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Detection and analysis of radio pulses from extensive air showers

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Abstract. Radio pulses from extensive air showers (EAS) at 30, 44, and 60 MHz frequencies have been studied, using wide band broad-side arrays of half-wave dipole antenna systems. The experimental results support the theoretical prediction that the field strength of radio emission depends on the shower size. An asymmetry has been noticed in the pulse height distributions of radio pulses detected by North-South and East-West directed arrays. These observations are in agreement with the theory that the charge separation mechanism is predominant in generating radio pulses from EAS and radio emission is polarised in the East-West direction. Experimental data are compared with those of earlier workers.

Keywords. Extensive air showers (EAS); radio emission; antenna; ultra high frequency (UHF); Cerenkov radiation.

1. Introduction

Since the first detection of radio pulses (at 44 MHz) from extensive air showers (EAS), by Jelley *et al* (1966), the phenomenon has attracted the attention of various research workers. Radio pulses of various frequencies (from 2 MHz to 550 MHz) from EAS have so far been detected and studied by several groups (Porter *et al* 1965, Allan and Jones 1966, Borzhkovskis *et al* 1966, Vernov *et al* 1967, Jelley 1970, Hough and Prescott 1970, Allan *et al* 1973, 1975, Dixon *et al* 1973, Atrashkevich *et al* 1975, Mandolesi *et al* 1976). Though the occurrence of radio emission from large EAS is well-established, the mechanism of the radio pulse production does not still have a concrete theory because of conflicting experimental results reported from different laboratories. Various mechanisms have been suggested as the possible causes of the radio emission from EAS. However, the charge excess (Askaryan 1962, 1965) and the geomagnetic separation (Kahn and Lerche 1966) seem to be the most effective reasons for the production of radio pulses from EAS. The phase coherence condition based on the charge excess sets an upper limit to the radio emission at $\sim$ 75 MHz whereas some laboratories have reported detection of UHF radio pulses up to about 550 MHz (Fegan 1970). According to Allan (1971), the second mechanism should be predominant (Turver 1973). Theoretically, radio pulses caused by the geomagnetic separation should exhibit polarisation effect. Consequently, the signals received by an E-W array should have greater amplitudes compared to those received by an identical N-S array. But Jelley *et al* (1966), and Porter *et al* (1967) reported insignificant difference in the pulse height distributions of the radiation detected by N-S and E-W array systems. On the other hand measurements of Vernov *et al* (1967) as well as that of Hazen *et al* (1969) gave better internal consistency when the polarisation was assumed as predicted by Kahn and Lerche (1966). But the charge excess theory suggests that the radio emission should be polarised radially with respect to the shower axis. Dependence of pulse height on the distance of the antenna system from the shower core, should be different for different mechanisms. However, the different theories agree in one factor that the radio signal field strength should be proportional to the number of particles in the shower front.

No doubt it is interesting to study the pulse height distribution of radio emission from EAS as well as polarisation effect which may throw light into the problem of production mechanism, and to compare the results with those of previous workers.

An experimental set up was installed in 1970 in the Gauhati University (G.U.) campus (26° 22′N; 91°23′ E; altitude 51·8 m msl) to study the radio emission from EAS. Since the frequencies in the range 30–100 MHz give the largest signal-to-noise ratio and are most convenient for study of radio emission, the pulse height distributions at three frequencies, namely, 30, 44 and 60 MHz, and the polarisation effects at the latter two frequencies are investigated.

The G.U. campus being situated at a distance of 15 km from the main city and surrounded by hillocks is almost free from human interference. But as the climate of the region is of monsoon type, the experimental observations were carried out only during dry seasons (extending to about 3 months) in the night so as to minimise atmospheric and man-made noise. The data were collected only during the winter months from 1972 to 1975. The experimental details are presented below.

2. Experimental arrangement

2.1. *Particle Detector*

The experimental set up shown in figure 1 consists of three GM counter trays as particle detectors arranged in the vertices of a triangle of sides 97·5 m, 97·5 m and 80·5 m respectively.

