Cherenkov Telescope Array Mirror Alignment Report

Francis Toriello[1]*
[1]The VERITAS Group, Department of Physics, Columbia University, New York, NY, USA

Introduction

The Cherenkov Telescope Array (CTA) is a groundbased observatory for gamma rays with very high energy characteristics within the range of 10 GeV to 100 TeV. It is currently still under development. As the title of the project suggests, it takes advantage of the Cherenkov radiation that is produced by the gamma ray's interaction with the earth's upper atmosphere, similar to the guiding physical principles of VERITAS. The primary differences are that CTA will feature more telescopes and possess a larger energy range.

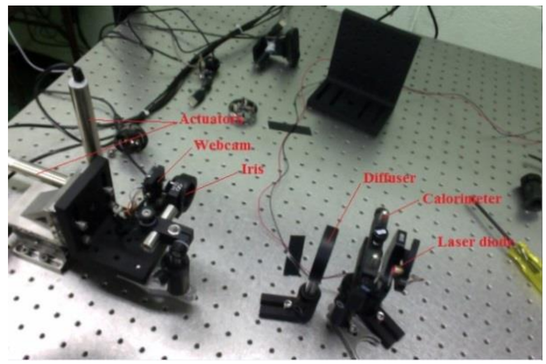
Cherenkov radiation will be collected by an array of dozens of optical telescopes of various sizes. These optical telescopes will be composed of hexagonal mirrors that must be aligned relative to each other so as to represent the shape of the telescope as a whole properly. It was in this area of research that my efforts were focused. The most recent proposed system with which to align the mirrors consists primarily of a laser and a webcam. Sixty to three hundred snapshots are taken of the laser and the position of the laser's centroid in each frame is measured and analyzed by a custom-written computer program executed via ROOT. One to ten microns was the ideal resolution that was required of the system to meet the needs of this project.

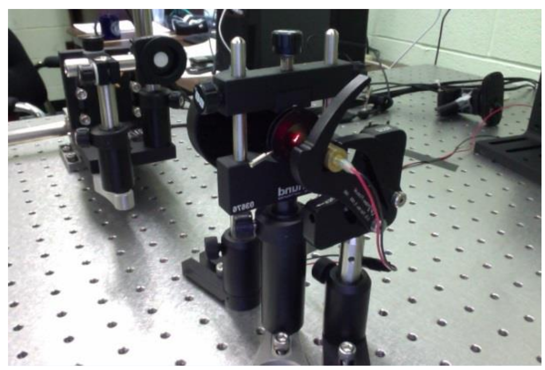
Since the position of the laser's centroid was given by pixel number, it was necessary to determine the ratio of pixels to millimeters via another ROOT program described in more detail on the following pages. It was also necessary to ensure by using an OPENCV analysis program that the pixels were not saturated. As will be shown, the consequences of saturation are bothersome edge effects that produce erroneous results.

Materials and Methods

Apparatus (basic setup)

1. Standard webcams (various models)
2. Voltage supply
3. Laser diode
4. L.E.D.
5. Iris
6. Calorimeter
7. Diffuser
8. Actuators





Results

The first task at hand was to determine if the pixels were saturating, since this was the prime suspect of the following odd results:

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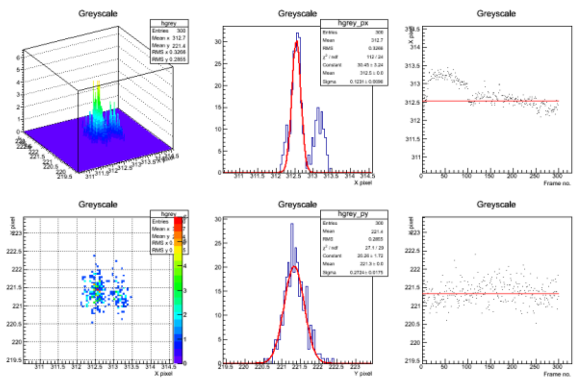
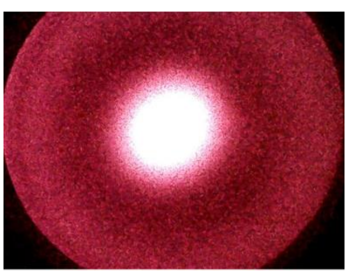
*To whom correspondence should be addressed: Francis Toriello, Columbia University, New York NY 10027, email: fet2105@columbia.edu.



