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A monocular spectrum analysis using FADC timing at HiRes

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Abstract. The High Resolution Fly's Eye detector (HiRes) employs an FADC data acquisition system at one of its sites. This data acquisition system allows for the binning of light from an EAS in equal duration time bins in time along the observed track. Time binning leads to different (and hopefully smaller) systematic uncertainties than the traditional binning by individual tubes and their angles. In addition, time binning has much finer longitudinal resolution for distant EAS's. We present the details of this analysis and a preliminary spectrum.

1 Introduction

In the reconstruction of an extensive air shower (EAS) using air fluorescence, the energy determination is quite sensitive to the inferred geometry of the event. With one viewing location, it is straightforward to determine the plane containing the detector and the EAS, but difficult to determine the angle of the EAS with respect to the ground within that plane. This ambiguity leads one to construct multiple viewing locations so the EAS can be viewed in stereo. However, for any separation between viewing locations there are numerous events which can be seen by only one; these events cannot be ignored.

The High Resolution Fly's Eye (HiRes) detector is a stereo EAS detector, with a separation between the two sites of 12.6 km. The first site to be constructed, HiRes-1, has one ring of mirrors covering elevation angles of 3–15° and uses a sample-and-hold data acquisition (DAQ) system. It has been running for four years. A monocular spectrum using data from this site is being presented at this conference (HiRes, 2001a).

With the construction of a second site, HiRes-2, stereo determination of the EAS became possible. We have been collecting stereo data for one year. A stereo spectrum is also being presented at this conference (HiRes, 2001b). One might think that with one long-exposure, monocular spectrum and one shorter-exposure, stereo spectrum would be enough, but the design and DAQ of HiRes-2 offer several advantages over what is available at HiRes-1. First, there are two rings of mirrors at HiRes-2, covering 3–31° in elevation. This allows for a more robust determination of the EAS geometry from timing alone. Second, HiRes-2 employs an flash analog-to-digital converter (FADC) DAQ system, which allows one to bin the light in time bins, rather than by photomultiplier tubes (PMT's). This leads to a more robust determination of the shower profile, especially for distant EAS which are seen in only a few tubes but are visible for an extended time. This allows one to extend the spectrum to lower energies.

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2 The FADC DAQ System

Each PMT at HiRes-2 is sampled every 100 ns at high-gain by an FADC. Analog sums, by rows and columns, of the PMT outputs are also sampled at low- and high-gain by an FADC. The high-gain sums are used for triggering while the low-gain sums are used for redundancy in case one of the high-gain PMT channels is saturated. If the trigger is satisfied, a 10 μs window of FADC readings about the signal pulse of all the active channels in a mirror is written into the data stream. Thus, for each active tube, we have essentially a 10 MHz digital oscilloscope reading of its response to the EAS. Two example FADC profiles are shown in figure 1.

3 Determining the Geometry of the EAS

The first task of the analysis is to find the EAS signal among the noise events. The principle used in our analysis was that an EAS should result in a collection of tubes and their times linearly associated in space and time. For this, and in determining the geometry of the EAS from timing, each channel's pulse is averaged to give a mean time. In this way, the analysis is not much different from how one would analyze data

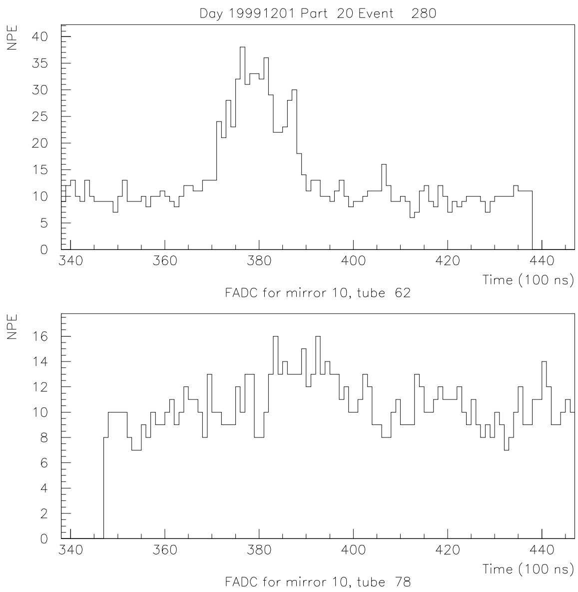

Fig. 1. A picture of two FADC profiles from the same event. The upper plot is from the center of the EAS, whereas the lower plot from an adjacent PMT just to the side and down. The two sequences have been arranged to have the same actual times aligned vertically.

from a sample-and-hold DAQ system, except that one has the mean time of the pulse rather than the leading edge.

