# Reconstruction Techniques and Tests Using the HiRes Prototype

D.J. Bird,[1] J. Boyer,[2] R.W. Clay,[3] S.C. Corbato,[4] H.Y. Dai,[4] B.R. Dawson,[3] R.W. Downing,[1] J.W. Elbert,[4] M.A. Hunan,[4] M.J. Kind,[1] D.B. Kieda,[4] S. Ko,[4] C.G. Larsen,[4] W. Lee,[2] E.C. Loh,[4] E. Mannel,[2] T.A. O'Halloran, [1] M.H. Salamon,[4] J.D. Smith ,[4] P. Sokolsky,[4] P. Sommers,[4] J.K.K. Tang,[4] and S.B. Thomas [4]

[1] Department of Physics, University of Illinois at Urbana- Champaign Urbana, IL 61801
USA
[2] Nevis Laboratories, Columbia University, Irvington NY 10533
USA
[3] Department of Physics and Mathematical Physics, University of Adelaide Adelaide, South Australia 5001
Australia
[4] High Energy Astrophysics Institute Department of Physics, University of Utah, Salt Lake City UT 84112
USA

## ABSTRACT

Shower geometrical reconstruction procedures for the proposed high resolution Fly's Eye ( HiRes ) have been developed using Monte Carlo simulations which include effects of optical aberrations and photomultiplier signal statistical fluctuations. These procedures have been tested using pulsed laser beams of known geometry, observed by the HiRes Prototype. Sets of laser shots fired with directional differences as small as 0.1 ° have been clearly resolved. Monte Carlo simulations have estimated the angular resolution of stereo reconstruction of showers with a 2 site HiRes. With these results, the estimated sensitivity of HiRes to any EeV point sources is about 1.5 orders of magnitude greater than that of the original Fly's Eye.

## 1. INTRODUCTION

A higher resolution Fly's Eye has been proposed and a 14 mirror unit prototype has been built near Fly's Eye 1. ( Other papers related to HiRes are found in D.J. Bird *et al.*, section OG 10 of these proceedings. ) The mirror units have a mirror area ( corrected for obscuration ) of 3.8 m$^2$ and a 16 x 16 array of hexagonal photomultiplier tubes ( pmts ) in the image plane. Each pmt views a much smaller angular region ( diameter 1 ° ) than a pmt in the Fly's Eye ( diameter 5.5° ). The sensitivity of HiRes is increased relative to Fly's Eye by a larger mirror area, by a lack of hexagonal light collectors, and by the smaller background sky noise in the smaller diameter pixels. For the geometrical reconstruction, the largest improvement is the smaller pixels. A second improvement is the improved mirror shape, with ~80% of the light collected in a 1 cm x 1 cm detector in a test with a light source and detector both located near each other and near the radius of curvature ( 4.8 m ) The improved mirror shape gives an image spot size dominated by predictable aberrations, allowing the detailed response of HiRes to be simulated.

The most precise determinations of shower trajectories for the Fly's Eye come from the stereo fits, whose accuracy is limited by the accuracy of the fitted shower-detector plane ( SDP ). The SDP is defined by a point ( the detector ) and a line ( the shower ). Given SDPs from a shower observed at two locations, the shower trajectory is the line of intersection of the two planes. If $\tilde{n}_1$, and $\tilde{n}_2$ are normal vectors for the planes, the shower direction is perpendicular to both normal vectors and is given by ± $\tilde{n}_1$, x $\tilde{n}_2$.

## 2. FITTING THE SHOWER DETECTOR PLANE

The data used to find the SDPs are the direction vectors of the centers of the fields of view of triggered pmts and the pmt anode pulse integrals ( referred to as amplitudes, below ). Because of the mirror quality mentioned above, the mirror orientation

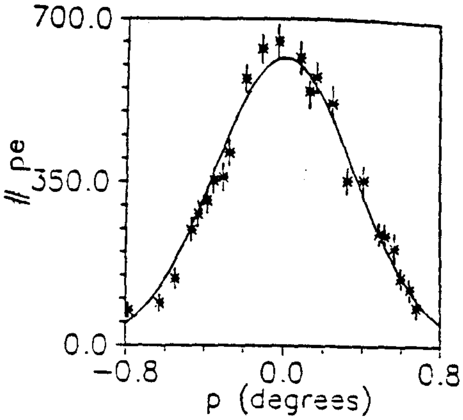

Fig. 1: Lateral Response Profile

( and consequently the pmt directions ) can be measured to an accuracy of 0.1°. Prototype tests using distant laser beams have shown that the pmt amplitude fluctuations are dominated by photoelectron ( pe ) statistical fluctuations, as expected. The most effective methods of fitting the SDP make use of the known amplitude response of the detector. With precise knowledge of the track geometry, as with a distant laser beam, we can study the pmt amplitudes as a function of the lateral angular offset, p, of the pmt direction from the track. ( For observations nearly perpendicular to the laser track, the variation of the amplitude along the track is small and is easily taken into account by a linear fit to the longitudinal dependence. ) Figure 1 is an example of a lateral response profile. Each point represents the mean amplitude ( in numbers of pe ) for a pmt which observed 993 vertical laser shots at a distance of 3.4 km. The signal is produced by scattered fight from 155 nJ $N_2$ laser pulses. The solid line plots $\text{á} = \text{á}e^{-P2\,/\,\text{â}2}$, with á = 600 pe and â = 0.5°. The two main causes of this shape are that track lengths within a pmt are shorter if the track is near the edge and aberrations cause some light to shift to adjacent pmts. The shape in Fig. 1 is reproduced well by ray tracing simulations which include the effects of track geometry, aberrations, spot size, and mirror obscuration by the pmt cluster.

