Checking the Pointing Accuracy of Air Fluorescence Detectors with Star Light

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Abstract

We have developed a method to check and monitor the mirror pointing of air fluorescence cosmic ray detectors with light from UV bright stars crossing the field of view of the photomultiplier tubes [2]. The method is applied to recent data from the HiRes 2 FADC system to evaluate the pointing accuracy of the cameras. In addition, we extract optical parameters like the spot shape, i.e. the shape of the image of point-like objects on the photomultiplier clusters.

1. Introduction

The High Resolution Fly's Eye (HiRes) detector in Dugway, Utah, is an air fluorescence detector designed for the measurement of the energy and arrival direction of cosmic ray particles with energy $E > 10^{18}$ eV. As an astronomical instrument, pointing accuracy is of crucial importance for HiRes. However, given the lack of cosmic ray standard candles, we have to rely on indirect information to estimate the optical properties of the detector.

The HiRes 2 detector has the capability of taking so-called pedestal snapshots. They allow the monitoring of drifts in the background light seen by each tube, for example caused by changing weather conditions or light sources (stars, planets) crossing the field of view. Snapshots are taken automatically with no trigger requirement at fixed intervals 4.8 times per second. No raw data is stored for snapshots. Instead, we average the mean and the variance for all measurements within a $25\,\mu$s time window, and report and store the average of 48 windows for each tube every 10 s.

A star crosses the field of view of a tube in about 4 minutes. Because the anode signal of the photomultipliers is AC coupled with a time constant of $500\,\mu$s, slow changes in the ambient light level like the drift caused by a star will be filtered and can not be observed in the *mean* of the snapshot measurements. However, an increase in the night sky background or a bright star in the field of view of a tube leads to additional noise and therefore to an increase in the statistical fluctuations, i.e. the *variance*, of the measurement. The variance therefore provides an indirect tool to determine the ambient light level or the number of arriving photons. Its actual value is approximately equal to the number of photoelectrons in 100 ns, so
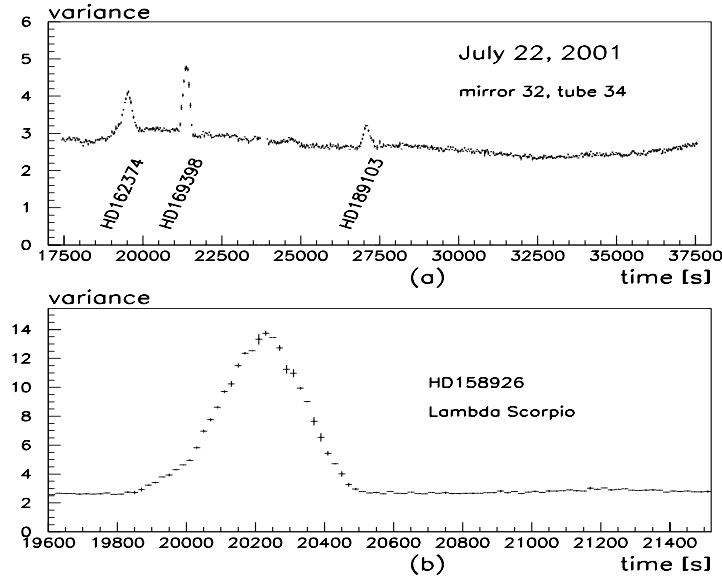
Fig. 1. (a) HiRes 2 snapshot data taken over the course of a night for one of the photomultiplier tubes. (b) Shape of the signal (variance vs. time) for the bright star Lambda Scorpio.

for the typical night sky noise the variance is 2 to 4 photoelectrons.

The signal of a star in the snapshot data has a typical shape as shown in Fig. 1. Depending on the brightness of the star, peak values for the variance range from 5 up to 50 photoelectrons over a background of 2 to 4 photoelectrons. As an example, Lambda Scorpio in Fig. 1, with a visible magnitude of 1.6 and a flux of $5.1 \cdot 10^{-9} \, \mathrm{erg \, cm^{-2} \, s^{-1} \, \AA^{-1}}$ at $2740 \, \AA$[3], has an intensity of about 14 photoelectrons in $100 \, \mathrm{ns}$ at the peak, *i.e.* when its image is near the center of the photomultiplier. In comparison, a typical airshower produces several hundreds of photoelectrons per tube near the shower maximum, but the air shower signal comes as short pulses of μs duration.

The challenge is to find the signature of a star in the presence of a slowly varying night sky background and sharp peaks and edges caused by noisy electronics. We use the second-derivative method as described in detail in [1]. It is a very general and typically very fast method to search for peaks on a slowly varying (linear) background. A detailed description of our use of the method can be found in [2].

The basis of the star search is the TD 1 Catalog of Stellar UV Fluxes [3], which is the result of a sky-scan experiment aboard the TD 1 satellite of the European Space Research Organization ESRO (now ESA). The catalog contains the absolute UV flux of 31,215 stars in four pass-bands ($1565 \, \AA$, $1965 \, \AA$, $2365 \, \AA$,

and $2740\,\text{Å}$). As HiRes works in the near UV, the flux at $2740\,\text{Å}$ is the most relevant parameter. HiRes can detect stars down to flux levels of approximately $10^{-11}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$ with high efficiency.

