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Stereo Reconstruction at HiRes

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Abstract: We describe a technique used to reconstruct the energy and Xmax of Ultra High Energy Cosmic Rays (UHECR) observed by the HiRes detector in stereoscopic mode. This technique calculates the relationship between the number of shower particles at a depth of the shower to the signal in either angular or time bins. This relationship is calculated for a given shower segment location. The estimated number of shower particles at a given shower depth is calculated using this relationship from the observed bin signals. The observed longitudinal shower profile is then fit using a technique developed by Martin Block which judiciously removes problematic data points. In simulation, energy resolutions of approximately 12% or better are obtained with high efficiency for energies above $10^{18.5}$ eV. The estimated Xmax resolution for this technique is approximately 35 g/cm^2 or better at these energies.

Introduction

The High Resolution Fly's Eye is an observatory designed to observe cosmic rays with energies in excess of 10^{18} eV. The indirect measurement technique of air fluorescence is used to maximize the detector aperture for greater probability of observing the highest energy events. The HiRes detector has the capability to measure the energy, arrival direction, and chemical composition of these high energy particles as they enter the Earth's atmosphere. Located in the West Desert of Utah, two groups of air fluorescence detectors (HiRes1 and HiRes2) separated by 13 kilometers make separate observations of air showers in stereoscopic mode. Each detector provides nearly full azimuthal coverage and can view between 3° and 17° (HiRes1) or 31° (HiRes2). By combining the geometrical and temporal information of both detectors, cosmic ray induced air showers can be reconstructed in a superior manner than by only one detector. Stereo operations began in December 1999 and ended in April 2006. Over that time period, HiRes collected over 3300 hours of stereo data providing an approximate exposure of 3200 km^2 sr yr at energies above 10^{20} eV. Over 12000 cosmic ray candidates were observed during this time.

Light collection

As a high energy cosmic ray primary particle enters the Earth's atmosphere it quickly interacts with an air molecule causing a cascade of secondary particles that result in an extended air shower (EAS). The electromagnetic component of the EAS excites N_2 molecules which fluoresce ultraviolet light most strongly at the 335 to 390 nm wavelengths. This UV light is isotropically emitted and propagates through the atmosphere to the HiRes detector where it is reflected by one of many large (~ 5 m^2) spherical mirrors and focused onto each mirror's associated cluster of 256 photomultiplier tubes, each providing a pixel size of approximately 1 degree. Using the timing and geometry of the recorded light profile, a shower-detector plane can be determined for each detector as well as the arrival direction and core location. In addition, by combining the information collected by the two individual detectors, a stereoscopic determination of the shower's properties can be made to refine these measurements. The recorded light flux is then binned using either geometry (angular bins) or timing (time bins) to construct the signal profile of the EAS, measured in photoelectrons/m^2/degree.

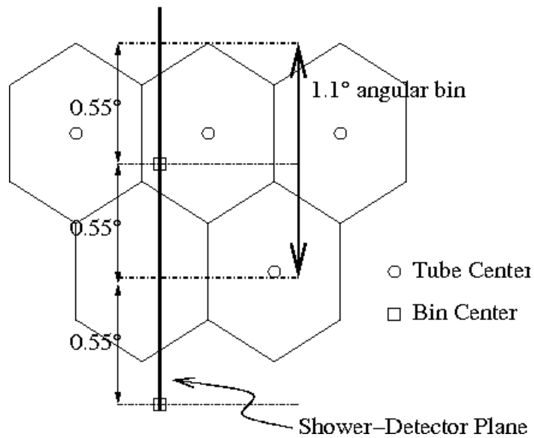

Figure 1: Example of relative size of angular bins on the photomultiplier tube cluster face.

Angular bins (figure 1) collate the light flux into 1.1 degree bins, where the bin flux is determined by

$$\phi_{\text{bin}} = \frac{1}{A_{\text{eff}} \cdot \Delta\theta} \sum_{i=1}^{N_{\text{tube}}} f_i \cdot N^i_{\text{pe}} \qquad (1)$$

where f_i is the fraction of the ith tube contained in the bin and N^i_{pe} is the number of photoelectrons. The weighted number of photoelectrons in the bin is then normalized by A_{eff}, the effective area associated with the bin, calculated from ray-tracing, and $\Delta\theta$, the bin angular size, to give us the signal for a particular angular or time bin.

