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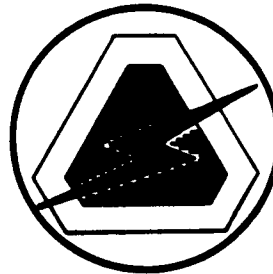
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ANALYSIS OF THE ELECTROSTATIC FIELD OF A LIGHTNING STROKE

H. W. Kasemir



November 1962

UNITED STATES ARMY
ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, N.J.

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ANALYSIS OF THE ELECTROSTATIC FIELD OF A LIGHTNING STROKE

H. W. Kasemir

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Abstract

During the summer of 1961 the electrostatic field of lightning strokes in the frequency range from 0 to 100 cps was recorded. Simultaneously, the distance from the lightning stroke to the recording station was determined by triangulation. This, combined with the electrostatic theory, allows a detailed analysis of the electric field of the lightning stroke. The results of this analysis are discussed.

U. S. ARMY ELECTRONICS RESEARCH & DEVELOPMENT LABORATORY
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ANALYSIS OF THE ELECTROSTATIC FIELD OF A LIGHTNING STROKE

INTRODUCTION

The electric field of a lightning stroke has been the object of extensive research in the past decade, and much of the knowledge of the lightning discharge has resulted from these investigations. However, it is the opinion of the author that much more information about the lightning itself and the charge distribution of the thundercloud can be obtained from a more quantitative evaluation of the electric field records.

To carry out such an evaluation it would be necessary not only to record the electric field, but also to determine the spatial configuration of the lightning channel. The complex form of the lightning and the invisibility of that part which is hidden inside the cloud make this goal very difficult to achieve. As a first step in this direction, one may compromise with the assumption that the lightning channel is a vertical straight line. Then the distance from the observation point and the length of the lightning channel would completely describe the geometrical configuration.

Very recently, Brook, Nitagawa, and Workman¹ published an excellent paper on the evaluation of the electric field of lightning discharges in a manner as outlined above. They concentrated their evaluation on the electric charge and the current flow of the lightning discharge, mainly to determine the differences of two kinds of ground strokes--the discrete and the hybrid flash. Also, much interesting and detailed data are communicated, such as the growth of the channel by each individual partial discharge, the electric charge involved in the single components of the stroke, and the electric field-distance relationship. Some of these data are confirmed or supplemented by this report, but their interpretation is often different.

The field-distance relationship could be extended from 30 to 90 km distances. Besides a more statistical evaluation, the different field curves of lightning strokes with one partial discharge are discussed. It is surprising to see that the field patterns of lightning strokes of the same storm are remarkably similar to each other, but are quite different from those of a second storm which developed right after the first one not more than 12 km away. As the second storm produced lightnings with extraordinary field patterns, this may lead to the conclusion that an unusual combination of the charge distribution of both storms may have caused the unusual lightnings in the first part of the second storm.

DISCUSSION

Description of the Equipment

The electric field of the lightning stroke was recorded with a Sandborn recorder. A flat frequency response from 1 to 100 cps was achieved by shunting the 5-megohm input resistor of the preamplifier by a 1- μ f condenser.² A horizontal wire antenna 4.5-m high and 10-m long, connected to the input of the apparatus, resulted in an overall sensitivity of 3.6 V/m per 1-mm pen deflection. The sensitivity was adjustable in ten steps to 7000 V/m per 1-mm pen deflection in the least sensitive range.

Two observation points were set up 23.5 km apart at small air fields of Fort Rucker, Alabama. Each one was equipped with a wireless communication set PRC-10 and a direction finder. The direction finder was an extremely simple device. It consisted of a face plate with polar coordinate engraving, and a pointer, which could be easily pointed in the direction of the lightning stroke by the observer. The location of the lightning was then calculated by triangulation from the angle readings and the base line. The accuracy of this very crude instrument was surprisingly good ($\pm 1^\circ$), provided the lightning stroke was clearly visible from both points. This was usually the case for ground strokes during and after sunset. Difficulties arose during daylight when lightnings could not be seen over a great distance, and in the observation of cloud strokes, which were usually hidden inside the cloud. The diffusely illuminated cloud mass did not yield a sharp focal point, and therefore the evaluation of field records was restricted mainly to ground strokes. The entire system could be operated by three persons.