To pick out signal channels among the noise we used a seeded clustering algorithm. The seed for the cluster was chosen acounting for both a PMT's total number of photoelectrons (NPE) and its proximity to other active tubes. Adjacent tubes with overlapping (in time) pulses were then attached to form the initial set of tubes. The elevation and azimuthal angles of all the selected tubes in the cluster were fit to determine the shower-detector plane.

The existence of a shower-detector plane implies an ordering of the tubes: the angle within the plane. This angle was required to be locally linearly dependent on the time of the tube. The times of the tubes within five degrees of a given tube were fit to a line. If the given tube, was not itself on this line, it was rejected. This insures that the selected tubes have the appropriate linear time dependence.

The tube times were then required to be globally consistent with the expected timing for light from an object moving at the speed of light,

$$t_i - t_0 = \frac{R_p}{c}\tan\left(\frac{\pi - \psi - \chi_i}{2}\right) \tag{1}$$

where t_i and χ_i are the time and angle of the ith tube, and R_p and ψ are the impact parameter and the angle with respect to the ground of the EAS within the shower-detector plane. Events with enough tubes (5) satisfying these requirements and moving apparently towards the horizon were kept for our spectrum sample.

There are three parameters to be determined in equation 1, R_p, ψ and t_0, all of which are quite correlated, making a χ^2 minimization difficult. To deal with this, we note that R_p and t_0 are linear parameters and thus easy to determine for fixed ψ. Thus, we scanned ψ in 1° steps from 5° to 175° for each event, determining the χ^2 at each angle step. To determine the χ^2, timing uncertainties for each tube were calculated using the RMS of the FADC slices in the pulse and the total NPE observed: $\sigma_t = t_{\mathrm{RMS}}/\sqrt{k\mathrm{NPE}}$. The factor k was adjusted using MC events to give a mean χ^2/DOF of one and appropriate fractions of events where the χ^2 at the generated value of ψ was within 1, 4 and 9 of the minimum. The best ψ value was chosen by minimizing the χ^2 from the scan.

The errors on the geometric parameters (and later the profile parameters) were taken from the uncertainty in ψ which was determined by finding the value for ψ where the χ^2 had increased by one from the minimum. It was assumed that this was that the dominant error and the errors on R_p and t_0 at a fixed ψ were insignificant. This is indeed the case for most, if not all, events.

A sample event (the same event as in figure 1) is shown in figures 2 and 3. Figure 2 shows the tubes in elevation and azimuthal angle. The size of the tube represents the NPE while the color represents the time. The blue and red circles at the edge of the mirrors represent the row and column sums for the trigger and for low-gain (at somewhat arbitrary positions on the plot, but corresponding to the respective row or column). Figure 3 shows the time of each selected tube (and some excluded ones) versus its angle in the shower-detector plane. Overlain are a linear fit, a fit to equation 1 with $\psi = 90^\circ$ and a fit to equation 1 with $\psi = 45.9^\circ$.

4 Looking at the Shower Profile

With the geometry of the EAS determined, one can relate the NPE of the PMT's to the number of photons generated by the EAS at a given instant as it passes through the atmosphere. Several factors go into this calculation, some of which are straightforward, such as the solid angle of the mirror with respect to a point in the shower, the reflectivity of the mirrors, the transmission of the UV filter and the quantum efficiency of the tube. The difficult factors to determine are the geometric acceptance of a given time bin, the fraction of the light which is transmitted through the atmosphere from the EAS and the fraction of light comes from nitrogen fluorescence as opposed to scattering of the Cerenkov beam. Each of these is discussed below.

