Duration of Lightning Strokes and Occurrence of Multiple Strokes

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Abstract

It is shown that the total duration of lightning strokes, the occurrence of multiple strokes and the time interval between them are partially influenced when measurements are made on direct strokes to tall objects. By recording the radiated electromagnetic field of lightning discharges in antenna circuits with cathode ray oscillographs at great distances from the lightning paths it was possible to obtain extensive data on the variation characteristics of lightning. Special methods were developed in order to analyse the lightning discharges with regard to the sequence of multiple strokes and the slow moving after-variation. A comparison of the discharge characteristics of lightning in Sweden with corresponding results from lower latitudes leads to the assumption that the intensity of thunderstorms is greater in low latitudes than in high latitudes. This involves researches of a geophysical problem of greatest interest from different points of view.

Introduction

During the decade before the second great war researches were carried out in several countries of the electrophysical conditions of lightning discharges. In many cases it was industrial electrotechnical enterprises which were responsible for this research work. Especially was this the case in the United States of America. As a matter of course the researches were to some extent carried out with reference to protective applications — hence directed on certain practical problems of lightning discharges. This did not prevent a more general treatment of the problem, which may be exemplified by the contents of a comprehensive article by WAGNER and MC CANN [1], entitled Lightning Phenomena. This article, which is of great interest from geophysical points of view, deals with results up to 1944.

As a result of the investigations described the authors consider certain characteristics of lightning that may be said to be quite definitely known. On the other hand, others are considered to be only partially answered.

To the first group they consider as solved the mechanism of the discharge, its polarity and its wave or impulse type. To the same group of solved problems they count the total duration of lightning discharges, the number of discharges in the lightning path and the time interval between them. Especially the three last mentioned characteristics of lightning discharges are of the greatest importance with regard to protective devices against lightning strokes. On the other hand, they are of the greatest interest from a purely electrophysical point of view.

Against the quoted authors' opinion that the last mentioned characteristics of lightning discharges have reached a definite and conclusive solution, I am of the opinion that the researches upon which the conclusions are founded must not be considered as definite.

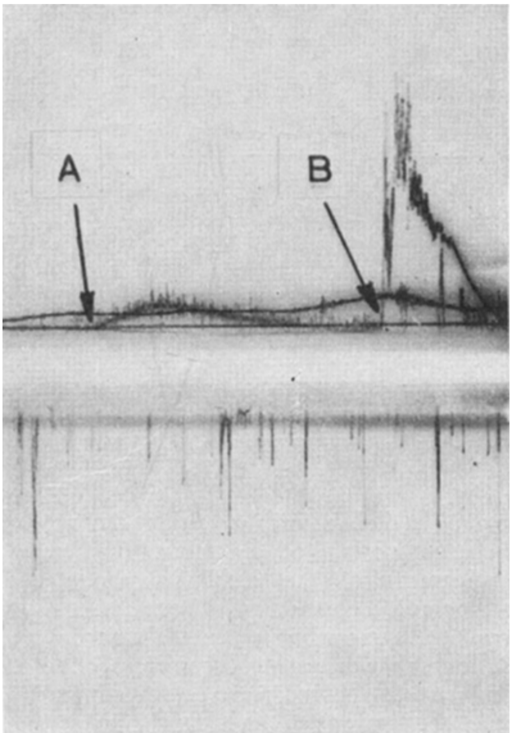

Fig. 1. Original cathode ray oscillogram of lightning discharge taken at the Uppsala Research Laboratory twenty years ago. The figure shows predischarges A—B and a steep, fronted main discharge with following multiple strokes.

