Shower Reconstruction Techniques for the Solar Tower Atmospheric Cherenkov Effect Experiment

JOHN KILDEA

McGill University, Montreal, Canada

on behalf of the STACEE collaboration*

ABSTRACT

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is an atmospheric Cherenkov detector that detects astrophysical γ-rays using the showerfront-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 showerfront reconstruction methodologies and gamma/hadron separation techniques that utilize the nanosecond timing and pulse height information provided by STACEE's Flash ADCs.

1 Introduction

1.1 STACEE

Figure 1: Photograph of the NSTTF in Albuquerque, New Mexico, showing the heliostat mirrors and the central receiver tower. STACEE uses the heliostats and tower as part of a showerfront-sampling atmospheric Cherenkov telescope.

STACEE is a showerfront-sampling atmospheric Cherenkov telescope that uses the facilities of the National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico, USA [1]. The NSTTF is a solar energy research facility that incorporates a central receiver tower and an array of heliostats (solar mirrors), figure 1.

A total of 64 heliostats are used to collect Cherenkov light from air showers, providing a combined reflecting surface of ~2,400 m^2. STACEE uses secondary mirrors, in the central receiver tower to focus Cherenkov light reflected by the heliostats onto photomultiplier tubes (PMTs), with a one-to-one mapping between the heliostats and the PMTs, figure 2.

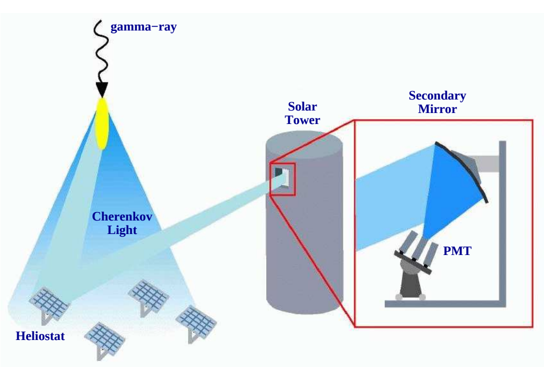

Figure 2: The showerfront-sampling technique as employed by STACEE. Cherenkov light from air-shower cascades is reflected by the heliostat mirrors onto secondary mirrors in the receiver tower, which in turn concentrate the light onto a bank of photomultiplier tubes.

Cherenkov events are selected from amongst the night-sky background using a custom-built trigger system. 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.

1.2 The Energy Range of STACEE

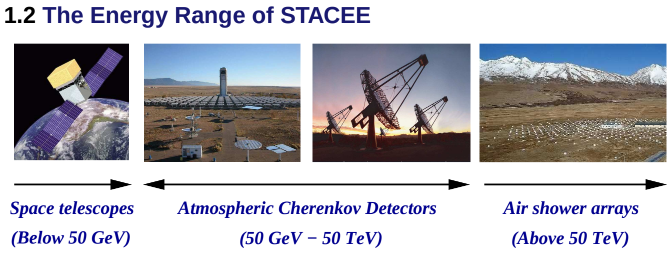

Figure 3: STACEE operates at around 100 GeV, in the energy region between space-based detectors and ground-based imaging atmospheric Cherenkov telescopes.

By using the very large mirror area heliostats of the NSTTF heliostats, STACEE achieves an energy threshold between 100 GeV and 200 GeV for the detection of γ-rays; the energy threshold of an atmospheric Cherenkov telescope scales approximately as $A^{-1/2}$ [2]. This relatively low energy threshold allows STACEE to detect γ-rays in the poorly sampled energy region below ~200 GeV, figure 3.

* The STACEE Collaboration

J. Ball[b], D.A. Bramel[c], J. Carson[b], C.E. Covault[d], D.D. Driscoll[d], P. Fortin[c], D.M. Gingrich[e,f], D.S. Hanna[a], A. Jarvis[b], J. Kildea[a], T. Lindner[a], R. Mukherjee[c], C. Mueller[a], R.A. Ong[b], K. Ragan[a], R.A. Scalzo[g], D. A. Williams[h], J. Zweerink[b]

(a) Dept. of Physics, McGill University, Montreal
(b) Dept. of Physics & Astronomy, UCLA, Los Angeles
(c) Dept. of Physics & Astronomy, Barnard College, Columbia University, NYC
(d) Dept. of Physics, Case Western Reserve University, Cleveland
(e) Centre for Subatomic Research, Univóf Alberta, Edmonton
(f) TRIUMF, Vancouver
(g) Lawrence Berkeley National Laboratory, Berkeley
(h) Santa Cruz Institute for Particle Physics, UCSC, Santa Cruz

2 Shower Reconstruction

2.1 Overview

In the development of shower reconstruction methods, simulated γ-ray and cosmic-ray air shower data were employed. STACEE uses the CORSIKA air shower simulations package [3]. Custom ray-tracing and Monte-Carlo algorithms are used to simulate the telescope optics and electronics.