Evaluation of the Data

Figure 1 shows a map of the location of the lightning strokes from three storms on 3 July 1961. The straight line is the base line, with the observation points 1 and 2 on each end. The field recorder was located at observation point 1. Lightnings of the first, second, and third storm are marked with crosses, dots, or X's, respectively.

The lightning strokes of the first storm were with few exceptions concentrated in a comparatively small area (circle with a diameter of about 9 km). The second storm was more than twice as long in duration as the first storm (74 minutes against 32 minutes). In the first half hour of the second storm, the lightnings were scattered over a wide area, with a largest diameter of about 30 km. The ground strokes of this period were without exception strokes with a partial discharge only. Each stroke had a long-lasting predischage (0.3 to 0.9 second). The electric field of these lightning strokes also showed an extraordinary pattern, which will be discussed later.

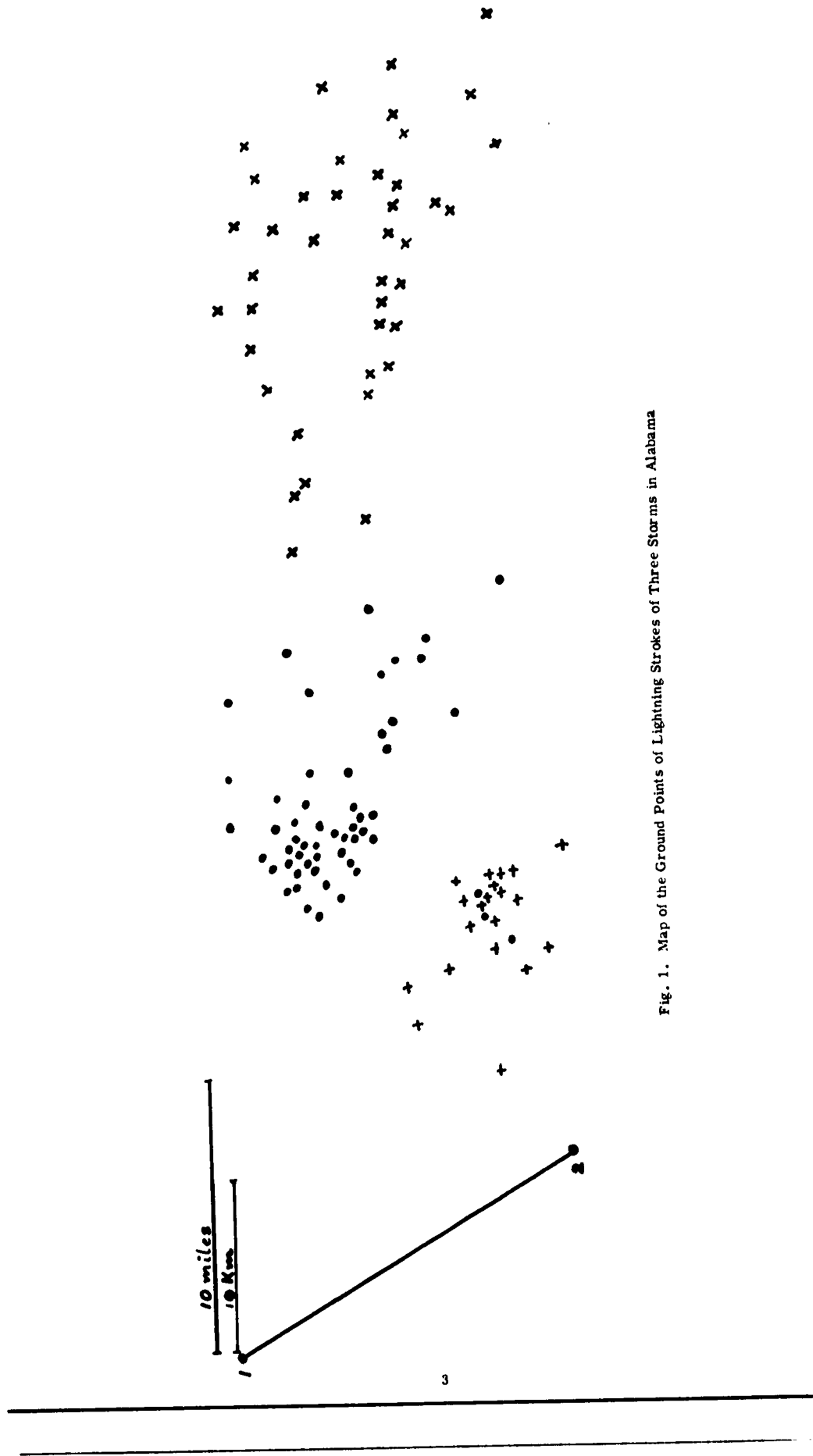


Fig. 1. Map of the Ground Points of Lightning Strokes of Three Storms in Alabama

In the last half hour of the second storm, the lightnings were concentrated in a smaller area, comparable in size to the area of the first storm. The third storm was also spread out over a larger ellipsoid-shaped area, with a small diameter of about 10 km and a large diameter of about 40 km. However, the distance of this storm from the observation points was already so great that small errors in the direction readings resulted in larger errors in the determination of the position of the lightnings. As the electric field records were also at the limit of detection, and details were often hard to decipher, this discussion is concerned with the first two storms.

Brook and Nitagawa³ defined two characteristic indices to describe different storms: 1) the activity index A , which gives the number of lightning strokes in a five-minute time interval; and 2) the intensity index I , which gives the average duration of the lightning strokes. With the subscripts 1 and 2 for the first and second storms. $A_1 = 4.75$ strokes/5 minutes, $A_2 = 5.05$ strokes/5 minutes, $I_1 = 0.35$ second, and $I_2 = 0.33$ second are obtained. It can be seen that both storms produced close to one lightning flash per minute, and also that in both storms the average duration of the strokes was almost the same. According to these indices, the storms would be labeled as weak storms of about the same activity and intensity. However, a closer analysis revealed that they were markedly different.

