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Measurement of the ultrahigh energy cosmic ray spectrum using monocular data from the High-Resolution Fly's Eye Experiment

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Abstract. The High-Resolution Fly's Eye Experiment (HiRes) has been making monocular fluorescence observations of cosmic rays above 3×10^{18} eV since June, 1997. Events collected through October, 2000, included about 1850 hours of good weather data. HiRes has made careful analysis and cross-checks of its photonic calibration, as well as the calibration of the atmospheric transmission. These have been incorporated into the spectrum analysis. Monte Carlo predictions for resolutions have also been verified with the smaller stereo data set. The resulting ultrahigh energy cosmic ray spectrum will be presented.

1 Introduction

The High Resolution Fly's Eye (HiRes) is a cosmic ray fluorescence experiment located at the U.S. Army's Dugway Proving Ground in the western Utah desert. The experiment consists of two detector sites separated by about 13 km. The first of the two sites, HiRes-1, located at Five Mile Hill has been taking data steadily since May of 1997. Details of the configuration of the HiRes-1 site can be found in reference (HiRes-Desc, 1997).

At the 26th International Cosmic Ray Conference (ICRC) in 1999, the HiRes collaboration presented a preliminary cosmic ray energy spectrum based on two years of monocular data taken from the HiRes-1 detector site. Since that time, HiRes-1 has analyzed an additional year of monocular data. The HiRes group has conducted an extensive review of the photon calibration (HiRes-Calib, 2001) for HiRes-1, along with a careful analysis of the atmospheric calibration data (HiRes-Atmos, 2001). The new spectrum will be presented at the 27th ICRC. The new results also contain a comparison between the monocular and stereo reconstruction on a smaller set of stereo events which has been collected since 1999 (HiRes-Stereo, 2001).

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2 Event Selection and Data Set

The results reported at the 27th ICRC are based on monocular data collected at HiRes-1 from June, 1997 through November, 2000. A total of about 2500 hours of observations were taken during this time. This period included two of the wettest years in recent history (1997-1999), over which the annual rainfall at Dugway Proving Ground reached 14 inches, twice that of the long-term annual average of seven inches. This interval also included a four month shut-down, mandated by the U.S. Army, during the summer of 2000. From the 2500 hour set, 1850 hours of good weather data were selected and analyzed, consisting of about 91 million events.

The transition from raw data to *reconstructible* events involves several stages of data processing and the application of various quality cuts. First, most of the collected events actually result from triggers related to sky background and other noise sources. A standard *Rayleigh filter* is used to reject events whose space-time correlations are representative of *random walk*. We keep only those events with less than 1% probability of being random noise. The filtering algorithm also allows for discrimination in apparent direction of the shower. A total of about 3.5 million downward events were kept for this analysis.

Next, the shower-detector plane is determined and the following cuts applied: (a) a minimum track-length of $8°$, (b) a maximum track crossing angular speed of 3.33 μs/degree (~ 5 km), and (c) a minimum average of 55 photoelectrons seen by triggered tubes. Both the cut on angular speed and that on the average number of photoelectrons serve to reject low energy events. In particular, the distance cut also minimizes the number of poorly reconstructed lower energy events spilling over to the high energy region, and lead only to a negligible reduction in the detector aperture at the highest energies. An additional cut is made on the time-spatial correlation to remove remaining noise triggers. These filters reduced the data sample to 8283 events.

3 Profile-Constrained Shower Reconstruction

The HiRes experiment is designed to operate in stereo. Events in the HiRes-1 monocular data set have typical angular spans of less than 12°. Without the added precision afforded by the FADC electronics at HiRes-2 (HiRes-2-Mono, 2001), track-lengths of more than 25° are needed with the sample-and-hold readout for reliable geometrical reconstruction from the tube trigger times alone. The solution adopted in this analysis was to include a fit to the shower profile itself along with the timing fit, and to constrain the shower parameters. This procedure is outlined below.

First, shower development is assumed to be described by the Gaisser-Hillas parameterization, which has been shown to be in good agreement at lower energies with data from the original Fly's Eye Experiment and from HiRes-MIA prototype coincidence studies. The shower longitudinal *width* of $500 - 550$ g/cm^2 has also been shown to be mostly independent of the energy and composition, in studies with the Corsika shower simulation code using the QGSJET model (Heck *et al.*, 1998; Kalmykov *et al.*, 1997; Song, 1999). Next, a mean value of $X_0 = 40$ g/cm^2 is assumed for the depth of the first interaction. This value is based on Corsika studies (Song, 1999). Finally, the depth of the shower maximum is allowed to vary in 35 g/cm^2 steps, within the range of $X_{max} = 680 - 900$ g/cm^2. This X_{max} range is also consistent with Corsika studies (Song, 1999).

