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THE SOLAR TOWER ATMOSPHERIC CHERENKOV EFFECT EXPERIMENT

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Abstract

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a ground-based atmospheric Cherenkov telescope for the detection of very high energy gamma rays from Galactic and extra-galactic sources. By utilizing the large collection area provided by the solar mirrors of the National Solar Thermal Test Facility in Albuquerque, New Mexico, STACEE achieves a low energy threshold, around 100 GeV, for gamma-ray observations. We describe the STACEE detector and detail recent observations and results.

1 Introduction

The Solar Tower Atmospheric Cherenkov Effect Experiment is an atmospheric Cherenkov telescope that uses the facilities of the National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico for the detection of astrophysical gamma rays with energies in the range 50 GeV to $\sim$1 TeV. The NSTTF is a solar power research facility which includes a central receiver tower and an array of heliostats (solar mirrors). For solar power research, the heliostats are used to track the sun and concentrate its light onto the tower. STACEE is one of four atmospheric Cherenkov telescopes which were built to employ the optical facilities of this type of solar energy research installation; the others include CELESTE (the Cherenkov Low Energy Sampling and Timing Experiment) [1], GRAAL (Gamma-Ray Astronomy At ALmeria) [2], and Solar Two [3].

By utilizing the very large mirror area provided by the heliostats of the NSTTF (each heliostat has a surface area of $\sim$37 m^2) to collect the Cherenkov light emitted by atmospheric particle cascades, STACEE achieves an energy threshold of around 100 GeV for the detection of cosmic gamma rays; the energy threshold of an atmospheric Cherenkov telescope scales approximately as $A^{-1/2}$ [4] (A is the mirror area). This relatively low energy threshold, compared to the second generation of imaging atmospheric Cherenkov telescopes, allows STACEE to detect gamma rays in a poorly sampled energy regime, until recently inaccessible to both satellite and ground-based instruments. Furthermore, since the gamma-ray horizon extends further for lower energy gamma rays than it does for higher energy gamma rays, which are attenuated by the Extragalactic Background Light (EBL), STACEE has a richer set of extra-galactic target sources than the more traditional imaging Cherenkov experiments. As such STACEE observations have the potential to address fundamental astrophysical issues such as the unobserved cutoff in the pulsed emission spectra of gamma-ray pulsars and the EBL-induced cut-offs expected in AGN spectra.

2 The STACEE Detector

STACEE was commissioned in several stages, commencing in 1997 and completed in 2001. The first stage, STACEE-32, comprised an array of 32 heliostats and was used to detect the Crab nebula with high statistical significance [5]. The second stage, STACEE-48, completed in 2000 represented an upgrade from 32 to 48 heliostats and included a number of important improvements to the optics and electronics of the detector. STACEE-48 was used to detect flares from the blazar Markarian 421 during the spring of 2001 [6]. The final upgrade of STACEE to 64 heliostats, STACEE-64, was completed in the fall of 2001 and has been in regular operation since.

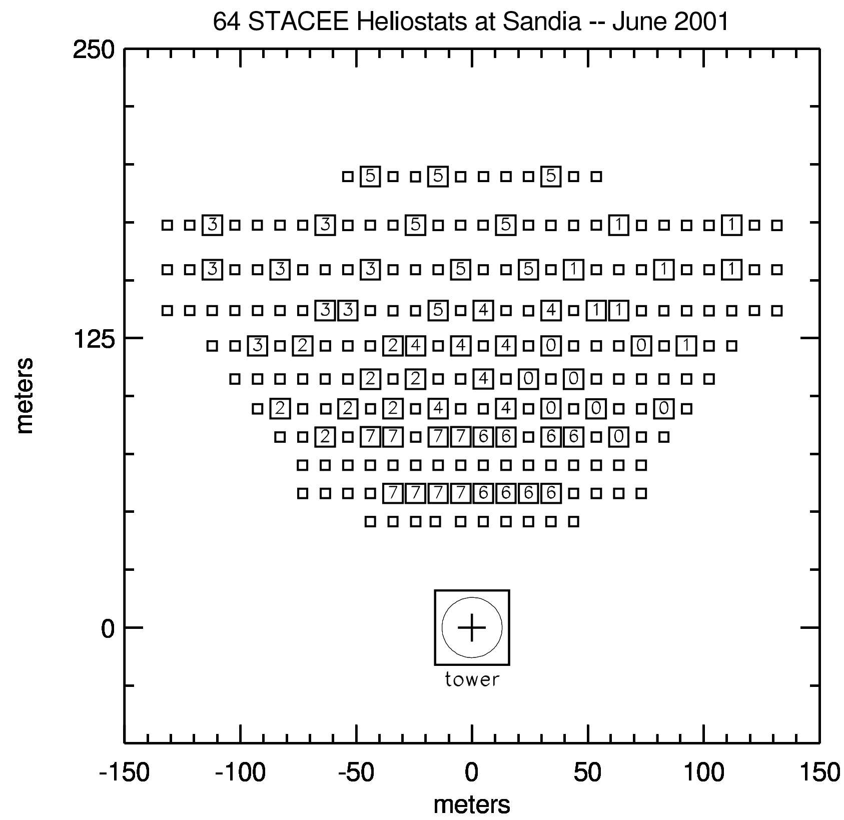

Figure 1: Map of the NSTTF heliostat field currently used by the STACEE experiment. Heliostats are numbered according to the trigger cluster to which they belong. The base of the NSTTF solar tower, which houses the STACEE optics and electronics, marks the origin of the coordinate system.

