Mirror Panel Edge Sensors for the Schwarzschild-Couder Telescope

Jonathan Sun[1], Brian Humensky[2] & Daniel Nieto Castano[2]

[1] Department of Computer Science, Columbia University, New York, NY, USA
[2] Department of Physics, Columbia University, New York, NY, USA

Gamma-ray Astrophysics and Motivation: Gamma-ray astrophysics is an exciting field of high-energy particle physics that has expanded dramatically in the past decade. The science of gamma-ray cosmology presents a way of looking at the most interesting parts of the universe. Very high energetic particles in space indicate the existence of exotic and extreme physical conditions. Looking for gamma-ray emissions allows us to map the universe, discovering high magnetic/electric fields, shock waves, and cataclysmic explosions. These emissions offer the only direct probe of the extreme conditions in these exciting phenomena [2].

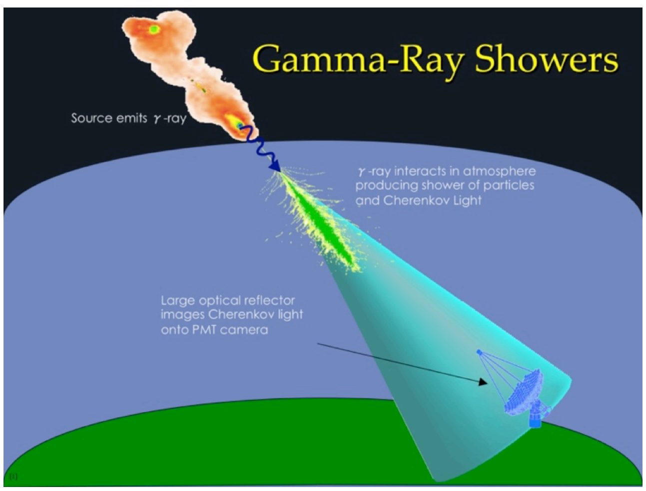

Figure 1: Gamma-ray showers and cherenkov light

Very energetic particles are extremely difficult to detect. Charged particles are affected by the incredibly strong magnetic fields of deep space, so when they reach earth it is impossible to deduce the origins of the particle. Gamma rays are unaffected by these magnetic fields. A gamma ray is a packet of electromagnetic energy photons. They are the most energetic photons in the electromagnetic spectrum, and they are emitted from the nuclei of unstable radioactive atoms. They travel in straight lines allowing astronomical instruments to determine the origins of the high-energy particles. However, there is an inverse relationship between particle energy and particle flux; higher energies result in very little flux. Space-based instruments are expensive and too small to properly detect higher energy particles. Modern projects use ground-based instruments designed specifically to detect gamma rays. It does so through secondary radiation detection. The process is visualized in figure 1: A source emits a gamma ray. The gamma ray interacts with the nitrogen in the atmosphere, producing a shower of electrons, positrons, and other particles as the gamma ray decays. This particle shower is seen as a radiation called "Cherenkov light." Large optical reflectors in the ground-based telescope then image the Cherenkov light onto a photomultiplier tube camera in the instrument. Multiple telescopes imaging the same Cherenkov radiation allow us to triangulate and pinpoint the origin of the particle shower with a 3D reconstruction of the shower in the sky [1].

Development of the MPES:

Overview: The new Cherenkov Telescope Array (CTA) is a next generation global-project ground-based observatory for high-energy (30 GeV—200TeV) gamma ray astronomy. The new Schwarzschild-Couder telescopes introduce a novel Imaging Atmospheric Cherenkov Telescope design featuring a Schwarzschild-Couder aplanatic two-mirror optical system (Fig 2). An integration of several tens of these new telescopes will yield an astronomical instrument accommodating a wider field-of-view, significantly improved angular imaging resolution, and expanded energy detection range. It is more economic and yields better image quality and background rejection. The new reduced plate scale design also makes it compatible with highly integrated cameras assembled from silicon photo multipliers.