2.2. *Antenna System*

To detect radio pulses in coincidence with an EAS already detected by the particle detector array, antenna systems for the three different frequencies were designed. In each case a wide band broad-side array of half-wave dipoles was selected (Colgate 1967) to provide maximum effective area for the array (Smith and Carr 1966; Markov 1965), and has length-wise polarisation.

The half-wave dipoles were installed in a horizontal plane on the roof of the physics building of the University at a height of $\lambda/4$ from the roof surface. The latter was used as a reflector, and being at a distance of $\lambda/4$ from the array plane the radiation reflected from the roof surface striking the array would be in phase with the incident radiation. This resulted in greater gain and high directivity. The spacing between two elements (both in X- and Y-plane) was maintained at

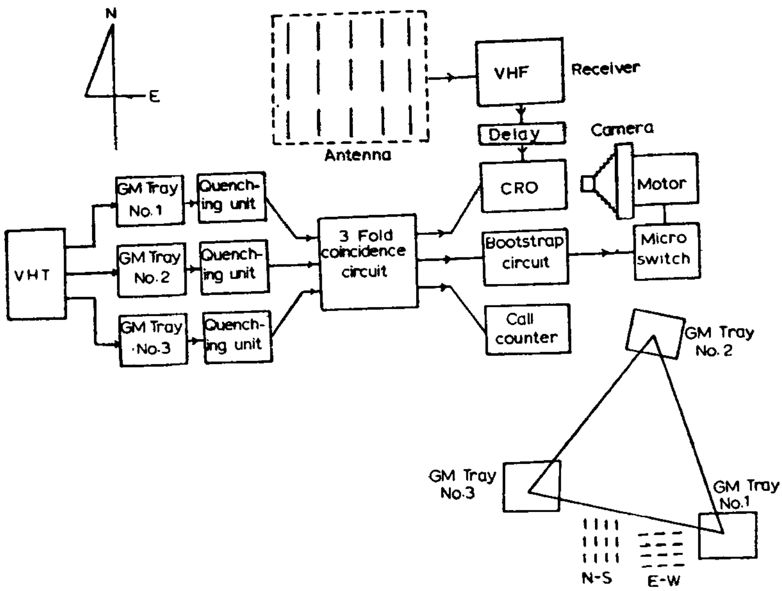

Figure 1. Flow-diagram of the EAS experiment.

$\lambda/2$ to obtain maximum gain (R A Handbook 1964). The different elements were connected in phase to a parallel transmission line, and the length of the feeder was multiple of $\lambda/2$.

Following sets (five) of arrays were installed for the experimental observations: (*a*) East-West oriented 36 dipoles with $n\,(=3)$ rows and $m\,(=6)$ sections for 30 MHz; (*b*) An East-West and another North-South oriented 30 dipole array with $n\,(=3)$ rows and $m\,(=5)$ sections for 44 MHz; (*c*) An East-West and another North-South oriented 36 dipole array with $n\,(=3)$ rows and $m\,(=6)$ sections for 60 MHz.

The arrays were properly matched and balanced with the transmission line to send the detected signal to the receiver with minimum loss.

2.3. *The receiver*

The receiver used for detecting the radio emission received by the antenna systems was an UHF 3 band superheterodyne receiver (model S–27) manufactured by Hallicrafters Co., Chicago, USA. The frequency range of the receiver was 28 to 144 MHz. The band-width of the receiver was, however, comparatively lesser ($\sim$ 1 MHz at 30 MHz).

The sensitivity and the selectivity of the UHF receiver was tested with the help of a standard signal generator and a dummy antenna. The receiver with different antenna arrays was tested with the help of a pulse transmitter. The transmitting antenna was broad-band (delta).

2.4. *CRO and the camera arrangement*

A 15 MHz Philips double beam CRO was used to observe the detected radio pulses from EAS against the background of the galactic noise. The rise time of the beam was 23 ns and the maximum sensitivity was 0·1 mv/div. The triggered beam with a time base of $20\,\mu s$ (full-scale) which displayed the received output, was photographed on a 35 mm fast film (ORWO NP-7) loaded in the camera (Cossor) attached to CRO.

