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The VERITAS standard data analysis

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Abstract: VERITAS is an array of Imaging Atmospheric Cherenkov Telescopes designed for very high energy gamma ray (E>100 GeV) observations of astrophysical sources. The experiment began its scientific observation program in the 2006/2007 observing season. We describe here the analysis chain for reducing the data, reconstructing the direction and energy of incident gamma rays and the rejection of background cosmic rays.

Introduction

The VERITAS instrument, described in more detail in [9], consists of an array of 4 telescopes each equipped with 499 pixel cameras [10] read out by 500 MS/s flash-ADCs (fADC) [5]. The traces are recorded into a custom data format before being archived for distribution to the collaboration and further analysis. Diagnostic plots – such as individual telescope and array trigger rates, deadtime stabilitity, atmospheric clarity, etc – are generated from these files and database stored information. These plots are made available through a web page for data integrity checks prior to an analysis being attempted. A separate web page listing plots showing the long term history of the camera pixels (trigger participation, voltage information, etc) in order to trace camera health is also available.

A number of packages have been developed for the analysis of VERITAS data. Having multiple, independent packages available guards against any systematic errors being introduced into the analysis chain. Every analysis of a putative source must then have an independent secondary analysis in order to confirm any results. This paper describes the chain appropriate to the eventdisplay [6] and the VEGAS [11] packages. There are others, such as GrISU [2] and the quicklook package (used for online analysis when an observation is in progress) which show consistent results to the ones given here.

Data Analysis

The data analysis chain has three distinct elements: firstly the pixel data is calibrated to get accurate charge information; after calibration the pixel data is parameterised to give telescope level images, which in turn can be combined to reconstruct the geometrical properties of the shower; finally an estimate of the background level of counts is made in order to determine if there are any statistically significant excesses (i.e. sources) in the field of view (fov). Once a source has been identified a data analysis can be further extended to look for variability in emission with a light curve and a spectrum calculated to try and distinguish between different models of the emission process; or if there is no significant signal an upper limit can be placed on the source emission. Specific details of the higher level analysis process are left to the papers describing the analysis of specific objects.

Calibration

The technical details of obtaining calibration information are covered in [4]. Laser runs are used to calculate the relative gain between the pixels and the timing offsets to counteract any time spread due to path length differences (e.g. differing cable lengths, etc) for each channel. Pedestal events are injected at 1 Hz during an observation run to give an estimate of both the expected voltage offset for

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each fADC trace and an estimate of the night sky background (NSB) and electronics noise from the variance of that value. VEGAS allows the pedestal variance to be calculated as a function of time into the run, with a default window of 3 minutes being the average time that a star will take to pass through a pixel's fov. Pixels with values outside of an expected range for the calibration parameters are then flagged as bad and removed from further analysis. The charge values for these problem tubes are set to 0 and typically this will apply to $\leq 5\%$ of channels across the array (depending on the number of bright stars in the fov).

The amount of charge in a good trace is then calculated by summing the samples for a given window size. In VEGAS this is defaulted to a 14 ns integration window that starts from a position calculated by averaging the pulse arrival time (defined as the half-height point on the pulse leading edge) of a representative number of events. In eventdisplay a two pass scheme is used. The first pass has a wide 20 ns window that begins at a fixed position in order to calculate the integrated charge and the pulse arrival time. The second pass tightens the integration window to 10 ns in order to increase the signal to noise ratio, placing the start of the integration according to the calculated time gradient across the image after it has been parameterised, as discussed in the next section.

Parameterisation and reconstruction

In the process of cleaning an image for parameterisation, pixels which produce an integrated charge greater than 5 times their pedestal standard deviation (picture pixel) and any pixel that is adjacent to these higher threshold pixels and having 2.5 times their own standard deviation (boundary pixel) are automatically assigned to the image. Isolated picture pixels, i.e. those with no other picture or boundary pixels neighbouring them, and all other pixels then have their charges set to 0. The resulting shower image is parameterised with a second moment analysis and for eventdisplay the time gradient across that image is found for the second pass of the charge integration.

