WAVEFORMS OF ATMOSPHERICS

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Abstract

More than one thousand useful waveforms of atmospherics were recorded at Banaras during 1952–55 by the automatic atmospherics-waveform recorder constructed in the laboratory. A classification of the observed waveforms has been made and interpretations given in the paper. Besides the known types of waveforms which were already recorded by the previous investigators, the oscillographic records showed evidence of 'stepped' pulses from the leader of one lightning discharge of near origin, superimposed on the waveform due to a different lightning discharge. A few oscillograms also revealed a long train of sinusoidal oscillations of nearly constant frequency. A large number of oscillograms was attributed to cloud-to-cloud discharges. The observations regarding discharges within the cloud are reported elsewhere.

Introduction

The atmospherics are usually associated with lightning discharges taking place between cloud and earth, between cloud and cloud and between cloud and air, of which the cloud-to-cloud and air-discharges are of more frequent occurrence in India. The present investigation was undertaken, since 1951, for a comprehensive study of the various waveforms of atmospherics with the help of the automatic atmospherics-waveform recorder constructed in the laboratory. The theoretical considerations underlying the method employed in the investigation were the same as those given by Appleton, Watson-Watt and Herd (1926), but the equipment and experimental arrangements were such as to enable automatic recording of full and accurate waveforms of atmospherics without overlapping and with sufficient amplification and time-resolution. A classification of the different types of waveforms has been made from a study of more than one thousand useful waveform patterns recorded during 1952–55. The characteristics of these waveforms and their interpretations are given in the present paper. The waveforms which were attributed to cloud-to-cloud discharges were found similar to those due to cloud-to-ground discharges in respect of (*a*) multiple strokes, (*b*) 'predischarges', (*c*) return stroke pulses and their reflections from the ionosphere, (*d*) slow field-changes and 'hook'-components and (*e*) junction field-changes. The waveforms attributed to discharges within the cloud have been described elsewhere (Tantry, Srivastava and Khastgir, 1957*a* and *b*).

Experimental Arrangements

The different parts of the automatic atmospherics-waveform recorder and their working are described in a separate paper (Tantry, 1958). A preliminary account of the recorder was also published (Tantry, 1952). We shall merely mention here the component parts of the entire equipment constructed and used in the present investigation:

(1) *Aerial Unit:* A horizontal open-wire aerial was used with a suitable damping resistance and a condenser in series with it.

(2) *Main Amplifier:* A wide-band high-gain amplifier having a flat frequency-response from 100 c/s to 100 kc/s was constructed and used for

amplifying the voltage developed across the aerial condenser during a lightning discharge.

(3) *Square-wave Trigger:* A square-wave trigger unit was constructed and used for the intensity-modulation of the cathode-ray oscillograph.

(4) *Low-frequency Tuned Amplifier:* A tuned amplifier was used, when necessary, for triggering the square-wave pulse-generator.

(5) *Delay Line:* A suitable delay-line circuit was inserted between the main amplifier and the oscillograph unit.

(6) *Oscillograph Unit:* An intensity-modulated cathode-ray oscillograph was used to delineate the waveforms which were photographed.

(7) *Automatic Film-moving Unit:* After each exposure, this unit would move forward the exposed film to the receiving casette.

(8) *Raster Arrangement:* With a raster arrangement the atmospheric pulses were recorded without overlapping on several horizontal 'sweep'-lines.

CLASSIFICATION OF THE WAVEFORMS OF ATMOSPHERICS

All the waveforms recorded at Banaras during the investigation are classified as follows:

Type I. 'Aperiodics' and 'quasi-periodics'.
Type II. Slow components.
Type III. 'Hook'-components.
Type IV. Ionospheric reflection types:
  (*a*) Peaked repeaters.
  (*b*) Smooth *quasi*-sinusoidal type.
  (*c*) Long and short wave-trains on the slow component.
  (*d*) Long wave-train of nearly constant frequency.

Type V. 'Predischarges':
  (*a*) 'Predischarges' followed by the return stroke.
  (*b*) 'Predischarges' of the isolated type.
  (*c*) 'Stepped' pulses from the initial leader.

Type VI. Cloud-to-cloud discharges:
  (*a*) Simple multiple strokes.
  (*b*) Multiple strokes with 'predischarges'.
  (*c*) Multiple strokes with ionospheric reflections.
  (*d*) Multiple strokes of twin pulses.
  (*e*) Multiple strokes with 'hook'-components.
  (*f*) Multiple strokes with junction-field changes.

