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Monte Carlo simulation of the HiRes experiment

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Abstract. The Monte Carlo simulation software used for the HiRes detector will be described. The status of development of the MC code is summarized. A preliminary comparison between data and simulated detector response for various physical observables is shown but more details will be shown in the presentation.

1 Introduction

Monte Carlo simulation for the High Resolution Fly's Eye (HiRes) detector plays an essential role in the data analysis. It is a tool to estimate the response of the detector, debug the air shower reconstruction and compute the detector aperture. Combined with a more fundamental air shower simulation tool, e.g. Corsika (D. Heck *et al.* , 2000), the simulation can be useful to calculate expectations for the HiRes detector under certain theoretical assumptions, e.g. pure composition, hadronic interaction models, air shower models and light propagation model through the atmosphere. In order to cover all the issues, a detector simulation package, named MC_Stereo, has been developed to have components including air shower generator, atmospheric attenuation, detector acceptance, electronic device and data formating. In this report, we will describe the configuration of the package and progress on each issue listed above.

2 Configuration of MC_Stereo

The detector simulation should mimic the real detector as exactly as possible. The HiRes detector is composed of two detectors. One of them located on top of 5-Mile Hill, Dugway, Utah, USA (at 112° W longitude and 40° N latitude.), called HiRes-1, has 21 mirrors with a 340° coverage in azimuthal and 12° coverage in elevation. The other, called HiRes-2, sits on top of Camel's Back range, 12.6 km away from HiRes-1. There are 42 mirrors covering similar azimuthal range as HiRes-1 but 24° in elevation. The minimal elevation is 3° for all mirrors in both detectors. The average vertical depth of the detector is about 860 g/cm^2. Each mirror has a focal plane camera composed of 256 hexagonal photomultiplier tubes. Each tube sees a specific direction in the sky with an aperture of $\sim 1^\circ$. When an air shower crosses the field of view of the detectors, its charged particles generate fluorescence and Cerenkov light by interacting with the atmosphere. The light caught by the detectors can make tracks possibly crossing multiple mirrors at both sites. A high energy shower can trigger the detector from up to 40 km away. MC_Stereo uses all the surveyed geometric and physical infomations to simulate the procedure from shower development to data acquisition.

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2.1 Air shower generator and light propagation

The longitudinal development of a shower induced by a nucleus A, atomic number, at energy E, is parameterized by using a certain functional form, e.g. Gaisser-Hillas (T. Gaisser and A. M. Hillas , 1977) function, with a set of parameters such as maximal number of charged articles, N_m, shower maximum location, X_m and others. The values and the fluctuations of these parameters are tabulated based on a full shower simulation with Corsika Ver6.03 under certain interaction model assumption. Fig 1. shows an example of those distributions for $E_0 = 10^{19}$ eV. For a given shower geometry, the number of fluorescence and Cerenkov light photons can be calculated using the shower size at certain height in the atmosphere. A measurement has been done (F. Kakimoto *et al.* , 1996) in the lab to determine the fluorescence yield of electrons at MeV energy. The number of photons arriving at the detector depends on the atmospheric transmission, which is determined by the light scattering on atmospheric molecules and aerosols and the light absorption by ozone molecules.

Since the shower-detector distance can be as long as $\sim$2 times of the extinction length, the atmospheric transmission places a crucial role in determination of shower maximum and the shower energy which is proportional to the integral