The researches have not been carried out during such general conditions that we will be able to consider the results as valid for general discharges in open country topographical conditions. The reasons for this are evident. To a great extent the quoted results have been obtained through the study of lightning strokes to tall structures. In other cases the discharge intervals have been determined by photographic methods without any consideration of the influence of the after glowing by ionization in the lightning path. In as much as the equivalence between the discharge time interval as carried out by photographic methods, and the corresponding measurement by electromagnetic methods has not been proved, we must critically consider the former method. The weakest point of the results hitherto gained must be, as has already been pointed out, that the measurements have been made on strokes to tall structures. They produce very pronounced and local disturbances of the electromagnetic field from which must follow lightning discharge variations typical for such a structure but not for open field conditions. The above mentioned authors themselves remark that the quoted results from tall structures are debatable from the considered point of view. The tall structure exposed in the field of a thunderstorm cloud will cause that a greater volume of the cloud will be ionized as compared with field conditions on open and flat ground and hence cause a heavier current in the lightning paths. This involves both a greater number of partial discharges and increased duration. This is evident the more as some of the discussed measurements have been obtained by using discharges to an earth-connected captive balloon at heights of 500 to 800 metres which must introduce very pronounced local disturbances of the electromagnetic field. Similar disturbed field conditions even more difficult to overlook follow from results obtained by measuring lightning strokes to a sharp pointed peak of a mountain. Graphs illustrating the discussed results will be quoted further on.

Considering these limitations of the method of measuring lightning strokes to tall structures it is astonishing that a more safe and convenient method to measure lightning discharges has not been extensively tried. Such a method is at hand by using the radiation of the electromagnetic field from lightning discharges. In this case it is possible to operate with open or closed antenna circuit systems — a method that has been extensively applied at the Institute of High Tension Research. For further information about the principles of methods see the authors' article in this journal, vol. 1, no. 2, [2] and NORINDER-DAHLE [3].

The General Aspects of the Lightning Discharges as Investigated with Cathode Ray Oscillographs

Before going into the details of the variation features of lightning discharges it will be necessary to consider the three characteristic stages of the lightning discharges: a) the initial — or the predischarges with a total duration of up to 20.000 μsec.; b) the rapid main and partial discharges with a total duration of up to 2.000 μsec.; c) the slow moving after-variation process with a total duration of about 10.000 μsec. or occasionally longer. Very often we have observed that the total duration is shorter than the values mentioned above. With the mentioned values at hand we have to estimate the total duration of a lightning stroke procedure to be of the order of up to 0.03 second. It is not easy to record with an oscillograph these long time variation characteristics of a lightning discharge with a satisfactory resolving of the details. During our experiments in Sweden, started nearly thirty years ago, we used an open antenna circuit in combination with a cathode ray oscillograph with a rotating drum arrangement inside the vacuum tube. At an early stage of our researches these records of the variation feature of lightning discharges enabled us to discover the existence of the predischarges, their amplitudes and their duration. From the same records it was also possible to verify in a more definite manner our earlier discovery that the lightning discharges were aperiodic. Earlier it had been claimed that they were oscillating of a high frequency and sometimes as high values as 10^6 periods were supposed to be characteristic of a lightning discharge. In fig. 1 we reproduce an example of such an old record where the visible predischarges are marked between A—B.

Experimental Considerations when Measuring Variations of Lightning Discharges with New Arrangements

We were during these earlier experiments constrained to operate the drum in vacuum during a certain time period which necessitated that several consecutive discharges had to be recorded on the same oscillogram. This must cause a certain merging of the variation curves of the different discharges. This earlier problem of analysing the total variation traits of lightning discharges seemed of different reasons to be of important value. Hence quite recently a special arrangement was introduced in our cathode ray oscillographs in order to take up these older investigations in a modernized way. The cathode ray oscillographs were provided with a time base variation sweep of an axial length of 20 centimetres. With such a linear time circuit, sweeping several times above the long time axis, it was possible to

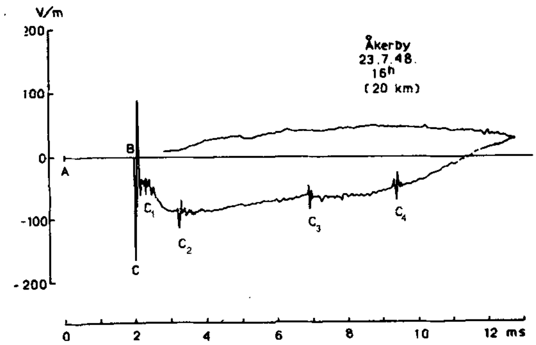

Fig. 2. Oscillogram of lightning discharge taken at one of the Institute's field station with recently developed recording device for long durations. Predischarges between A—B, main discharge at C followed by partial discharges from C_1 to C_4. Long after-variation.

