Abstract

The goal of this project is to develop high-level algorithms for the middle sized telescope known as the prototype Schwarzschild-Couder Telescope Array, or simply as the pSCT. The Algorithms consist of recreating Cherenkov showers through steps such as setting a pedestal cut of the charges, acquiring parameters to describe its direction and distinguishing gamma-ray and cosmic showers.
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Introduction

Reconstructing a gamma-ray is a multistep process that is essential for the observation of exotic astronomical sources using ground based instruments such as VERITAS or the Cherenkov Telescope Array, which is in development at this time. The purpose of these studies is to understand various cosmic events and a good way to do this is to study cosmic rays that are bombarding earth constantly, but studying these cosmic rays can be quite difficult. Cosmic rays are difficult to study for a number of reasons, for one they don’t trace back to a source, which is essential to understanding what type of environment created it. Due to this, observing other byproducts of these astrological events are much easier to observe and trace back to the source such as high energy gamma-rays. Where gamma-rays are high energy photons that travel through the vacuum of space unaffected by the galactic magnetic background unlike its cosmic ray counterpart which due to its charged nature are affected by the magnetic background. Gamma-rays are the product of high energy processes occurring in sources such as supernova remnants, active galactic nuclei and pulsars which can create these high energy gamma-ray. These gamma-rays are perfect for studying from the ground using telescope instruments, but as the high energy photons can not make it past our atmosphere, but its resulting emissions can.

Once a gamma-ray photon hits the atmosphere it turns into high energy particles that travel through our atmosphere at speeds exceeding the speed of light in the medium and emitting Cherenkov radiation which can be detected by ground based telescopes. Telescope arrays such as VERITAS (Very Energetic Radiation Imaging Telescope Array System) use four telescopes to observe these cosmic showers in an effort to gain insight into these far away and relatively
unknown sources. VERITAS has been used to observe many galactic and extragalactic sources and help develop a better understanding of the various astro-gamma events that go on constantly in the galaxy, yet this telescope array will be replaced by a new telescope array, the Cherenkov Telescope Array (CTA). CTA is being designed to have a sensitivity an order of magnitude higher than the telescope arrays that preceded it. Developing this system also means developing hardware and software that can accurately acquire the data and quickly analyze it and store it.

CTA will cover an energy range of about 10 GeV to 100 TeV and consist of roughly four large telescopes, and anywhere up to twenty five medium sized telescopes plus several small telescopes. A prototype medium sized telescope, known as the Schwarzschild-Couder Telescope is the United States collaboration contribution to the Cherenkov Telescope Array. The medium sized pSCT will be able to observe very high energy gamma- rays in the 100 GeV to 10 TeV energy range. The prototype is being designed and created in order to run various test in order to determine if going forward with this specific model is worth it. Along with this telescope software would need to be developed in order to analyze showers that are seen by the camera, display diagnostic values, be able to quickly look at real time data and change various parameters if necessary. The events are analyzed through the software and displayed in a graphical user interface or graph that depicts each pixel and whether it has been triggered or not. When a pixel is triggered it turns a color depending on how much charge is associated with that pixel. There are 11,328 pixels in the graphical user interface representation of the camera and each one represents a pixel in the actual camera that observes the particle shower that has been detected. Due to all the background light and random hadronic showers that the camera also sees every few microsecond methods must be programmed and developed in order to sift through possible gamma-ray showers and the noise the background light creates. Due to all these issues facing
recreating a clean shower image it can be done through a series of steps that ensure a clean shower that represents what was seen by the camera.

Reconstruction Overview

Given a simulation file where an almost ideal shower is stored you can begin the process of developing steps and procedures to analyze the shower like the event display software does for VERITAS. The reason event display is not currently used with the prototype telescope is due to the amount of time it would take to analyze the shower. So in order to fix this issue faster procedures must be developed in order to analyze the shower for the new prototype telescope. The pSCT is in the process of being built therefore creating a system that allows a user to look at the image in real time and make changes if necessary is essential. The ability to do this would require the software to run continuously and quickly in order to handle the amount of data you can acquire from a shower. Creating a quicklook or a component that will allow real time analysis for the active runs and past runs that are stored somewhere. This quicklook should allow a user to change various parameters if necessary like the threshold cut or charge cut where necessary. Creating the components of the gamma-ray reconstruction to ultimately get this software up and running is necessary for the pSCT. These reconstruction steps will be efficient and effective in recreating the camera image that is clean and allow further analysis that will describe properties of the galactic source that created the gamma-ray shower.