The image data from the individual telescopes is then tested against standard quality criteria for the number of tubes present in an image is ≥ 5 (to ensure a robust image axis), the minimum amount of charge in an image is $size > 400$ digital counts (providing run-to-run and NSB fluctation stability) and the angular distance in the camera is $0.05 \leq dist \leq 1.3$ degrees (avoiding bias due to image truncation) If a sufficient number of telescope images for an event pass the quality cuts the analysis proceeds to extract stereoscopic information like the direction on the sky and the shower core position on the ground for each event. The image information can then be compared to lookup tables of the parameters for simulated gamma rays as a function of image size, impact distance to the shower core and the zenith angle of observation to achieve a greater rejection power of the uneven light distribution of cosmic ray events to that of the smooth compact gamma ray ones. Details of simulations of the VERITAS array can be found in [8]. For VEGAS the default method follows the prescription given in [3] where a mean scaled parameter (MSP) is given by

$$MSP = \frac{1}{N_{tel}} \sum_{i=1}^{N_{tel}} \frac{p_i}{\bar{p}_{sim}(\theta, size, r)} \qquad (1)$$

where p_i corresponds to the parameter in question (width or length) for telescope i and $\bar{p}_{sim}(\theta, size, r)$ is the mean value for simulations of a given $size$ at a given impact distance (r) and zenith angle θ. Cuts based on the mean scaled parameters for VEGAS are $0.05 \leq MSW \leq 0.95$, $0.05 \leq MSL \leq 1.15$ (where W stands for width and L for length) and have a quality factor of $Q \sim 1.8$. In eventdisplay the normalized width method described in [7] is utilised to reduce the impact of outliers in the distributions.

$$MSCP = \frac{1}{N_{tel}} \sum_{i=1}^{N_{tel}} \frac{p_i - \tilde{p}_{sim}(\theta, size, r)}{\sigma_{90}} \qquad (2)$$

where $\tilde{p}_{sim}(\theta, size, r)$ is the median value; and σ_{90} is the width of the distribution for 90% of the events. The cuts are $-1.2 \leq MSCW \leq 0.5$, $-1.2 \leq MSCL \leq 0.5$ with a quality factor of this form of cut is $Q \sim 4$. The values of the cuts given here should be considered standard for all results presented, but are not necessarily considered as fully optimised.

Background estimation

There is no set prescription for background estimation that can cope with every circumstance or source morphology. As such the best way to keep systematic uncertainties under control is by applying several methods to the same data set and comparing the results, a detailed description of commonly used background estimation models can be found in [1].

Wobble mode observations [3] are favoured for point-like (or limited extension) sources since a background estimate can be derived from the events recorded during a run, allowing more on-source time and systematic effects in the background estimation due to variation in weather or performance changes effectively cancel out. The background estimate is made from a region reflected from the source position around the camera centre (the telescope pointing position). In order to gain a better estimate of the number of background events multiple background regions can be used, each region set in a ring the same offset distance from the camera centre, but still avoiding the region around the suspected source position to ensure that poorly reconstructed gamma ray events do not bias the background estimate. Point sources show up as an excess of reconstructed shower directions close to the assumed source position. Figure 1 shows just such a plot for 5 background regions on 4 good quality Crab nebula $0.5°$ wobble offset observations of 20 minute duration each. The spread of events closely matches that of a point source with an angular resolution of $\sim 0.14°$ [8]. After a cut for a point like source of $\theta^2 < 0.025$ for three telescope data ($\theta^2 < 0.035$ for two telescope data) the quality factor for all cuts is $Q \sim 24$.

The reflected region methodology for wobble mode observations can essentially be applied to any part of the field of view displaced from the observation position. This allows a 2-d map of events to be built up for the fov, figure 2 shows the 2-d distribution of significances for the same Crab dataset using this method. A 2-d map like this will show up emission offset from the speculated source position, sources of extended emission and a modest number of multiple sources in the same fov that a 1-d analysis would miss.