obtain detailed records covering the whole discharge period of lightning. The relay arrangement of the author's cathode ray oscillograph construction (ACKERMANN [4]) prevented a recording when the cathode ray oscillograph was passing the regions of zero. This part of the recording is sometimes interpolated by dotted lines in the following curves of lightning discharges. The oscillograph, when operated with the long time axis, was connected to an open antenna circuit and the observations were taken with the E method which thus resulted in direct records of the field force in volts/meter. (See ref. [2]) Some results of such investigations are reproduced in fig. 2—6. The distances between the lightning paths and the observation stations vary between 18 to 40 km, and when possible to observe, these distances are given (in km) in the figures. A control that local influences did not affect the results was introduced by recording the discharges simultaneously on two stations at a distance of 18 km between them. This arrangement also made it occasionally possible to record the same lightning discharge at the two stations. As will be observed later on, the amplitude of the electric force of the predischarges of a lightning stroke is much smaller than the corresponding values of the main discharge. Hence it is not always possible to obtain a balance value in lightning discharges of the amplitudes mentioned such as can be recorded in full with a voltage sensibility of the oscillographs suitably fitted to one of the two amplitudes. Field variation curves drawn from an oscillogram taken with the method mentioned above at one of the field station of the Institute, Åkerby, at a distance from the lightning path of 20 km, is reproduced in fig. 2. The oscillogram does not show the predischarges, because they were too faintly

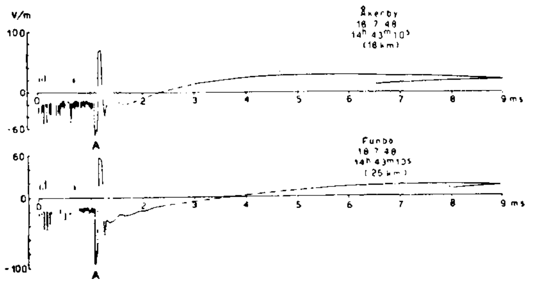

Fig. 3. Simultaneous records of lightning discharge from two field stations. Typical recorded predischarges before main discharge A. No partial discharges are following.

recorded. The predischarges were thus estimated to have a duration of 2 msec (milliseconds) marked A—B fig. 2. The main and partial discharges and the slow moving after-variation are reproduced from the original oscillogram. The predischarges are followed by the rapid main discharge C and first partial discharge at C_1. On the slow moving after-variation superimposed traces of subsequently occurring partial discharges are marked as C_2—C_4. The discharges in the lightning path which are carrying the heavy currents are evidently the ones marked with C and C_2 to C_4. Most frequently it is so that the greatest amplitudes are reached by the heavy current carrying discharges in the *first* lightning stroke. Sometimes we observe exceptions from this rule. See fig. 3, where simultaneous records from the two stations at a distance of 18 km apart are drawn. The typical predischarges with a duration of up to 1.1 msec are visible. The lightning is in this case characterized by only one main discharge marked with A and followed by a slow moving after-variation.

In fig. 4 oscillograms of three separate lightning paths with unipolar variation type are reproduced. We observe how variable are the durations of the partial discharges or multiple strokes. In A_1 and A_3 all partial discharges are concentrated within a time period shorter than a millisecond and in A_2 they extend over more than two milliseconds.

Oscillograms of two lightning paths ocurring within a short time interval and recorded on the two stations and characterized by multiple strokes are reproduced in fig. 5. How shifting the variation type of a lightning may be, is shown by a comparison of the simultaneous records of the oscillograms of the two stations in fig. 6 with the foregoing curves. In this, as in the foregoing cases with exception of fig. 3, the predischarges were developed with such a low amplitude that they failed to be recorded within the sensibility of the oscillographs used. Hence the time is marked to begin with the first main discharge A_1, which is followed by 6 discharges up to A_7, of which the third attains the highest amplitude. Later on some additional discharges are visible superimposed on the slow moving after-variation.

