The Cosmic Ray Background as a Tool for Relative Calibration of Imaging Atmospheric Cherenkov Telescopes

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Abstract

Ground based Cherenkov γ-ray telescopes are sensitive to unpredictable changes in the atmospheric transparency which are difficult to measure and interpret in the absence of a calibrated beam of high energy γ-rays. We use the detector response to Cherenkov emission from cosmic ray initiated air showers to obtain a relative calibration for data obtained under different instrumental and atmospheric conditions as well as over a range of source angles to the Zenith.

1. Introduction

Estimating the sensitivity of atmospheric Cherenkov detectors relies heavily on Monte Carlo simulation programs which usually assume a set of fixed conditions while the overall efficiency of the experiment can vary in time due to a number of factors, the most important of which is the atmosphere itself. When measuring the γ-ray flux from a source, one must correct for these effects.

We present a method used for the Whipple Atmospheric Cherenkov Imaging Telescope to estimate an overall relative efficiency factor. We also validate the method using observations of the Crab Nebula. In its basic form the method is based on the analysis of data taken toward the Zenith (Mohanty, 1995) and this is presented first. We have realized that the method can be generalized (LeBohec & Holder 2002, hereafter SLB&JH) in a way which incorporates the effects of the Zenith angle at which observations are made. While detailed simulations will always be necessary in order to understand variations in telescope sensitivity, a simple correction such as that presented here is a useful tool which may be particularly important when studying the time variability of γ-ray sources.

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2. Relative calibration at fixed Zenith angle

For data obtained with the Whipple 10 m telescope (Cawley 1990 and Finley 2001), we define the luminosity Q of an event as the sum of the signals in all the photomultiplier tubes (PMTs) that gave a significant contribution to the image (Reynolds 1993). A relative throughput factor, F, between two observation times can then be defined as the ratio between the luminosity produced by the same atmospheric shower observed at the same Zenith angle but under the two different conditions. In order to effectively estimate the throughput factor we use the fact that the cosmic ray spectrum is constant at the energies we observe (Gaisser 1990), and therefore differences in the distribution of Q obtained at the same Zenith angle with the same detector should only reflect variations in light collection efficiency and gain of the experiment. Practically, in the Whipple data analysis, we construct the histogram of Q obtained from the Zenith observations during a specific night. This is then used as a reference for the other nights to be calibrated. For each of the other nights we construct the histogram of $F \times Q$, with F being a test value for the relative gain between the night to be calibrated and the reference night. We then adjust F until the distribution best fits the reference one.

3. Relative calibration at any Zenith angle

3.1. Generalization

The relative throughput calibration as described above is based on data obtained at a fixed Zenith angle, which cannot be strictly contemporaneous with the astronomical observations of interest. It is, in principle, possible to apply the same method to compare data obtained at different Zenith angles. The value of F then results from differences in atmospheric transparency as well as differences in the detection geometry which affect both the energy threshold and the effective γ-ray collection area.

3.2. Test and application of the method

In figure 1. the throughput factor is shown as a function of θ_z, the distance from the Zenith. The reference data were taken at $\theta_z \sim 30^o$ from the Zenith and so F is close to one at this point. It can be shown that if the atmospheric density profile is assumed isothermal, the area of the Cherenkov light pool is proportional to $\frac{1}{\cos^2\theta_z}$ (see SLB&JH). Using this, for a luminosity distribution of differential power law index $-\Gamma$, the throughput factor is expected to vary as

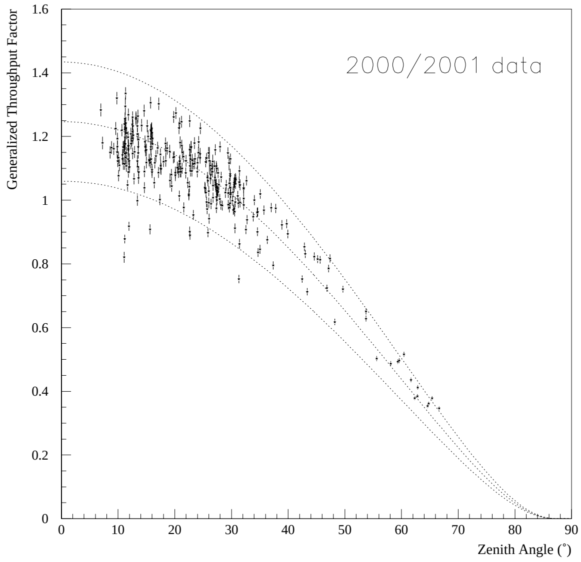

Fig. 1. The throughput factor as a function of the distance from the Zenith. Each point represents a 28 minute observation (with statistical errors). The curves correspond to a simple isothermal model for the atmosphere with three different values for atmospheric attenuation.

$$F \propto (\cos\theta_z)^{2(\frac{\Gamma-1}{\Gamma})} \times e^{-\frac{K}{\cos\theta_z}} \qquad (1)$$

where the exponential term is used to describe the atmospheric attenuation of Cherenkov light. For our observed $\Gamma = 2.3$, this function gives the curves shown on figure 1. for three different empirically derived values of K. Points falling near the upper curve would correspond to data obtained under the best atmospheric conditions while points on the lower curve correspond to data obtained under poorer conditions. We can see on this figure that variations of $\pm 20\%$ arise in the event luminosity even when the observer estimated the sky quality to be good (more than 90% of these observations where graded as A or B weather by the observer). Variations of this magnitude must be corrected for in order to establish accurate γ-ray fluxes, particularly in the case of sources with steep spectra.