THE DIFFERENT TYPES OF WAVEFORMS OF ATMOSPHERICS AND THEIR INTERPRETATIONS

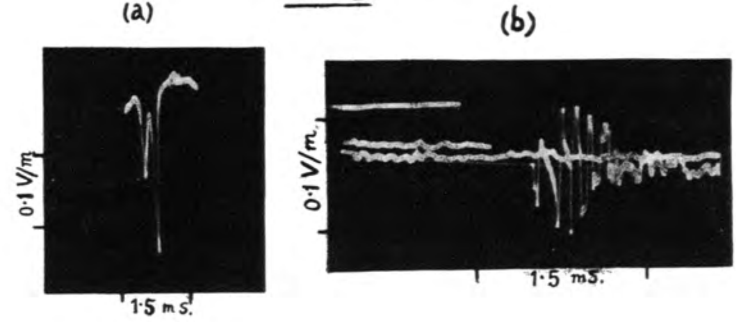
Type I

'Aperiodics' and 'quasi-periodics'

A number of 'aperiodics' was recorded of which a typical oscillogram is shown in Fig. 1(*a*). The 'aperiodics' were characterised by unidirectional pulses of about 50–500 μs duration. The patterns recorded during the day and the night were alike. The peak-amplitude was found to vary from 0·1 to 1·0 volt/m.

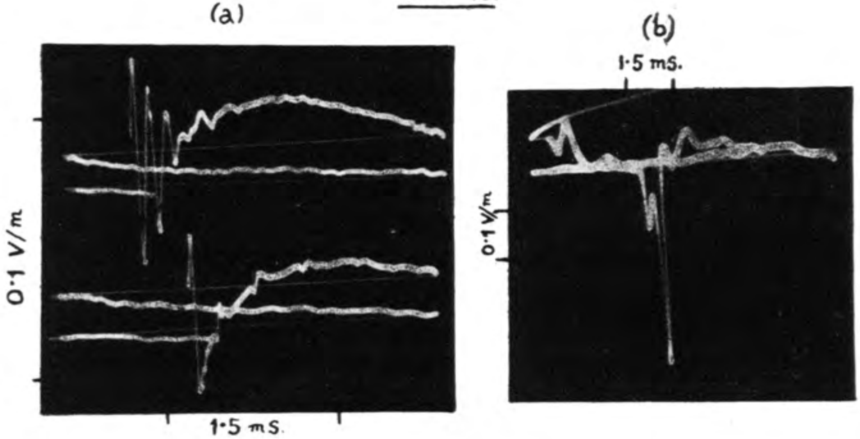
The '*quasi*-periodics' were found to have a duration of about 40–300 μs per half-cycle. The peak-amplitude ranged between 70 mv/m and 0·2 v/m. From a

FIG. 1.


(a)

(b)

FIG. 2.


(a)

(b)

FIG. 3.

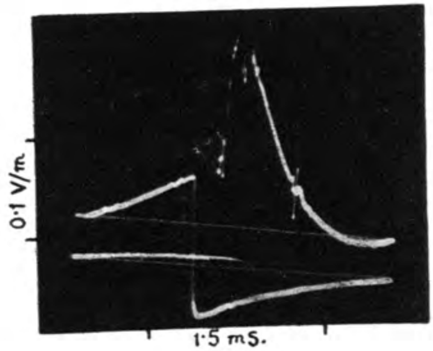


FIG. 1. (*a*) Aperiodic pulse. Date: 24.8.52, Time: 0.30 p.m.
(*b*) *Quasi*-periodic pulse. Date: 25.6.54, Time: 11.20 p.m.

FIG. 2. (*a*) 'Aperiodic' and '*quasi*-periodic' followed by a slow component. Date: 7.7.55, Time: 11.5 p.m.
(*b*) Slow component on both sides of the return stroke pulse. Date: 25.8.52, Time: 6.50 p.m.

FIG. 3. 'Hook'-field changes. Date: 14.7.55, Time: 10.50 p.m.

FIG. 4.

