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# Stereo Measurements of Cosmic Ray Events at the High Resolution Fly's Eye Prototype

**L.R. Wiencke[1] for the**
**High Resolution Fly's Eye Collaboration and the Telescope Array Collaboration**
1 *Physics Department, University of Utah, Salt Lake City, UT 84112, USA*

## Abstract

The High Resolution Fly's Eye cosmic ray observatory operated two prototype detectors to develop techniques for measuring cosmic rays using two stations separated by 12.6 km. This paper reports on the results of this study that includes stereo reconstruction methods using precise timing constraints. Distributions of shower geometry, energy, and arrival directions will also be presented.

## 1 Introduction:

The original Fly's Eye experiment[1] demonstrated the advantages of measuring cosmic ray air showers in stereo. The shower geometry could be determined from the intersection of two planes rather than from monocular timing measurements to determine the direction and distance to the shower. Besides providing cross checks and a cross calibration of the two detectors, the two independent measurements of the same shower improved the energy and angular reconstruction. This technique has been extended to two prototype High Resolution Fly's eye (HiRes) detectors with the added improvement of a stereo fit that includes precise timing. These two detectors collected data for 880 hours of stereo observation. A sample of 309 air showers were observed and reconstructed in stereo using this technique.

## 2. The HiRes Prototype Detectors

To extend the fluorescence measurement technique to a higher resolution and greater aperture, the High Resolution Fly's Eye (HiRes) experiment installed and simultaneously operated two prototype detectors. Briefly, they consisted of $3.5 m^2$ mirrors, each with 256 photomulitiplier (PMT) tubes at the focal plane. Each PMT viewed approximately $1^\circ$ degree solid angle of sky. Signals were digitized by sample and hold electronics that measure the pulse area and trigger time of PMT signals above a threshold. The thresholds were dynamically adjusted to

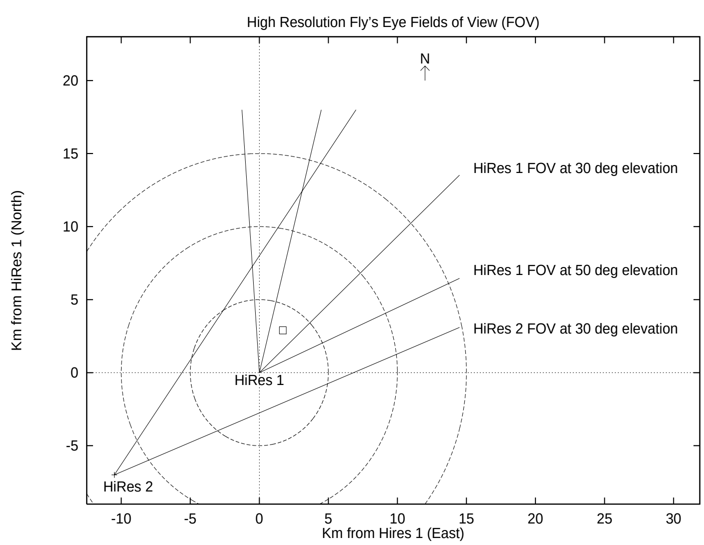


Fig. 1 The location and fields of view of the two HiRes prototype detectors.

