29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Preliminary Results on the High Energy Cosmic Ray Spectrum from the Stereo Analysis of the HiRes Fly's Eye Data.

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The HiRes Fly's Eye experiment, operating in Dugway Utah, has been collecting stereo data on extensive air showers from cosmic rays since October 1999. In this paper we describe the stereo reconstruction technique, including daily gain and atmospheric corrections, along with a discussion of the Monte Carlo simulation used to determine the detector aperture.

1. Introduction

Interest in the high energy cosmic ray spectrum continues since the Fly's Eye Experiment first reported the observation of a cosmic ray induced extensive air shower with an energy in excess of 10^{20} eV [1] and subsequent reports from the AGASA ground array experiment of the observation of multiple extensive air showers produced by cosmic rays with energies in excess of 10^{19} eV [2]. The GZK[3] mechanism implies that observations of cosmic rays above 6×10^{19}eV should be suppressed unless the source of the cosmic rays is nearby, making the confirmation of the observation of events above GZK cutoff interesting.

The High Resolution Fly's Eye experiment (HiRes) started data taking in October 1999 and has now collected over 3000 hours of stereo data. We will present preliminary results of the analysis of data collected through April 2005. The results are based on a full stereo reconstruction of events and includes corrections for hourly variations in detector response and atmospheric conditions.

2. The HiRes Detector

The HiRes experiment employs a second generation air fluorescence detector located on two sites separated by 12.6 Km on the Dugway Proving Grounds, Dugway Utah. The detector has an aperture greater then 10^4 km^2 sr for extensive air showers generated by cosmic rays at energies of 10^{20} eV, more then 10 times the Fly's Eye aperture. Both sites consist of optical telescopes instrumented with a camera consisting of 256 hexagonal photo-multiplier tubes (PMT's) close packed and located at the focal plane of the telescope to record the image of the extensive air shower as it passes through the field of view of the telescope. The first detector (HiRes-1) is located at the site of the original Fly's Eye experiment. The HiRes-1 detector consists of 20 telescopes covering 320 degrees in azimuth and 3° to 17° above the horizon. These telescopes are instrumented with a sample-and-hold data acquisition system that integrates signals from the PMT's for a fixed gate time. A full description of the HiRes-1 detector electronics can be found in [4]. The second detector (HiRes-2), located on Camelsback Mountain, consists of 42 telescopes covering 336 degrees in azimuth and 3° to 32° above the horizon. These telescopes are instrumented with a Flash ADC (FADC) data acquisition system allowing the integration window to be adjusted during the analysis stage. A full description of the HiRes-2 data acquisition system can be found in [5].

3. Photometric Response

In order to understand the energy scale of the HiRes detectors, it is necessary to both calibrate and monitor the electronic gain of the detectors and measure the photometric response to a known light source. The electronic calibration is done periodically using a roving xenon light source (RXF) which can be placed at at the center of the mirror. This RXF provides a stable uniform calibrated light source which can be transported to all mirrors at each site to provide a site-wide and an inter-site calibration. The RXF data is analyzed using photo-statistics for each channel to determine the individual channel gains. This method takes into account variations in the active area and quantum efficiency for the PMT's.

Since the RXF calibration procedure is both labor and time intensive, a monitoring system was developed to track the individual channel gains on a nightly basis. The nightly monitoring uses YAG laser systems with the laser light distributed to each detector via optic fibers. Variations in the light intensity seen by each camera do not allow for an absolute calibration, however used in conjunction with the RXF gain calibrations, allows the gains to be measured on a daily basis. A full description of the calibration systems can be found in [6].

The total photometric response is determined periodically using a mobile laser system that is placed 4Km in front of each telescope to record the response of the detector to a known light source. These roving laser calibration studies are done during regular data taking and are reconstructed using the standard HiRes reconstruction package. Corrections for gain and atmospheric variations as described above are incorporated and the reconstructed laser energy is compared to the laser energy as monitored during data taking. This front-to-back calibration allows for a cross check on the calibration of the HiRes Detector.

Steerable laser systems are located at each site and observable by the opposite site. Sweeps of the lasers probe the atmosphere throughout the field of view of the two detectors allowing atmospheric conditions to be monitored on an hourly basis. These laser events are reconstructed using the standard HiRes reconstruction techniques to determine the hourly atmospheric conditions which are entered into a database and used for data reconstruction and Monte Carlo simulation. A summary of the atmospheric monitoring can be found in [7]. In addition to the hourly sweeps, the lasers also fire along the trajectories of high energy shower candidates shortly after the events are recorded allowing for additional checks on the atmospheric conditions shortly after the event occurred.

4. Reconstruction

The first step in the reconstruction of extensive air showers is to time match the events observed at each of the two sites. Time matched stereo candidates are then filtered to accept shower like events and laser events. The shower geometry is reconstructed by performing a simultaneous fit using the pointing vectors of the phototubes, the observed signals, and signal timing from both sites. The detector shower plans may calculated from the results of the fit. The second step of the reconstruction is to determine the shower profile. We use an iterative approach to simulate the longitudinal and lateral profile of the shower which includes isotropic emission of fluorescence light that is propagated to the detector and wavelength dependent attenuation in the atmosphere. Wavelength dependent detector responses, mirror reflectivity, UV-filter transmission, and photomultiplier response are also included. If all of the details of the shower development, light emission, transport and detection are correct and enough of the profile is observed to determine the total energy deposition in the atmosphere, then the parameters of the shower have been measured: energy and shower geometry.

5. Monte Carlo and Aperture Determination

In order to properly describe the HiRes detector aperture as a function of energy, it is necessary to simulate not only the detector electronics, but the atmospheric conditions which affect the transmission of the fluorescence light to the detector. A detailed Monte Carlo has been developed for the HiRes detector that incorporates the nightly gain measurements and the hourly atmospheric conditions. Cosmic ray showers are generated using the CORSIKA [8] generator for both proton and iron primaries with energies ranging from 10^{17} to 10^{21}eV. The showers are parameterized and entered into a shower library that is used as input to the detector simulation portion of the Monte Carlo.

Cosmic Ray showers from the library are chosen and assigned random geometries. The fluorescence and Cerenkov light from the shower is simulated and photons are ray traced to the detector. Variations in the transmission of the photons due to differences in the nightly atmospheric conditions are accounted for by using the atmospheric database. The detector response is simulated for photons traced to the camera, accounting for variations in mirror reflectivity and UV filter transmission differences of the individual telescopes. Mirror and channel dead-times, variations in gain, and non-linearity effects are also included in the simulation of the electronic response to the showers.

The resulting Monte Carlo event sample is reconstructed using the same reconstruction programs used to reconstruct the raw data to determine the effective stereo aperture of the Hires detector. As a cross check, the parameters of reconstructed shower candidates, geometry and energy, are used as input to the Monte Carlo to simulate the detector response for observed shower candidates.

6. Acknowledgments

This work is supported by US NSF grants PHY-9321949, PHY-9322298, PHY-9904048, PHY-9974537, PHY-0098826, PHY-0140688, PHY-0245428, PHY-0305516, PHY-0307098, and by the DOE grant FG03-92ER40732. We gratefully acknowledge the contributions from the technical staffs of our home institutions. The cooperation of Colonels E. Fischer and G. Harter, the US Army, and the Dugway Proving Ground staff is greatly appreciated.

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