

ENERGY CALIBRATION OF THE FLY'S EYE DETECTOR

Baltrusaitis, R.M., Cassiday, G.L., Cooper, R., Elbert, J.W., Gerhardy, P.R., Ko, S., Loh, E.C., Mizumoto, Y., Sokolsky, P. & Steck, D.

Department of Physics, University of Utah, Salt Lake City, UT 84112

ABSTRACT

The methods used to calibrate the Fly's Eye detector in order to evaluate the energy of EAS is discussed below.

1. Introduction. The energy of extensive air showers (EAS) as seen by the Fly's Eye detector are obtained from track length integrals of observed shower development curves(1). eg

$$E_{em} = \frac{\epsilon_0}{X_0} \int N_e(x) dx$$

where E_{em} is the total energy of the shower dissipated in the electromagnetic channel, ϵ_0/X_0 is the ratio of the critical energy of electrons to their radiation length in air(2) and $N_e(x)$ is the observed size of the EAS as a function of atmospheric slant depth x . The energy of the parent cosmic ray primary is estimated by applying corrections to account for undetected energy in the muon, neutrino and hadronic channels (3,4). These corrections amount typically to about 10% in the energy range 0.1-100 EeV (1 EeV = 10^{18} eV). Clearly, absolute values for E depend most critically upon the measurement of shower sizes $N_e(x)$. Knowledge of three essentially different processes are involved in leading to a measurement of $N_e(x)$. (i) An assessment of those factors responsible for light production by the relativistic electrons in an EAS and the transmission of light thru the atmosphere (ii) Calibration of the optical detection system, i.e., measuring and continually monitoring those factors required to convert measured electronic pulse integrals into absolute numbers of photons received by the Fly's Eye detector from the EAS light source and (iii) A knowledge of the trajectory of the shower which is necessary to convert apparent optical "brightness" into intrinsic optical brightness.

2. Light Production. The factors involving light production by EAS and transmission of light thru the atmosphere have been discussed in great detail in Ref.(1). These factors include:

(i) The Fluorescence Efficiency of Electrons in Air. Our values are taken from the work of Bunner(5).

$$\text{We find that } \frac{d^2N_\gamma}{dtd\Omega} = \frac{N_f N_e}{4\pi} \text{ where } N_f \text{ is the}$$

fluorescent yield in photons/electron/meter and N_e is the shower size. Roughly, $N_f \approx 4-4.5$ photons/electron/meter depending on altitude and temperature(1).

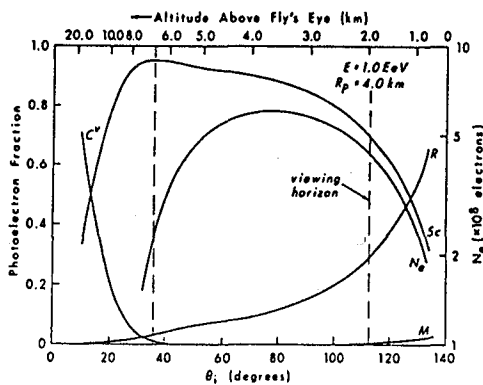
(ii) The Production of Cerenkov Light. This factor has been calculated most recently by Elbert(6) who finds that

$$\frac{d^2N}{d\Omega d\gamma} = \frac{dN}{d\gamma} \frac{\exp^{-\theta/\theta_0}}{2\pi \sin\theta} \quad \text{and} \quad \theta_0 \approx 0.83 E_t^{-0.67}$$

where dN/dl is the Cerenkov photon yield per meter of air, θ is the emission angle and E_t is the Cerenkov threshold energy in air in MeV. We have measured the angular distribution of Cerenkov light with the Fly's Eye by observing light from the same EAS source simultaneously at different emission angles by Fly's Eye I and Fly's Eye II (separated by 3.3 km). We find that at altitudes corresponding to threshold energies of about 30 MeV our measured value of $\theta_0 = 5.0 \pm 0.5^\circ$ is in excellent agreement with the value $\theta_0 = 4.87^\circ$ obtained from Elbert's above expression.

(iii) The Scattering of Light. Both Rayleigh and Mie Scattering affect the transmission of light thru air. Our estimates for these effects are based respectively on the work of Flowers(7) and Elterman(8), they are discussed in detail in Ref.(1).

Finally, we show in Figure 1 an example of calculated relative photoelectron yields obtained by the Fly's Eye detector as



generated by the various light production methods discussed above for a shower of size $N_e(x)$ whose total energy was 1 EeV observed at an impact parameter of 4 km.

3. Optical Calibration. Converting measured pulse integrals into numbers of photons incident upon the Fly's Eye detector requires a knowledge of the overall efficiency-gain product ϵG_i of each of the approximately 1000 Fly's Eye data channels. An

Figure 1. Relative photoelectron yields as a function of altitude (upper scale) and observed shower emission angle (lower scale). Sc=scintillation light, C=direct Cerenkov, R=Rayleigh and M=Mie Scattered Cerenkov light. N_e is the shower size.

absolute measurement has been made on a single channel and the ϵG factors for all others determined by relative normalization. In situ Argon flash bulbs triggered on command by computer are used to continually monitor all ϵG factors during data taking at all times subsequent to the time of absolute calibration. Measured efficiency-gain factors are: $\epsilon_{\text{pmt}} = 0.212 \pm 0.015$, $\epsilon_{\text{cone}} = 0.80 \pm 0.05$ and $\epsilon_{\text{mirror}} = 0.83 \pm 0.04$ giving an overall efficiency of $\epsilon = 0.141 \pm 0.016$. The gain factor G includes PMT gains, preamp transconductance, finite cable DC resistance, charge-integrator input impedance and voltage-time input to digitized output conversion factors. The resultant overall gain is $G = 0.757 \pm 0.076$ mv/photoelectron. Hence, errors in absolute quanta measurements, δN_γ , are on the order of $\pm 16\%$.