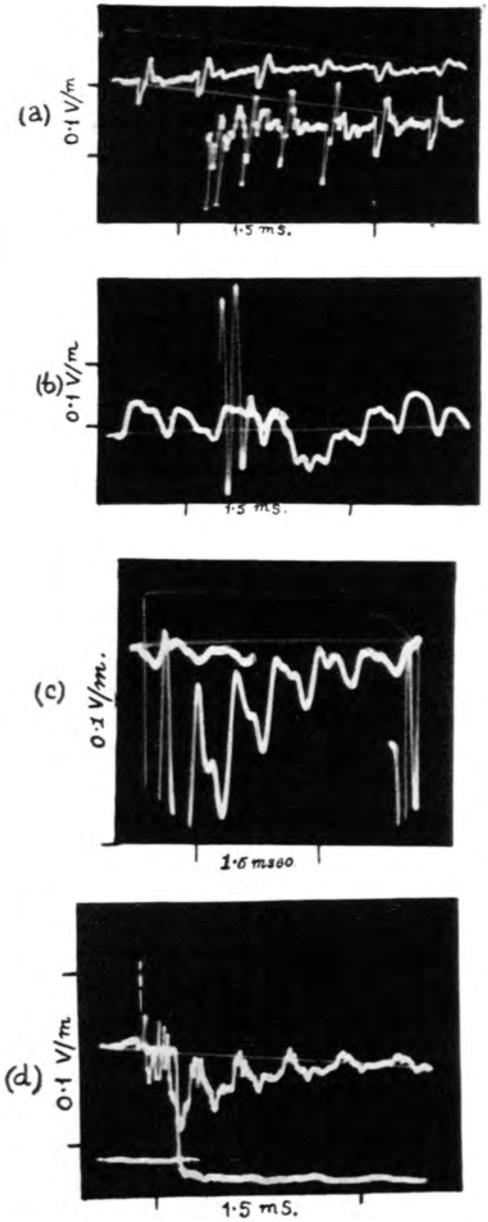


FIG. 5.

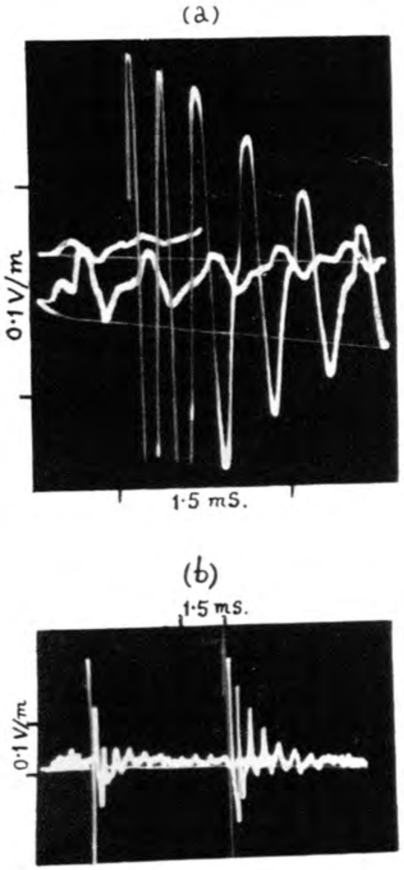


FIG. 4. (*a*) Peaked repeaters. Date: 22.8.55, Time: 11.25 p.m.
(*b*) Rounded type repeaters. Date: 30.6.52, Time: 9 p.m.
(*c*) Saw-tooth type repeaters. Date: 13.9.53, Time: 7.20 p.m.
(*d*) Complex type repeaters. Date: 7.9.55, Time: 9.30 p.m.

FIG. 5. *Pseudo*-damped oscillatory type. (*a*) Date: 7.9.55, Time: 9 p.m.
(*b*) Date: 23.8.52, Time: 8.5 p.m.

number of '*quasi*-periodics' recorded, one representative pattern is shown in Fig. 1(*b*).

The 'aperiodics' and '*quasi*-periodics' are known to have been recorded by the earliest workers in the field. It is well known that the vertical field E due to the destruction of the thundercloud moment consists of (i) electrostatic, (ii) inductive and (iii) radiative field components. At a distance r (on the ground) much greater than the height of the thundercloud, this field is given by:

$$E=\frac{M}{r^3}+\frac{1}{cr^2}\cdot\frac{dM}{dt}+\frac{1}{c^2r}\cdot\frac{d^2M}{dt^2} \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where M is the retarded electric moment of the thundercloud at time $\left(t-\frac{r}{c}\right)$, and c is the velocity of light. It was first shown by Appleton, Watson-Watt and Herd (1926) that the resultant of the above three field-components would give rise to an 'aperiodic' at near distances and to a '*quasi*-periodic' at comparatively large distances. The electric self-oscillation mechanism of Simpson (1926) to explain the damped oscillatory nature of the observed '*quasi*-periodics' was ruled out, as there was no direct evidence in the moving camera photographs of the lightning strokes by Malan and Collens (1936). From the extensive work of Norinder (1951), it is now possible to explain the transformation of an 'aperiodic' observed at short distances to a '*quasi*-periodic' at comparatively large distances. If the current in the return-stroke channel shows a sudden sharp rise followed by a continuous fall, the radiative field-change, which alone determines the shape of the waveform at large distances, would give a waveform of only one *quasi*-period. When, however, there are more discontinuities in the return stroke current, a number of half-cycles of '*quasi*-periodics' would be expected.