Additional quality cuts were made on the reconstructed events in order to optimize reconstruction accuracy at high energies. Reconstruction of simulated events using the above procedure yields an energy resolution which improves with energy. At 1 EeV and below, the reconstruction error is typically 45% or worse. The situations improves significantly at energies above 3 EeV. Figures 1 and 2 show the fractional reconstruction error in energy for simulated events generated according to the old Fly's Eye stereo spectrum, with 10 times the exposure of the current data set. Only events above 3 EeV are included in Figure 1, and only events over 10 EeV are included in Figure 2. Not including atmospheric variations, an energy resolution of better than 25% was achieved at energies above 10 EeV.

The primary cause of the poor energy resolution at lower energies was the limited elevation coverage of HiRes-1 (up to only 17°). Air showers at 1 EeV or below need to be within a few kilometers of the detector to produce sufficient light. But at these distances, they tend to be at high elevation angles. Therefore the HiRes-1 detector typically makes a poor sampling of events at 1 Eev and below. For the HiRes-1 monocular spectrum measurement, we considered only energies above 3×10^{18} eV.

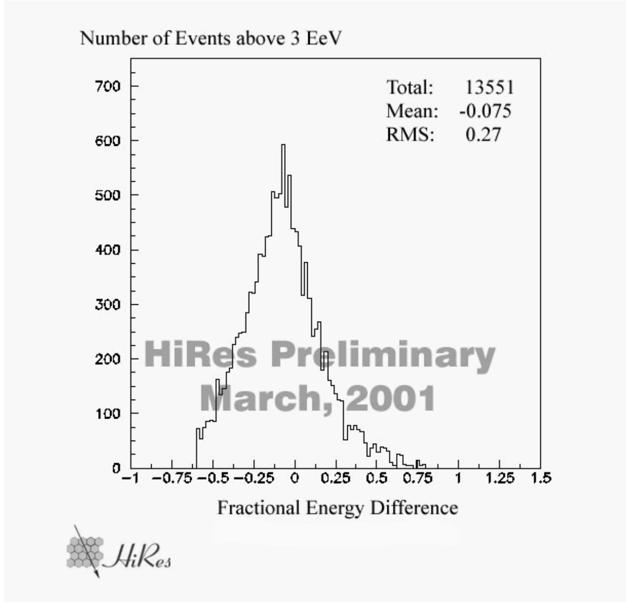

Fig. 1. Fractional Energy Reconstruction Error for simulated events above 3 EeV

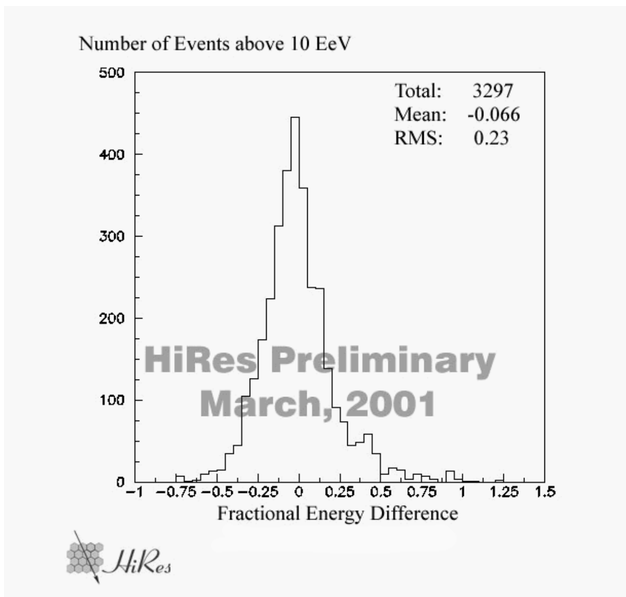

Fig. 2. Fractional Energy Reconstruction Error for simulated events above 10 EeV

4 Comparison with stereo reconstruction

Between 1999 and 2000, the two HiRes detector took a significant amount of stereo data. The results from that analysis will also be presented at the 27th ICRC (HiRes-Stereo,

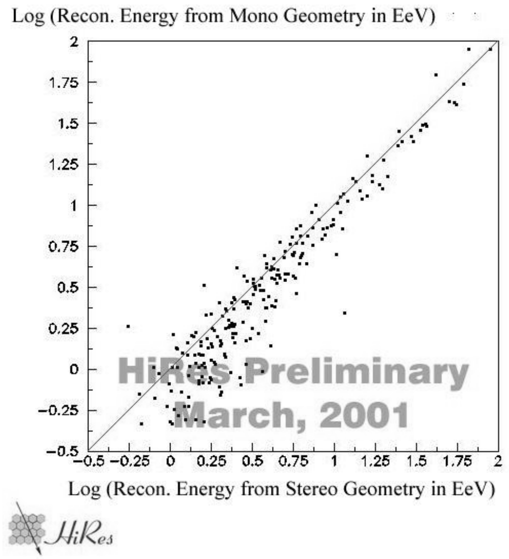

Fig. 3. Scatter-plot of the monocular energy versus the energy reconstructed from the stereo geometry