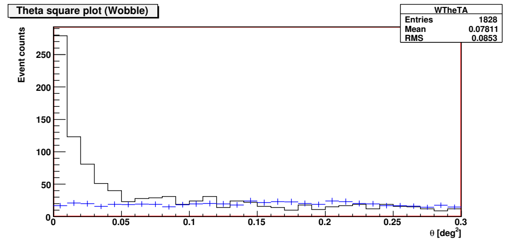

Figure 1: θ^2 plot for 4 runs of Crab nebula observations taken with a wobble offset of 0.5 degrees is given by the line. The background estimate, made from 5 circular regions of 0.22 degree diameter each, is given by the crosses.

An alternative 2-d mapping method is the ring background model. In this model a ring (in celestial co-ordinates) around a trial source position is used to give the background estimate. Since the ring covers areas with different offsets from that of the trial source position an acceptance correction function must be used in the normalisation for each position on the ring. Any part of a ring that crosses an assumed source position is also excluded from the background estimate.

The source location accuracy can be seen in figure 4 which shows the results for the fit of a 2-d Gaussian to the excess source counts. It can be seen that a source position can be accurately reconstructed to less than $0.05°$ for each run.

Summary

The standard VERITAS data analysis chain and the use of independent software packages to keep systematic errors under control has been described. The use of different background estimation models allows hypothesis testing of different source morphologies and searching for unidentified sources within the field of view. The results from two different analysis packages and three different background estimation proceedures provide consistent results of $\sim 30\,\sigma/\sqrt{hour}$ for 3 telescopes on the Crab nebula for a wobble offset of $0.5°$.

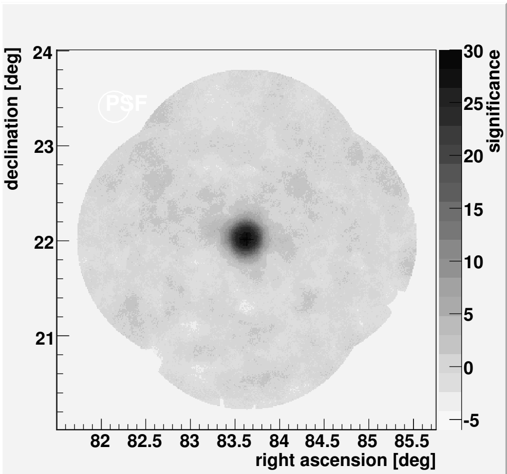

Figure 2: 2-d sky map of significances with the reflected region model for the same observations as figure 1.

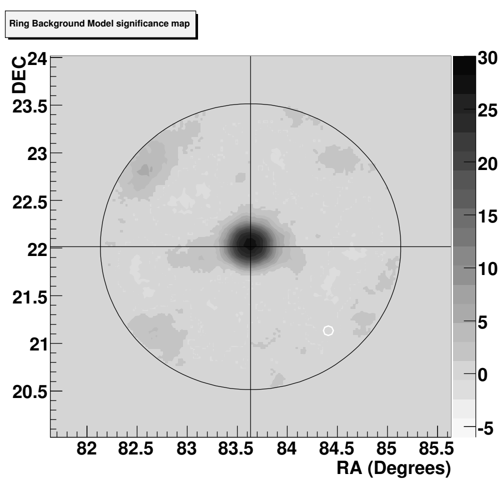

Figure 3: 2-d sky map of significances with the ring background model for the same observations as figure 1. The white circle corresponds to the position of zeta tau.

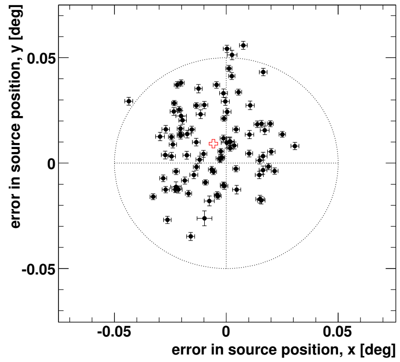

Figure 4: Reconstruction of the source position for a large number of Crab nebula runs (black squares). The red open cross is the overall reconstructed source position.

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