Time bins are constructed by dividing the light flux that falls upon a photomultiplier tube cluster over the individual 100 ns clock cycles of the flash ADC electronics that comprise the HiRes2 detector[1]. Angular bins may be constructed for HiRes1 and HiRes2 observed showers, but time bins are available only for HiRes2. Time bins are not available for HiRes1 because it uses sample and hold electronics that do not repeatedly measure a shower profile during an event trigger. Figure 2 shows an example of a calibration laser event observed by HiRes2 where angular and time bins have been constructed from the resultant track on the cluster.

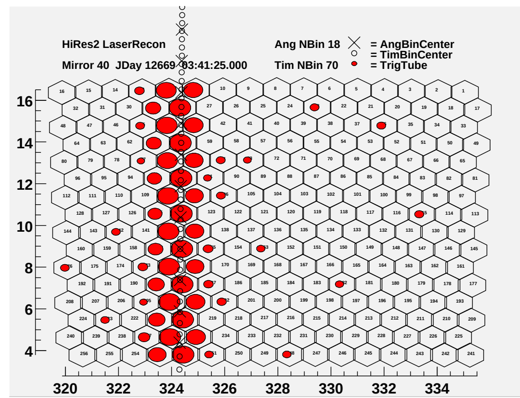

Figure 2: Typical vertical calibration laser shot as seen by HiRes2 from the night of 30 January 2003. Note that there are many more time bins than angular bins. Here angular bin centers are separated by 1.5°.

Profile reconstruction

The depth of the shower at each bin is determined using the reconstructed geometry and the density profile. The shower flux as a function of depth is then calculated from the light flux in each bin. This function needs to be converted to the shower size as a function of depth (the shower profile). Using standard shower parameters a simulated shower is then generated and the light is propagated using the measured atmospheric parameters, fluorescence yield, mirror reflectivity, UV filter transmission, and quantum efficiency to determine the number of expected photoelectrons for a given number of scintillation inducing particles in the shower (termed the propagator). Applying this calculated propagator, we obtain the shower profile. This shower profile is then fit using a Gaussian in age function[2], where the number of shower particles is a function of shower age described by

$$N(s) = N_{\max} \exp\left(-\frac{1}{2}\left(\frac{s-1}{\sigma}\right)^2\right) \qquad (2)$$

where the shower age $s(x) = 3x/x + 2X_{\max}$. Transforming eq. 2 into a function of shower depth, x, we see that the fitting routine is solving for three parameters.

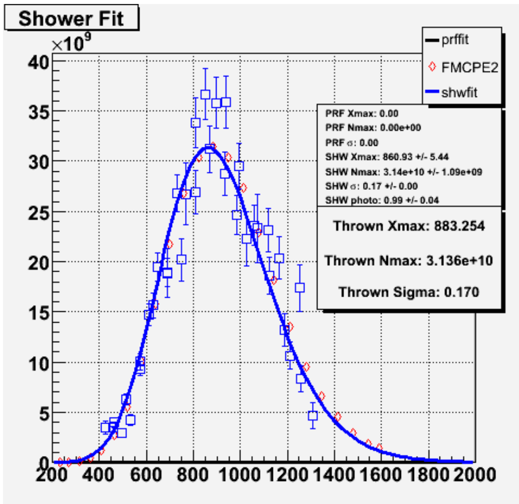

Figure 3: Example of a monte carlo generated air shower and the fit to the shower profile. The abscissa is depth in g/cm^2 and the ordinate is the number of charged particles. Diamonds are the thrown shower profile, squares are the reconstructed shower profile and the solid line is the Gaussian in age fit found to best match the shower.

$$N(x; N_{\max}, X_{\max}, \sigma) = N_{\max} \exp\left(-\frac{2}{\sigma^2}\left(\frac{x - X_{\max}}{x + 2X_{\max}}\right)^2\right) \quad (3)$$

The shower fitting routine is iterative and utilizes the adaptive sieve fitting algorithm described by Martin Block[3], which finds the best χ^2 solution by removing data bins with large residuals until an acceptable solution is found. Typically the algorithm throws away those bins that are near the edge of mirrors where the effective area correction contains large systematic errors. Once a solution is found, the shower is fitted again using the last set of parameters as the starting point of the simulated shower generation and fitting routines and this procedure is repeated until the parameters converge to the best solution. Figure 3 shows an example a monte carlo generated shower and the fit that was found using the method described above.