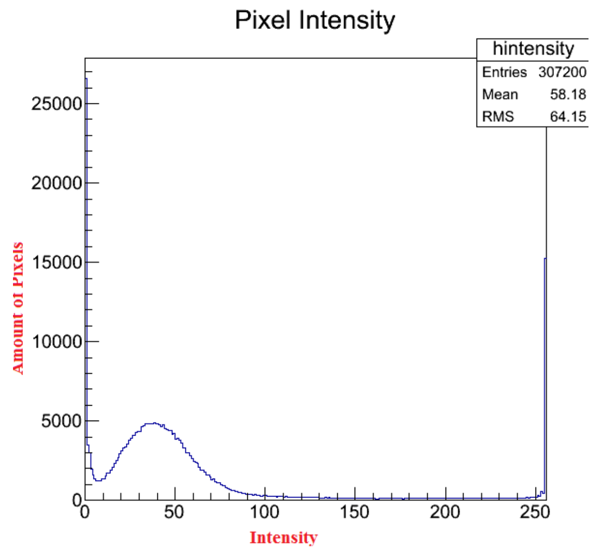
The data shown above represent a series of three hundred successive photos of a static laser with an applied voltage of 4V and a calorimeter setting of 2mm. As may be seen, the centroid does not appear to be very well behaved. In fact, it appears as though it moved dramatically in the first 100 frames as may be seen in the upper right hand graph.

As previously mentioned, the prime suspect for this odd result was pixel saturation. Below is one of the photographic images of this 4V 2mm laser point rendered by the webcam itself.



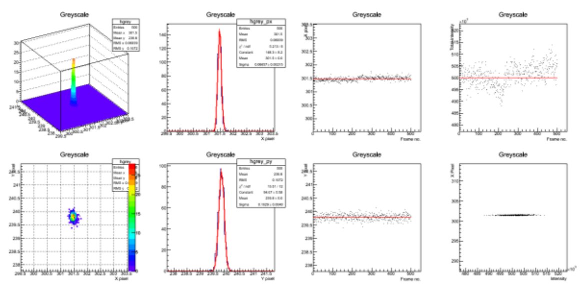
The pure white center represents clear evidence of saturation. The more disconcerting feature of this, however, is the ring of reflected light visible around the edge of the iris. These are edge effects due to saturation that cause the centroid to appear to move when it has, in fact, not done so.

This problem was made most apparent after writing an OPENCV executed program that analyzed this very image and produced a histogram consisting of the amount of pixels versus the intensity values they maintain (see image below):



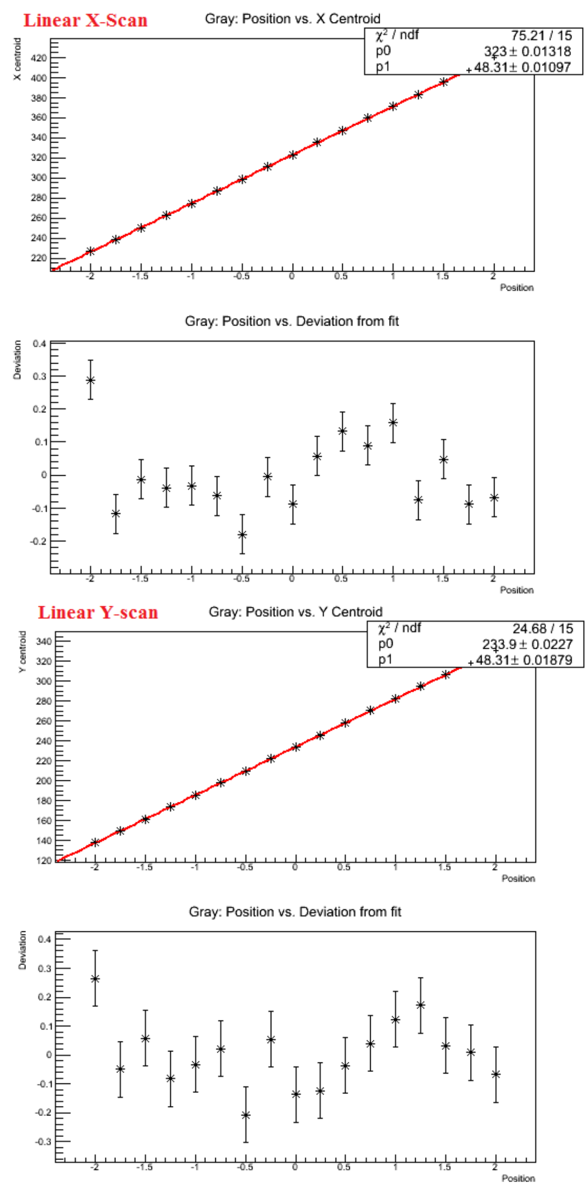
As can be seen, there is an initial spike at zero intensity. This spike represents the pixels that make up the area outside the iris while the spike all the way to the right, at the 255 mark, represents the saturated pixels that can be found at the center and throughout the image.