The typical after-variations of sometimes very long duration are caused by rapid dislocations of charges within those regions of the thunderstorm cloud which are taking part in the charge transportation by the main and the partial discharges. Hence this procedure is provoking slow moving after-variations within the regions of the thunderstorm cloud which are active in the transportation of charges by the lightning. If we suppose the transported charges to be distributed within homogeneous

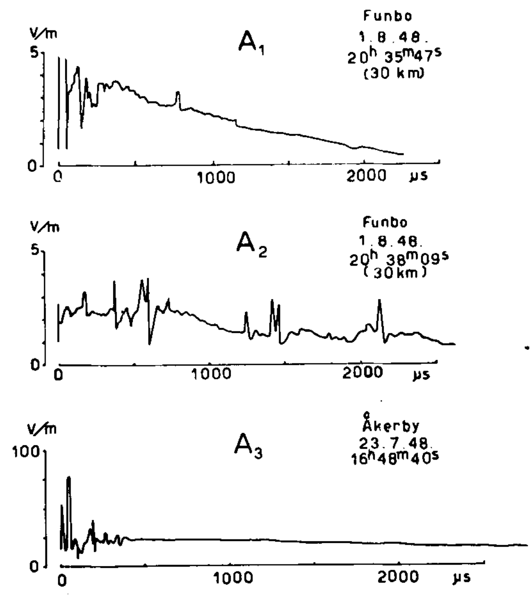

Fig. 4. Typical unipolar lightning discharges recorded from the Institute's field stations. Limited discharge time.

volumes of a sphere, a cylinder or a cone, it is rather easy to calculate the field changes and their polarity. The above mentioned variations of the thunderstorm fields have all been measured above open, flat extended surfaces. Thus local disturbances in the electric field conditions are eliminated.

If we, on the other hand, consider the corresponding variations when we are dealing with the field conditions in the vicinity of tall structures, other field variations are developed. As a prominent influence of the intensified field conditions in the vicinity of the tall structures, we have to expect both a lengthening of the time variation of the slow moving after-variation in the lightning discharge and also an intensification of the field charges. This will result in increasing values of the currents in main and partial discharges.

Results from Variations of Magnetic Field as Produced by Lightning Discharges

A typical consequence of such extended discharge periods in the lightning paths must be that transported electric charges, in the

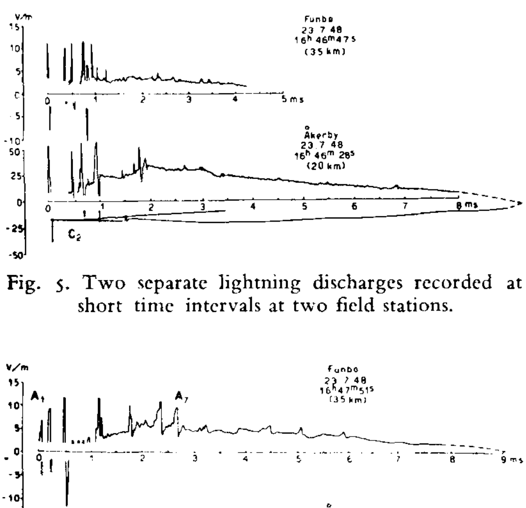

Fig. 5. Two separate lightning discharges recorded at short time intervals at two field stations.

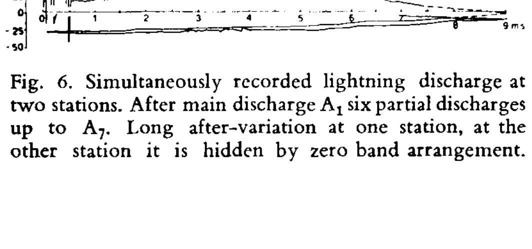

Fig. 6. Simultaneously recorded lightning discharge at two stations. After main discharge A_1 six partial discharges up to A_7. Long after-variation at one station, at the other station it is hidden by zero band arrangement.

