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Shower Reconstruction Techniques for STACEE

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The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is an atmospheric Cherenkov detector that detects astrophysical gamma rays using the shower-front-sampling technique. STACEE is a fully operational detector utilizing 1 GS/s Flash ADCs on all channels, providing important pulse height and timing information for discriminating between γ-ray and hadron events. We discuss shower-front reconstruction methodologies and gamma/hadron separation techniques that utilize the nanosecond timing and pulse height information provided by STACEE's Flash ADCs.

1. Introduction

Ground-based atmospheric Cherenkov telescopes are well suited to the task of Very High Energy (VHE) γ-ray astronomy (in the energy range from 50 GeV to 50 TeV). Given the non-thermal power-law spectra of γ-ray emitting sources, a large collection area is vital at very high energies, where the flux of photons diminishes rapidly. By incorporating the atmosphere as part of the detector, ground-based γ-ray telescopes offer a distinct collection area advantage when compared to their lower-energy (below 50 GeV) space-based counterparts. Unlike space-based detectors, however, ground-based instruments suffer the lack of an anti-coincidence shield to guard against background cosmic rays. To overcome this disadvantage, sensitive detection techniques have been developed that distinguish γ-ray air showers from the large background of air showers induced by hadronic cosmic rays. We describe here the main shower reconstruction methodologies currently employed and/or under investigation by the STACEE collaboration for gamma/hadron separation.

2. The STACEE Detector

STACEE is a shower-front-sampling atmospheric Cherenkov telescope that uses the facilities of the National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico [1]. The NSTTF is a solar power research facility incorporating a 200 ft central receiver tower and an array of heliostats (solar mirrors). STACEE uses secondary mirrors, in the central receiver tower, to focus Cherenkov light reflected by the heliostats onto cameras having a total of 64 photomultiplier tubes. A one-to-one mapping between heliostats and PMTs allows the Cherenkov shower-front to be sampled independently at 64 different locations in the heliostat field.

STACEE uses a custom-built trigger system to select Cherenkov events from amongst the background of night-sky light fluctuations. In the event of a Cherenkov trigger, amplified and AC-coupled signals from the PMTs are recorded, together with a GPS timestamp, using 8-bit FADCs (one per PMT). The FADCs provide important temporal and intensity information, at a sampling rate of 1 GS/s, which is fully utilized in the offline analysis procedure.

A careful investigation of candidate gamma/hadron separation parameters requires extensive use of air shower and detector simulations. For γ-ray and hadronic air shower simulations, STACEE uses the CORSIKA package [2]. Custom ray-tracing and Monte-Carlo algorithms are used to simulate data generation by the telescope. Measured optical and electronic throughputs are incorporated into the simulations package.

3. Shower Reconstruction

In order to reconstruct the properties of the primary photon, an accurate estimate of the shower core location is essential. The shower core position on the heliostat field is the point at which the primary would impact, were it to travel unobstructed through the atmosphere. Three methodologies used by STACEE for shower core location are described below.

Template Fitting Method The template fitting method, detailed in [3], involves the generation of a large number of Monte-Carlo simulated charge templates that represent the charge from each PMT under various conditions. Templates are compiled using showers simulated over a large range of zenith angles, azimuth angles, and core locations. By finding the template which best matches a particular event, an approximate core location for that event is obtained. The mean core resolution for γ-rays obtained using this method is about 22 m, when applied to simulated γ-rays with energies between 20 GeV and 5 TeV generated on a differential spectrum of $E^{-2.4}$.

Early Shower Method The early shower method exploits the temporal profile of a γ-ray shower's Cherenkov front. The front of a γ-ray air shower comprises light originating at different heights along the particle cascade [4]. Light from shower maximum forms the bulk of photons in the shower-front, resulting in a spherical shape at ground level. However, since particles in the shower travel faster than the Cherenkov light that they produce, light that is emitted lower down along the shower's trajectory is detected first, before it has had time to move far from the core. This results in an apparent distortion of the sphere into a more conical profile. By calculating the center-of-gravity of the light in the first few nanoseconds of the shower-front, the shower core position can be accurately determined. Furthermore, given that the light pool at the beginning of the Cherenkov front is much smaller than that of the complete front, truncation effects, due to the finite sampling area, that otherwise would impact on the center-of-gravity calculation, are diminished.

By accounting for time-of-flight delays from the heliostats to the PMTs, and by applying a type of software trigger condition across each nanosecond sample of the FADC traces, the first nanosecond sample of the shower can be determined. With the beginning of the shower identified, the centre-of-gravity of the first few nanoseconds is calculable. The mean core resolution obtained using this method is $\sim$26 m.

Grid Alignment Method The grid alignment method was recently developed by the CELESTE collaboration, [5, 6], and was shown to work well when applied to their data. Since the Cherenkov front originating at shower maximum is roughly spherical, Cherenkov photons arrive at different heliostats at different times, depending on the heliostat positions relative to the front. A simple sum of the FADC traces provides, as a result, a pulse that is short and wide. By realigning the traces, however, such that the different propagation times from shower maximum to the heliostats are fully accounted for, the summed FADC trace will be narrower and have larger amplitude. Hence, by iterating over a grid of potential shower maximum positions, and calculating the resultant height to width ratio (H/W) of the realigned FADC traces for each grid point, the shower maximum position can be determined. The grid point with the narrowest and tallest resultant pulse ($[H/W]_{max}$) lies