The ideal (and necessary) situation is to have no pixels saturating or otherwise stated at the 255 intensity mark in the above graph. At the time we were using a calorimeter that possessed a smallest possible aperture of 0.1mm. We found that, even with this smallest aperture and various voltage values, there was still saturation that, in effect, would produce erroneous results as shown previously. We were finally able to eliminate saturation by using a different calorimeter that possessed a smallest possible aperture of zero millimeters. We used the very same 4V laser except with an aperture of less than 0.1mm, achieving successful results shown below.



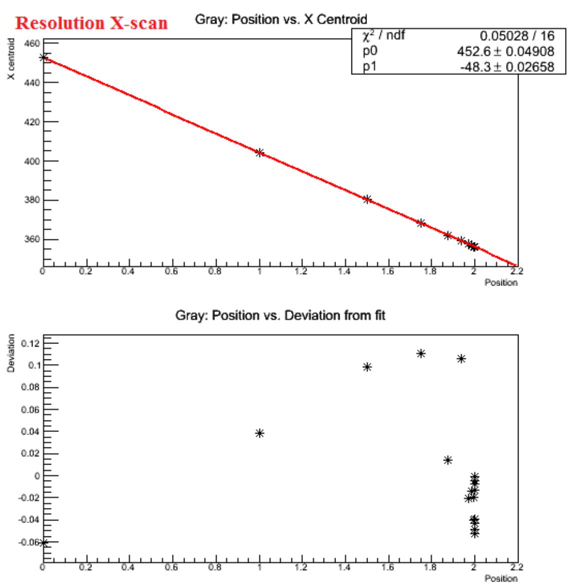
While the exact values accompanying the above image are admittedly difficult to decipher, it is clearly apparent in the first two upper left hand graphs that the laser's centroid is much more defined and better behaved. In fact, the sigma value for the x value of centroid is 0.06657+/-0.00215 pixels while the sigma value for the y value is 0.1029+/-0.0040 pixels. This discrepancy is bothersome since both the x and y value should be the same. However, this could be due to a slight tilt of the camera that would affect the geometry in such a way as to elongate the spot subtly in the y direction. The x sigma value, however, is auspicious as it falls within the few micron range that is required of the position resolution we are seeking.

The next task involved determining the pixel to millimeter ratio so we could obtain a better sense of the positional resolution provided by the sigma values previously mentioned and whether or not the pixels are square. This required performing two linear scans in which the camera is moved by the actuators in increments of .5mm in the x direction and then once again in the y direction. The slope of the fitted line should yield the amount of pixels per millimeter and both slopes should be equal to one another if the pixels are indeed square (see images below).



As may be seen, both linear scans produce an approximate slope of 48.31 pixels/mm showing that the pixels are square and that our x sigma value of 0.06657 pixels translates to approximately one micron while our y sigma value of 0.1029 pixels translates to approximately two microns, both well within the range of our desired positional resolution. The second graph of each scan (position vs. deviation from fit) gives us an idea of the mechanical uncertainty of the apparatus; that is the uncertainty introduced once the apparatus is set in motion. We see that in both scans there is a spread amongst the values of approximately .5 pixels or 10 microns. Of course, this is subject to change as the setup we were using is far from the configuration that will eventually be used in the field.

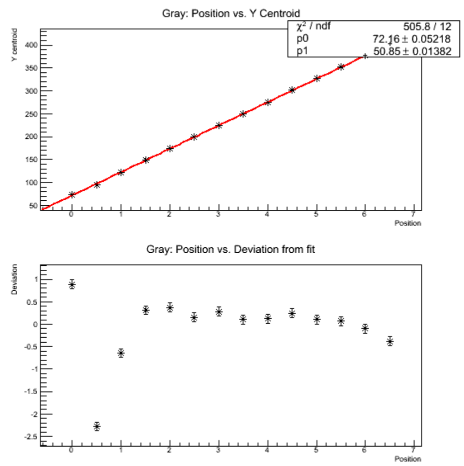
Once the pixel to millimeter ratio was determined, the next task required us to confirm the apparent positional resolutions provided by the sigma values. This was achieved by performing a scan in the x direction similar to that of the previous linear scan. However, the difference this time was that, instead of keeping constant the increments by which the camera moved, we instead halved the distance every time. If our positional resolution was indeed approximately one micron then, once the increments reach one micron and below, the program should fail to recognize any change in position (see image below).



