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Operation and Performance of the Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE)

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Abstract

STACEE is a new experiment for ground-based gamma-ray astronomy. Located at the National Solar Thermal Test Facility (Sandia National Laboratories, Albuquerque, NM), STACEE uses an array of large heliostat mirrors designed for solar power applications. These mirrors are used at night to collect Cherenkov light from gamma-ray air showers. The large mirror area enables STACEE to operate in the energy range from 50 to about 250 GeV. Construction of STACEE began in 1998 and will continue through 2000. Currently, STACEE is operating with 32 heliostats, with plans to expand to 64 heliostats. We present a summary of the STACEE instrument design and performance based on preliminary observations.

1 Solar tower Cherenkov detectors:

Two new "solar tower" Cherenkov detectors have recently begun gamma-ray astronomy observations. These are the CELESTE experiment in France (Smith 1999) and the Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) at Sandia National Laboratories in Albuquerque, New Mexico, USA. A third experiment is under development at the Solar Two facility near Barstow, California, USA (Zweerink 1999).

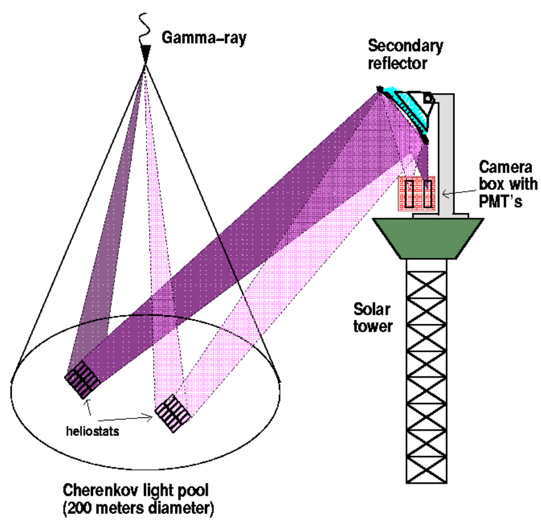

Figure 1: Concept of solar tower Cherenkov detection of gamma-ray air showers.

Figure 1 shows a conceptual drawing of how solar tower experiments detect gamma-ray air showers. Large heliostat mirrors are oriented to reflect Cherenkov light from air showers onto secondary mirrors located near the top of a central tower. The secondary mirrors reflect this light into a camera box containing photomultiplier tubes (PMT's). Each PMT is positioned to collect light from a single heliostat. A trigger is formed from a narrow time coincidence of several discriminated PMT signals. Accurate pulse timing is used to reconstruct the arrival direction of the primary, while pulse height measurements are used to determine the primary's energy. The relatively large light collection area provided by heliostat mirrors allows solar tower detectors to achieve a substantially lower energy threshold than conventional imaging air Cherenkov telescopes.

2 STACEE design:

A detailed description of STACEE's design and a summary of various site tests are available elsewhere (Chantell 1998). The NSTTF site (106.51°W, 34.96°N) has over 200 fully steerable heliostat mirrors, each with 37 m^2 of light collection area. The STACEE instrument, consisting of secondary optics and PMT cameras, is mounted on a platform on the solar tower 52 meters above the ground. Since October 1998, STACEE has been operating with 32 heliostats as shown in Figure 2.

Each secondary is a 1.9 meter diameter front-surface aluminized spherical mirror composed of seven individual facets arranged in a hexagonal pattern. Each secondary mirror concentrates light onto sixteen PMT's in the camera box. Non-imaging concentrators (Ning 1973) mounted on each PMT restrict the field of view and further concentrate the collected light. Each PMT may be positioned at any location or heading within the camera box to maximize light collection.

Each PMT signal is fed through a high-pass filter and amplifier and is then discriminated. Programmable delays compensate for variations in pulse arrival time as the source tracks across the sky. STACEE currently uses a two-level trigger (four sub-clusters of eight heliostats each) and requires a minimum of 15 out of 32 PMT's firing within a 12 nanosecond coincidence window. Multi-hit TDC's measure the shower front arrival time at each heliostat. Pulse heights, discriminator rates, and PMT currents are also recorded. Each event is time-stamped using a GPS clock.