To show this clearly, a number of characteristic features of the lightning strokes are listed in Table 1. The first storm and the first and second parts of the second storm are indicated by the numbers 1, 2a, and 2b, respectively. From the second row it can be seen that the second storm had an overall duration of $34 + 40 = 74$ minutes, which is an unusually long lifetime. If the map did not show that the lightning strokes occurred in the same area, one would be inclined to assume that 2a and 2b were two separate storms.

Rows 3, 4, and 5 give the number of cloud strokes, ground strokes, and the ratio $g/c =$ ground to cloud strokes. Here, again, the difference between the two storms can be seen. The first one had an abundance of ground strokes with $g/c = 2.4$. The first part of the second storm had an abundance of cloud strokes with the ratio $g/c = 0.6$. In the second part, ground strokes prevailed again, with $g/c = 1.8$.

An even more striking difference existed in the number of partial discharges of the ground strokes and the duration of the predischARGE. The first storm had more than three partial discharges per stroke. In the first part of the second storm, all twelve ground strokes had only one partial discharge. These strokes were distinguished by unusually long predischarges, which lasted 0.44 second on the average. From row 9 it is seen that in the second part of storm 2 the ground strokes with one partial discharge had predischarges of a duration of 0.04 second; i.e., only 1/10 the value in 2a. This extraordinary feature will be explained later.

Table 1. Lightning Characteristics of Storms 1, 2a, and 2b

	Storm		
	1	2a	2b
1			
2 Duration of storm (minutes)	32	34	40
3 Number of cloud strokes	10	19	15
4 Number of ground strokes	24	12	27
5 Ground strokes/cloud strokes	2.4	0.6	1.8
6 Number of partial discharges	76	12	50
7 Number of partial discharges/strokes	3.2	1	1.9
8 $\frac{\text{Number of partial discharges - ground strokes}}{\text{Number of cloud strokes}}$	5.2	0	1.5
9 $\frac{\text{Duration of predischage}}{\text{Number of ground strokes}}$	0.07	0.44	0.04
10 $\frac{\text{Duration of predischage}}{\text{Number of ground strokes with one predischage}}$	0.32	0.44	0.07
11 $\frac{\text{Duration of predischage}}{\text{Number of ground strokes with two predischages}}$	0.01	-	0.01
12 $\frac{\text{Duration of predischage}}{\text{Number of ground strokes with three or more predischages}}$	0.01	-	0.04
13 $\overline{M}$ (A sec. km)	324	224	126