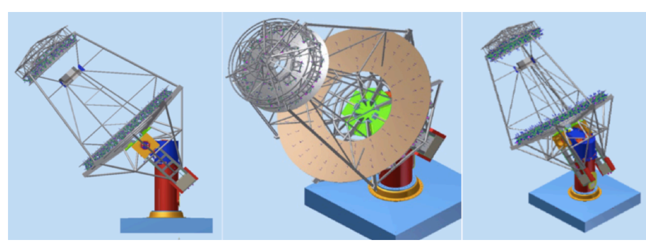

Figure 2: The new SCT design

Each SCT plate is composed of several individual mirror panels. Each mirror panel needs to be precisely adjusted and positioned in order for accurate viewings of the sky. Traditionally, ground-based telescopes needed to be manually adjusted. The new telescope array plan renders this process extremely tedious. Thus, the project of developing edge sensors for the mirror panels began. The general concept is seen in Figure 3. Three edge sensors are placed between all adjacent plates for six degrees of freedom, allowing for location knowledge of a singular mirror panel in 3D space. The edge sensors will measure the relative displacements between mirror panels as an input for the panel-to-panel alignment system. When the edge sensors give information to the alignment system that indicates a mirror panel is displaced, the system will command the actuators underneath that mirror panel to correct its position accordingly. The edge sensors are required for a positional resolution of just a few µm over an operational area of around 10mm by 10 mm.

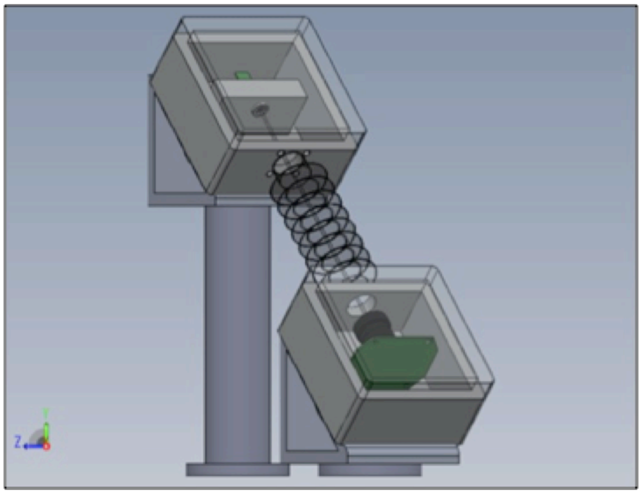

Figure 3: MPES design component

Edge Sensor Design: The sensor design is very basic. A single sensor consists of a photo sensor and a corresponding light source fundamentally. The sensor presents a single optical axis defined by a laser beam, which is orthogonal to the photo sensor plane. The primary components of the edge sensor consist of an economic USB webcam and an economic laser diode module. These components are both adequate for precise measurements and economically efficient. The laser diode emits its light at the webcam. The webcam will record an image of the laser dot (Fig. 4). The positioning of the overall mirror panel is thus calculated and measured via the position of the laser dot in the webcam image; a displaced dot infers a displaced mirror panel.

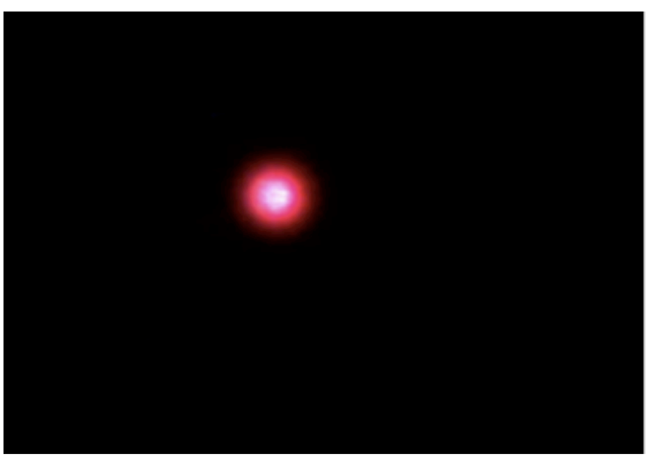

Figure 4: Sample laser image

Positioned in-between the photo sensor and the light source are two components to assist the accuracy and precision of the sensor module. The first component is a collimator. It acts as a diaphragm and allows the laser to pass through a small pinhole (300 µm diameter) that narrows the laser beam. The second component is an opal glass screen to diffuse the laser light just before the webcam.

Webcam Testing and Disassembly: The project ordered a total of 380 webcams to be used for the edge sensors. Like the laser diodes, the quality of the webcams was expected to vary. Consequently, the webcams needed to be opened and tested for resolution and image quality. The defective cameras would be returned. The webcams were tested using a resolution test chart (Fig. 5). Next, the cameras needed to be disassembled to install them in custom sensor housings in the sensor unit.

