Uncovering fluctuations in atmospheric transmission using the VERITAS pointing monitors

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Abstract

Our project encompasses the creation of software that provides nightly estimates of atmospheric transmission and tracks its long-term fluctuations for the VERITAS telescopes. Using archived image files taken from the pointing monitors of the VERITAS telescope, we wrote software that selects stars of appropriate brightness and quantifies their intensity. We then plotted the star intensity as a function of the secant of the telescope angle from the zenith and observed a linear relationship. The ratio of this slope divided by its intercept has a value that is independent of the stars chosen and is proportional to the length of attenuation of light travelling through the atmosphere. By analyzing nightly data for all four telescopes, one can measure the magnitude of the fluctuations in atmospheric transmission using the ratio of the slope over the intercept. This method will allow improvements in the quality of the measurements taken by the VERITAS telescopes, by giving VERITAS control over the effects of the atmosphere on their star intensity data.

Keywords: *Gamma rays, Cherenkov Radiation, Atmospheric transmissions, VERITAS.*

Glossary

Telescope zenith angle: Angle between the vertical and the direction in which the telescope is pointing.

CCD camera: A charge-coupled device camera measures the motion of electric charges created by the passing of a photon, thus forming an image of the source of photons.

Flux: Amount that flows through a unit area per unit time.

Attenuation length: Characteristic distance required for a signal to reach of its initial strength.

Flat fielding: Calibrating the array of pixels in a CCD camera so that all pixels respond equally to excitation.

Introduction

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four telescopes, each 12 m in diameter and located at the base of Mt. Hopkins near Tucson, Arizona. A collaboration of more than 100 scientists from institutions in Canada, the U.S., Ireland and England operates VERITAS to find and measure astrophysical sources of gamma rays with energies in excess of 100 GeV. The VERITAS base camp is shown in Figure 1.

Very high energy gamma-ray astronomy relies on the measurement of Cherenkov radiation in the atmosphere. Gamma rays coming from space collide with the nuclei of air molecules in the earth’s atmosphere roughly 10 to 20 km above ground level, producing an “air shower” of secondary particles—mostly electrons and positrons—that hurtle toward the ground. In this process, the entire energy of the gamma-ray is converted to the mass and kinetic energy of the secondary particles. Although the secondary particles travel slower than the speed of light in vacuum, they travel faster than the speed of light in air due to their higher energies. This results in an electromagnetic shock wave comparable to a sonic boom. The shock wave comes in the form of bluish light called Cherenkov radiation. Cherenkov radiation is emitted by all the charged secondary particles and propagates to the ground where it can be measured by optical devices (Hanna, 2007). Using optical telescopes and extremely fast cameras[1], it is possible to measure the Cherenkov radiation and generate an image of the air shower. Typically, a thin, tubular shape is observed that can be used to trace backwards to the origin of the gamma ray (Figure 2).

The image generated from a single telescope is not sufficient to determine the origin of a gamma-ray induced air shower, since there is no indication where the signal originated from along the long axis. However, multiple telescopes positioned in an array allow researchers to view the air shower from several perspectives, resulting in images with different orientations (Figure 3). By superimposing images of the same air shower, the source of the gamma rays can be determined by the intersection of the lines drawn through the long axis of each image.

M.K. Daniel (2007) has shown that the atmospheric regions surveyed by VERITAS display substantial changes in atmospheric transmission both daily and annually. Fluctuations in atmospheric transmission alter the levels of scattering or absorption of Cherenkov radiation, which affects telescopic measurements. To improve gamma-ray detection from the ground, we hope to quantify the effect of atmospheric transmission from archived images taken by the VERITAS pointing monitor, a CCD camera directed towards the telescope’s field of view. From these images, it is possible to determine the telescope zenith angle and the intensity of the star that is being examined. By relating these two values, we can calculate the amount of atmosphere that a star's light will have to penetrate before reaching the telescope. Since the amount of atmosphere that the Cherenkov light must travel through increases with the zenith angle, we expect the extinction curve to display a decrease in intensity as a function of the telescope's angle from the zenith.