A method of finding the SDP which uses our knowledge of the lateral response profile is the amplitude-fitting method. In Monte Carlo studies it gives very precise plane fits by finding the plane which yields the actual pmt amplitudes. It assumes the lateral response curve plotted in Fig. 1. If we ignore the longitudinal dependence of the amplitudes, the fit minimizes $\text{Ó}( a_i( o ) - a_i( c ) )^2 / (a_i( o ) + B )$, where $a_i( o )$ and $a_i( c )$ are the observed and calculated signal amplitudes, respectively, and B is the background light. The units of a, and B are numbers of pe. The expected $a_i( c )$ are found by fitting a parameter( á ) to the amplitude at p = 0.

A small Monte Carlo program has been used to find the typical error in evaluating $lp_i|$ for a pmt as a function of á. The error is caused by random fluctuations in the number of pe in the presence of a background, B, of 35 pe ( appropriate for a 1.2 ìs integration time ). The result, in degrees, is ó = 0.7 / á + 0.003. For example, a weak track with á = 50 photoelectrons gives ó = 0.1 °.

Fitted planes pass very near to the track centroid direction, defined as = $\text{Ó}\, a_i ø_i / | \text{Ó}\, a_i ø_i |$ where $ø_i$, is the unit vector defining the direction of the $i^{th}$ pmt. The main error in fitting the plane is a rotation of the plane about the centroid by an rms angle $\text{ó}_b$, in degrees. A simple model ( Elbert ) gives the following estimate of this error, in degrees, where ρ is the density ( per degree ) of pmts along the track, and L is the track length in degrees.

$$\text{ó}_b = ( 180 / \pi ) \quad \text{ó} ( 12 / \quad \rho ) L^{-3/2} \qquad ( 1 )$$

The model gives rough estimates of the accuracy of planes fitted to laser shots. For cosmic ray air showers one complication is that the received light intensity ( á ) varies along the track. !n the fitting process the predicted amplitudes can be normalized by the amplitudes of neighboring pmts or by some other method. A second complication is that a cosmic ray air shower has an intrinsic width which broadens the lateral response function. Calculated HiRes response distributions using realistic shower lateral distributions together with the HiRes lateral response function can be approximated quite well by adding one more parameter to the fitting process. This procedure works well for showers at various distances and ages.

## 3. RESULTS OF LASER SHOT STUDIES

On July 31, 1992 a series of vertical and near-vertical $N_2$ laser ( ë = 337 nm ) shots were done from a site 3.4 km from the HiRes Prototype ( Elbert and Corbato ). The shots were detected by 3 mirror units. The reconstructed planes were compared with the planes expected from the known laser position and orientation. Corrections were made for the parallax arising from the mirror separations. The vertical shots were done with the laser mounted on a level platform that could be rotated. Shots were done at 3 azimuthal angles ( -90°, 0°, 90° ) relative to the direction to the detector. The shots were done at three intensities: unattenuated, attenuated by 2, and attenuated by 4. All combinations were done, giving 9 sets of 200 shots each. The values of $ó_b$ were obtained within each set. For shots attenuated by factors of 1,2, and 4, the observed average ( over 3 azimuths ) $ó_b$ values were 0.0190,0.0230, and 0.0330 and these values are in good agreement with Equation 1. However, there were systematic discrepancies of about 0.3° between the normal vector at different azimuthal angles. These are presumably due to an offset of the laser beam from vertical, so that azimuthal rotation changed its direction. If we compare shots at the same azimuth but at different amplitudes, the maximum shift is 0.16°.