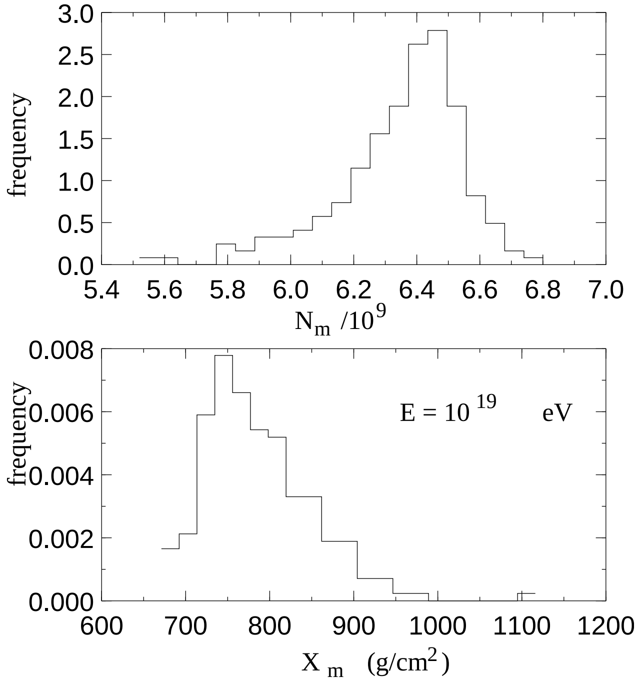

Fig. 1. N_m and X_m distributions for E=10^{19} eV showers. The showers are generated using Corsika at zenith angle of 0°.

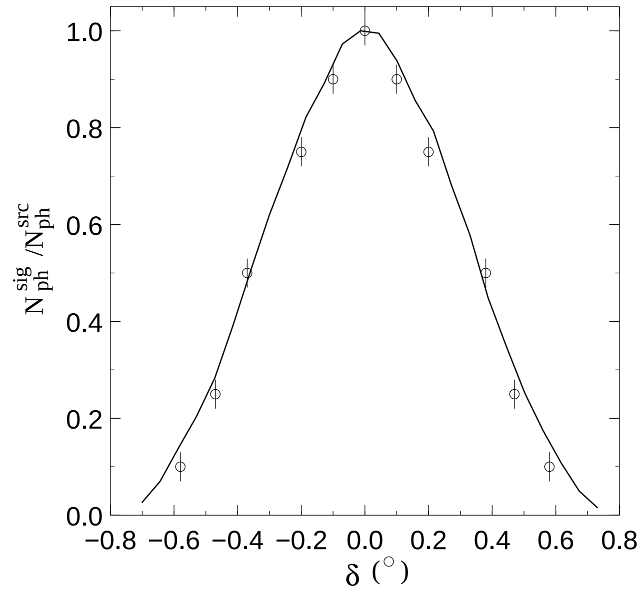

Fig. 2. The response of a tube to a line-shaped vertical light source. The tube is near the center of the camera. Angle δ is the angular distance from the source line to the center of the tube. The circles refer to a calibration result using a laser as the source. The vertical axis represents the ratio of the total number of photons caught by the tube and the total number of source photons.

of the shower transition curve. The atmospheric model is built based on an independent study using an atmospheric monitoring system with steerable lasers, see (L.Wiencke, , 2001) in the same proceeding.

Since the charged particles spread out laterally in a shower, in MC_stereo, the real position of the light source can be off the track by a certain distance. The NKG function is used to describe the lateral distribution of shower electrons which varies with s, the age of the shower.

2.2 Detector Acceptance

The HiRes detector consists of a spherical mirror and a flat camera placed near the focal plane of the mirror. Because the light spot is ∼3 cm in diameter due to the defocusing, gaps between tubes and the non-uniform response of the photo-cathode of tubes. The response of the detector has a complex pattern across the camera. A ray tracing technique based on individual photons is developed to simulate this complex response. Fig 2 shows the response of a tube, located near the center of a camera, to a line-shaped light source as a function of the angular distance from the source to the tube center. The data shown in the figure as dots is from a on site calibration using a laser beam as the source.

The mirror size, reflectivity, transmission of UV light filter and quantum efficiency of the photo-cathode are considered in the detector response simulation. Most of them are implemented with their frequency dependences over a band of wavelength from 280nm to 424 nm.

2.3 Online Electronics

HiRes-1 has a sample and hold electronic data acquisition system. It integrates the pulse from a tube within a 5 μs time window when the tube is triggered. HiRes-2 has a 10 MHz flash ADC installed for each channel. Once a mirror is triggered with a relatively low threshold, a DSP scans through a buffer, which holds all tube signals, for hit tubes to confirm the trigger. When this trigger is confirmed, the DSP rescans the buffer with a lower threshold to read out the pulses which is digitized within every 100 nsec. In this way, the detector records the history of how the shower sweeps through each fired tube.