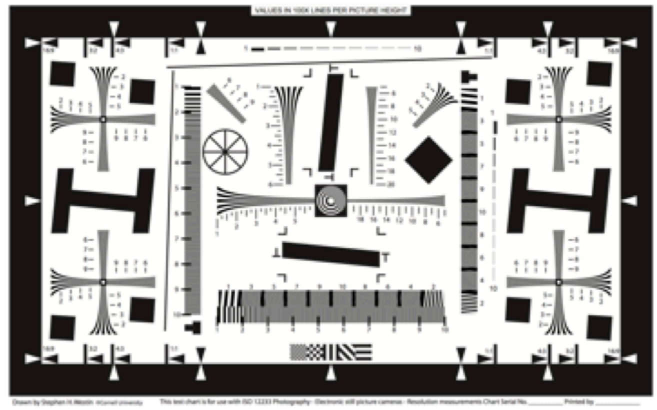

Figure 5: Resolution test chart

Webcam Image Distortion: An issue became evident as the webcams were tested. Many of the cameras exhibited a “fishbowl,” or distortion affect where the captured image was slightly warped. The severity of the warping varied from camera to camera, with some exhibiting barely any warping and some exhibiting significant warping. An experiment was performed to test this. Three cameras were used, one exhibiting negligible warping, one exhibiting some warping, and one exhibiting severe warping. The lenses were permuted between the camera circuit bodies to test if the lenses caused the distortions (Fig. 6). The results are surprising. The distortions did not follow the lenses as predicted. In figure 6, a similar distortion pattern remains consistent between the lens permutations on body *C*. This suggests that the photo sensor holder causes the distortion instead of the lens.

Environmental Stress Tests: The final project to be discussed is the project regarding environmental variables and their effects on edge sensor stability and performance. The primary environmental factor of concern is temperature–it seems to have the most significant effect on laser intensity. An alteration of laser intensity can have damaging impacts on the sensor accuracy. If the intensity is too high and the webcam exposure level does not account for this, the image becomes extremely oversaturated. The center is impossible to determine. If the image is too underexposed, it becomes very difficult to determine the center of the laser as well. The ultimate purpose is to visualize the relationship between the environmental stresses and image intensity.

The project began with using data from a prototype edge sensor tested in the field last summer and an edge sensor tested in a laboratory. Laser images taken and regular intervals over a period of several weeks were compiled with <.log> files detailing the time, temperature, and humidity at the