STACEE is essentially a wavefront sampling atmospheric Cherenkov detector, using as its primary optic an array of 64 heliostats. The heliostats are used to reflect Cherenkov light from extensive air showers onto 5 secondary mirrors located on the 200 ft solar tower adjacent to the heliostat field (see figure 1 for a map of the heliostat field currently used by STACEE). The secondary mirrors in turn focus the Cherenkov light onto a camera of 64 photomultiplier tubes. A one-to-one mapping between heliostats and PMTs allows the Cherenkov wavefront to be sampled independently at 64 different locations in the heliostat field. Extraneous background light from the night sky is reduced by using optical concentrators based on the DTIRC design [7] which widen the aperture of each PMT from 5 to 11 cm and limit their fields of view to include only light from the direction of the target heliostat.

Amplified and AC-coupled signals from the PMTs are fanned out to 8-bit FADCs (one per PMT) and to a three-level digital trigger and dynamic delay system. The first level of the trigger system provides fixed discrimination of the PMT pulses for input into a programmable delay pipeline. Dynamic delays are required to account for the combined effects of the sidereal motion of the source during observations and for the geometry of the Cherenkov wavefront, both of which result in time-of-flight differences for Cherenkov photons detected from different heliostats. The STACEE delay system is a custom built VME and FPGA based unit which provides programmable delays in 1 nanosecond steps over a one microsecond range [8]. The second and third levels of the trigger system demand sub-cluster and inter-cluster coincidences of the delayed pulses within a short time window, typically 16 nanoseconds. Trigger clusters are groups of eight heliostats which are located near each other on the heliostat field; STACEE-64 comprises eight such clusters (see figure 1). Cherenkov events which meet the trigger criteria are recorded for offline analysis, with a typical trigger rate of about 5 Hz.

The installation of FADCs represented a major part of the STACEE-64 upgrade. Fully digitized waveforms from each PMT provide valuable timing and pulse shape information for use in the wavefront sampling technique. The STACEE FADCs are a commercial system produced by *Acqiris, Inc* and are operated using custom software running on a real-time Linux operating system. Each FADC samples at 1 GHz with a dynamic range of 1 V.

STACEE uses non-event information such as atmospheric monitoring data, heliostat tracking data, PMT anode current monitoring data, and laser flasher calibration data in offline calibration and detector stability monitoring. A modification to the STACEE electronics system during the summer of 2004, to move the FADC system closer to the PMTs and to install new high-gain pre-amplifiers at the PMTs will allow STACEE to operate with a faster, cleaner, electronic system at a lower energy threshold during the upcoming seasons. Figure 2 presents an overview of the STACEE electronics and monitoring system.

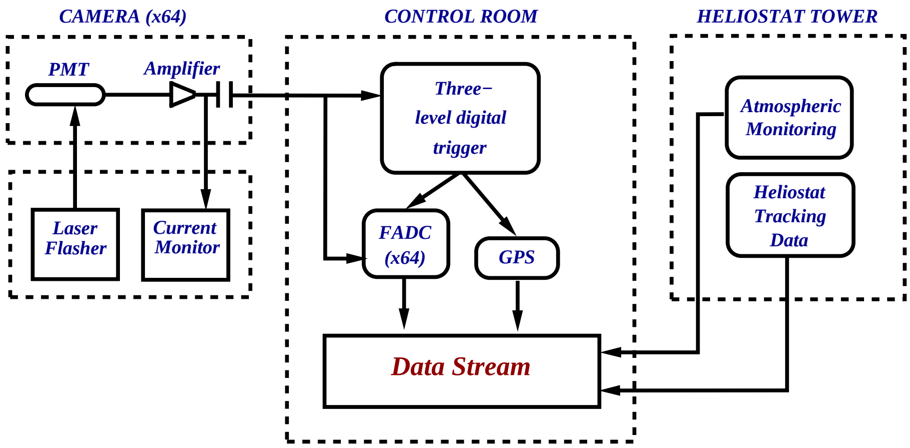

Figure 2: Overview of the STACEE electronics and monitoring system. Cherenkov signals from all 64 PMTs are amplified and fanned out to a three-level dynamic delay and trigger and to a FADC system. Events which meet the trigger criteria are time-stamped by a GPS clock and written to the data stream. Monitoring and calibration data are also periodically written to the data stream.