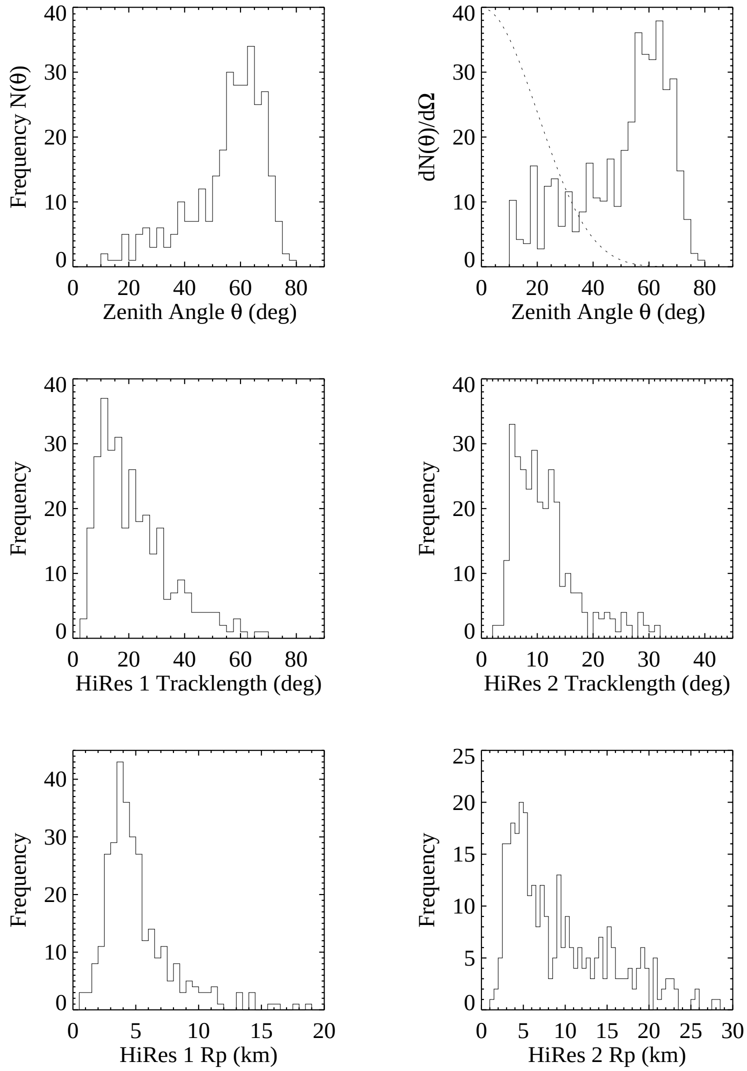


**Figure 2** Zenith angle (scaled for solid angle), Track length and Rp distributions for the 309 stereo events recorded by the HiRes prototype detectors.

maintain an individual PMT count rate of 200 hz. Typical thresholds correspond to approximately 30 photoelectrons. A six-fold coincidence was required to form a mirror trigger that was then digitized and written to a file. The energy threshold for monocular observation of showers via scintillation light was approximately $10^{17}$ eV

Figure 1 shows the relative locations of the two detectors and their fields' of view. The field of view of the 14 mirror HiRes1 detector was configured to overlook the CASA-MIA ground array so that a subset of events could be measured by these two detectors[2]. The four mirrors of the HiRes2 detector pointed toward HiRes1.

This configuration poses a challenge for stereo reconstruction. The two detectors point in nearly the same direction along the imaginary line passing through the two sites. Thus the opening angle between the shower planes as measured by each site can be relatively small. Therefor uncertainties in the shower planes will propagate to larger errors in the reconstructed shower axis. We note that although the geometry of the full HiRes detector will cover 360 degrees of azimuth at both sites, the average distance to reconstructible showers above the GZK cutoff is expected to be 25km. At this distance, the opening angle between the two shower planes will not exceed 30 degrees. Stereo reconstruction techniques that include timing to reconstruct the shower geometry more precisely will be very important for physics measurements such as searches for correlations between shower arrival directions.

## 3. Stereo Reconstruction of Laser Shots

A reconstruction technique was developed that made use of precise timing provided by GPS clocks[3] located at both sites. The GPS clock system allowed relative time of triggers between sites to be determined with a precision of about 200 ns. The technique[4] was first tested by reconstructing the direction of tracks produced by light scattered out of a precisely steered laser beam. The portable laser system[5] used stars as a reference to provide an absolute alignment accuracy of 0.1 degrees. Error in the reconstructed direction