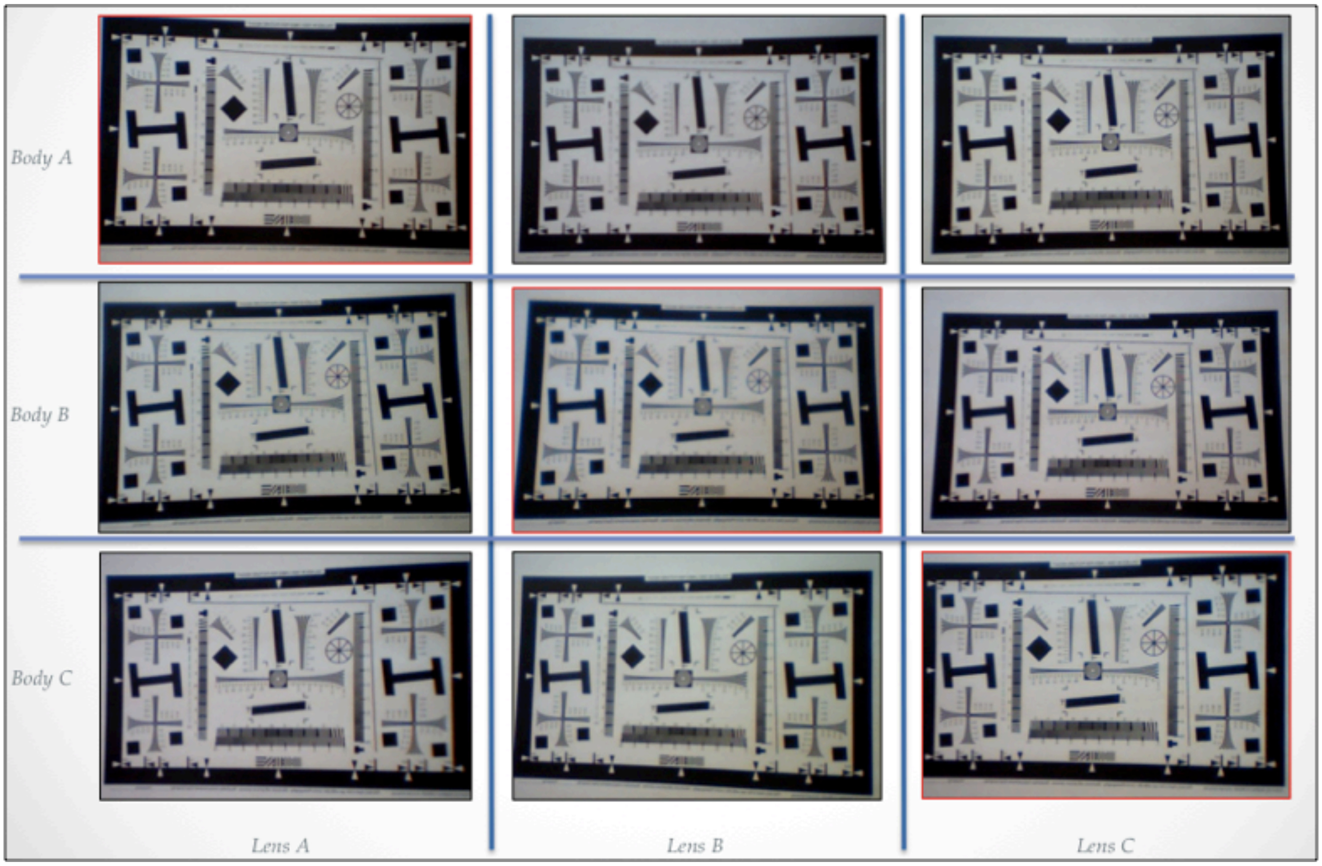

Figure 6: Lens permutation tests. Images highlighted with a red border indicate lenses paired with their original bodies.

moment of each image capture. All together, this served as a database for the next step.

A perl script was written to scour the database of images and environmental variables. This script needed to account for errors in the database such as missing images, inconsistent time intervals, missing times and environmental information, inconsistent orderings of images and scalar data, and images that were completely unusable. The script ran the images through another pre-constructed C++ function called "snapshot" that scanned the image and produced the image intensity and the *X* and *Y* centroid values. This information was compiled with environmental information to produce a single <.log> file containing all of the information.

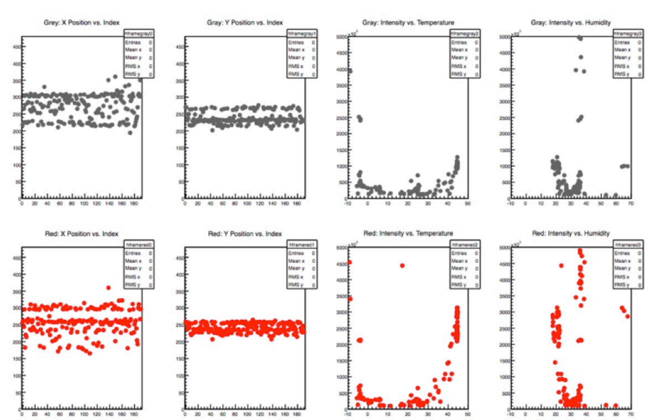

Figure 8: "Extreme" stress tests data

A subsequent R00T macro (an extension of C++) was written to handle the <.log> file. The macro gathered all the data and produced graphs that mapped the relationships between environmental variables and sensor performance. The results are shown in Figures 7 and 8. [Editor's Note: Figure 7 can be found on the next page.]

Stress Tests Analysis: The results are very interesting and inconclusive. The top rows of graphs (in both figures) show the data after the laser image is converted to grey-scale. The bottom set of graphs comes from the original colored images. The first two columns of graphs show the *x*-centroid position and *y*-centroid position respectively. Each dot is an image taken at a unique time. The *x*-centroid is much less consistent than the *y*-centroid position. There also appears to be two 'bars.' The investigation into this phenomenon is ongoing.

Originally, it was hypothesized from preliminary testing that there would be an inverse, linear relationship between temperature and laser intensity. As the temperature became colder, the intensity was increase. However, the outdoor stress test results show no clear relationship in this manner. The spray of intensity levels is extreme and strange. The lab 'extreme' stress tests show a similar inconclusive result.

The outlying and severely varied intensity values may have been due to faulty images in the database. Some of the images appeared to be distorted in terms of color and intensity. The analysis is ongoing in the CTA project.