Integrating Pulses

The first thing we do is examine a single pixel to get an estimate of how much charge a single pixel can have. Also examine what the ADC curve and what it looks like and how it relates to how much charge that pixel now has. By examining this curve you can discern how much charge is in the pixel and also how much noise from the hardware that pixel may be
experiencing. By setting a cut value or pedestal value you can eliminate the pedestal value so that you can look at the charges each pixel has without such a value distorting that value. Once

![Figure 1. Image showing the pulse and the area of integration](image1.png)  
**Figure 1. Image showing the pulse and the area of integration**

![Figure 2. Depicting the camera after being cleaned](image2.png)  
**Figure 2. Depicting the camera after being cleaned**

this value has been set you can create an integration function that gets the charge under the curve without any noise associated with the pixels. Then creating a histogram to better see and understand what the pedestal value is when it summated of all pixels in the camera. Also, you can use the histogram to display individual pixel pedestal value that can describe and better see the individual pedestal values in those situations. Once this is done we can now recreate the shower image in a graph or graphical user interface that shows charges in each pixel whether it is a part of the shower or random light that the camera has, and it is these random light that the camera sees that needs to be removed in order to clean the image and leave behind only the shower image.

**Cleaning the Image**

As the camera observes an air shower and sees the Cherenkov radiation, which triggers the silicon photomultiplier (SiPM) detector, which then causes the hardware to record the signal
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trace observed. Due to the background light hitting the camera this can populate the shower images with random hits. Due to this the camera would show a shower, but also background light which can distort the image and cause future calculations to be distorted. Therefore creating a charge cut can depopulate the amount of pixels that were affected by the background light and other random particles and make analyzing such an event much easier for the software. In order to do this you must sum up the charges of each specific pixel which yields huge numbers that represent the overall charge of that pixel. Making an initial charge cut of 900 cleans most of the image of the noise and background pixels that are plaguing the shower image. Once this is done there might be left over pixels that made the cut and are above the threshold that was set. These pixels that might be in other areas of the camera and nowhere near the shower could affect further analysis of attaining direction and other parameters of the shower. In order to deal with these isolated pixels an algorithm to remove them must be used that checks whether or not the pixel or its neighbors has charge and ensuring that if a pixel is isolated it will be removed. Creating a distance value which in this case allows for checking to see if there are pixels in the immediate area of the pixel and if so the pixel is left alone and proceed to the next pixel location

Figure 3. The moments parameters, taken from the Veritas wiki page.
and repeat this for all the pixels in the shower image. Once this is done the remaining pixels should be those that are relevant to the shower and will be used for calculating parameters to determine the direction and energy of the shower.