Methods

Analysis Procedure

Our software finds individual stars in images that are taken from the telescope's pointing monitors every fifteen minutes. The software then filters those stars and selects the fifteen brightest stars from the image, excluding stars that have pixel values above the highest value that the camera can measure (Figure 4). For each star that is chosen, a histogram is created of all the pixels that contribute to its background noise. Each of these histograms is used to measure the mean pixel noise in the neighbourhood of that star.

The mean pixel noise is subtracted from the sum of all

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[1] The VERITAS cameras contain 499 photo-multiplier tubes (PMT) that are digitised at a rate of 500 mega-samples/sec (Swordy and Brocious, 2007). Each PMT is capable of measuring a single photon and can determine its arrival time to within a few billionths of a second.

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Figure 1: The VERITAS telescope array, located at the base of Mt.Hopkins, Tucson, Arizona

the pixel values within a given radius to obtain the intensity of the star. To determine the most accurate radius to use, the intensity is plotted as a function of the radius. The radius that demonstrates the least change in intensity will best describe the star's actual intensity. The error in the star's intensity can be computed using the error in the radius.

The software tracks the intensity of each star through many images and plots its intensity values as a function of the secant of the telescope zenith angle. Theoretically, it can be shown that the flux of light from a star, Φ (1), follows the relation:

$$\Phi(l) = \Phi_0 - \left(\frac{\Phi_0 h}{l_0}\right) \sec\theta$$

Eqation (1): where θ is the telescope's angle from the zenith, h is the height of the atmosphere, lo is the attenuation length of light in the atmosphere and Φ is the flux as measured above the atmosphere (Hanna, D. 2008). Thus, a plot of star intensity versus the secant of the telescope zenith angle should be linear (Figure 5).

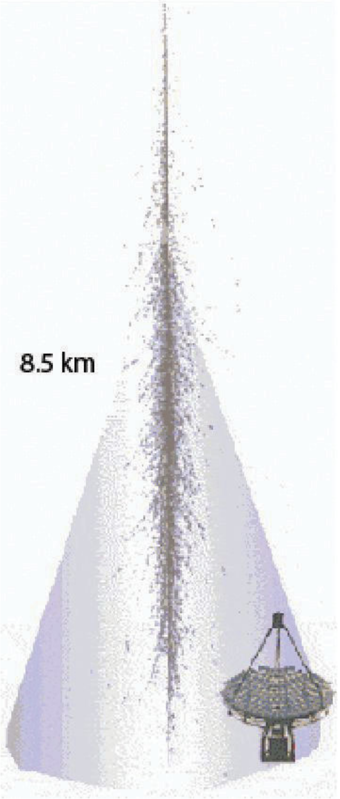

Figure 2: An air shower produced by an incoming gamma ray colliding with the nucleus of a molecule in the atmosphere. (Courtesy of the VERITAS Education Website, veritas.adlerplanetarium.org)

Results

From Figure 5, we see that the intensity of the stars in the pointing monitor images follows a linear relation when plotted against the secant of the telescope's angle from the zenith (Equation 1). Moreover, the ratio of the slope over the intercept of this relation, which is - h/ l_0 , is independent of the stars used (Figure 6). In Figure 7 all of the , - h/ l_0 values that were extracted from each night's images are plotted with their date (yy/mm/dd) on the x-axis. These are the weighted sums of each value from all four telescopes. The few points with very large errors in Figure 7 are cases where too few stars were found to fit the plots of intensity versus secant of the telescope zenith angle meaningfully, so only a few of these plots were considered in the averaging of data. Figure 7 clearly shows significant fluctuations in - h/ l_0 which implicates daily and monthly fluctuations in the atmosphere, as supported by previous research (Daniel, 2007). Due to the large variation in intensity values as a function of the secant of the telescope zenith angle, we cannot be certain that the variations in - h/ l_0 , are strictly from fluctuations in atmospheric transmission.