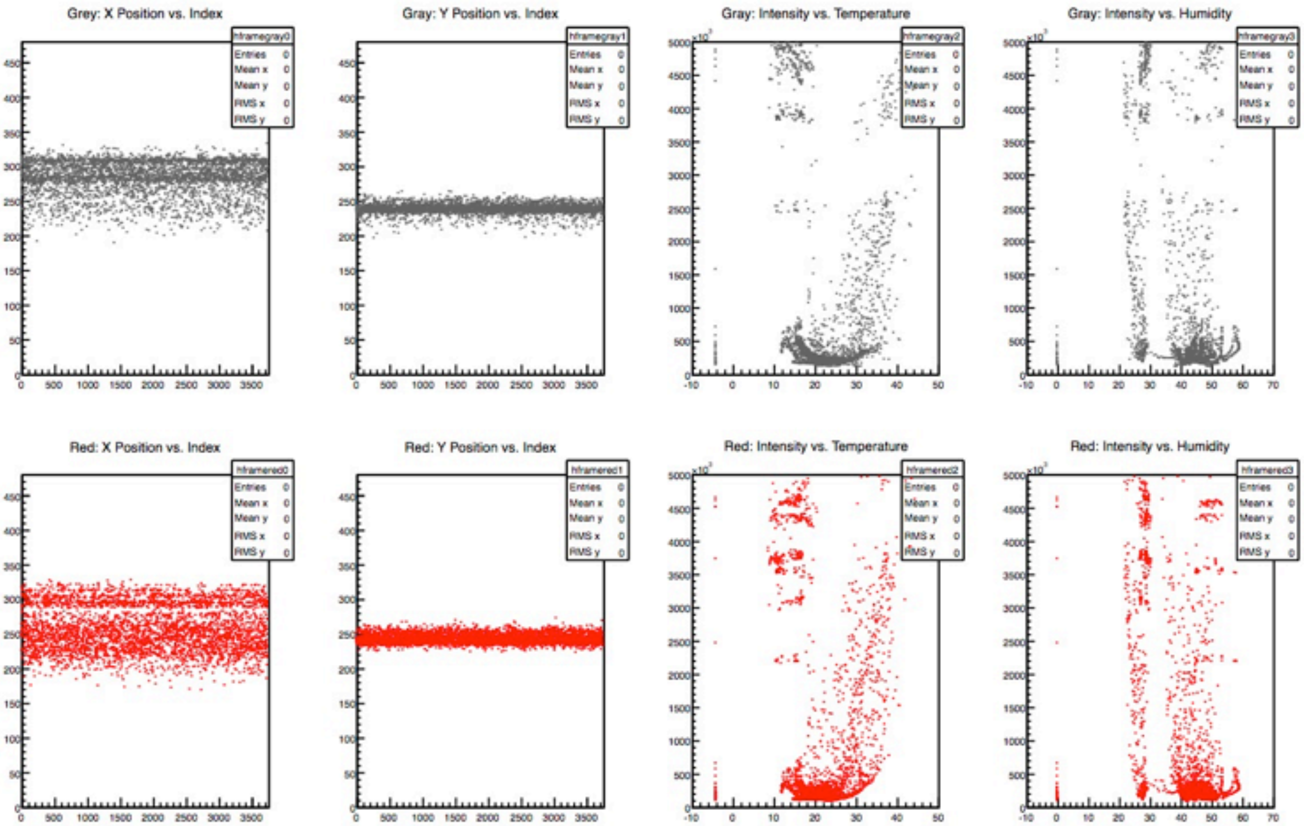

Figure 7: Outdoor stress tests data

Acknowledgments:

This research was supported by Columbia University in the City of New York. Dr. Brian Humensky and Dr. Daniel Nieto of the Nevis Laboratories guided this research. The authors would like to thank the primary author's research advisor Dr. Gasperov.

References:

[1] G Humensky, Brian. "Some Helpful Slides."
[2] <http://veritas.sao.arizona.edu/about-veritas-mainmenu-81/atmospheric-cherenkov-technique-and-veritas-technologies-mainmenu-87>
[3] "SCT-OPT/MEC Design Report for SCT Review." MAN-PO/120920.
[4] arXiv:1307.4072 [astro-ph.IM]
[5] Nieto, Daniel. "Development of the Prototype SCT Mirror Panel Edge Sensors." CTA Consortium Meeting Chicago / May 28, 2013.
[6] "Resolution Test Chart." <http://www.graphics.cornell.edu/~westin/misc/ISO_12233-reschart.pdf>.