming of the front-end and back-end VME modules and also handles the transfer and storage of buffered data. The back-end modules employ two memory buffers that switch on 20 ms interrupts. The VME CPU transfers data from the inactive buffer to disk while the active buffer fills with incoming data from the front-end modules. The throughput of the system is limited at this point, but the time required to transfer the data does not impose a constraint under normal operating conditions. Currently, 16 MAPMTs are installed for a total of 256 pixels each having an angular width of $0.086^\circ$. They are read out using a customized ASIC that digitizes continuously at 53 MHz over a dynamic range of 16 bits. The back-end modules handle the decoding of the front-end raw data into a calibrated data for each channel.

A charge injection system is built into the front-end electronics and is controlled by the data acquisition system. The injection system is used to calibrate each channel before observations. The conversions are applied to the raw data from the QIE's in the back-end electronics prior to buffering. The data transferred to disk are already calibrated to remove pedestal offsets and relative gain differences due to effects of the electronic modules.

## Discussion

The DC method has potential for identifying high energy cosmic rays on an event by event basis. TrICE uses novel optics to enhance the time delay between the DC light and the extensive air shower, as well as small pixel spacing to enhance the angular separation between the broad air shower and the narrow Cerenkov cone emitted by the primary particle. First observations of the TrICE telescope are complete and presented in this conference[6].

## Acknowledgements

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