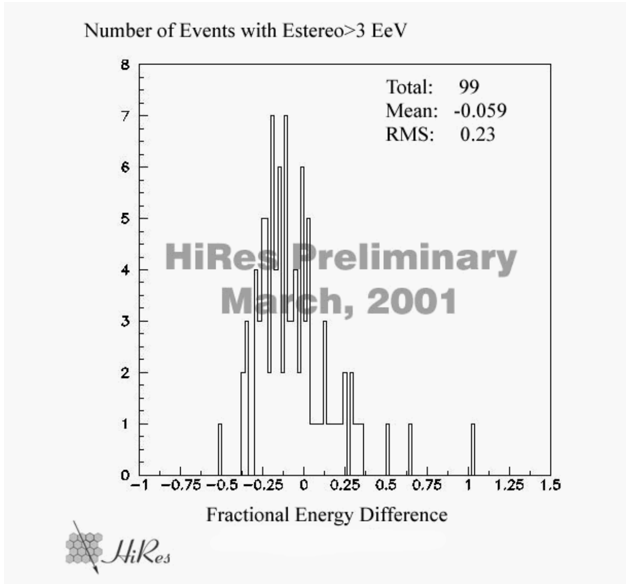

Fig. 4. Fractional Energy difference between monocular and stereo reconstructions for events above 3 EeV

2001). A subset of the stereo events were also reconstructible using the HiRes-1 data alone following the profile-constrained fitting procedure described above. For these events, the monocular reconstruction was also repeated, but using the shower trajectory determined from the stereo information. A comparison of the reconstructed energies from these two methods thus gives a measure of the geometrical accuracy of the monocular method.

Figure 3 shows a scatter-plot of the monocular energy plotted against that reconstructed from the stereo geometry. A clear correlation is seen in the plot. The distribution is also seen to become narrower with increasing energy. The histogram of fractional difference in the reconstructed energies for events above 3 EeV is given in Figure 4. The corresponding histogram for events above 10 EeV is given in Figure 5. While the event statistics are poor, the resolutions seen in these figures are clearly comparable to the simulated results shown previously in Figures 1 and 2.

5 Results and Discussion

The studies of energy resolution based on simulation and comparison to stereo events do not take into account the uncertainties in the atmospheric corrections. The concentration of aerosols in the atmosphere is one of the largest contributors to the systematic errors in the spectrum measurement. Specifically, in a scenario where the atmosphere contained less aerosol than was assumed, the reconstruction program would systematically overestimate the energies of the showers, while the simulations would systematically underestimate the aperture of the detector. Both effects result in an overestimate of the actual flux of cosmic rays. In the re-

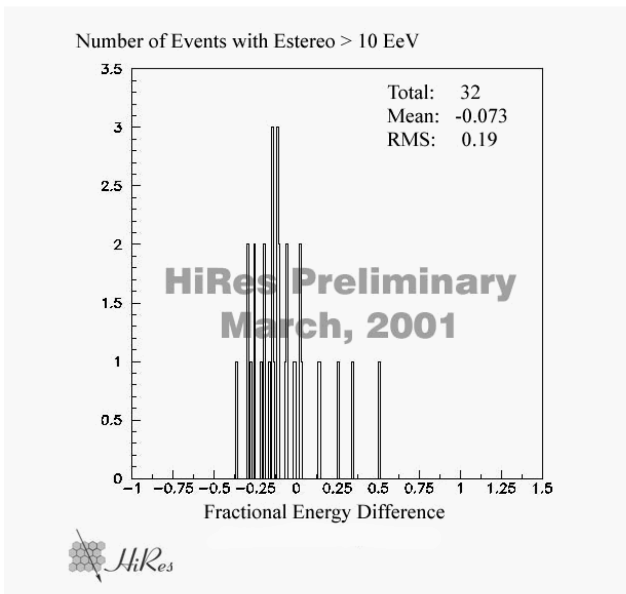

Fig. 5. Fractional Energy difference between monocular and stereo reconstructions for events above 10 EeV

verse scenario where the aerosol concentration is lower than assumed, the measured flux would be lower than the actual value.

At the time of writing, HiRes is in the process of finalizing the characterization of the atmospheric conditions over the data collection period. The preliminary results presented at the 26th ICRC in 1999 had assumed an aerosol concentration equivalent to the *U.S. Standard Desert Model*. The studies have shown that the average atmosphere at Dugway is definitely more transparent than predicted by the Standard Desert Model, but is also not completely free of aerosols. The spectrum corresponding to the mean atmospheric conditions of the data set will be presented at the 27th ICRC along with estimates of the systematic uncertainties associated with the aerosol variations.

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