The Schwarzschild-Couder Telescope for the Cherenkov Telescope Array Observatory

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Abstract

The Cherenkov Telescope Array Observatory (CTAO) will greatly improve upon sensitivities in the field of very-high-energy gamma-ray astrophysics. The dual-mirrored Schwarzschild-Couder Telescope (SCT) is a candidate medium-sized telescope (MST) for CTAO-South and is capable of observations in the energy range of 100 GeV to 10 TeV. Inaugurated in January 2019, the prototype SCT (pSCT) located at the Fred Lawrence Whipple Observatory in southern Arizona observed gamma-ray emission from the Crab Nebula at a significance of 8.6 sigma. An upgrade of the pSCT camera is underway to fully instrument the camera with 11,328 pixels and an 8.04-degree diameter FoV. Upgraded electronics will lower the front-end electronics noise, allowing for a lower trigger threshold and improved event reconstruction and background rejection.

Introduction

The pSCT dual-mirror optics reduce optical aberrations and achieve near isochronism, leading to an improved point spread function (PSF) and reduced trigger coincidence window. The SCT 9.66 m primary and 5.4 m secondary mirrors focus images to a reduced plate scale allowing for effective use of a SiPM camera. The mirrors were aligned to achieve an on-axis optical PSF of approximately 3 arcminutes. During the detection of the Crab Nebula [1], only 25 modules were produced and installed in the central sector, resulting in a 2.7-degree square FoV [2].

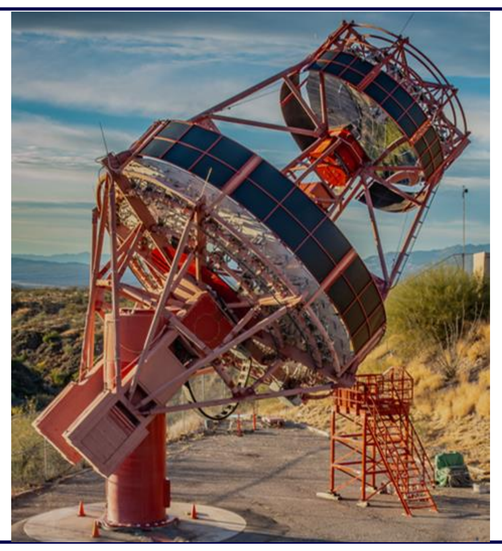

Fig. 1: Photograph of the pSCT at Fred Lawrence Whipple Observatory in Arizona.

Camera Upgrade

The pSCT camera upgrade includes updates to both the camera mechanical design and the module electronics. The upgraded pSCT modules' main components are:

- Focal-plane module (FPM)
  - Fondazione Bruno Kessler Near Ultra-Violet High-Definition SiPM pixels [3]
  - SMART application specific integrated circuits (ASICs) [4] - shape the SiPM pulses, adjust the fine bias of the SiPMs, and monitor the SiPM currents
- Front-end electronics (FEE)
  - CT5TEA ASIC - responsible for the low-level trigger and the readout voltage baseline
  - CTC ASIC - samples the FPM signal at 1 GSa/s and stores the charge measured signal in a 16,384-sample ring buffer switched-capacitor array for readout via Wilkinson ramp ADCs [5]

The combination of ASIC designs replaces the single T7 ASIC design used in the camera during initial operations. The division of triggering and digitization electronics into multiple ASICs will reduce the data path noise.

ACKNOWLEDGEMENTS

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https://www.ctao.org/for-scientists/library/acknowledgments/