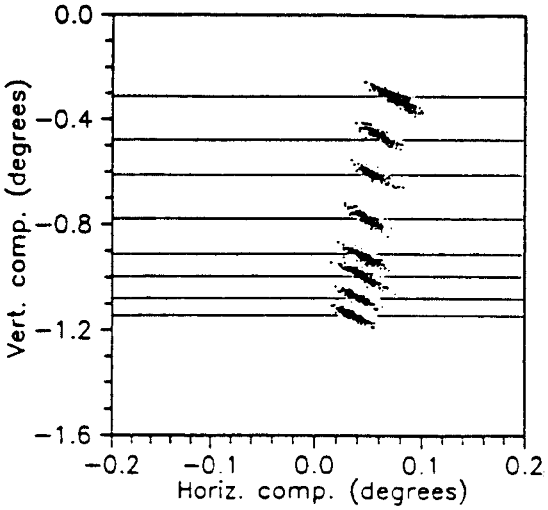

Fig. 2: Normal Vector Directions

The near-vertical shots were unattenuated and at an azimuth of 90°. Again there were 9 sets of 200 shots. For each set the elevation angle of the laser was adjusted and was read using an inclinometer with a precision of 1'. Sets 1 and 9 were done with the inclinometer indicating 90° 0'. For sets 2-8, each elevation angle was reduced by from 4' to 10' from the previous measurement. Figure 2 shows a scatterplot of the normal vector directions from the 9 sets. The upper sets ( sets 1 and 9 ) are superimposed in the upper group. If the shots had been reconstructed as accurately vertical, the vertical component would have been precisely 0. However, this group is displaced by about 0.3° from the vertical, as were the vertical shot sets at an azimuth of 90°. The horizontal component is also displaced by 0.08° from zero, the expected direction. The dotted lines are drawn with the expected separations of the vertical components of the normal vectors for the sets, but one free parameter was used to match the ~0.3° offset of all the data. The separations agree very well with the expected values.

Each set in Fig. 2 has an elongated pattern. The deviations along the longer axis correspond to errors in slope of the fitted planes and the deviations along the narrow axis are due to lateral offsets of the fitted planes. The lift of the pattern arises because the slope errors are expected to be perpendicular to both the track centroid vector ( c ) and the normal vector of the SDP. The lift results because the centroid is not horizontal and the tilt is amplified by the unequal axis scales. The mean values of the horizontal component show a systematic shift of 0.04° between sets 1 or 9 and set 8. For all sets, $ó_b$ is near 0.02°, in good agreement with Equation t.

The laser shots show that great precision and accuracy are possible in the plane fitting. Further tests will be needed to test the small systematic effects noted above. It should be noted that if the mean horizontal and vertical components from the 9 near vertical sets are corrected for their expected elevation angle differences, the mean directions all fall within a circle of 0.05° diameter.

## 4. MONTE CARLO SIMULATIONS OF THE EXPECTED RESOLUTION

Simulations have been done of the shower reconstruction accuracy of two HiRes sites. Each site was assumed to contain 54 mirror units. The separation was 13.2 km, the actual separation between two likely HiRes sites Showers produced scintillation and Cherenkov light which was scattered and attenuated by Rayleigh and aerosol scattering. The aberration effects of the optics were included. Showers were generated with realistic primary spectra and realistic triggering requirements were imposed, including simulation of the electronic pulse shapes at the trigger.

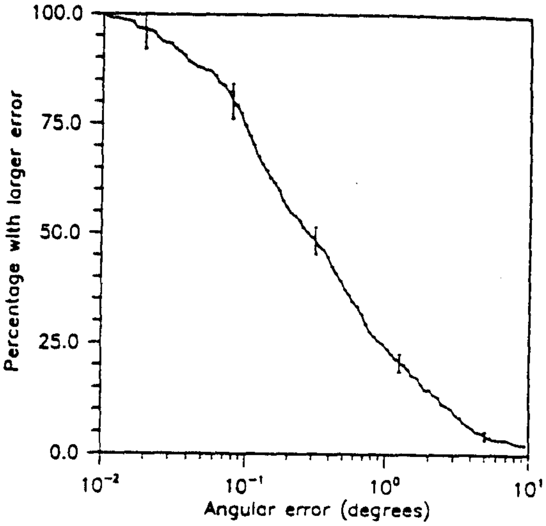

Fig. 3: Integral Angular Resolution, 10 EeV

Amplitude fluctuations of received signals were included. The Monte Carlo generated 500 triggering showers each at 1, 10, and 100 EeV. No cuts other than the triggering requirements were made. SDPs were fitted using the simulated data. The shower directions were obtained by the stereo method and were then compared with the original Monte Carlo directions. For the 10 EeV showers, Figure 3 shows the percentage of showers with errors larger than the angular errors shown on the x-axis. The figure shows that ~ 75% of the triggering showers have errors greater than 0.1 °, ~ 50% have errors greater than 0.3°, and ~ 25% have errors greater than 1 °. The distribution for 1 EeV is slightly better than shown by the figure, while at 100 EeV it is slightly worse. All distributions would be broadened somewhat if the intrinsic widths of the showers were included.

The results of the Monte Carlo show that HiRes will have a greatly improved sensitivity for point sources compared to the previous Fly's Eye. In searching for EeV point sources the estimated sensitivity achieved by HiRes in 6 years would allow sources to be detected at a flux level of about 3% of the flux level detectable by the Fly's Eye. The directional error of any such detected source would be a small fraction of 1 °.

## ACKNOWLEDGEMENTS

We are indebted to Colonels Frank Cox and James King and the staff of the Dugway Proving Grounds for their continued cooperation and assistance. This work has been supported in part by the National Science Foundation ( grants PHY-91--00221 at Utah and PHY-89-21320 at Columbia ) and the U.S. Department of Energy ( grant FG02 91 ER40677 at Illinois ).

## REFERENCES

Elbert, J.W. : 1992, HiRes Technical Note 920404.
Elbert, J.W. and Corbato, S.C. : 1992, HiRes Technical Note 920930.