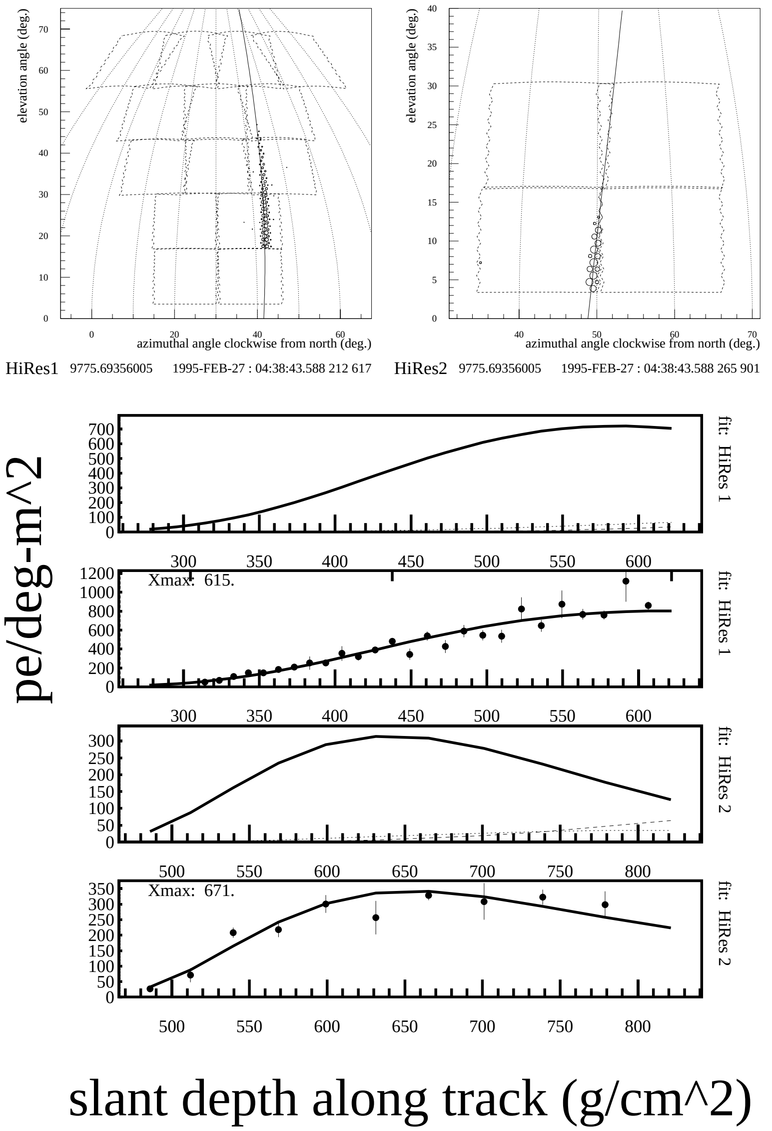


**Figure 3** Air shower observed in stereo. The energy determined by a stereo profile fit is 5.0+/-0.5x10$^{19}$ eV.

was found to depend on track length and opening angle. For laser shots for which the opening angle was greater than 10 degrees, the space angle error for the combined geometry and timing fit was less than 1 degree for 90% of the shots and less than 0.4 degrees for 50% of the shots. degrees. For smaller opening angles, the error improved from 2.75 degrees for a geometrical reconstruction to 0.9 degrees for a reconstruction that included timing.

## 4. Stereo Events

The two prototype detectors were operated simultaneously for 880 hours. During this time 4.2x10$^{7}$ triggers were recorded and HiRes1 and 8.4x10$^{7}$ were recorded at HiRes2. 4.6x10$^{5}$ of these triggers occurred within a 200 microsecond window of each other and were selected as stereo candidates. Most of these triggers were coincidences of night sky noise. The next most frequently occurring stereo triggers were caused by man-made sources including airplanes and upward going laser and flasher shots. Air shower candidates were selected based on a vector sum of the difference in pointing directions of time ordered tube pairs within 2.5 deg of each other. The vector from each site was required to have a random walk probability of less than 5% and the vector for at least one site was required to point downwards. The trajectories of these candidates were then reconstructed by the stereo fitting algorithm that had was developed using the laser shots. This process reconstructed 682 events, or approximately 0.75 events per hour of stereo observation. The atmospheric depth of shower maximum (Xmax) and the energy of the primary particle were then estimated using the fitted trajectory and track profile. The shower profiles were fit to a Gaisser-Hillas shower development function.