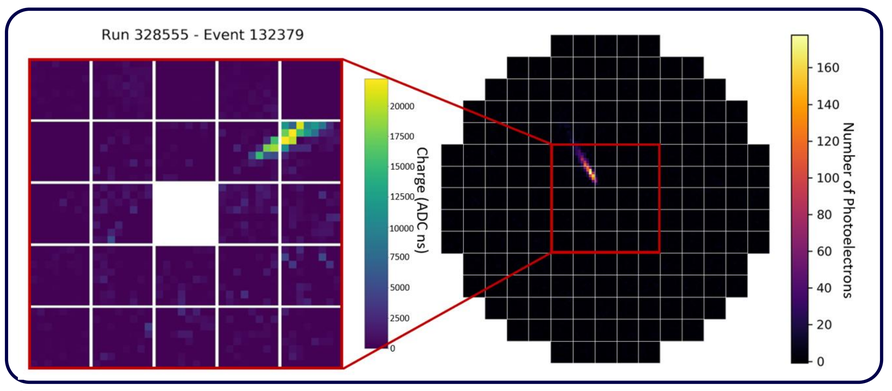

Fig. 2: The first gamma ray detected by the pSCT on January 17, 2020 during observations of the Crab Nebula is shown on the left. On the right is a simulated 2.72 TeV gamma ray in the upgraded pSCT camera. The red box outlines the central sector that was populated in the initial camera.

Performance

The lower electronics noise and increased FoV of the upgraded camera is expected to significantly improve upon the performance of the pSCT (see figure 2). The performance of a test camera module was evaluated in the lab using a custom LED flasher. A histogram of charges, sometimes called a "finger plot", was fit to extract parameters that describe the camera module's performance. The individual photoelectron peaks in the histogram can be modeled by Gaussian fits. The fit parameters are:

- Gain - each Gaussian has a mean equal to the channel gain multiplied by the number of photoelectrons
- Electronics noise and the gain noise - the variance of each Gaussian is the sum in quadrature of two contributing sources of noise.
- Offset - accounts for the waveform baseline by shifting the Gaussian means by a constant value
- Optical crosstalk and mean number of photoelectrons – input parameters for generalized Poisson distribution described in [6] that determines the relative amplitude of each Gaussian

By fitting the sum of these Gaussians the channel gain, electronics noise, gain noise, charge offset, average number of photoelectrons per event, and channel optical crosstalk can be extracted (see figure 3).

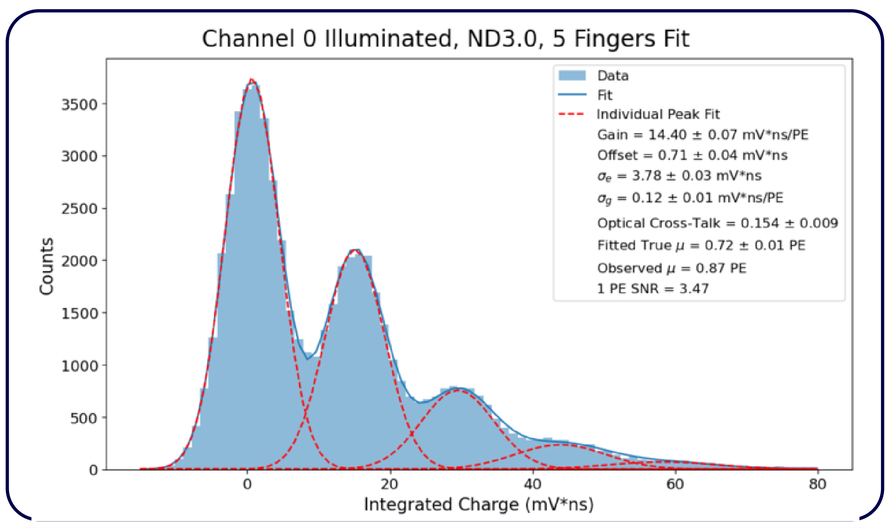

Fig. 3: Histogram of calculated charges for a run of low intensity LED flasher events. A fully constrained fit was performed as a sum of Gaussians. The red lines indicate the individual Gaussians while the light blue line indicates the sum of the Gaussians.

The charge resolution - defined as the standard deviation of the charge divided by the mean of the charge in a single run - can be calculated at different intensities for each channel. CTAO previously released a charge resolution requirement and goal for CTAO telescopes and to evaluate our camera module performance, we compared our charge resolution to these values and the Poisson limit (see figure 4). The differences between the two sets of runs are likely due to the differences in systematics of the fit methods.