It is in determining the acceptance of a given time bin that the FADC binning method really shines. Because a number of PMT's contribute to the signal in any time bin, the effect of any given tube is diluted. This is important for two reasons. First, a given tube may have only a small acceptance, leading to a large, poorly determined correction factor. However, when this tube is combined with other PMT's with larger acceptances, the total acceptance is much better determined. One can then restrict oneself to time bins where the total acceptance is large and well understood. The second advantage

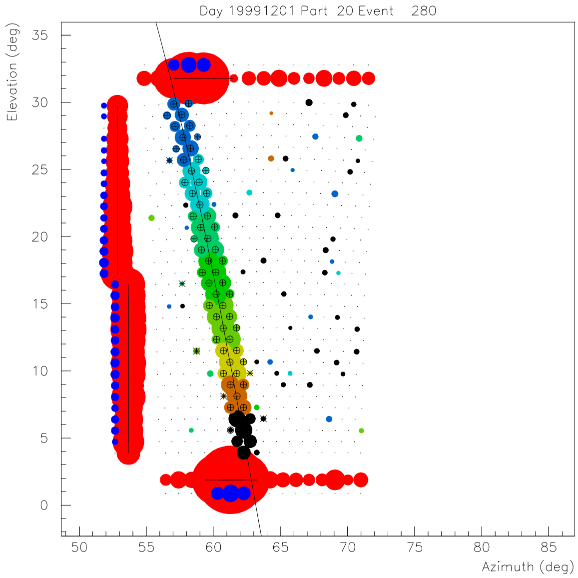

Fig. 2. A picture of the PMT's and their response as projected onto the sky. Each dot represents one PMT. Active PMT's has a colored circle whose area is proportional to the NPE it observed. The color of the circle represents the relative time, going from blue to red. The blue and red circles on the edges represent the trigger and low-gain sums corresponding to rows or columns. (The two tubes from figure 1 are in the fourth and fifth rows from the top, being the third tube from the left in each case.)

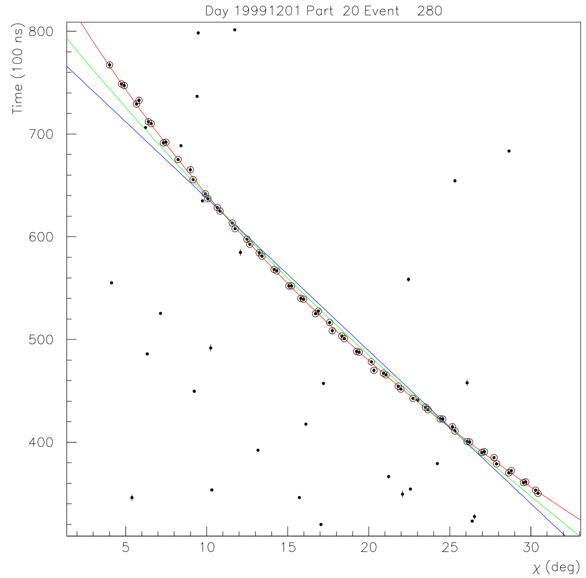

Fig. 3. A plot of the selected PMT signal showing their time (in 100 ns units) vs the angle in the detector shower plane. Some non-selected signals are plotted as well. The three lines represent fits to a line, a tangent fit with $\psi = 90°$ and a tangent fit with $\psi = 45.9°$.

of time binning in acceptance is that the uncertainty in acceptance is often correlated between tubes, with what is lost from one being gained by its neighbor. By summing over all the tubes at a given time we thus reduce the overall systematic uncertainty associated with the geometric acceptance of the tubes.

The attenuation length of light in the atmosphere has two principle components: Rayleigh scattering from air molecules and Mie scattering from aerosols suspended in the air. The former is quite constant and easy to model while the later is quite variable. For this analysis the aerosol horizontal scattering length was assumed to be 20 km, with an exponential scale height of 1.2 km, which is indicative of the average conditions at Dugway Proving Grounds. This compares to the molecular horizontal scattering length of 17 km with a scale height of 7.5 km. Since the highest energy showers are several tens of kilometers away, the aerosol content of the air can have a significant impact on the reconstructed energy and longitudinal profile of an EAS.