To reconstruct the properties of the primary photon, an accurate estimate of the shower core location is required. 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 techniques used by STACEE for shower core location are described below.

2.2 Early Shower Method

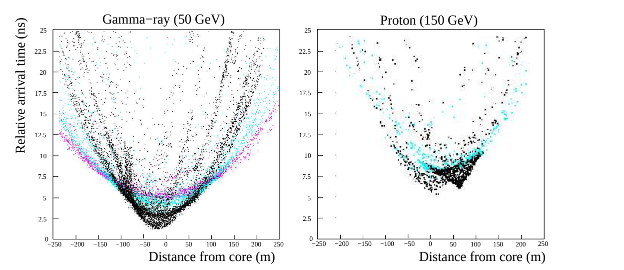

Figure 4: Monte-Carlo generated arrival times of Cherenkov photons as a function of distance from the shower core for a 50 GeV γ-ray air shower and a 150 GeV proton air shower. The time is relative to the arrival time of the incident particle if it had continued at speed c. The colors indicate the altitude of emission of the photons (purple: emitted above 10,000 m, blue: between 6,000 m and 10,000 m, black: emitted below 6,000 m). Images taken from [4], courtesy of G. Sembroski.

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, figure 4. 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. By calculating the center-of-gravity of the light pool in the first few nanoseconds of the shower-front, the shower core position can be accurately determined.

The mean core resolution obtained using this method is ~26 m, when applied to simulated γ-rays with energies between 20 GeV and 5 TeV generated on a differential spectrum of $E^{-2.4}$.

2.3 Grid Alignment Method

The grid alignment method, developed by the CELESTE collaboration, [5, 6], exploits the nature of the Cherenkov showerfront. Since the temporal profile for photons originating at shower maximum is roughly spherical [4], 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 wide and has low amplitude, figure 5 (a).

By realigning the FADC traces 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, figure 5 (b).

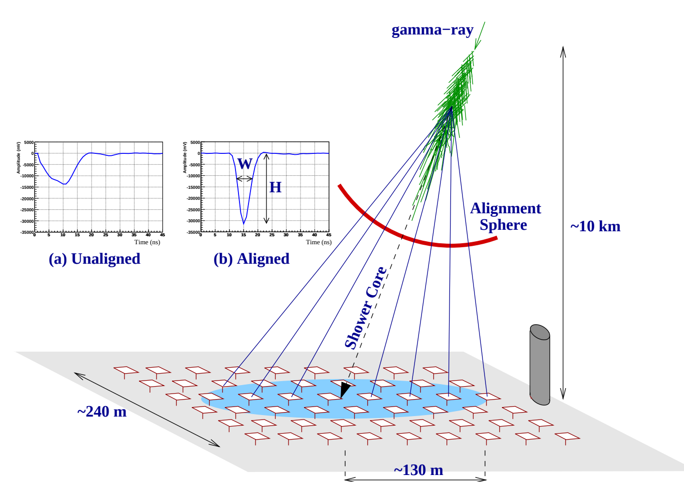

Figure 5: Schematic of the grid-alignment method. (a) A simple addition of the Cherenkov pulses, as recorded by STACEE's FADCs, provides a resultant pulse that is short and wide. (b) A sum of the Cherenkov pulses after re-alignment, to account for photon propagation times from shower maximum to each of the heliostats, provides a resultant pulse that is tall and narrow. The true shower maximum position (and hence the shower core) may be estimated by iterating over a grid of assumed shower maximum positions and finding the resultant pulse that is tallest and narrowest.

The shower maximum position can be determined by iterating over a grid of potential shower maximum positions, and calculating the resultant height to width (H/W) of the realigned FADC traces for each grid point. The grid point with the narrowest and tallest resultant pulse ($[H/W]_{max}$) lies closest to the true shower maximum, figure 6 left. A straightforward projection of the shower maximum point to ground level provides the position of the shower core. The mean core resolution for γ-rays obtained using this method is ~21 m.