Experimental evidences are available regarding the current discontinuities in the return stroke. The moving camera photographs of the structure of the return stroke by Schonland, Malan and Collens (1935) revealed certain maxima in luminosity in relation to time. It was shown later by Malan and Collens (1936) that the observed luminosity-maxima in the upward discharge corresponded to the time when the return stroke reached the points where the leader in its downward course had previously branched out. Malan and Collens also showed that the velocity of the return stroke decreased when it passed in its upward journey through the branching points. It is also significant that the oscillograms taken by Lutkin (1939) of the field-changes due to lightning discharges at very short distances (1 km. and 5 kms.) showed abrupt discontinuities. As the electric field at such short distances is predominantly *electrostatic*, the discontinuities indicated changes in the amount of charge flowing through the lightning channel during the return stroke. The direct measurements of Norinder and Dahle (1945) also showed discontinuities in the return stroke current.

All the waveform patterns recorded during the investigation showed that the *quasi*-periodic or the damped oscillatory waveforms which were not due to successive reflections from the ionosphere were usually of a somewhat irregular periodicity. The irregular nature of the '*quasi*-periodics' confirms the view that they must be due to sudden changes in the return stroke current at the branching points which are irregularly distributed.

Type II

Slow components

The slow or low-frequency (100–1000 c/s) component following the return stroke pulse had long been known. It is sometimes called a 'slow-tail' component, especially when it appears slightly detached from the return stroke pulse. A detailed study of the slow component was first made by Watson-Watt, Herd and Lutkin

(1937). Some quantitative studies of the 'slow-tail' component were later made by Hepburn and Pierce (1954).

About sixty oscillograms showing slow components following the return stroke pulse were recorded during the investigation. Two typical patterns in one oscillogram are shown in Fig. 2(*a*). In the oscillograms of this type a slow field-change of smaller amplitude was found to last for about 1-2·5 milliseconds following an 'aperiodic' or a '*quasi*-periodic' of larger amplitude. Only in few oscillograms, the slow field-change of smaller amplitude appeared on both sides of the return-stroke pulse. One such oscillogram is shown in Fig. 2(*b*). Such oscillograms were previously reported by Khastgir and Roy (1949*a*).

Appleton and Chapman (1937) attributed the slow field-change to either the *a*-field change (leader) or the *c*-field change. Similar view was put forward by Bruce (1941) and Khastgir and Roy (1949*a, b*). According to Schonland the *c*-field stage involves the removal and the passage down the channel of the residual charge on the cloud-centre tapped by the stroke and is marked by the continuance of the channel luminosity for a comparatively long duration of 1–3 milliseconds after the return stroke has reached the cloud. Malan and Schonland (1947) suggested that a modification of the *c*-field change was also possible by the upward movement of the upper positive charge of the bipolar cloud. Hales (1948) explained the 'slow-tail' component by the mode-theory of propagation between a perfectly conducting earth and the ionosphere of finite conductivity. Accepting Hale's theory Hepburn and Pierce (1953) estimated the values of the ionospheric reflection height and the specific electrical conductivity of the ionosphere.

Type III

'Hook'-components following the return-stroke pulse.

The luminosity maxima were first observed by Malan and Collens (1936) during the return stroke. The later investigations by Malan and Schonland (1947) revealed luminosity bands even after the return stroke and the observed luminosity bands during and after the return stroke were shown to be associated with subsidiary changes in the electric field. As the minor electric field-changes after the return-stroke pulse appeared in the form of 'hooks' at short distances (3-4 kms.) from the lightning source, they were called 'hook'-components. At a distance of 10–15 kms., however, these field-changes appeared as wavy pulses in the records of Malan and Schonland (1947). At larger distances Caton and Pierce (1952) recorded them as sudden bursts of oscillations.

A number of oscillograms showing the 'hook'-field changes were recorded during the investigation. A typical record of the 'hook'-components is shown in Fig. 3.

The 'hook'-field changes were explained in a general way by Malan and Schonland (1947).