3. Selection criteria

The correct position of the time base for observing an associated radio pulse was determined by using a lump delay line ($2\cdot5\,\mu s$) inserted between the CRO and the receiver output. A pulse appearing at the expected position of the time base, with height larger (about $1\cdot5$ times) than any other pulse (background noise) on the trace having a clear leading edge was considered as a genuine one. However, because of the background interference it was probable that a few spurious events might also be included as genuine. But their amplitudes would be very small. Pulse heights of the selected events were measured in arbitrary units, keeping the CRO gain always constant.

4. Experimental data and analysis

The particle detection array in the present experiment was designed to detect near zenith EAS of primary energy $\geqslant 10^{16}$ eV. From the call-counter records and the triggered CRO beams, the rate of such showers at Gauhati, during the winters from 1972 to 1975 is estimated to be $= 2\cdot46 \pm 0\cdot32$ per hr.

The aim of the experiment at 30 MHz with E–W directed array was to detect radio pulses in coincidence with EAS to study the pulse height distribution of the same. Further at 44 and 60 MHz, polarisation effects were also studied by installing E–W and N–S arrays for distinguishing between various theories. The period of observations, mean shower rate, number of selected events, and the average slope of the pulse height distribution for the three frequencies are given in table 1.

First, a search was made for small events (background noise) by scanning all triggered CRO beam at regular interval on the time base. Figure 2 shows the frequency of occurrence of received radio pulses along the time base between zero

Table 1.

Frequency (MHz)	Period and number of hours of observations	Total No. of showers recorded	Rate of showers recorded per hour	Number of selected events	The average slope (−ve)	Ratio of the r.m.s values of the E_{EW}/E_{NS}
30	October 1972–March 1973 240 hours	619	$2\cdot6\pm0\cdot1$	301	$1\cdot9\pm0\cdot25$	
44	November 1973–March 1974 300 hours for each array (N–S and E–W)	665 (E–W) 721 (N–S)	$2\cdot3\pm0\cdot06$	315 (E–W) 244 (N–S)	$2\cdot0\pm0\cdot21$	$2\cdot0\pm0\cdot71$
60	October 1974–March 1975 100 hours for each array (N–S and E–W)	267 (E–W) 240 (N–S)	$2\cdot5\pm0\cdot3$	204 (E–W) 141 (N–S)	$2\cdot0\pm0\cdot24$	$2\cdot0\pm0\cdot75$

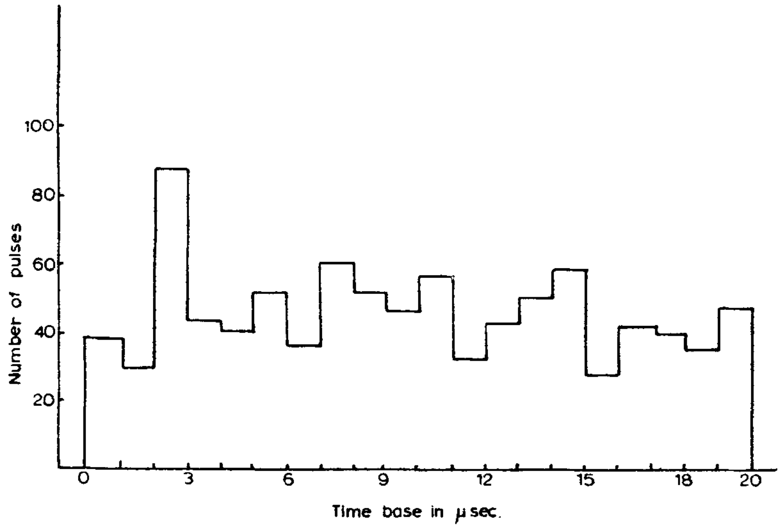

Figure 2. Histogram showing the occurrence of radio pulses along the time base of the CRO.