The Cerenkov beam accompanying an EAS depends on the number of charged particles at each stage. The light from the beam is scattered into the detector, confounding the calculation of the shower size from the NPE. We want to find the shower size at each point, but we also need to know it to calculate the NPE from scattered Cerenkov light. We solve this problem by first assuming that all the light comes from fluorescence. Here, as in all the transmission calculations, the light is divided into wavelength bins of 1 nm, from 300-420 nm, which covers the transmission of the HiRes UV filters. The yield of photons per charged particle per meter are taken from the measurement by Kakimoto *et* al (Kakimoto, 1996). This uncorrected number of charged particles in the shower at a given slant depth in the atmosphere (determined from the geometry an time) is fit to the Gaisser-Hillas profile

$$N_e(X) = N_M \left(\frac{X - X_0}{X_M - X_0}\right)^{\frac{X_M - X_0}{\lambda}} \exp\left(\frac{X_M - X}{\lambda}\right) \quad (2)$$

where X is the slant depth in the atmosphere, X_0 is the slant depth of the first interaction, X_M is the slant depth with the maximum number of charged particles and N_M is the number of charged particles at this point. In our fits we set $X_0 = 40$ g/cm^2 because we aren't very sensitive to the beginning of the shower and take $\lambda = 70$ g/cm^2.

Once we have the preliminary profile, the Cerenkov contribution is computed by iteration, using the previous profile fit to give the number of charged particles in the shower and thus the number of Cerenkov photons in the beam at any point. Because the Cerenkov contribution is small for most reconstructible events, this iteration proceeds quickly and only two additional iteration are allowed. The result for the same event shown above is shown in figure 4.

By integrating the number of charged particles versus the slant depth and multiplying by the average energy lost per particle, 2.19 MeV/(g/cm^2) (Song, 2000), we find the energy of the initial particle. To compute the flux of cosmic rays,

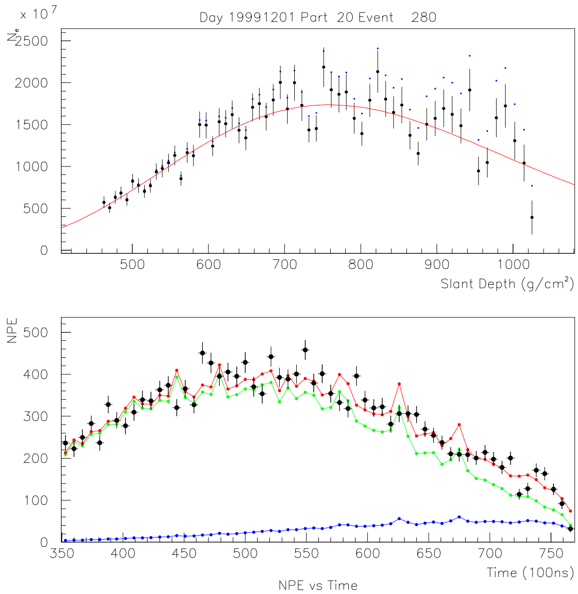

Fig. 4. A plot of the longitudinal profile of an EAS. The top plot shows the reconstructed number of electrons in the shower as a function of the atmospheric depth the EAS has traversed (in g/cm^2). The small blue circles represent the number of electrons before a Cerenkov correction was applied. The lower plot shows the observed NPE in each corresponding time bin along with the expected number of photoelectrons from fluorescence (green), Cerenkov scattering (blue) and their sum (red).

we must divide the observed number of events at a given energy by the aperture of the detector at that energy and the exposure time. The aperture of the detector was determined using a sophisticated Monte Carlo simulation of our detector combined with a shower library generated with Corsika. Details of the Monte Carlo will be presented in another paper at this conference (HiRes, 2001c). The input spectrum used by the Monte Carlo simulation was based on the measured Fly's Eye stereo spectrum.

The final event selection criteria and the resulting spectrum will be presented at the conference.

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