A few remarks are necessary about row 8, which gives the number of partial discharges (not counting the first one) in relation to the number of cloud strokes. It is suggested by Brook and Nitagawa³ that the number of partial discharges of a ground stroke is related to the number of preceding cloud strokes. The mechanism, as follows, is suggested: The cloud stroke leaves a pocket of negative charge in the cloud, which descends slowly with the precipitation into lower regions of the cloud. Three successive cloud strokes would form three negative-charge pockets, one below the other. The next ground stroke would tap these charge pockets with its successively higher reaching junction streamer and discharge them to the

ground as partial discharges. In effect, the negative-charge pockets would produce the partial discharges. If this is true, the number of partial discharges would be given by the number of preceding cloud strokes. In checking this relationship, the first partial discharge should be discounted because it is a necessity for the ground stroke regardless of whether or not cloud discharges preceded it. If n denotes the number of partial discharges, and c the number of preceding cloud strokes, then the equation $\frac{n-1}{c} = 1$ should be fulfilled if the above-outlined mechanism for the formation of partial discharges is correct. Row 8 shows this relationship for the two storms. It is fulfilled in neither case. Even if the first partial discharge is included, as Brook and Nitagawa propose, and the ratio of the number of partial discharges is built to the number of cloud strokes using rows 6 and 13, the result would be 7.6, 0.6, and 3.3 for storms 1, 2a, and 2b. In this case the correlation is even worse.

There are also two theoretical objections to this formation process of partial discharges. First, if a cloud stroke has occurred at a certain place, the electric field is weakened in this part of the cloud and it is most unlikely that the next cloud stroke would happen in this area. The displacement of the negative charge pocket of about 300 m downwards, as assumed by Brook and Nitagawa, would not be enough to restore the breakdown field in the region higher up. Secondly, the cloud stroke with its negative polarity has negative influence charge at the upper end and positive influence charge at the lower end.^{2, 4} The up-coming junction streamer of the next ground stroke, which carries positive influence charge, will not meet the negative charge pocket of the upper end, but the positive charge pocket of the lower end of the preceding cloud strokes, and avoid it instead of tapping it. The reason partial discharges are formed is that the ground stroke loses contact with the ground to a certain extent and takes on a potential different from ground potential during the junction-streamer process. If this potential difference reaches a certain level, the breakdown to the ground in the next partial discharge re-establishes ground connection again.²

Schonland⁵ found that lightnings with a small number of partial discharges are likely to form a tail that becomes weaker or absent with an increasing number of partial discharges. This observation could not be confirmed in these storms. In the first storm with an abundance of multiple strokes, 75 percent of the multiple strokes and 66 percent of the strokes with one partial discharge had a very distinctive tail. In the second storm there were periods when a tail was formed by strokes with one or more partial discharges, and other periods when the tail was missing on all ground strokes regardless of the number of partial discharges.

The last row indicates the average electric moment M in A sec km of the ground strokes of the specific storm for which the distance could be determined. These numbers show that the first storm had by far the strongest

lightning discharges, even if the intensity or activity index for both storms is almost the same.

Figure 2 is a graph of the field strength F ($\frac{V}{m}$) against the distance R (km). Data taken from the publication of Brook, Nitagawa, and Workman¹ are marked by dots, and data from the Alabama storms reported here are marked by crosses. These data supplement each other very nicely. The Texas data¹ cover the distances from 7 to 28 km and the Alabama data the distances from 26 to 90 km. The solid line is the best fit of a function $F = \frac{A}{r^3}$, where A has the value of 1.8×10^6 if r is measured in km and F in V/m. As $A = \frac{M}{4\pi\epsilon}$, M may be calculated and the average electric moment of a ground stroke obtained as 200 A sec km. If the average electric moment of storm 2 is built, using the numbers in row 13, weighted by the number of ground strokes in row 4, $M = 156$ A sec km is obtained. This shows that the second storm was about 25 percent below average and the first storm 60 percent above average.