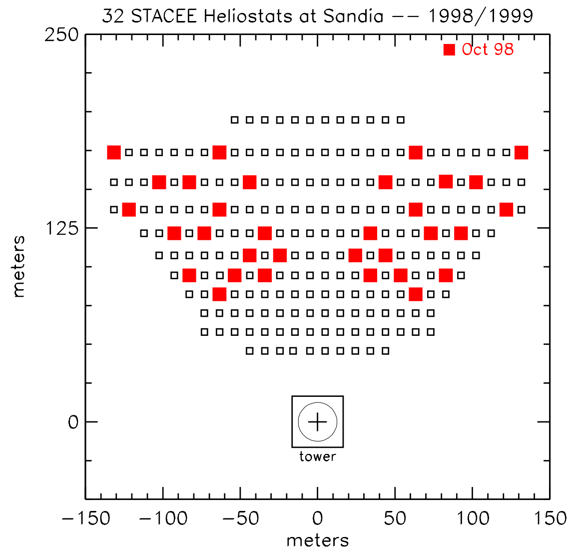

Figure 2: Plan view of NSTTF facility in Albuquerque, NM indicating 32 heliostats used for STACEE since October 1998. STACEE will expand to 64 heliostats in the year 2000.

3 Optics:

The ability to achieve a low energy threshold depends critically on the throughput of the STACEE optical system. To maximize efficiency, we wish to align the optical components as precisely as is practical. During September and October 1998, the positions and angles of all optical components, including mirrors, cameras, and PMT's, were carefully surveyed using a precision theodolite. Alignment was cross-checked using point light sources in the field.

We also used light from the full Moon to determine azimuth and elevation encoder offset "bias" values (absolute headings) for each of the 32 heliostats. Moonlight from each heliostat was projected onto a screen mounted at each secondary and imaged using a CCD camera. CCD data was reduced in real time, and biases were adjusted accordingly. These corrections were made to a precision of approximately one bit on the shaft angle encoders, corresponding to an angle of about 0.05°.

Heliostat performance has been also monitored and logged during astronomical observations. Heliostat reliability has been high, with less than one heliostat malfunction per month for STACEE heliostats. Weather conditions that can impact heliostat performance, such as wind speed and dew-point temperature, are also monitored by our own local weather station and logged to a file.

4 Timing and event reconstruction:

Angular reconstruction is determined from the arrival times of the Cherenkov photons at each heliostat. Therefore calibrating and characterizing STACEE's timing resolution is critical. The transit time between when the Cherenkov pulse strikes a heliostat and when the resulting PMT pulse reaches the TDC has been carefully measured using a combination of geometrical surveying of the optical components, and in situ measurements of pulse transit times through the phototubes and electronics with both an LED flasher and a laser calibration system. These effects are now understood to within 0.2 nanosecond, and are routinely corrected for. In addition, timing variations as a function of pulse height (slewing) have been measured with the laser calibration. After all timing corrections have been applied, the residual pointing bias is reduced to $< 0.1°$, comparable to the tracking accuracy of the heliostats. Figure 3 shows the timing residuals for one channel relative to the best fit spherical wavefront. With RMS residuals of $\sim$1 ns, we expect an overall angular resolution of approximately $0.25°$.

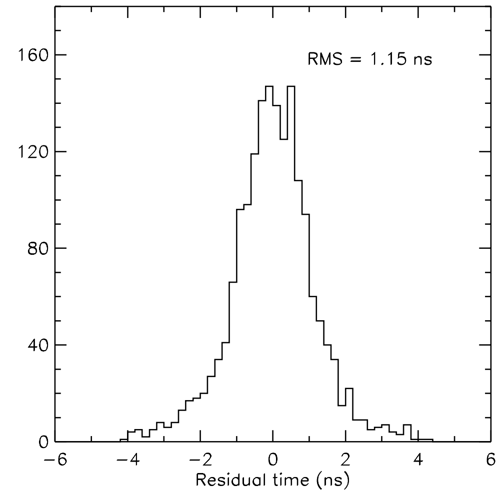

Figure 3: Timing residuals for one STACEE channel relative to the best fit spherical wavefront.

We can independently verify our angular resolution by dividing STACEE into two overlapping arrays of 16 heliostats each and reconstructing showers separately in each sub-array. Figure 4 shows the distribution of space angle differences between the two sub-arrays for cosmic ray showers that trigger STACEE. The median difference of about 0.3° supports our estimate of STACEE's angular resolution.

5 STACEE response to air showers:

Air showers at sub-TeV energies produce maximum Cherenkov output at an altitude of about 10 km above sea level. We therefore expect that the rate of Cherenkov triggers will be optimized when the heliostats are pointed at this location (shower maximum). In practice, this means that the heliostats are slightly canted inward relative to a source at infinity. We define a "canting parameter" which is simply the inverse of the tracked point's altitude in kilometers above sea level. A value of zero corresponds to tracking a source at infinity, while negative values indicate divergent canting.