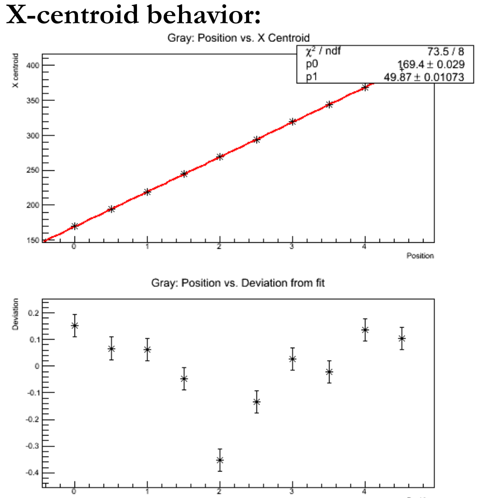
As may be seen in the second position vs. deviation from the fit graph, there is a point very close to two millimeters where we reach the limit of our positional resolution. That position is actually 1.999023188 mm, exactly the point where the change in position dips below one micron (9.765625 x 10^-4 mm) as was apparent in the table of data used to create these graphs. Therefore these results show that the positional resolution achieved was, in fact, approximately one micron (with regards to the x value of the centroid).

To get a better idea of the mechanical uncertainty, a series of diagonal scans were performed. Just as the name implies, these were contemporaneous scans in both the x and y direction. We should see the same mechanical uncertainty of approximately 10 microns or .5 pixels that had been reflected in the linear scans.

Y-centroid behavior:



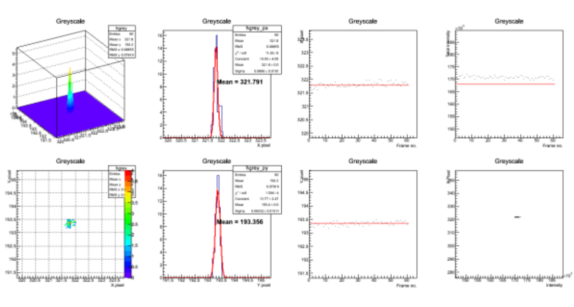
X-centroid behavior:



Notice that, similar to the linear scan in the x-direction, the x-centroid behavior yields a mechanical uncertainty of approximately .5 pixels or 10 microns (given by the spread of points in the position vs. deviation from fit graph) while the y-centroid behavior yields a mechanical uncertainty of approximately 3.5 pixels or 73 microns. This discrepancy is similar to the difference between the x sigma and the y sigma mentioned earlier. It was determined that this inconsistency could also be due to some very slight tilt of the camera that may affect the geometry of the how the laser beam impinges on the camera's lens.

The next task required testing other webcams of similar design in order to evaluate the robustness of the current configuration of the apparatus. For the sake of brevity I have excluded these results as they were very similar to previous ones.

The last task we completed before the end of the semester was the evaluation of an alternate light source, a light emitting diode. Due to the fact that the light emitted from an LED is considerably more spread and less concentrated, it was necessary to build a makeshift housing unit in which we passed the light though two custom-made calorimeters, both of which, of course, possessed an aperture of less than 0.1mm. We proceeded to taking sixty successive images of the LED laser point and analyzing them in much the same fashion as we had done for the three hundred successive photos of the 4V laser diode.



The results are no doubt promising as, much like the laser diode, a well-defined centroid is reflected in the analysis as can be seen in the first two upper left hand graphs. We get an x-sigma value of 0.0666 +/- 0.0161 pixels or once again approximately one micron and a y-sigma value of 0.09032 +/- 0.01511 pixels or once again approximately two microns.

Discussion

In our final analysis, the use of webcams while promising is not without its discrepancies, such as the difference between x and y positional resolutions given by their respective sigma values, and it reflected some mechanical uncertainties. It is of interest to me why, when the linear scans were not diagonal but done separately and dedicated to one direction at a time(x or y), the same mechanical uncertainty of about 10 microns was reflected by both the x and y scans while this did not occur for the diagonal scans. If the geometrical argument that I have proposed throughout this report is correct, then perhaps some corrective measure may be investigated during further research anticipated to be done in months to come. With regard to most recent developments concerning the LEDs, it would be interesting to perform some diagonal and linear scans to not only gain a more advanced understanding of how we may use these light sources, but also to see if these discrepancies persist, and in effect learn more about them and the subtleties of the system as a whole.