4. Geometrical Reconstruction. The techniques of geometrically reconstructing an event seen either by Fly's Eye I alone or stereoscopically by Fly's Eyes I and II in coincidence have been discussed in Ref.(1). Essentially, the chief contribution of inaccurate geometrical reconstruction to uncertainty in energy measurement stems from inaccuracies in determining the shower impact parameter R_p , or distance of closest approach to the Fly's Eye I detector. These uncertainties are typically on the order of 5-10%. Hence, overall uncertainties in energy measurements from all factors listed above are expected to be on the order of $\pm 20\%$.

5. Tests. Several tests have been made to check the validity of all calculations and measurements of the energy determining factors described above.

(i) A Monte-Carlo simulation of the response of the Fly's Eye detector has been carried out in order to check the validity and self-consistency of the analysis procedure(1). Shown in Figure 2 is the Monte-Carlo response function for shower energies measured by the simulated detector. The effects of night sky noise fluctuations in measured pulse integrals have also been included. As can be seen from the plots, overall energy determinations appear to be accurate to within $\pm 20\%$.

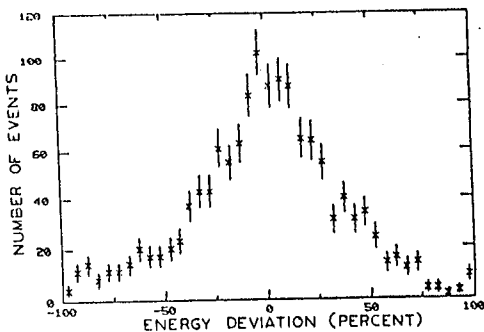


Figure 2. % Differences
Between Measured Shower Energy
and Known Monte-Carlo Input
Energy.

(ii) A pulsed nitrogen laser was positioned at Fly's Eye I at a variety of different zenith, azimuth angles and impact parameters. The scattered light from the upward-going laser light pulse simulates light emission from an EAS. Absolute light yields measured by the Fly's Eye for each laser pulse can then be used to calculate the number of photons in the upward-going beam after reconstructing its trajectory and calculating the amount of light both Rayleigh and Mie scattered from the beam as outlined above. Resultant estimates of the laser's photon output based on Fly's Eye measurements agree with direct measurements of its output to within $\pm 20\%$ and is virtually independent of scattering angles over a range of $20^\circ < \theta < 120^\circ$. The agreement implies that Fly's Eye optical calibration is well known and the treatment of Rayleigh and Mie scattering and light attenuation of a light beam propagating thru the atmosphere has been treated adequately.

(iii) About 500 showers have been observed stereoscopically i.e., by Fly's Eye I and Fly's Eye II (separated by 3.3 km) in coincidence. Shown in Figure 3 is an example of a shower reconstructed stereoscopically and whose longitudinal development sizes, $N_e(x)$, have been measured by data obtained by each detector. It is impossible to tell which data points belong to Fly's Eye I or Fly's Eye II. Again, since the light source was observed simultaneously from different emission angles as

well as optical path lengths, the implication is that the angular distribution of both direct and scattered Cerenkov light, its relative strength to fluorescence light, and the effects of the atmosphere on light propagation is being treated properly.

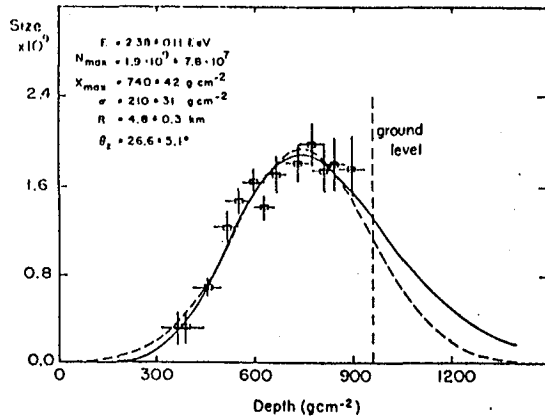


Figure 1. Longitudinal profile of an EAS observed by both Fly's Eye I and II simultaneously. Size estimates are composed of mixed data points, i.e., some from FEI, some from FEII.

(iv) During Fly's Eye prototype experiments, a direct intercalibration experiment of shower size measured by the Volcano Ranch experiment and the Fly's Eye optical detector was carried out at Volcano ranch(9). The obtained sizes in that experiment agreed to $\pm 10\%$. This intercalibration established the validity of the absolute values we currently use for the nitrogen fluorescence yield used to derive absolute shower sizes. It cannot, therefore, be argued that this normalization is in doubt. Any current systematic failure to properly assess energy could therefore only occur thru failures to properly calibrate the optical detector or reconstruct shower trajectories. We believe that we have demonstrated that errors inherent in these latter two procedures are well-understood.

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