Type IV

Ionospheric reflection types

From the investigations of Laby, Nicholls, Nickson and Webster (1937), Laby, McNeil, Nicholls and Nickson (1940), Schonland, Elder, Hodges, Philips and van Wyk (1940) and Rivault (1943), it was well established that the waveform of an atmospheric pulse, received from a source within 2,000 kms., usually consisted of a ground pulse followed by a series of pulses produced by successive reflections between the ionosphere and the earth, the time-separation between the successive pulses being determined by the distance travelled and the height at which ionospheric reflection takes place. In our investigations we were able to record a few hundred waveforms, each showing a family of pulses successively reflected from the ionosphere and preceded at times by the ground pulse, the number of reflected pulses ranging from about five to about twenty. From the observed time-intervals between the successive pulses as applied to the relevant formulae based on the ray-theory of ionospheric reflection, the ionospheric reflection height was found to lie between 80 kms. and 90 kms. and the distance of the lightning source was found to range from 150 kms. to 3,000 kms.

(*a*) *Peaked repeaters*

Many of the waveforms showing multiple reflections from the ionosphere were found to have reflected pulses of the peaked type. Usually it was noticed that the first reflected pulse was the largest in amplitude. At greater distances from the lightning source, sometimes the second or the third reflected pulse was found to have the maximum amplitude. A change in the shape of the reflected pulses was often observed, either from one waveform to another or among the pulses in the same waveform with the increasing order of reflection. The reflected pulses were found to be either symmetrical or unsymmetrical with respect to the sweep-line. The sharp peaks often tended to assume a round shape in the higher orders. A change of sign from the positive to negative or *vice versa* was also observed with the increasing order of reflection. Sometimes the reflected peaks were found to be of the saw-tooth form due to the doubling of the peaks and the accentuation of one of them. Some of the peaked repeaters recorded by us are shown in Fig. 4. In Fig. 4(*a*) the first few peaks are predominantly negative and they became symmetrical in the higher orders of reflection. Fig. 4(*b*) shows rounded peak repeaters. The repeaters of the saw-tooth form shown in Fig. 4(*c*) ultimately transformed into rounded peaks. A few oscillograms showed complex peaks characterised by high frequency ripples or *harmonic* components, superposed on the reflected peaks. One such complex-peak type of repeaters is shown in Fig. 4(*d*). The various types of peaked repeaters mentioned above were previously observed by Rivault (1945), Caton and Pierce (1952) and Hepburn and Pierce (1954).

In a number of oscillograms, the location and the spacing of the peaked repeaters were such as to give the appearance of *quasi*-periodic or damped oscillatory pulses. Since the successive peaks fitted well with the ray-theory of ionospheric reflection and since they only looked like the *quasi*-periodic or damped oscillatory pulses, they may be classed under *pseudo*-damped oscillatory type. Fig. 5 illustrates two such oscillograms.

A number of oscillograms were recorded where a few cycles of irregular '*quasi*-periodics' were followed by a series of pulses successively reflected from the ionosphere. Two typical waveforms of this mixed variety are shown in Fig. 6. They can be regarded as a definite confirmation of the final conclusion of Laby *et al.* (1940) that there exist *quasi*-periodic pulses due to parent discharges followed by pulses due to successive reflections from the ionosphere. They also set at naught the view of Schonland *et al.* (1940) that the '*quasi*-periodic' or damped oscillatory type of waveforms observed at night are all due to successive ionospheric reflections of a simple atmospheric pulse.

The height at which an atmospheric pulse is reflected from the ionosphere and the distance of the source are given by:

$$h = 150.\sqrt{\frac{t_1t_2(t_1+t_2)}{t_1(r^2-q^2)-t_2(q^2-p^2)}} \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

$$D = \frac{d}{1-\frac{h}{R}} = \sqrt{\left[\frac{1}{150}\cdot\frac{h^2(q^2-p^2)}{t_1}-150t_1\right]^2-4p^2h^2} \quad \ldots \quad (3)$$

where d is the great-circle distance on the earth's surface in kms. between the source and the receiving point, R the radius of the earth in kms., $t_1 = t_q - t_p$ and $t_2 = t_r - t_q$, t_p, t_q, t_r being the time-intervals in milliseconds between the emission of the primary pulse and the arrival at the receiver of the pulses of the pth, qth and rth orders of reflection. For the evaluation of h and D from the observed time-intervals of the reflected pulses, a graphical method based on the two formulae was adopted. The method was similar to the one followed by Caton and Pierce (1952).