Electric Field Patterns of Strokes with One Partial Discharge

The great variety of the electrostatic field patterns of lightning strokes is at first sight more confusing than enlightening. Nevertheless, if they can be interpreted, they bear much important information. It is very surprising to see that for a certain period the same pattern is repeated several times by successive strokes until a gradual or abrupt change occurs. This can usually be noticed only if one single storm is in progress at a time or if, by a direction-finding system, the lightning from several storms can be separated.

The most extraordinary field records of lightning strokes of the here-reported storms were these of strokes with only one partial discharge. In Fig. 3 the field pattern of these strokes is shown in chronological order. Additional information is given at the side of the field pattern. The first column number indicates the number of the stroke, the second number the time of occurrence, and the third number the distance from the recording station. Lightning No. 22 and 26 belong to the first storm, Nos. 31 to 45 to storm 2a, and 56 to 114 to storm 2b. A differentiation can be made between strokes with or without a long predischARGE, with or without tail, and with a positive or negative net field. It can be seen that the first nine strokes have long predischarges. This indicates that the leader does not come down nearly vertical to the ground, but travels a long way in a horizontal direction until finally the ground contact is made. This statement is supported by the fact that all these strokes with one partial discharge and a long predischARGE lay outside the core of the storm. On the map (Fig. 1) these strokes are the widely scattered dots mentioned before.