MC_stereo simulates the pulse shaping, trigger formation, discrimination A/D and Q/D conversion for both sites. All electronic parameters such as filtering time constants, gains, thresholds and event trigger algorithm are set identically to the actual detectors. The simulation of DSP for HiRes-2 uses very similar codes to the online programs.

A sky background noise of about 40 photoelectrons (pe) per μsec per channel was measured on site (J.W.Elbert *et al.* , 1993). It is smeared into the signal pe sequence randomly. A star-related noise tube distribution is implemented throughout the camera based on an average over the measured mirrors in the real data.

The final output of the electronic readout is formatted to be the same as the real data into a DST bank structure. All the input parameters for the simulation are stored in the same data file but in different banks.

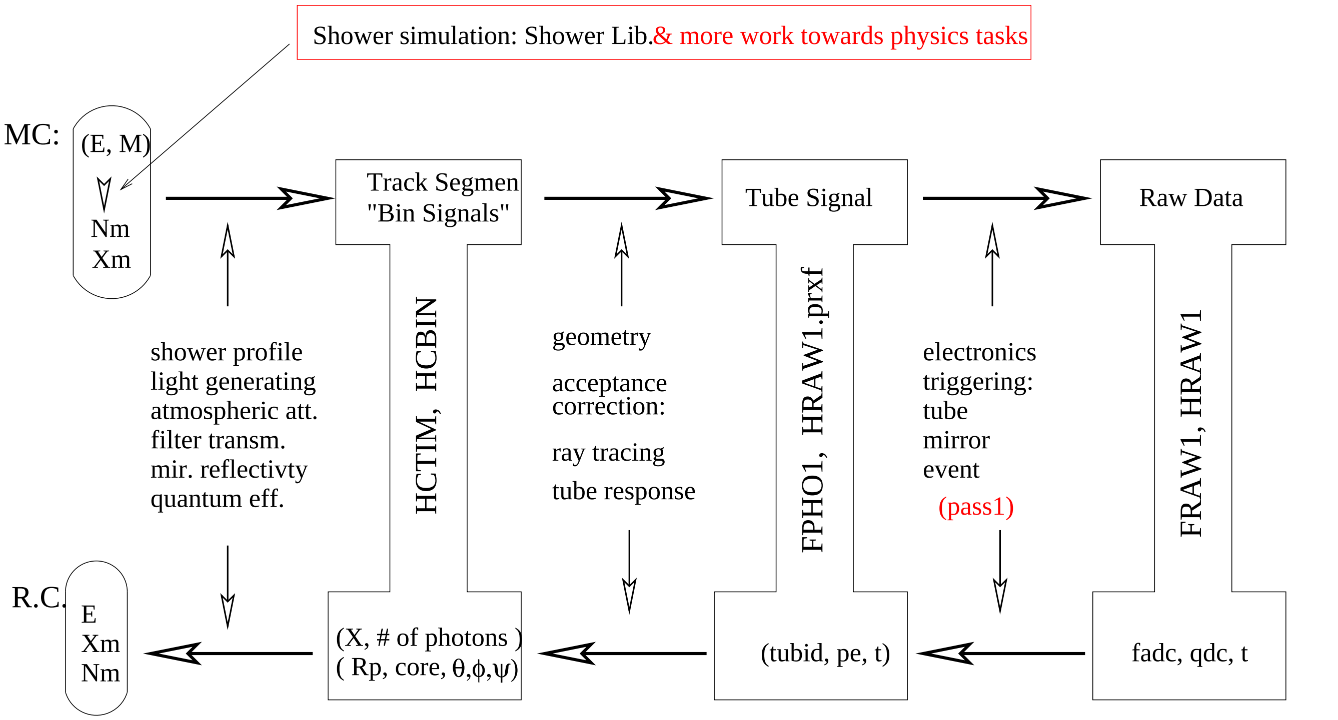

Fig. 3. The diagram of the detector simulation and the shower reconstruction. The two processes flow in opposite direction. The vertical bars represent the data structure of banks which short-cut the generating-reconstruction chain at different stages. This makes the step by step debugging possible.