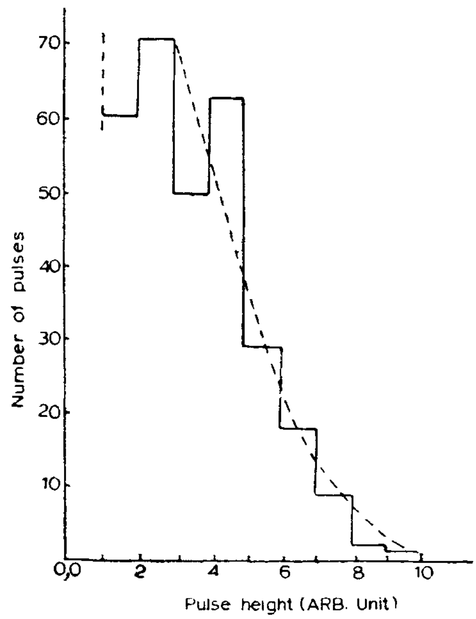

Figure 3. Pulse height distribution of radio pulses at 30 MHz.

and 20 μs. The pattern of frequency is uniform with a peak in between 2 and 3 μs markings.

Of the 619 events recorded from the CRO film, only 301 clear events were selected for analysis (*see* table 1). The frequency distribution of all the selected pulses given in figure 3 shows that it falls off with the pulse height and the average slope is $= 1{\cdot}9 \pm 0{\cdot}25$ (table 1).

A similar analysis was also made at 44 and 60 MHz for data from East-West (E-W) as well as North-South (N-S) arrays. The dates of observations and the number of events recorded and selected for analysis are given in table 1. The pulse height distribution for output from East-West (broken line) and North-South (solid line) arrays are superimposed in figures 4 and 5 for 44 and 60 MHz respectively. In all cases, the frequency distribution falls off with the pulse height, and the average slopes are $(-2 \cdot 0 \pm 0 \cdot 21)$ and $(-2 \cdot 0 \pm 0 \cdot 24)$ respectively, as shown in table 1.

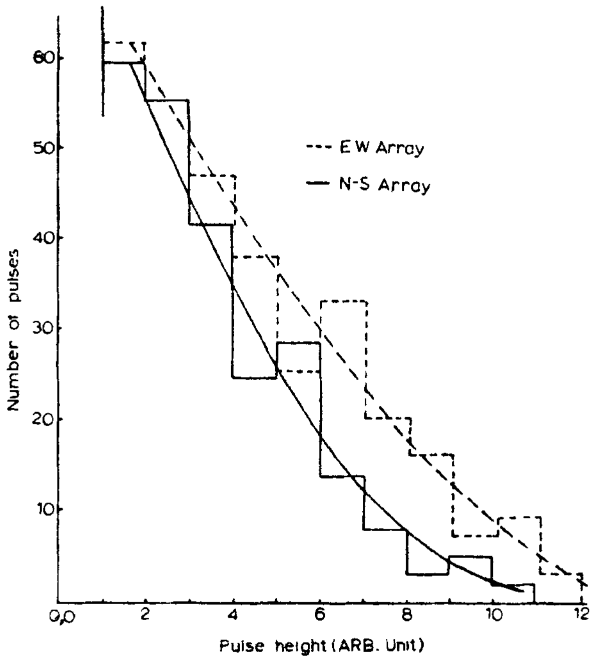

Figure 4. Pulse height distribution of radio pulses at 44 MHz (N–S and E–W array).

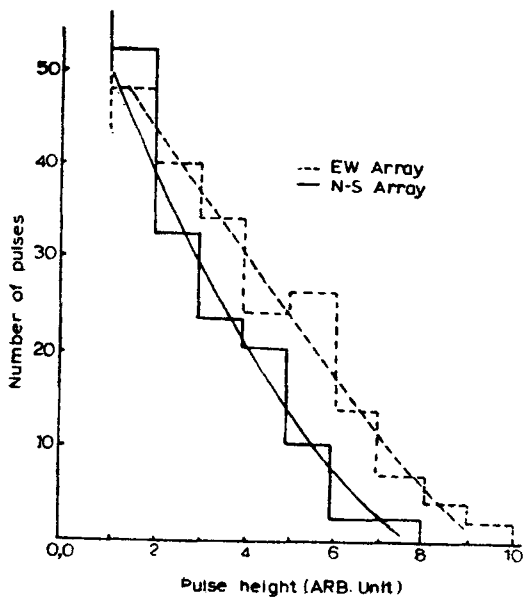

Figure 5. Pulse height distribution of radio pulses at 60 MHz (N–S and E–W array).