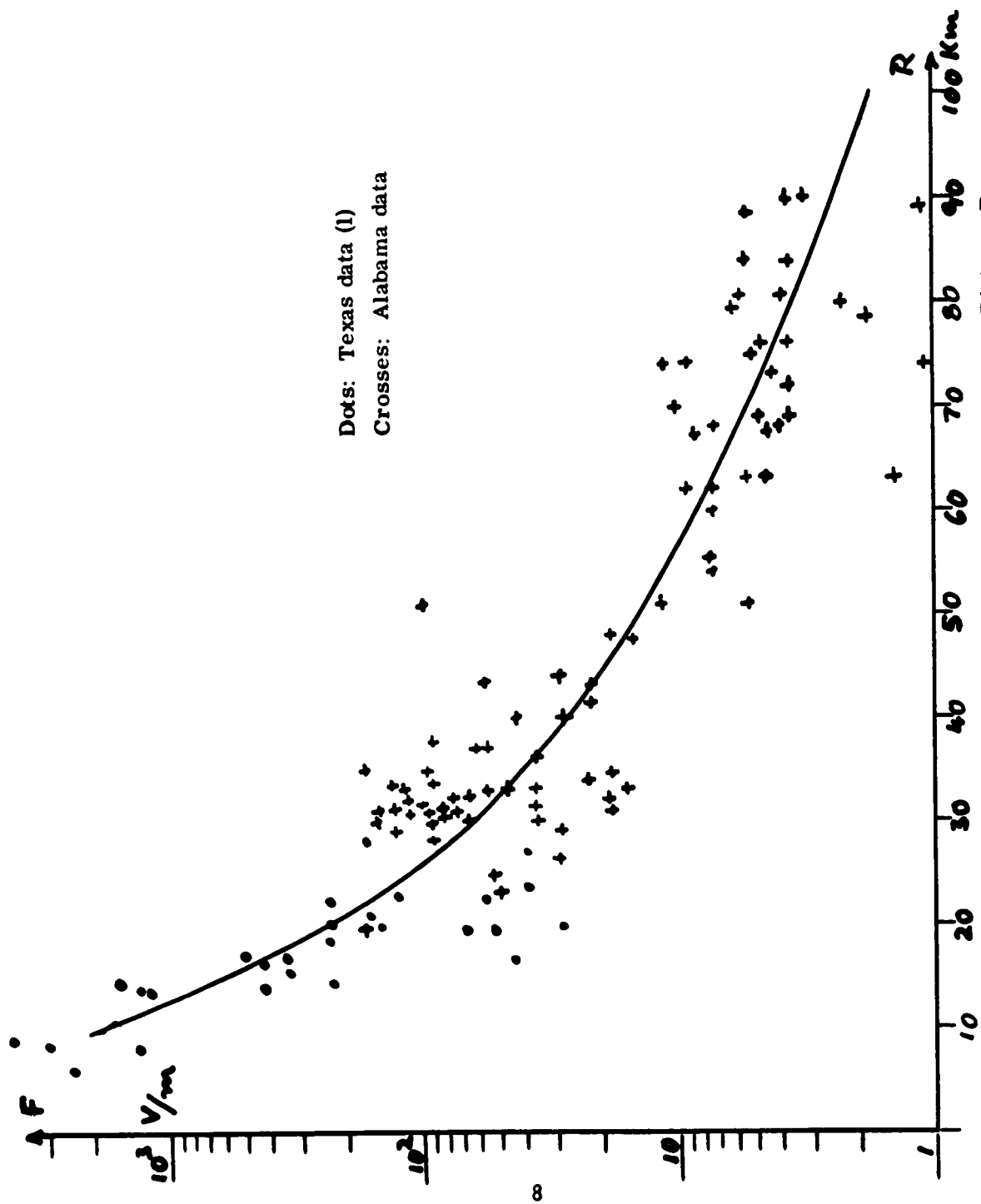


Fig. 2. Electric Field F of Lightning Strokes versus Distance R

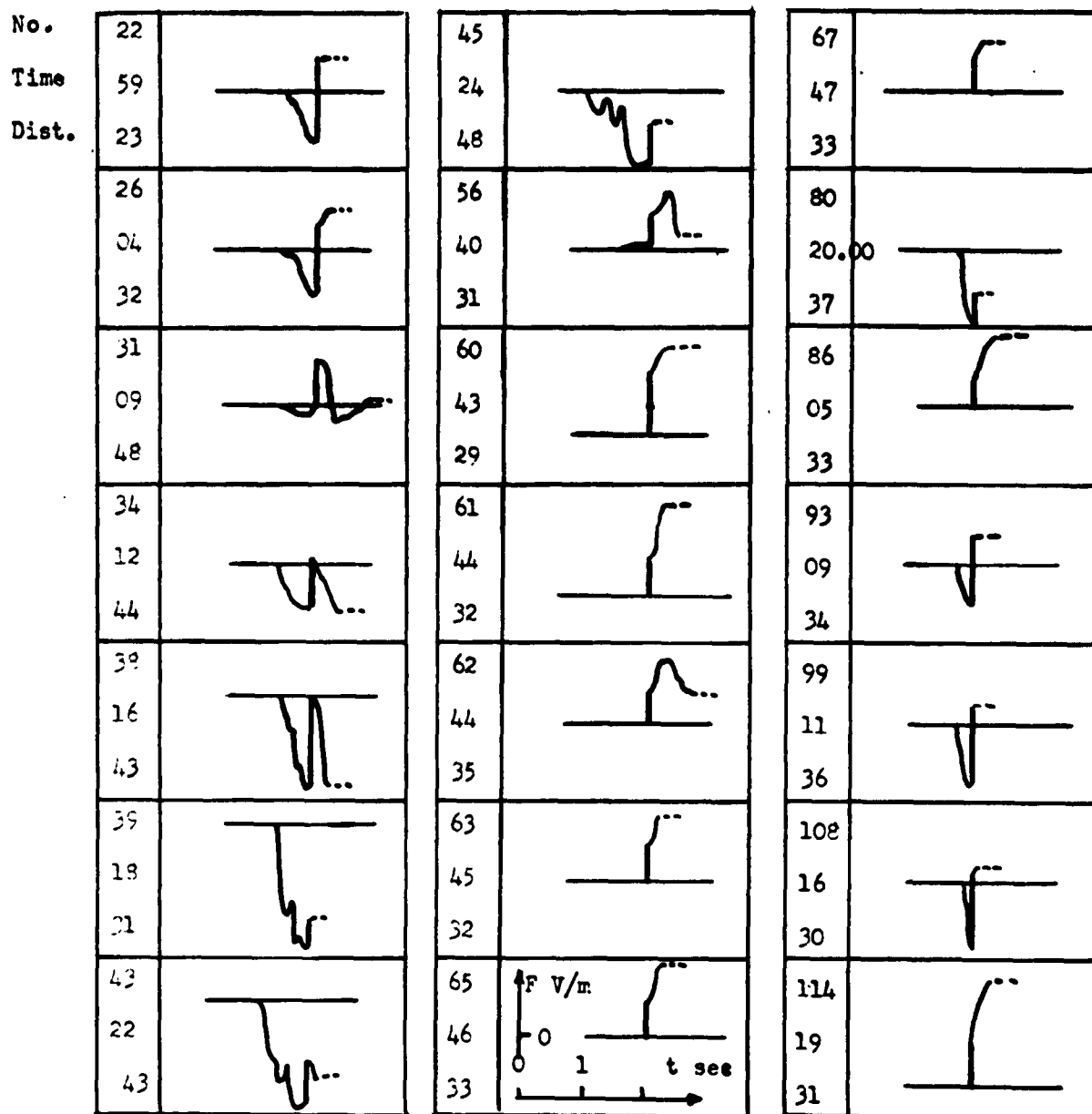


Fig. 3. Electric Field Pattern of Lightning Strokes with One Partial Discharge

It is interesting to see how the negative field of the predischARGE gets successively larger and larger from stroke No. 31 to stroke No. 45 until it out-weighs the positive field of the main stroke (heavy black line in the field curve of Fig. 3). This phenomenon has a number of consequences.

It is usually assumed that, in case of a negative predischARGE field and a positive main stroke field, this fact can be explained by the field reversal of a dipole. During the predischARGE, negative influence charge flows to the lower end of the channel, while the positive influence charge concentrates in the upper end. The field in an area with a radius of 7 to 10 km below the negative end of the lightning is determined by the negative charge. In contrast to the sign convention in physics, this field is called negative.

Outside this area the field is determined by the upper positive charge and will be positive. If contact with the ground is made, the negative influence charge will be discharged to ground and only the positive charge remains in the channel (or in the cloud). The field will then be positive everywhere. Therefore, if the field recording station is located inside the reversal area (distance from the lightning smaller than 10 km), a negative field of the predischARGE may be recorded, followed by a positive field of the main dischARGE.

This explanation cannot be applied to these cases because all strokes were far outside the reversal area, and for strokes Nos. 34 to 45 the final net field charge was negative in spite of a positive main stroke field.