3 Shower Reconstruction Debug

An advantage of this bank structure is that it records the history of the analysis for every single event. In practice, shower reconstruction is the reverse of the simulation procedure: starting from the raw data, FADC/QDC counts and timing, it calibrates the data to recover the number of photoelectrons as a function of arrival time for each tube, then corrects the detector acceptance to build the track in the form of number of photons as a function of elevation angle or arrival time. As the final step, the shower longitudinal development profile is fit to the angular/timing bin data by taking the atmospheric transmission into account. At the end of each stage of the reconstruction procedure, a corresponding bank is written into the data stream, e.g. FRAW1/HRAW1, FPHO1/HPHO1, HCBIN, HCTIM and PRFA/PRFC store raw data from HiRes-2/HiRes-1, calibrated HiRes-2/HiRes-1 data, binned data, shower geometry and profile informations, respectively, as shown in the Fig 3. In the reverse direction (the upper flow shown in Fig 3.), the MC_stereo can write all the banks at the end of each stage of the generation. This offers an opportunity to debug the reconstruction chain stage by stage.

A bug-free reconstruction allows a comparison between the simulated and measured showers. This checks the "accuracy" of the simulation. The distribution of shower geometric parameters, shower maximum and shower energy are compared. Results from the comparison will be presented.

4 Detector Resolution and Detector Aperture

A main task of the detector simulation is to calculate resolution functions for various measured parameters, such as the shower arrival direction, shower core location, shower maximum location and shower energy. Using the difference between the input value for the simulation and the output value from the reconstruction of the same shower, we can evaluate the quality of the reconstruction. The distribution of the difference provides a quantitative assessment of the reconstruction quality. A relevant issue is that the reconstruction quality depends on the cuts applied on the data. Since the "true" values of the variables are known for the simulated events, the simulation enables an exploring for "right" cuts, which should lead the sample towards the "true" values with a minimized bias.

An energy resolution function is usually studied since it is a basic parameter for all physics tasks. The width of the function is crucial for any sort of fine structure search in the cosmic ray spectrum. Its tail behavior strongly affects the search for super-GZK events at the highest energy region.

The X_m resolution function is important for the mass composition study. The separation between proton and iron in terms of the average X_m is about 100 g/cm^2 based on the Corsika simulation with various models. A sufficiently narrow resolution in X_m is required for the study of the mass composition. A healthy tail behavior is essential for the measurement of the proton-air interaction cross section

Good spatial geometric resolution is useful for the anisotropy search in the cosmic ray arrival direction.

All these resolution functions will be presented.

Another task of the detector simulation is to calculate the aperture of the HiRes detector. It is necessary for the measurement of cosmic ray spectrum.

5 Summary

The Monte Carlo simulation package for the HiRes detector is described. Each of the three components of the simulation, shower generation, detector response and electronics, are able to write their own output into DST data file. Using these banks, the reconstruction has been tested step by step. Detector resolution functions are being studied. All results will be ready and be presented at this ICRC.

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References

D. Heck *et al., preprint of Institut fur Kernphys., Univ. of Karlsruhe*, FZKA-6019, Feb., 1998 (Kernforschungszentrum, Karlsruhe, 1998).

T. Gaisser and A. M. Hillas, *Proceedings of the 15th International conference, Plovdiv, 1977*, (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977), Vol.8, p.353.

L. Wiencke for HiRes Coll., HE1.4.??, this proceeding,Hamburg,2001

F. Kakimoto *et al.*, Nucl. Instrum. Meth. **A 372**, 527 (1996).

J.W.Elbert,*Proc. Tokyo Workshop on Techniques for the Extremely High Energy Cosmic Rays, Tokyo, Japan, 1993*, edited by M. Nagano, (Institute of Cosmic Ray Research, Tokyo, 1993) p. 232.