5. Discussion and conclusion

The radio pulse produced by EAS depends on several shower parameters. The amplitude of the frequency component, F_ν at the frequency ν, is expected to chiefly depend on: (*a*) direction of the shower axis, (*b*) perpendicular distance R from the antenna to the shower axis, and (*c*) the primary energy E_p.

The direction of the shower axis may be specified with the help of the zenith angle Θ and the angle α between the earth's magnetic lines and the shower axis. The radio pulse amplitude for any shower, according to geomagnetic charge separation mechanism, will depend on the transverse acceleration of the shower particles because of the Lorentz factor ($eV \times B$) where V and B are unit vectors along the direction of the shower axis and the earth's magnetic field respectively. So the radio pulse amplitude should be proportional to $\sin \alpha$. Further, the radio pulse amplitude should be proportional to $| r(V \times B) |$, where r is the unit vector in the direction of the polarisation of the antenna. The polarisation of the radio signals on the ground will be in a direction of the projection of the vector product of the shower direction and the geomagnetic field.

For vertical showers at the site of the experiment, $\alpha = 53°$, and so $| V \times B |$ $= 0 \cdot 8$. The predicted value of E_{EW}/E_{NS} for geomagnetic mechanism should be equal to $2 \cdot 8$ rms values of the signal. But the measured values of this ratio for 44 and 60 MHz are found to be $2 \cdot 0 \pm 0 \cdot 71$, and $2 \cdot 0 \pm 0 \cdot 75$ respectively. Thus the observed ratios are smaller than the calculated values. There are several factors which may affect the observed values. Firstly, errors of measurements on electric field strength through gain and temperature variations, etc., in the electronics are sufficiently high ($\approx 30\%$). Secondly, the assumption made in the present experiment that the cores were coincident with the circumcentre of the particle detector array was not true for all the showers, and consequently the antenna systems were not symmetrical with the cores of all the detected showers. And this might be manifested in the field strength picked up by the two array systems. Thirdly, the assumption that the distribution of the primary cosmic rays was isotropic in the place of observation during the period of observation may not be true. Nevertheless, within experimental errors, the direction of polarisation manifests the predominant effects of the geomagnetic field.

The average values of the pulse height distribution for 44 and 60 MHz decrease with frequency as shown in table 2.

Table 2. Average values of the pulse height distribution at 44 and 60 MHz.

Frequency in MHz	Orientation of the array	Average pulse height in arbitrary units
44	E–W	$4 \cdot 8 \pm 0 \cdot 13$
	N–S	$4 \cdot 1 \pm 0 \cdot 13$
60	E–W	$4 \cdot 19 \pm 0 \cdot 14$
	N–S	$3 \cdot 15 \pm 0 \cdot 15$

This indicates that the average field strength appears to decrease with frequency. But according to the theoretical calculations of Hough (1973), the field strength should be independent of frequency over this range.

The pulse height distribution for all the three frequencies as shown in figures 3, 4, and 5 indicate that lesser the frequency of the events the larger is the amplitude of the signal. The present experimental results depict an average pulse height distribution of radio signals at a fixed position in the array. The inherent drawback of the detecting system is that it cannot detect the fluctuation of the field measured from shower to shower. In any case, the general pattern of the distributions for the three frequencies has similarity in slopes with that of the primary cosmic ray spectrum ($= -2\cdot24 \pm 0\cdot04$ for $10^{17} < E_p < 10^{19}$ eV). The almost identical nature in the exponential fall of the two distributions may not perhaps be fortuitous. This may be due to the fact that the radio field strength is proportional to the primary energy. Such an explanation is in agreement with the theoretical predictions of Kahn and Lerche (1966) and Allan *et al* (1971).

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