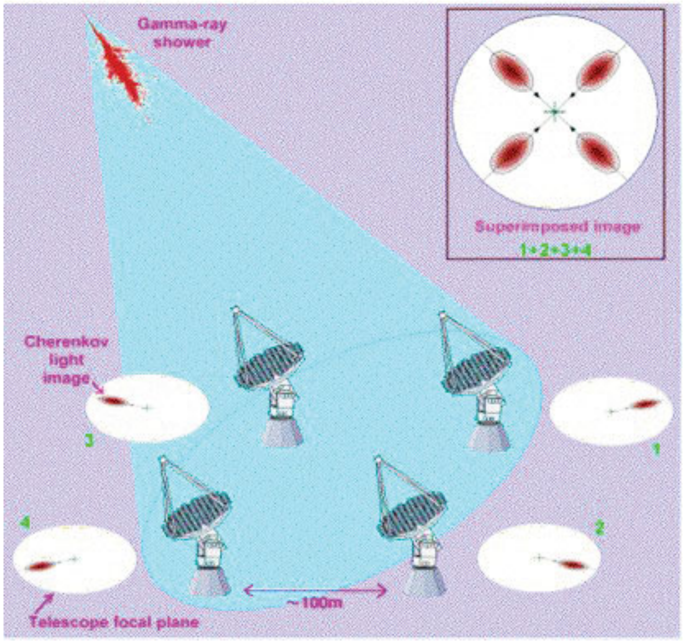

Figure 3: Stereo imaging of a gamma ray induced air shower with multiple telescopes. The turquoise colour represents the Cherenkov radiation. (Courtesy of the VERITAS Education Website, veritas.adlerplanetarium.org)

Discussion

The systematic error in the intensity

In the course of our research, we discovered that the pointing monitors capture images every two seconds and store the star's peak pixel value and its coordinates in a database for the 30 brightest stars in the image. In Figure 8, we see the peak pixel value of one star for four hours as a function of time in minutes. The blue triangles represent times when the telescope changed positions with respect to the star to get a sample of its background in a process called wobbling. We see that when the star changes positions in the image, its peak pixel value jumps significantly. This is emphasized by the plot in Figure 9, where we see a particular star's intensity versus secant of the zenith angle plot compared to the same star sampled every two seconds in the database. The jumps in intensity follow a pattern that is characteristic of a star moving in the image of a non-flat-

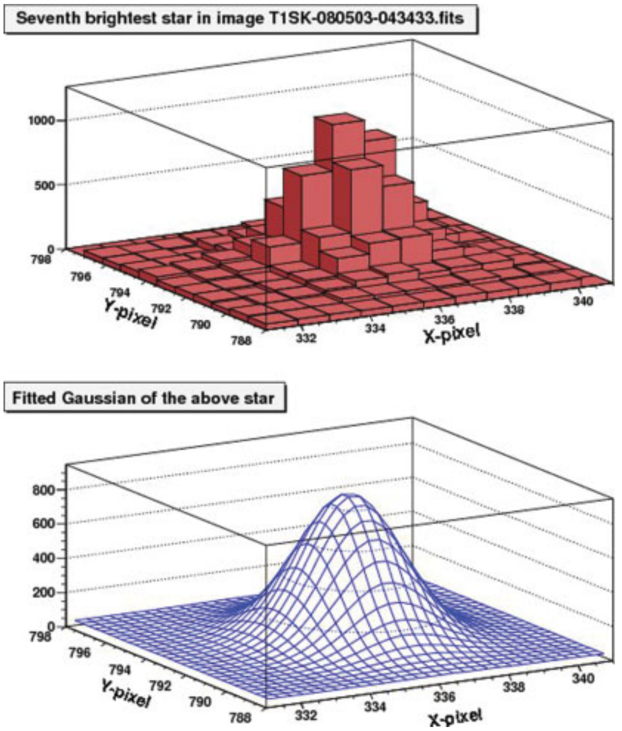

Figure 4: A two dimensional histogram of a star in an image taken by the pointing monitors, along with a fitted Gaussian function. Each bin in the histogram corresponds to a pixel in the image.