2. Geometry Calibration

The first application of the calibration using star light is a check of the pointing accuracy of the HiRes 2 mirrors with snapshot data taken between April 2001 and February 2003.

A star should be closest to the center of the tube when the signal in the tube peaks. For every tube in which a star is identified, we calculate the distance between the center of the tube and the true position of the star image on the cluster at the time of the peak. The sum of the squares of all these distances for a given mirror is then minimized with a χ^2-minimization with four free parameters representing (1) a scaling of the tubes away from the center of the tube cluster, (2) rotation of the tube cluster around the mirror axis. (3,4) horizontal and vertical shifts in position of the entire cluster with respect to the mirror axis. We use data of all tubes in which stars are detected for a complete night of data taking. Applying the χ^2-minimization to a set of stars (e.g. a complete night) rather than to single stars guarantees that most sections of the mirror are covered by data points. This minimizes systematic effects from single stars only seen in one of four quadrants, which lead to biases especially in the tilt parameter. We have applied this method to correct for tilts and offsets in several mirrors and to continuously monitor the mirror pointing. For most of the mirrors, the corrections are small, but several mirrors show an offset in the horizontal or vertical direction as large as 0.8 to 1.5 cm, corresponding to angular errors of 0.2° to 0.3°.

3. Spot Shape

To correctly estimate the energy of a cosmic ray air shower, air fluorescence detectors need to recover all the light that reaches the detector. This requires detailed knowledge of the response of the tubes to the light collected by the mirror. A bright star with its precisely known position provides an almost perfect point source. Star light therefore provides a tool for understanding the basic optical properties of the mirror/camera system, such as (1) the width of the image of a point source on the photomultiplier cluster (the "spot shape"), (2) the spread of light over neighboring tubes, and (3) the fraction of light lost in gaps between neighboring phototubes. The quality of the ray tracing routines used for simulating and reconstructing air shower tracks depend on the accuracy of our knowledge of these basic parameters.

Using bright stars, we analyze the spot shape for points on the camera with increasing distance from the camera axis. Close to the mirror center, the spot
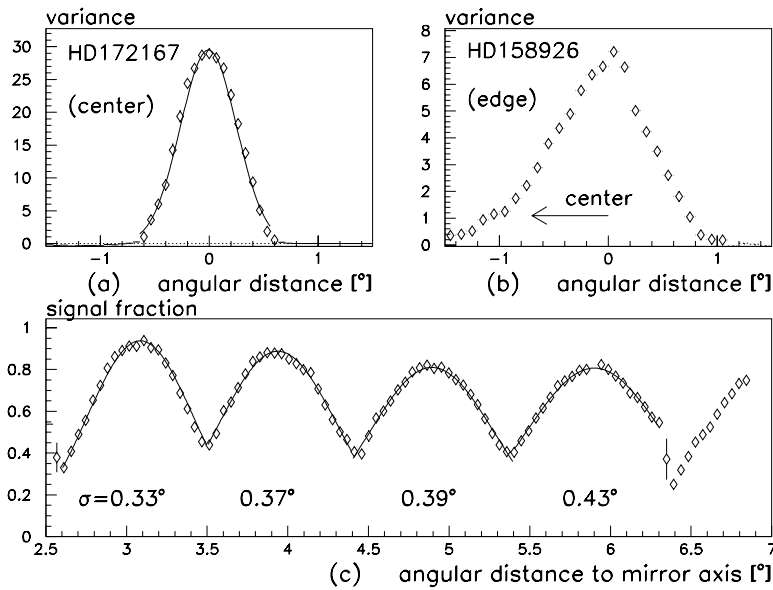
Fig. 2. Variance of a tube (a) near the mirror center and (b) close to the edge of the mirror as a function of the distance between the passing star and the tube center (the arrow indicates the direction to the mirror center). (c) Variance of tubes along the track of a star vs. distance from the center of the mirror.

shape can be expected to be symmetric. Fig. 2 (a) shows the variance of a tube as a function of the angular distance to a bright star. The spot shape function is well-described by a Gaussian with $\sigma = 0.30° \pm 0.01°$. Close to the edge of the mirror, the spot shape shows a considerable tail and the shape becomes more and more asymmetric (Fig. 2 (b)). The width of the spot shape function increases with the distance from the mirror axis, from $0.33°$ at $3°$ angular distance from the axis to $0.43°$ at $6°$.

1. Mariscotti M.A. 1967, Nucl. Instr. Meth. 50, 309
2. Sadowski P.A. et al. (HiRes Collaboration) 2003, Astroparticle Physics 18, 237
3. Thompson G.I. et al. 1978, in "Catalog of Stellar Ultraviolet Fluxes," The Science Research Council