Many oscillograms showed that for the waveforms recorded within 1,000 kms. distance from the source, the time-intervals between two successive reflected pulses assumed an almost constant value t after the twelfth order of reflection. The approximate value of h was then easily determined from the formula:

$$h = 150t \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

where h is expressed in kms. and t in milliseconds. In some cases, when there were ambiguities in assigning the correct order for any reflected pulse, the correct assignment was sometimes obtained from the formula:

$$p = \frac{t_1(t_1+t_2)(5t_2-3t_3)-t_3(t_2+t_3)(3t_1-t_2)}{2t_1(t_1+t_2)(t_3-t_2)-2t_3(t_2+t_3)(t_2-t_1)} \quad \ldots \quad \ldots \quad (5)$$

where $t_1 = t_q - t_p$, $t_2 = t_r - t_q$, $t_3 = t_s - t_r$, t_p, t_q, t_r, t_s being the time-intervals between the emission of the primary pulse and the arrival at the receiver of the pulses of the pth, qth, rth and sth orders of reflection.

In Table I are entered the calculated distances of the lightning discharges which yielded the waveforms shown in Figs. 4–6.

TABLE I

Figure number	Date and time of record	Distance in kms.
4(*a*)	22-8-55, 11.25 p.m.	550
4(*b*)	30-6-52, 9.00 p.m.	250
4(*c*)	13-9-53, 7.20 p.m.	280
4(*d*)	7-9-55, 9.30 p.m.	430
5(*a*)	7-9-55, 9.00 p.m.	550
5(*b*)	23-8-52, 8.05 p.m.	550
6(*a*)	22-8-54, 11.20 p.m.	1,600
6(*b*)	6-9-55, 7.40 p.m.	1,000

(*b*) *Smooth quasi-sinusoidal type*

By the application of the 'mode'-theory to long distance propagation between the perfectly conducting earth and the ionospheric layer of finite conductivity, Budden (1951, 1952) showed how a sharp atmospheric pulse would transform into a smooth sinusoidal waveform with gradually increasing time-interval between the successive crests. It was Caton and Pierce (1952) who identified the smooth and damped oscillatory waveforms (type 3.3.2), recorded by them, with the Budden type of *quasi*-sinusoidal oscillations. Type 3 of Rivault (1948) corresponded to such waveforms. Perhaps Lutkin (1939) included them under his group 1.

Our records revealed a number of smooth *quasi*-sinusoidal waveforms of this type, of which only one is shown in Fig. 7(*a*). It is significant that the crests of these waveforms do not fit in with the ray-theory of ionospheric reflection. Such waveforms with initial negative field-changes were more often recorded than those with positive field-changes. The *quasi*-period was found to increase steadily from

FIG. 6.

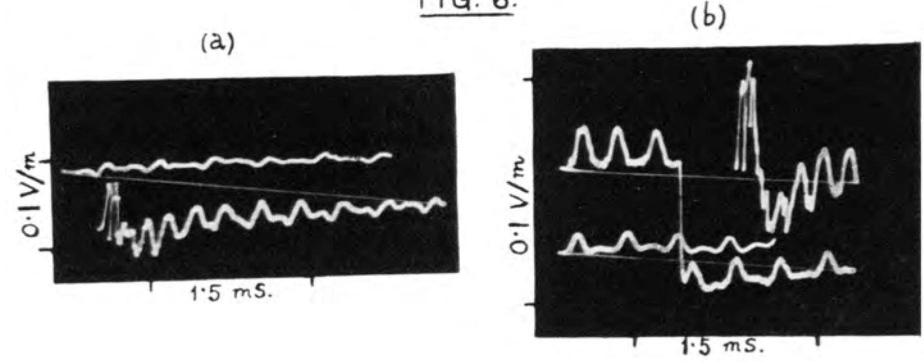


FIG. 7.