2.4 Template Fitting Method

The template fitting method, detailed in [7], involves 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 ~22 m.

3 Gamma/hadron Separation

3.1 Overview

At present two main γ/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.

3.2 Grid Ratio

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 earlier.

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 6, 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 typically not spherical [4] and the pulses are poorly aligned to begin with, the H/W distribution is much flatter.

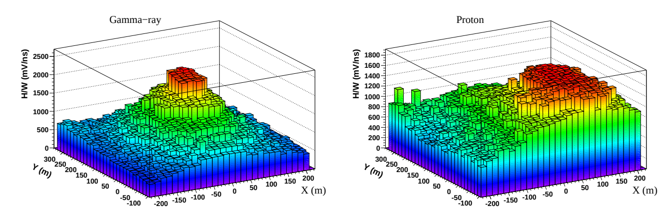

Figure 6: (Left) Distribution of H/W values for points on a grid constructed at shower maximum altitude (12.5 km a.s.l.), for a simulated γ-ray air shower. The grid point with the tallest and narrowest summed FADC trace $[H/W]_{max}$ corresponds to the best estimate of the shower maximum location. Grid point coordinates correspond to their projection onto the heliostat field. (Right) Distribution of H/W 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].

The CELESTE group parameterize the H/W fall-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 7, left. Application of a **grid ratio** cut, determined from simulations, to STACEE Crab Nebula data has proven quite successful [8].

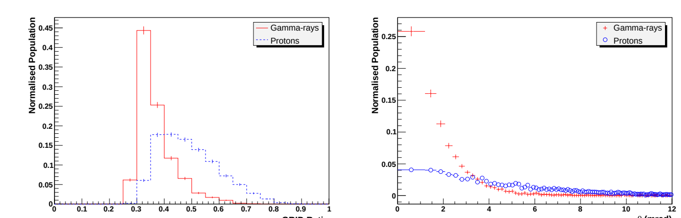

Figure 7: (Left) Distribution of the grid ratio parameter for γ-rays and hadrons. (Right) Distribution of θ for γ-rays and protons. θ is the angle between the source direction and the reconstructed shower direction. γ-rays, from the source at the centre of the field-of-view, have small values of θ. Bins have equal area on the sky.

3.3 Shower Direction

The **shower direction** is determined by fitting the measured Cherenkov front 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, figure 8.

Since γ-rays are anticipated from the source direction (center of the field-of-view), an excess of events is expected with reconstructed directions close to the center, see figure 7, right. Using the reconstructed direction alone, STACEE can detect the Crab Nebula with good statistical significance [8].

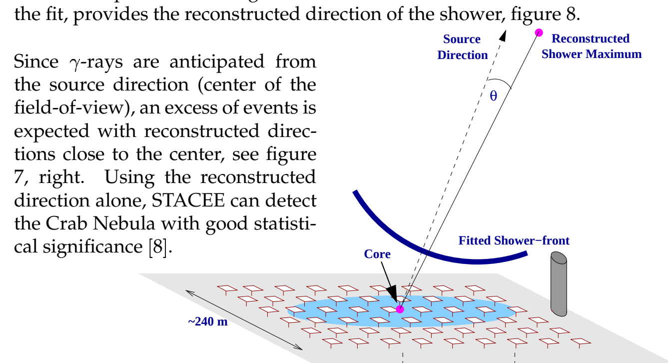

Figure 8: Schematic of the shower direction reconstruction method used by STACEE. θ is the direction between the source and the reconstructed direction. The shower maximum position is estimated using a fit to the wavefront, the shower core is located as described in section 2.

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 to improve STACEE's sensitivity to γ-rays..

References

[1] Gingrich, D. M., et al., (astro-ph/0506613)
[2] Weekes, T. C. 1988, Phys. Rep., 160, 1
[3] Heck, D., et al., 1999, Rep. FZKA 6019, Forschungszentrum Karlsruhe
[4] Sembroski, G., et al., 1997, 4th Compton Symposium on γ-ray astrophysics
[5] Bruel, P., et al., 2004, Proc. Frontier Science, Physics & Astrophysics in Space
[6] Manseri, H., et al., 2005, AIP Conference Proc., Vol 745 645-650
[7] Scalzo, R. A., et al., 2003, Proc. 28th IRCR, Tsukuba, Japan
[8] Kildea, J., et al., 2005, these proceedings