3 Data Acquisition and Analysis

STACEE observations are conducted in ON/OFF mode. In this mode conterminous observations of the source and a control region of sky, at the same azimuth and elevation as the source, are undertaken. A gamma-ray signal from the source manifests itself as an excess of ON events. Any night-sky background brightness differences between the ON and OFF sky regions, which might otherwise introduce bias into the analysis, are accounted for through the use of software padding; the quieter ON or OFF FADC trace for a particular channel is padded up to the same noise level as its counterpart, through the use of a library of measured FADC noise traces.

As is the case for all atmospheric Cherenkov telescopes, the sensitivity of STACEE for the detection of gamma rays is limited by the abundant background flux of hadronic air showers. Unlike imaging Cherenkov telescopes, however, which reject hadronic events by exploiting pronounced differences between the focused images of gamma-ray and hadronic air showers, wavefront sampling experiments distinguish signal and background events on the basis of subtle differences in the lateral and temporal profiles of their Cherenkov light pools. Event reconstruction for STACEE involves the fitting of the shower front after the application of necessary timing corrections, the use of simulated optical efficiency values to account for photon losses between heliostat and PMT, and the location of the impact point of the shower core on the heliostat field. An accurate knowledge of the shower core position is vitally important in order to reconstruct the direction of origin of the instigating photon and to allow for an estimate of its energy.

STACEE is currently experimenting with two independent methods for finding the shower core. The first method, detailed in [9], involves the generation of a large number of Monte-Carlo simulated charge templates which represent the charge at each PMT under various conditions. In the simulation process, the CORSIKA air shower simulation package [10] is used for the production of air shower events and custom ray-tracing and Monte-Carlo algorithms are used to simulate data generation. By finding the template which best matches a particular real event both an approximate core location and an estimate of the shower energy for that event are obtained. The templates used are compiled over a large range of energies, zenith angles, azimuth angles, and core locations. The mean core resolution for gamma-rays obtained using this method is about 22 m, when applied to simulated gamma-rays with energies between 20 GeV and 5 TeV generated on a spectrum of index -2.4.

The second method exploits the full pulse profile information provided by the STACEE FADCs and is independent of simulations. It locates the shower core using a simple centre-of-gravity calculation for the early part of the Cherenkov wavefront. Although a rather crude shower core position may be obtained by simply finding the centre-of-gravity of the complete Cherenkov wavefront, truncation of the front due to the finite size of the heliostat field typically degrades the accuracy of the result. It is fortuitous however, that the shape of the Cherenkov wavefront for gamma-ray showers around 100 GeV is approximately spherical. As such, while the complete light pool of a triggering shower can extend beyond the heliostat array, the early part of its Cherenkov wavefront (the first few nanoseconds) are likely to be contained within it. By accounting for the 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 for the same gamma-ray simulated events used in method 1.

4 Recent Observations

During the 2003/2004 observing season STACEE undertook observations of AGN, plerions/pulsars, and Gamma Ray Bursts (GRBs). In total 184 hours of on-source data were recorded of which 139 were spent observing blazars (namely W Comae, 3C 66A, H1426+428, OJ+287, and Markarian 421), 40 were dedicated to plerions/pulsars (the Crab nebula/pulsar) and 5 were GRB follow-up observations. An equal amount of time was spent on off-source observations.

While recent observations have not yielded any new source detections, the BL Lac object Markarian 421 was detected in a high state during the spring of 2004, at the level of about 6σ in approximately 11 hours of clean data. Work is ongoing to derive a spectrum from these data.

STACEE data on the BL Lac object W-Comae, detected by EGRET (spectral index $\alpha = 1.73$) but not by ground-based imaging telescopes operating above 250 GeV, have been used to produce upper limits on its gamma-ray flux [11]. Using 10.5 hours of STACEE W-Comae data 95% CL upper limits on the integral flux above 100 GeV for leptonic emission models and above 150 GeV for hadronic emission models were obtained. Although the leptonic models predict fluxes below the STACEE limits, extrapolations of the best-fit EGRET power law, and some synchrotron-proton hadronic models, predict fluxes close to or above the STACEE upper limits.

5 Conclusions

STACEE has undertaken regular observations of known and potential sources of TeV gamma rays since the STACEE-64 upgrade of 2001. A number of results have been produced using these data and future improvements are expected as the development of STACEE offline data analyses advances. Exploitation of important charge and timing information provided by the STACEE FADCs is just commencing and should provide significant improvements in sensitivity, through better gamma/hadron separation, for application to archival and future data. Given that STACEE is one of the lowest energy atmospheric Cherenkov telescopes operating in the northern hemisphere, and considering recent hardware improvements, which provide a faster, cleaner, detector with a lower energy threshold, the motivations to continue STACEE observations into the GLAST era (mid 2007) are stronger than ever.

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