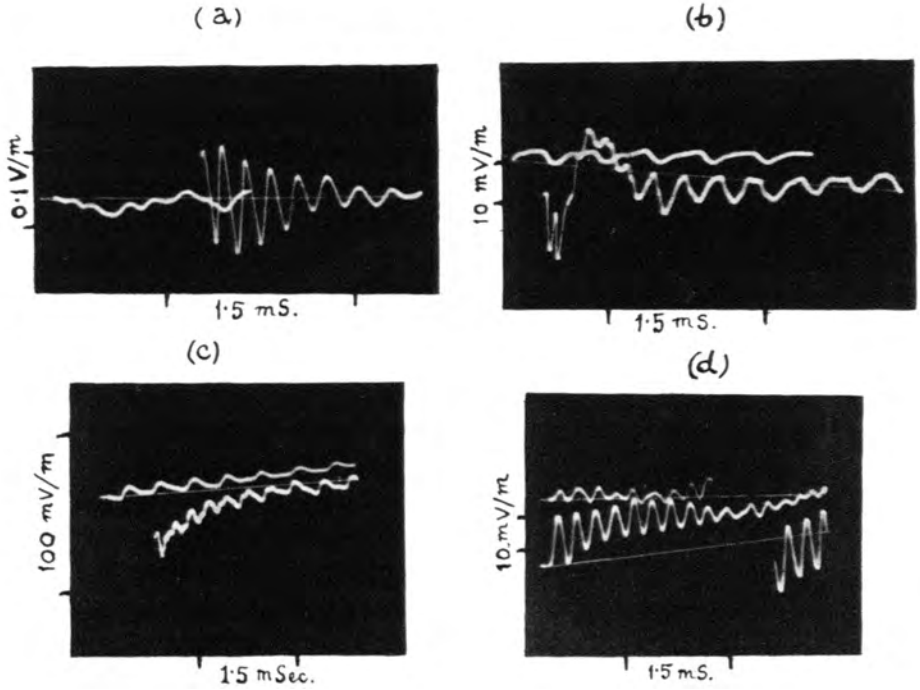


FIG. 6. (a) *Quasi*-periodics followed by reflected pulses. (a) Date: 22.8.54, Time: 11.20 p.m.
(b) Date: 6.9.55, Time: 7.40 p.m.

FIG. 7. (a) Smooth *quasi*-sinusoidal type. Date: 29.6.52, Time: 8 p.m.
(b) Reflected wave-trains on the slow component. Date: 17.8.54, Time: 11.30 p.m.
(c) Reflected wave-trains on the slow component. Date: 18.9.55, Time: 11.30 p.m.
(d) Sinusoidal waveform of nearly constant frequency. Date: 9.9.55, Time: 9.15 p.m.

FIG. 8.

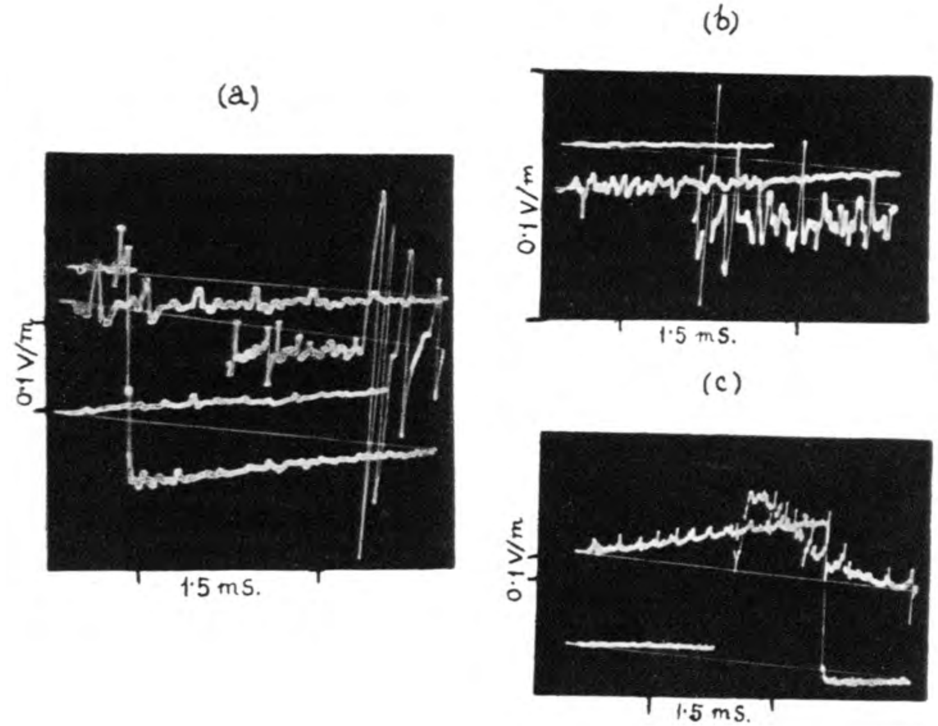


FIG. 8. (*a*) 'Predischarges' followed by return stroke pulses and their reflections. Date: 22.8.54, Time: 11.10 p.m.
(*b*) 'Predischarges' of the isolated type. Date: 4.8.55, Time: night.
(*c*) 'Stepped'-pulses from a near lightning discharge superposed on the waveform due to a different lightning discharge. Date: 14.8.55, Time: 6.30 p.m.