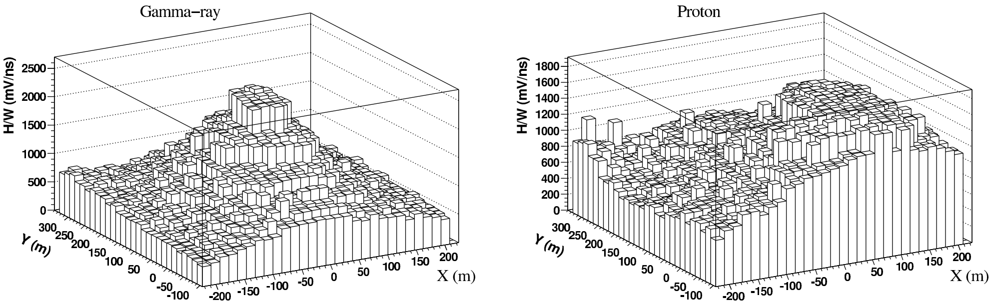

Figure 1. (Left) Distribution of H/W values for each point on a grid constructed at shower maximum altitude (12.5 km a.s.l.), for a simulated γ-ray air shower. The grid point with the tallest and narrowest summed FADC trace $[H/W]_{max}$ corresponds to the best estimate of the shower maximum location. Grid point coordinates correspond to their projection onto the heliostat field. (Right) Distribution of H/W values for a simulated proton air shower. The flatness of the proton distribution compared to the peaked γ-ray distribution can be used as a gamma/hadron discriminant [5, 6].

closest to the true shower maximum, figure 1 left. A straightforward projection of the shower maximum point to ground level provides the position of the shower core.

The core-finding procedure, as developed by CELESTE, is a two step process, whereby a coarse grid is used to find the approximate shower maximum position, followed by a fine grid around this point to improve the accuracy. Application of the method in STACEE's analysis code requires just one step—the fine grid—since an approximate shower core location is already provided by the template and early shower methods. The mean core resolution obtained using the combined grid-alignment and early shower methods is $\sim$21 m.

4. Gamma/hadron Separation

Gamma/hadron separation for atmospheric Cherenkov telescopes typically involves selection of γ-ray-like events, based on fitted parameters with measurable differences for γ rays and hadrons. Selection cuts for each parameter are determined using simulations and/or optimization on real data from a known source. At present two main gamma/hadron separation parameters are employed by STACEE; the *shower direction* and the *grid ratio* (referred to as ξ by the CELESTE collaboration). Both require an estimate of the shower core position.

The *shower direction* is determined by fitting the measured Cherenkov front for a conical time profile, with the point of shower maximum as a free parameter. A line from the estimated core position on the ground to the shower maximum, as determined by the fit, provides the reconstructed direction of the shower. Since γ rays are anticipated from the source direction (center of the field-of-view), an excess of ON-source events is expected with reconstructed directions close to the center, see figure 2 left. Using the reconstructed direction alone, STACEE can detect the Crab Nebula with good statistical significance [7].

The *grid ratio* parameter was developed by the CELESTE collaboration [5, 6], and is closely related to the grid alignment method for finding the shower core, described above. When correctly realigned for the shower maximum position, the parameter H/W of the summed FADC traces is at its greatest value. As shown in figure 1, H/W for γ rays falls off rapidly from the shower maximum location, since the FADC pulses quickly fall out of alignment. For hadrons, however, where the Cherenkov front is not spherical [4] and the pulses are poorly aligned to begin with, the H/W distribution is much flatter. The CELESTE group parameterize the H/W fall-

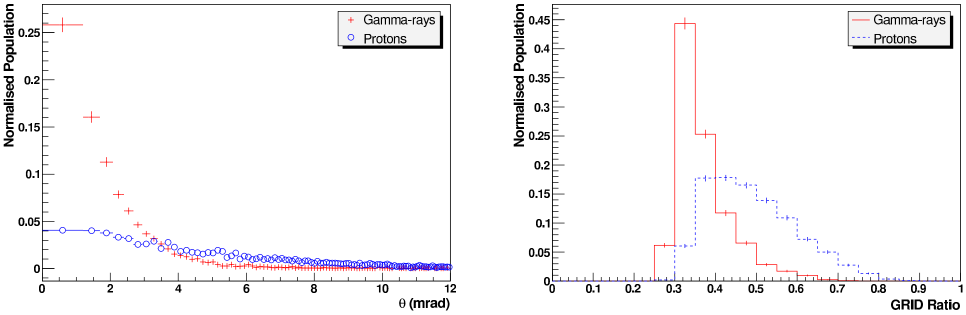

Figure 2. (Left) Distribution of θ for γ rays and protons. θ is the angle between the source direction and the reconstructed shower direction. Gamma rays, from the source at the centre of the field-of-view, have small values of θ. Bins have equal area on the sky. (Right) Distribution of the grid ratio parameter for γ rays and hadrons.

off using the ratio of the average H/W calculated at a distance 200 m away from shower maximum, to H/W at shower maximum, $\{\frac{(H/W)_{200m}}{(H/W)_{max}}\}$. This ratio, referred to here as the *grid ratio*, is a powerful gamma/hadron discriminant for the shower-front-sampling technique. Its power in STACEE simulations is demonstrated in figure 2, right. Application of a *grid ratio* cut, determined from simulations, to STACEE Crab Nebula data has proven quite successful [7].

5. Conclusion

Using FADC data STACEE can locate the core of γ-ray showers with an accuracy of ∼21 m, according to simulations. Two gamma/hadron discriminators, the reconstructed *shower direction* and the *grid ratio* parameters, show great potential in STACEE simulations and have been used to improve STACEE's detection of the Crab Nebula [7]. While work on other potential gamma/hadron separation parameters is ongoing, a planned optimization of the *shower direction* and *grid ratio* selection cuts, using Crab Nebula data, is expected to yield an improvement in STACEE's sensitivity for other γ-ray sources.

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