Figure 5 shows the STACEE trigger rate from the zenith directly above the array as a function of canting parameter. This curve demonstrates that the maximum rate is obtained for cosmic ray air showers with maximum Cherenkov output at $\sim$10 km above sea level as expected. Also shown for comparison are rates calculated using the Hillas air shower Monte Carlo together with a detailed optical and electronics simulation of the STACEE instrument. The match between simulation and observations reflects our understanding of the end-to-end response of the STACEE optical system and allows us to use our simulations with confidence to determine effective areas and

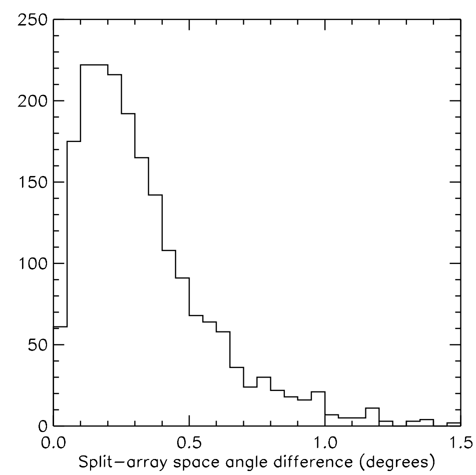

Figure 4: Distribution of space-angle differences between overlapping sub-arrays for cosmic rays detected by STACEE. The median difference of about 0.2–0.3 degrees provides an independent estimate of STACEE's angular resolution.

to maximize the performance of the instrument in the future.

6 Observations:

The partially constructed STACEE instrument has been operated on most clear moonless nights since October 1998. Most of the data were obtained with the heliostats oriented to track a source at the zenith. In this mode, all observed triggers are presumed to result from (hadronic) cosmic rays. The trigger rate is about 2 Hz. These data are used to verify performance and calibrations.

The primary astrophysical source observed from November 15, 1998 to February 18, 1999 was the Crab Nebula. Approximately 50 hours of data on the Crab were collected. A preliminary analysis indicates that STACEE detects the Crab with high statistical significance (+7σ) (Oser 1999).

Observations during the next year or two will concentrate on AGN. Scientific goals and plans for observing AGN with STACEE are described elsewhere (Mukherjee 1999).

7 Future plans:

STACEE is under construction and will be completed in the year 2000. We plan double the number of heliostats used from 32 to 64, with additional secondaries to obtain full coverage of the NSTTF heliostat field. We will also implement 1 GHz flash ADC's (and associated VME-based data acquisition system) for simultaneous timing and pulse height measurements on every channel. We expect with these changes to lower the energy threshold and improve the sensitivity with better reconstruction and hadron rejection.

8 Acknowledgments:

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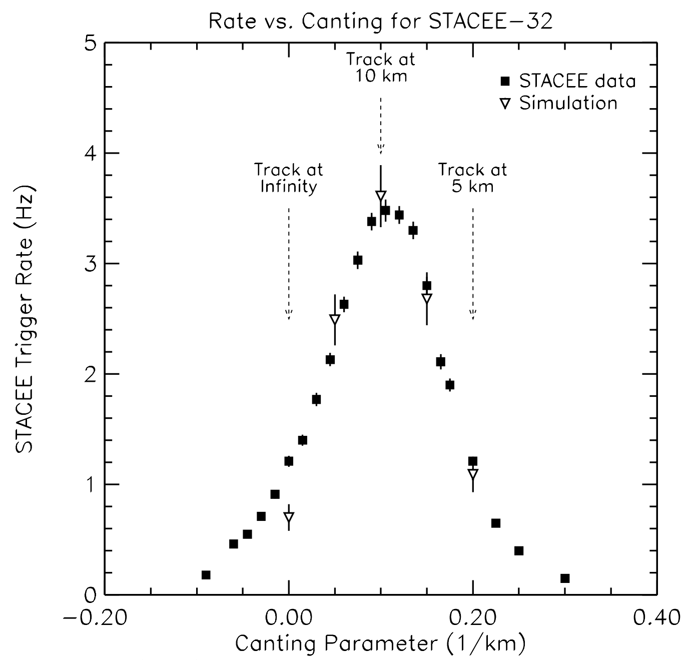

Figure 5: STACEE trigger rate vs. canting parameter = 1/height (km) above sea level.

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