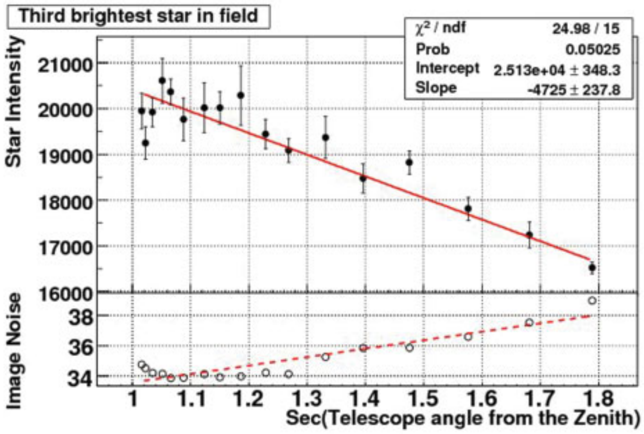

Figure 5: The upper plot in this figure is the star intensity as a function of sec θ, where θ is the zenith angle of the telescope, for a star in a group of 17 images. The smaller plot below is the entire image noise as a function of sec θ.

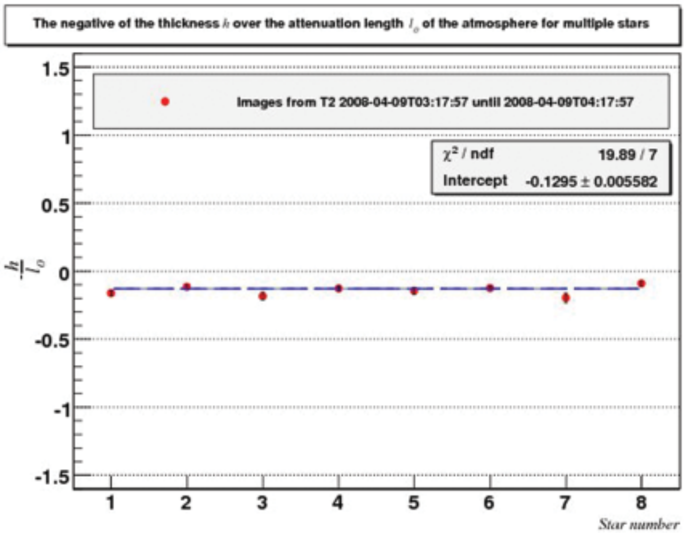

Figure 6: The ratio of the slope over intercept, - h/l_0, of linear fits as that in Figure 5. The blue dashed line represents the best fit of the constant that we expect.

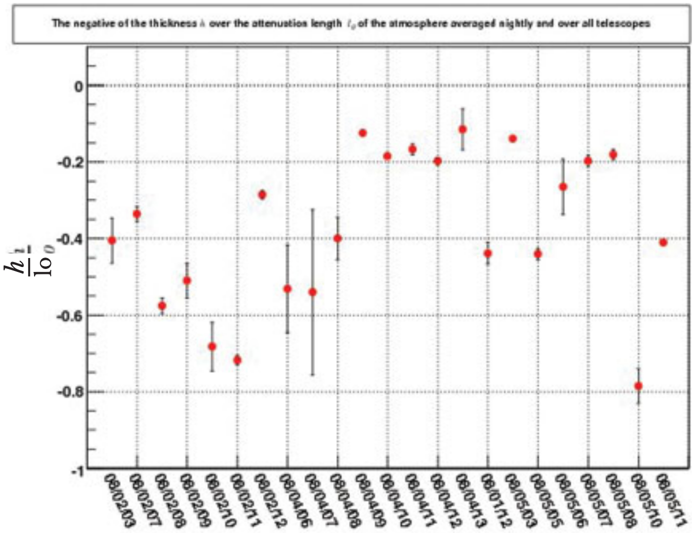

Figure 7: The ratio of the slope over the intercept, - h/l_0, weighted for each night by fitting a constant to all the values obtained from that night (as in Figure 6) and then further averaged over all four telescopes.

