ANALYSIS OF CERENKOV PULSES RECORDED SIMULTANEOUSLY AT TWO SITES.

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ABSTRACT

The agreement between measured distances to maximum for ~ 49 simultaneous Cerenkov pulse profiles from different sites is ± ~ 0.1 km near 4.5 km and ± 0.5 km near 7 km. Uncertainty in depths of maximum are ~ ± 10 g cm^2 and ± 30 g cm^{-2} respectively. Usually the Hillas-Patterson simulation is able to fit both pulse shapes satisfactorily using a single N(x) profile.

1. Introduction. Measurement of the widths of optical Cerenkov pulses from cosmic ray air showers has proved to be a most useful means of studying shower development, in particular the distance to maximum. Several theoretical studies have been published including that by Patterson and Hillas[1] (1983) which forms the basis of the present study. Because of a lack of published data on simultaneous measurements on individual cosmic ray showers, the theories have not previously been tested for consistency of measured distances or for the goodness of the fit with a single longitudinal development curve, N(x).

2. Experimental Data. We make use of part of an extensive data set obtained by Liebing[2] at Buckland Park in 1981-82 in which detectors were located at 200 m North of the centre of the air shower array and 200 m South East. The Cerenkov pulses were obtained in coincidence with showers recorded by the array for which a full NKG shower analysis giving directions, core locations, and hence radial distances, and shower sizes was available. Each detector comprised a 125 mm diameter fast-response photo-multiplier (Philips XP2040, with S11 response) and mechanically collimated at 45° from the zenith, the cut-off being sharp. Few showers detected have greater inclinations than 40°. Short wide-band ($\gtrsim$ 400 MHz or 2 ns rise time) cables (with no preamplifiers) and independently triggered storage oscilloscopes (Tektronix 7834) were used with photographic recording. Impulse responses (~ 5.0 and 5.7 ns FWHM, non-oscillatory and non-Gaussian[1]) were routinely checked for each system using the narrowest sky pulses. Because of a 2s dead time associated with each oscilloscope trigger, a dead time ~ 30% was associated with each system.

Of ~ 138 analysed pulses recorded at the 200 m N site and 166 at the 150 m N site, and ~ 170 at the 200 m SE site, a subset of 49 showers were observed with analysable pulses in two sites. A full analysis of these data treating the systems as quite independent and looking at the variation of depths of maximum with shower size is given in ref. 3. It clearly showed the effect of array selection effects in the data which arise because of the limited dynamic range of the optical detectors and the array bias. However, these are not relevant to the present discussion, except to say that many pulses were lost either because they went off scale or did not trigger the oscilloscopes.

Three representative showers were studied in detail and fits to the experimental profiles are given in figures 1, 2 and 3. They were chosen because the radial distances from the two detector sites were markedly different. Few usable pulses were observed further than 250 m from the shower axis; and sensitivity of the pulses to shower development becomes much less inside 150 m. We also imposed the requirement that for reliable shower analysis, the core should fall inside the perimeter of the array. On the figures the full lines are the oscilloscope traces and show the effect of sky background pulses especially at the more distant site.

3. Theoretical Fits. Hillas[4] has described a method of mapping back from the pulse profiles to the N(x) profiles using absolute timing, not available in these cases. However, a timing zero can be fixed for each pulse by using the width of the pulse to determine the distance to maximum first. In a preliminary investigation we found the N(x) profile derived from the data very sensitive to the sky noise and divergent below the maximum. This was not surprising as Patterson and Hillas[1] showed that the pulse profile was very insensitive to large changes in shower attenuation. The alternative approach adopted therefore was, knowing the measured distance to maximum, to select the closest match from a library of previously simulated N(x) profiles by Hillas[4] which varied in depth of maximum but not very much in shape. Primary energies of 10^{15}, 10^{16} and 10^{17} eV were available, but do not markedly affect the shape.

The simulation calculation of pulse shape was then performed including the photomultiplier resolution for angles 0°, 15°, 30° or 40° and radial distances increasing by 25 m steps. The simulations are not very sensitive to zenith angle so the closest angle was chosen. However, the shape appropriate to the measured radial distance was interpolated graphically from the calculation. The results are fairly sensitive to the radius, which is subject to ± 5 m errors and small changes in distance to maximum.

The theoretical fits are shown as dashed lines and enable the agreement with experiment to be checked over the full profile, whereas it is more usual to be only concerned with the Full Width at Half Maximum. For this comparison the theoretical pulse has been normalized to the experiment at the peak and the relative times adjusted to give the best fit.

The agreement in shape on the rising edge and near the top of the pulse is considered fairly satisfactory. There is a tendency for the theory to underestimate the flux in the tail. This cannot be attributed to a slower attenuation in the N(x) profile because the preliminary study showed the required N(x) to diverge. It arises partly because of the limitation in the simulation to 10 GeV subshowers. The simulation in fig. 1 using 100 GeV subshowers improves the fit in the tail of the pulse.