In order to use the throughput value to correct the measured γ-ray rate, we must verify that the γ-ray showers are affected by changes in Zenith angle, instrument efficiency and atmospheric transparency in approximately the same way as the background cosmic ray showers which are used to derive the throughput factor. We do this by looking at the γ-ray rate observed in the direction of the Crab Nebula. If the throughput factor is applied correctly, the Crab Nebula γ-ray rate after correction should remain stable within statistical errors over all elevations and weather conditions

We try here to correct the γ-ray rate separately for the Zenith angle and atmospheric transparency effects. This is only strictly accurate if the spectrum of γ-rays from the source follows a simple power law of known spectral index (see SLB&JH). The Zenith angle dependence of the γ-ray rate is ideally calculated using Monte Carlo simulations; here we use a simple analytical model which provides a good approximation. The effective collection area, A, and threshold energy, E_{th}, are both proportional to $\frac{1}{\cos^2\theta_z}$ and so the γ-ray rate $\Phi \propto (\cos\theta_z)^{2(\alpha-1)}$ where α is the integral γ-ray power law spectral index. For the Crab Nebula, $\alpha = 1.5$ (Hillas 1998) and so $\Phi \propto \cos\theta_z$. This can be used to correct the measured γ-ray rate to the rate expected at a fixed Zenith angle; we choose to calculate the corrected rate for a Zenith angle of 30°, Φ_{30}.

To apply the throughput correction we first calculate the expected throughput factor, F_{exp}, normalized to a Zenith angle of 30° (because the measured throughput factor F_{meas} has been calculated with reference to an observation taken at a Zenith angle of 30°) such that :

$$F_{exp} = \left(\frac{\cos\theta_z}{\cos 30°}\right)^{\frac{\Gamma-1}{\Gamma}} \quad (2)$$

This is equivalent to equation 1 but without atmospheric attenuation. The effects of atmospheric attenuation are automatically incorporated in the throughput correction , which we use to calculate the corrected rate as follows:

$$\Phi_{corr} = \frac{\Phi_{30}}{(F_{meas}/F_{exp})^{\alpha}} \quad (3)$$

Figure 2. shows Φ_{30} as a function of Zenith angle and of F_{meas}/F_{exp}. The γ-ray rate is constant with Zenith angle after the Zenith angle correction, while there is clearly still a correlation with the throughput correction which is well fit by a power law of index $\alpha = 1.5$, as expected for the Crab. It can be seen that the measured γ-ray rate varies by a factor of two in the right hand plot making the correction is very worthwhile.

4. Conclusion

We have shown that cosmic ray background events observed at fixed Zenith angle can be used to establish a relative calibration for a single atmospheric

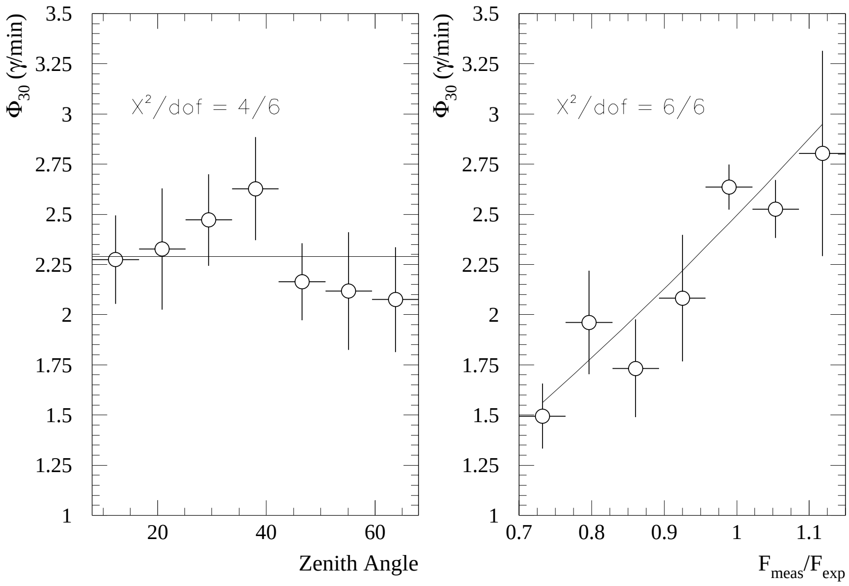

Fig. 2. The averaged Crab nebula γ-ray rate after correction for the Zenith angle as a function of Zenith angle (left) and F_{meas}/F_{exp} (right).

Cherenkov imaging telescope in order to account for the many unavoidable temporal changes in light collection efficiency, gain and, most importantly, atmospheric conditions. Generalizing the method, we have shown that it can be used for the relative calibration of data obtained at different Zenith angles, taking into account both the geometrical effects due to Zenith angle and the variations in atmospheric conditions.

This calibration method can be used to introduce corrections at various levels. At the most basic level, it can be used to select which data were taken under good conditions. We have also shown that it can be used to rescale the measured γ-ray fluxes in order to make observations taken under different conditions more comparable. One method of estimating the background due to cosmic rays for γ-ray observations taken without dedicated background control observations is to choose archival background observations taken under conditions as similar as possible to the source observation being considered. The throughput factor can be used as one of the criteria to judge which background runs are most suitable (Horan 2002). The next generation of Cherenkov imaging telescopes are currently being developed. Using data from CELESTE (D.A.Smith 2001, E.Paré 2002) it was shown that the method described here can be very useful for intercalibration between the elements of a detector array (SLB&JH).

The VERITAS (Weekes 2002, Ong 2002), HESS (Hofmann 2003) and CANGAROO III (Mori 2003) projects all involve using multiple telescopes on the same site. Inter-calibration of these telescopes will be difficult without a dedicated test beam. For VERITAS, simulations indicate that an energy resolution of 15% should be possible; in practice, this will require a relative calibration accurate to $< 15\%$. The throughput method described here may well prove to be very useful to achieve such accuracy.

5. References

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