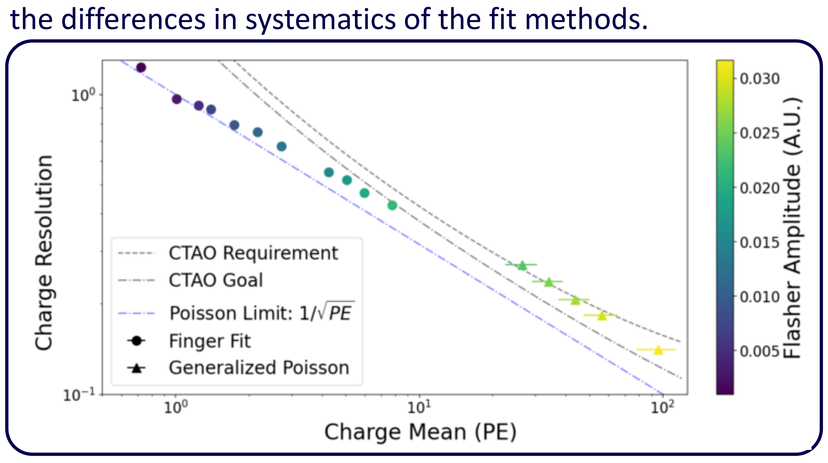

Fig. 4: Charge resolution of 16 LED flasher runs as a function of mean charge. The circle and triangle markers indicate different data analysis, the light blue dash-dot line indicates the physical limit to charge resolution set by the Poisson limit, while the other two gray lines indicate the former CTAO charge resolution requirement and goal.

Conclusion and Outlook

Simulations show that the addition of SCTs as an upgrade to CTAO-South would maximize the improvements to the array's angular resolution and sensitivity, particularly off-axis (figure 5). Through its detection of the Crab Nebula, the pSCT has already proven its scientific capabilities. The upgraded camera has been installed in the telescope and mass production of the upgrade modules is imminent. The upgrade camera module will lower the electronics noise, improving trigger performance and event reconstruction. With an upgraded camera, the pSCT will demonstrate the capabilities of a single SCT.

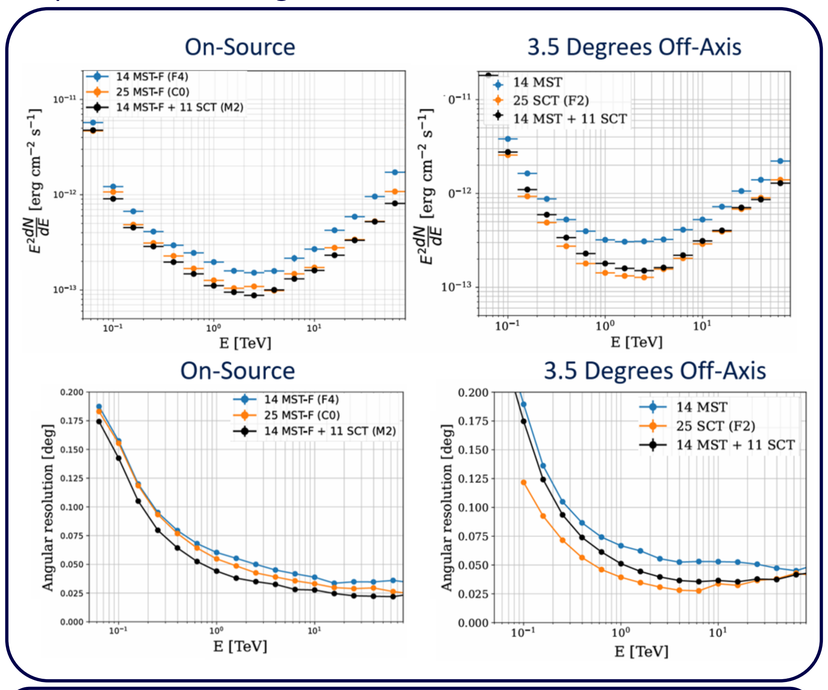

Fig. 5: Flux sensitivity and angular resolution as a function of energy for different MST and SCT configurations. The left column shows on-source observations while the right column displays observations 3.5 degrees off-axis. The values were calculated using the CTAO prod3b IRFs.

References

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