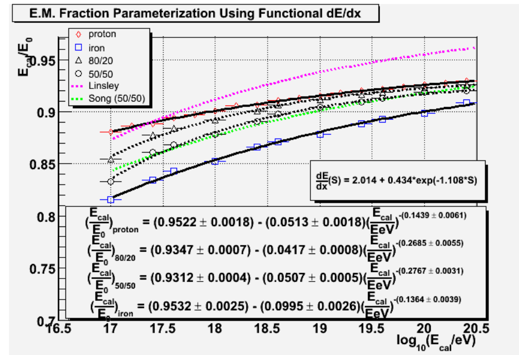

Figure 4: Parameterization of the fraction of missing electromagnetic energy expected in an EAS. Several parameterizations are shown for comparison. The one used for this study assumes a primary species ratio of 80% proton to 20% iron.

Energy determination

After the shower profile parameters have been determined, the profile is integrated using dE/dx energy deposition rate determined by a study of CORSIKA showers. A similar method has been previously described by Song, et. al. in [4]. We use CORSIKA with QGSJet II as the hadronic model. The calorimetric energy of the shower found by this integration is also corrected for missing energy lost from nuclear excitation, muons, and neutrinos and other processes that do not produce fluorescence light (figure 4).

Monte carlo resolution studies

Monte carlo has been generated that simulates the operating conditions of the HiRes detector in a time dependent manner. Measurements of stereo on time, atmospheric conditions, and trigger thresholds are used to generate simulated showers and the resultant signals recorded by the detector. Using the reconstruction routines described above the energy and Xmax resolutions were examined and found to be 12% and 32.3 g/cm^2 respectively (figures 5 and 6). All events considered for this resolution study have reconstructed energies greater than $10^{18.5}$ eV. This work is near completion but

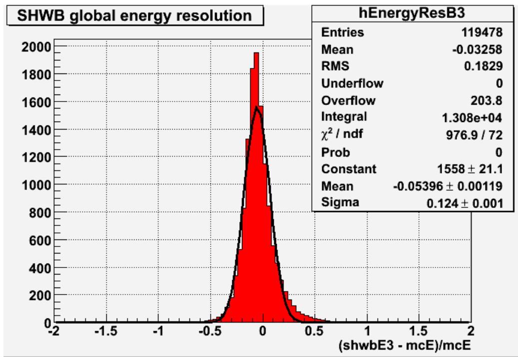

Figure 5: Energy resolution of monte carlo simulated showers representative of the entire lifetime of stereo operations at HiRes. The resolution is seen to be 12% for events with reconstructed energy greater than $10^{18.5}$ eV.

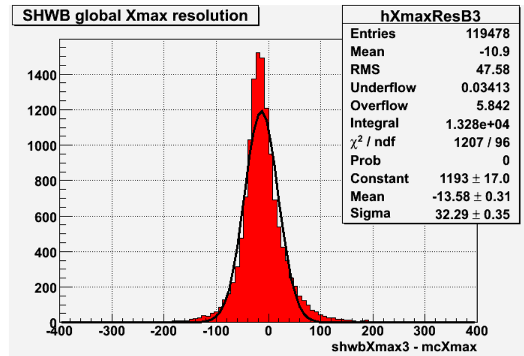

Figure 6: Xmax resolution of monte carlo simulated showers representative of the entire lifetime of stereo operations at HiRes. The resolution is seen to be 32.3 g/cm^2 for events with reconstructed energy greater than $10^{18.5}$ eV.

further improvements to the energy and Xmax resolutions may be possible for this energy range.

Conclusions

A monte carlo that simulates the operating conditions of the HiRes detector during stereo running has been used to simulate air showers over the seven years of operations. A new reconstruction method using an iterative adaptive sieve algorithm has been adopted to reconstruct showers. The energy resolution using this method is 12% and the Xmax resolution is found to be 32.9 g/cm^2.

Acknowledgments

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