The last point may bear an important conclusion. Investigators (including the author) have assumed that the sign of the charge brought down to earth by a ground stroke is given by the sign of the net field change. Strokes with a positive net field dischARGE negative charge to the ground, and strokes with a negative field dischARGE positive charge. That this does not have to be true in general can be deduced from the field records in the following way. It has been pointed out by the author ^{2,4} that the predischARGE and the main stroke of a ground dischARGE must be distinguished as two different kinds of dischARGE processes. In the predischARGE, a charge separation occurs under the influence of the cloud field. The positive and negative influence charge on the upper and lower end of the channel are of the same amount, and the net charge is zero. During the main stroke there is a genuine charging process of the lightning channel, whereby the charge is taken from the ground; its amount depends only on the potential difference between the lightning and the ground before contact is made and the capacity of the channel. The influence charge distribution on the channel of the predischARGE remains unaltered during the main stroke. The recorded field is a superposition of the predischARGE and the main stroke field. So, if there is a long predischARGE, as indicated by its long duration, a strong negative predischARGE field may be expected. If, in addition, the potential difference between the predischARGE and the ground is small, this will result in a weak positive

field of the main stroke. The net field will be negative. (See Nos. 39 and 43 in Fig. 3.) It is also very likely that these strokes have only one partial discharge, as was the case in these examples.

But in spite of the negative net field, the current, which flows during the main stroke, brings still negative charge to the ground. So the earlier statement that lightnings with a negative net field change bring positive charge to the ground is not true.

In general, the abundance of ground strokes generates positive net field changes and the exceptional ones with a negative field would have to be re-examined in regard to the current flow in their main strokes. It may develop that even a greater percentage, if not all, of the ground strokes carry negative charge to the ground regardless of their net field change.