Fitting an Ellipse

In order to calculate the various parameters associated with the properties of the shower using the moment’s method accomplishes this which was developed by A.M Hillas which was developed by the ctaobservatory group on github. The moment’s method or Hillas parameters calculates the size of the shower, the width, the length, direction relative to the center of camera and various angles associated with the center of the camera along with the center of the shower image, as shown in figure 4. First we calculate the size of the shower by summing up all the charges that are associated with the pixels in shower then we can also calculate the center of the shower by dividing by this size variable and multiplying the x coordinate pixels and y coordinate pixels by the charges and summing up all the values each produces. By calculating the center of the shower gives an idea of where the shower is located so that an ellipse can be fitted and attain the direction of shower relative to the center and its rotation. Once the center and size are calculated you can calculate the Hillas Parameters in order to better understand the shower, by calculating the length and width of the shower. To gain an understanding of the head and tail of
the shower the brightest pixel or charge can be used to discern which way the shower is pointing. In the case of the simulation data being used, the brightest pixel is a pixel closest to the center of camera or pointing toward the center of the camera. Other parameters such as the miss, which is the perpendicular distance from the center of the camera to the image axis, and also the distance from the center of the camera to the center of the shower are calculated. The parameter “azwidth”, which is the width measured perpendicular to the radius passing through the shower center is also attainable and also helps with fitting an ellipse to the shower. Also, being able to calculate the angle of the shower relative to the center of the camera and the rotation angle of the shower relative to its axis is extremely important in fitting the shower with an ellipse and understanding its overall direction with respect to the center of the camera. In the case of simulation data, the various Hillas Parameters agree well with the characteristics of the showers that were injected. From the image above(figure 4) you can see that the shower is in the fourth quadrant of the camera plane, and is pointing almost directly to the center of the camera. The rotation angle which is based on the image suggests that the shower could be concentrated in that direction along that line. Once the moment parameters have been calculated being able to fit an ellipse to the shower will be the last step. Fitting an ellipse is essential, because the agreement could indicate if the shower is due to a gamma-ray or a hadron which is essential and the software should be able to make such decisions every few microseconds as the observation of sources would yield continuous data.

Sort Gamma-Ray Cosmic Ray Showers

Cosmic rays also create a shower and emit Cherenkov radiation the camera detects, but they differ compared to the shower of its gamma-ray counterpart. As soon from the results of the Hillas Parameter a gamma-ray shower was described to be elliptical where the width was small
and the length was much greater. The cosmic shower is more circular or spread out compared to the gamma-ray and being able to discard the showers that are hadronic is essential. By detecting from the Hillas Parameters and fitting a shape to the shower you can almost immediately get rid of any shower that gives parameters resembling those of a circular. As mentioned previously, parameters such as the width and length being almost equal should be a flag and being that the analysis is real time a user can go in and double check to see what is being reconstructed if it is a hadron shower it can be thrown out or placed somewhere else away from the gamma-ray showers. Doing this quickly and in real time is essential, being that hadronic showers are always occurring being able to develop an algorithm that distinguishes between a hadronic or gamma-ray shower is essential.

Conclusion

Moving forward with this software requires a few more steps in order to fully ready to begin its analysis on the pSCT. Going forward it is necessary to calculate and recreate the direction of the shower in order to discern where it came from and gain an understanding of the galactic environment that produced. Being that the pSCT is only one telescope at the moment, using an algorithm like the DISP method allows for recreating direction very accurately. Also, creating a sky map which describes and gives information on the event that captured is necessary. Ultimately creating a graphical user interface or web display that can be accessed by those in the collaboration is the goal so that the data can be made quickly and analyzed by those in the collaboration. In closing in order to create this quicklook system in real time reconstructing the gamma-ray shower is essential and necessary. This process begins with
integrating pulses and gaining an idea of a possible pedestal cut to eliminate noise and once this value is found subtracting that pedestal to only be left with the charge. Doing this allows the reconstruction of the camera in the form of a graph or graphical user interface. The step next step would be cleaning the image to the point that it shows only the shower image. Doing this requires a charge cut which will eliminate most of the pixels that are not near nor the shower. Once this is done applying an algorithm that deletes pixels that made the charge cut, but are scattered in various parts of the camera is essential since these pixels could affect the parameters of the shower image. Using a method of checking each pixel to see if they have a nearby active neighbor was used to solve this problem and quickly removed the scattered pixels. Once this is done calculation of the moment’s parameters in order to discern length, width and orientation are achievable. Also, knowing these parameter can also help to sort out whether a shower is a gamma-ray shower or a hadron shower. Observing gamma-rays can be insightful to the many galactic processes that happen in our galaxy and being able to observe them with ground based telescope arrays are a convenient way to gain insight into the great universe around us. The current telescope array VERITAS has led the way in gamma-ray observation and its replacement CTA(Cherenkov Telescope Array) which is a whole order of magnitude more sensitive will be able to do things VERITAS was not able to do.
Reference Page


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