100–150 μs at the beginning to about 250 μs at the end of the waveform. In many of the oscillograms, the *quasi*-sinusoidal pattern degenerated into rounded form towards the end.

(*c*) *Long and short wave-trains on the slow field-change*

Two typical oscillograms showing long and short wave-trains superposed on the slow field-change are shown in Figs. 7(*b*) and 7(*c*). The successive crests of the wave-train agreed with the ray-theory of ionospheric reflection. The distances of the lightning sources for the two oscillograms were found according to the ray-theory to be 1,550 and 1,300 kms. respectively. The wave-train must have originated from a distant lightning discharge and were superposed on the waveform of the same or a different lightning source. Some of the waveforms showing superposed wave-trains are included in type 3.4 of Caton and Pierce (1952). Many such wave-trains observed by us on the slow field-change are exactly similar to those observed by Hepburn and Pierce (1954).

(*d*) *Long wave-trains of sinusoidal oscillations of nearly constant quasi-period*

The waveforms under this category, though often visually observed at night only, were seldom recorded, because of their small amplitudes. In Fig. 7(*d*) is shown a long train of twenty-five or more oscillations of nearly constant frequency (4 kc/s), the characteristic feature being the perfectness of their sinusoidal form except at the end of the waveform. Considering these oscillations as the later part of a long wave-train due to successive ionospheric reflections, it can be shown from (4) that the observed constant frequency would give the ionospheric reflection height as 37 kms. which is too low. This rules out the ray-theory of ionospheric reflection as the cause of the observed sinusoidal oscillations. The smoothness of the oscillations, however, suggests that the mode-theory of propagation over a large distance between the ionosphere and the earth may provide a suitable interpretation.

Type V

(*a*) *'Predischarges' followed by return-stroke pulse*

The 'precursors' of *quasi*-frequency, 20–30 kc/s, had been observed by Appleton and Chapman (1937) and were considered as due to radiations from the points of discontinuities or branchings in an initial leader. Norinder (1951) also observed these oscillations of irregular nature before the main discharge (or return stroke) and called them 'predischarges'. These 'predischarges' were later recorded by Caton and Pierce (1952) and were classified as 'Irregular high-frequency pulses'. In Fig. 8(*a*) is shown an oscillogram from our records which reveals the 'predischarges' followed by the return stroke pulses and their reflections from the ionosphere. Considering all such oscillograms recorded by us, the amplitude ratio of the 'predischarges' to the return stroke pulses was found to vary from 0·1 to 0·5. Some regularity observed in the 'predischarges' are to be attributed to the 'stepped' leader.

(*b*) *'Predischarges' of the isolated type*

More than a hundred oscillograms showing 'predischarges' of the isolated type were recorded of which a typical record is shown in Fig. 8(*b*). In all our oscillograms showing 'predischarges' which were not followed by the return stroke pulse, they appeared as irregular series of high-frequency pulses of 8–20 kc/s. The fluctuations in amplitude were often uneven, but there was, in general, a gradual decrease from the beginning to the end of the waveform.

Norinder (1951) had previously recorded such 'predischarges' of the isolated type. They are considered as due to radiations from the points of discontinuities as well as from the steps in a β-type leader or in an 'air-discharge', whereas the 'predischarges' followed by the return stroke pulse must be associated with an α-type leader.

(c) *'Stepped' pulses from an initial leader*

Some regularity in the irregular high-frequency pulses of the 'predischarges' should be due to the 'steps' in an initial leader. A few oscillograms recorded by us showed strikingly regular 'stepped' pulses. In Fig. 8(*c*) is shown a record of such 'stepped' pulses. The 'stepped' pulses are believed to originate from the 'steps' of an initial leader of a near lightning discharge and were found to be superimposed on the waveform due to a different lightning discharge. Such superimposed 'stepped' pulses from the leader of one lightning discharge on the waveform due to another lightning discharge were not recorded by previous investigators.

Type VI

Cloud-to-cloud discharges

A large number of waveforms attributed to discharges within the cloud and their interpretations are published elsewhere.

CONCLUSION AND ACKNOWLEDGEMENTS

The investigations on the waveforms of atmospherics are still in progress. The results of further studies will be reported in due course. The authors record their thanks to the Council of Scientific and Industrial Research for sponsoring a research scheme on the nature of atmospherics. They are grateful to Professor S. R. Khastgir, D.Sc., F.N.I., for constant help and supervision.

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