4. Conclusion. Comparison of simulation fits for a single N(x) development profile to experimental pulses at the different sites has shown satisfactory agreement with the Patterson-Hillas simulations. Independent estimates of distance to maximum indicate errors of ± ~ 0.1 km near 4.5 km and ± 0.5 km near 7.0 km, again consistent with predictions[1]. These correspond to errors in depth of maximum of approximately 10 g cm^2 and 30 g cm^{-2} respectively.

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References.

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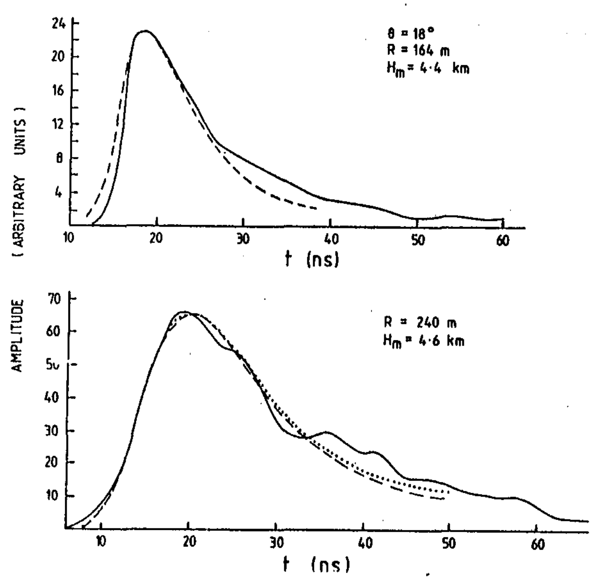

Fig. 1 shows a comparison of the experimental trace (full lines) for a shower with $N_e = 4.6 \times 10^6$, $E = 2 \times 10^{16}$ eV and S=1.28, and the Patterson-Hillas simulation using 10 GeV subshowers (dashed lines) and 100 GeV subshowers (dotted). The N(x) profile used[1] has H_m = 4.5 km, and depth of maximum 640 gcm^{-2}.

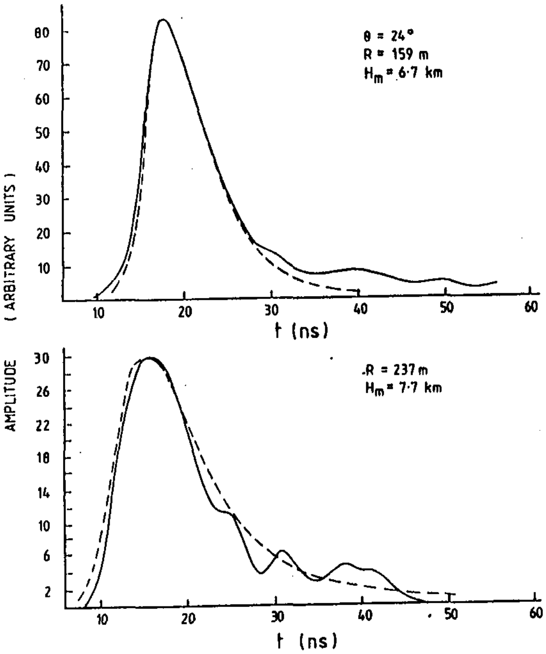

Fig. 2. shows a comparison of experiment and simulation for a shower with $N_e = 6x10^5$, $E = 8x10^{15}$ eV and S= 1.56. The N(x) profile has $H_m = 7.4$ km and depth of maximum 470 gcm^{-2}.

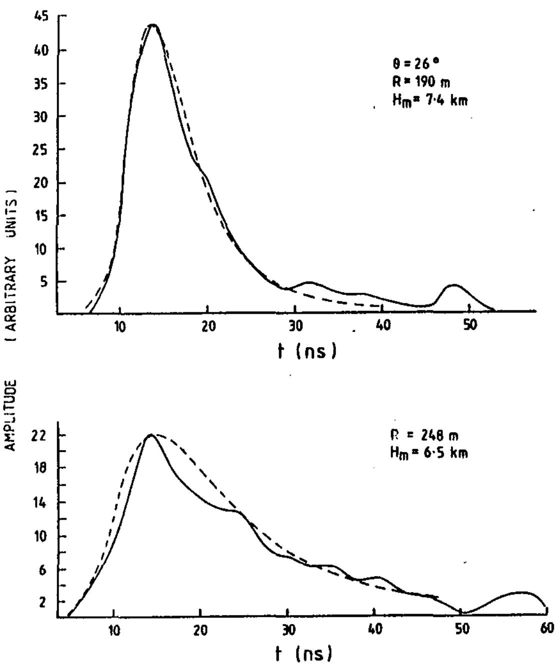

Fig. 3 shows a comparison and experiment and simulation for a shower with $Ne = 1.7 x 10^6$, $E= 3x10^{16}$ eV and S= 1.19. The N(x) profile has HM = 7.4 km and depth of maximum 490 gcm^{-2}.