The reason why a ground stroke with a negative predischARGE and a positive main stroke field may end with a negative net field change has been explained. Still to be answered is why a lightning stroke outside the reversal zone may have a negative predischARGE field.

The extent of the reversal zone is calculated under the assumption of a vertical lightning channel. There are two indications that this is not the case in these examples: first, the widely scattered locations of the ground points and, secondly, the long duration of the predischARGE. (It can be seen from the samples in Fig. 3 that none of the strokes with a short predischARGE--shorter than can be recorded by the slow paper speed that was used--has a negative net field change.) Under the condition of a largely horizontal predischARGE, the shape and the extent of the reversal zone are drastically altered. A strong negative field would be recorded at far greater distances than 10 km if the lower end of the predischARGE channel moves in a more horizontal direction towards the observation point, and the upper end, with the positive influence charge, moves away from it. It is the opinion of the author that most of the field reversals accredited to the reversal effect are caused by a shift of the lightning channel. This point could be easily cleared up by field recordings of two stations at opposite sides of the lightning stroke. Also, the influence of branches will modify the predischARGE field; otherwise the three reversal points in the predischARGE of stroke No. 45 could not be explained.

A most mysterious behavior occurred in the tail discharge of strokes 31, 34, 38, and 43. After a positive field change of the main stroke, the field change of the tail was negative. This result is very hard to fit into the picture of a weak but continuous current flow from the ground into the lightning channel during the tail discharge. It must be assumed that the direction of the current flow in the lightning channel cannot change in the different phases of the lightning stroke. This would mean that the lightning can grow into space-charge areas of opposite sign. It has been shown by the author²

that, for example, the upper part of the ground stroke is confined to the negative space charge area of the cloud. By an approach of the positive space-charge area, the field at the tip of the lightning would drop to zero and, even before that happened, the lightning would stop its growth in this direction.

So if the current flow in the channel cannot change its direction, the tail discharge current has the same direction as the current of the main stroke and brings charge of the same sign to the ground as the main stroke does. Consequently, the field generated by the tail discharge has to be of the same sign as that of the main stroke. But as the field records show, this is not true for many lightning discharges. Therefore the whole hypothesis must be abandoned. The generation of a negative tail discharge field after a positive main stroke field is possible only in a manner similar to the predischage process. To this effect the contact with the ground has to be interrupted; at least no appreciable amount of charge from the ground should flow into the channel. The lightning will grow at its upper end, and the negative charge pushed down along the channel by this process will be deposited in one or more of the lower branches. Thereby these branches may start to grow again. This will bring negative charge in the neighborhood of the observation point, and a negative field may be recorded during the tail discharge even after a positive main stroke field.

It is very well known that during the junction streamer the ground stroke loses its contact with the ground, otherwise multiple discharges would not be possible. Also, direct measurements of the lightning current point this way.⁵ Furthermore, the field of the junction streamer is sometimes of opposite sign as to that of the main stroke. Here the same reasoning as before on the tail discharge would apply, leading to the conclusion that the field change of the junction streamer is not due to a current flow from the ground, but is caused by displacement of charge in the lightning channel in a similar manner as by a predischage. If this hypothesis can be proved valid in general, it would lead to the following conclusion. If an attempt is made to calculate the amount of charge brought down to earth by a ground stroke from an electric field record, only the field generated by the different main strokes is taken into account, and field changes due to the predischage, the junction streamer, and the tail discharge are disregarded.

In contrast to this, the continuous luminosity and the sometimes appreciable field change of the junction streamer led Brook, Nitagawa, and Workman to the conclusion of long continuous currents during the junction process, which flow from the ground into the channel. The field change could be explained in the way outlined above, but the long-lasting luminosity points to a current flow. However, the strength of this current is difficult to estimate. So it will be best to keep an open mind to both possibilities. Probably both effects are present, and which one predominates is more the question.

Besides direct current measurements of the lightning discharges, which are always very difficult to achieve, there is one method to check this point; namely, the simultaneous measurement of the electric field at different places and measurement of the earth current. This would give the current flowing into the ground (or from the ground into the channel) and the accompanying field.

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