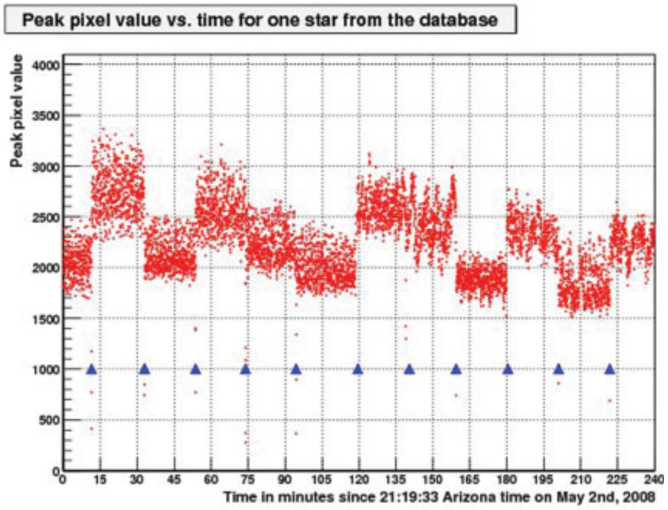

Figure 8: The peak pixel value from the database, plotted against time for a single star tracked for four hours. The blue triangles represent times when the telescope wobbled, which corresponds to the star making a jump to a new location in the image.

fielded CCD camera (Roper Scientific, 2006) and provides a reason for the large spread in intensities. As a result of our research, measures are being taken to flat-field the CCD cameras so that this process of measuring the atmospheric fluctuations may be further studied.

Conclusions

By analyzing the pixel intensity for the stars chosen by our software for the VERITAS telescope array, we have found that the relation between the intensity and the secant of the telescope zenith angle is linear. We have also found that the ratio of the slope over the intercept of this relation is independent of the star used to measure this data. Since we have shown that the fluctuations of star intensity values are due to wobbling, this suggests that our method of measuring the atmospheric effects on the telescope data can quantify atmospheric transmission. Remaining work includes flat-fielding the VERITAS pointing monitors and implementing our software at the level of the base camp. This would allow more sophisticated values that our software extracts from the images to be stored at two second intervals in the database by the pointing monitors, including each star's pixel coordinates and relative and absolute intensities. In the long term, this would provide VERITAS scientists with a robust and precise method of quantifying and correcting for atmospheric effects on their gamma-ray measurements.

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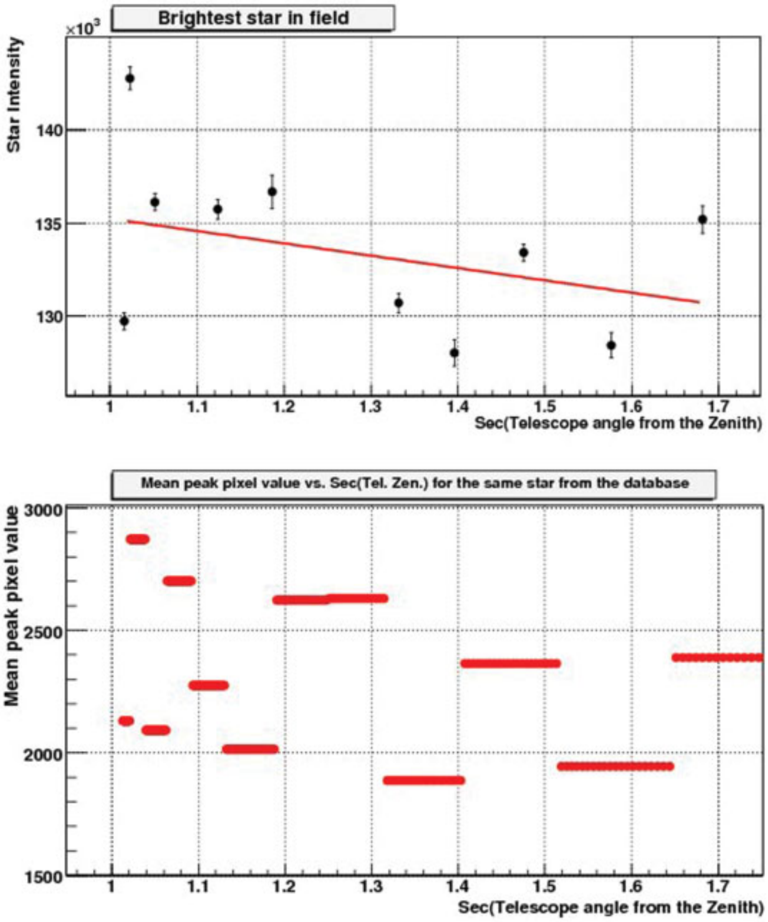

Figure 9: The top plot is the extinction curve for a star tracked through the pointing monitor images. Below is the peak pixel value of the same star shown above but sampled every two seconds from the database values.