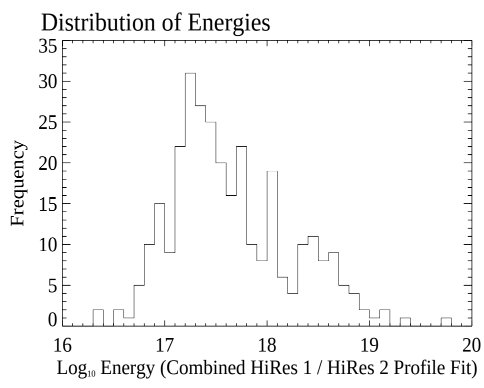


**Figure 4**. Energy distribution of showers measured by HiRes1 and HiRes2 prototype detectors.

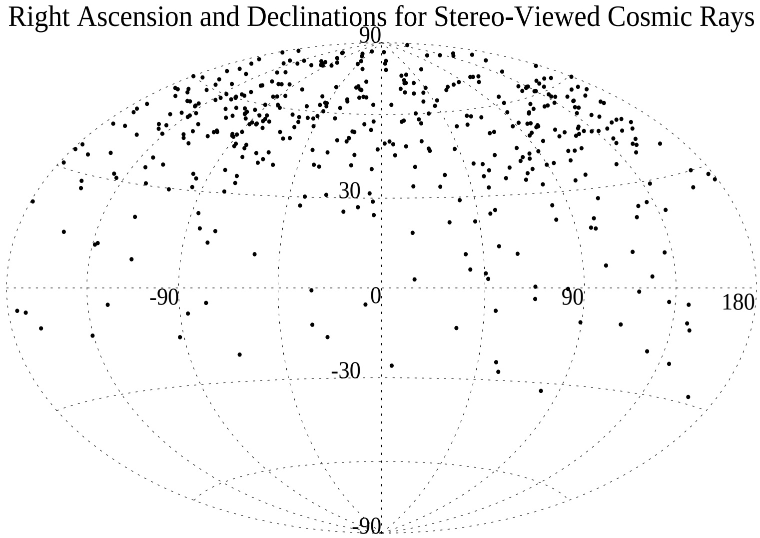


Figure 5. Sky Map of 309 events reconstructed in stereo.

The reconstruction fitting algorithm performed three calculations of shower energy and Xmax using the Hires1 measurement, the HiRes2 measurement, and the combined HiRes1 and HiRes2 measurements. The calculations included a correction for atmospheric attenuation derived from measurements[6] by the HiRes1 detector of scattered light from a columinated xenon flashbulb system[7]. A sample of 309 events were selected for further study. For these events the difference in reconstructed energy as found from the stereo fit and the HiRes1 fit was less than 20% and the reconstructed Xmax was atleast 100g deeper than Xo. The energy distribution for these events is shown in Fig 4. Distributions showing the distance of closest approach of these showers (Rp) to the two detectors are shown in Fig 2. We note that this distribution extends to 25km, the most likely distance at which the full HiRes detector may observe showers above the GZK cutoff. The highest energy event was found to be $5.0 +/- 0.5 x 10^{19}$ eV with an Rp of 11.5km for HiRes1 and 23km for HiRes. Although it is not corrected for detector exposure, Fig 5 shows the arrival directions of these events.

## Conclusion

Stereo reconstruction techniques including precise timing were developed and to identify and reconstruct air showers recorded by the HiRes prototype detectors. These techniques will be applied to data from the full HiRes detector as it comes on-line.

## Acknowledgements

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