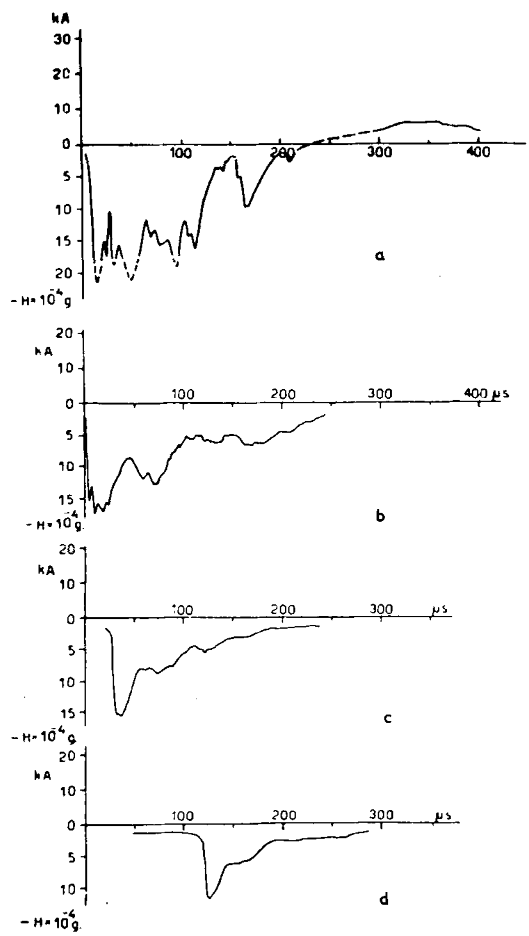

Fig. 7. Current variation diagrams of concecutive lightning strokes in same path. Typical diminuation of amplitudes from first occurring discharge. After ionization effects at c and especially d.

lightning attain very high values of the order of 100 coulombs or more. On the other hand, the author's measurements in open field conditions by using the electromagnetic frame aerial method (ref. [3]) resulted in values of up to 10 coulombs and only in some exceptional cases somewhat higher values. Accepting the transported high charge values, e.g. of the order of 100 coulombs, as generally valid also in lightning discharges under open field conditions one is led to field force values within the charge delivering thunderstorm cloud of quite another order of magnitude than the one generally accepted. This discrepancy is not eliminated by the absurd and against all experience contradictory explanation that the surface of the thunderstorm cloud which should be necessary to maintain a lightning discharge, must be 100 square kilometres.

The above mentioned tendency of the maximal current values of successive strokes in the same channel to decrease in most cases can easily be explained. The successive transportations of charges in the multiple strokes must diminish the available charge within the regions of the cloud which are active in the discharges. We have another way to check this typical decreasing tendency of the current intensity in lightning discharges. An extensive investigation of the variation of the magnetic field as caused by vertical lightning discharges has been carried out in Sweden (ref. [3]). Under certain conditions these researches have allowed a calculation of the current variation of successive discharges in the same lightning channel. The decreasing amplitude values are illustrated by fig. 7. In the vertical lightning from which the 4 discharges (a—d) have been oscillographed, they are evidently passing consecutively in the same path. Of special interest is that consecutive discharges in the lightning channel very often possess similar variation forms. From an electrophysical point of view this is quite easy to explain. The reason is that the transportation of the charges takes place in the same channel and hence is fed from the same ionized and active region of charges of the thunderstorm clouds. Worthy of note is the retardation of the steep front especially in d, where a weaker current amplitude precedes the rapidly increasing current front. Evidently this must be explained as being caused by a retention of the ionization from the foregoing discharge in the same channel. Very characteristic is the gradual diminuition of the amplitude of the consecutive current impulses and hence a diminuition of the transported charge. This is easily observed in the curves a — e of fig. 8, which represent the consecutive current discharges in another vertical lightning path.

Of special interest in this connection is the distribution of the total durations of main and partial discharges which constitute vertical lightning paths. Such an analysis has been carried out for 106 individual discharges in the above mentioned earlier investigation at the Institute of High Tension Research (ref. [3] and fig. 9). The real duration values are in this case insignificantly longer, depending on the fact that weaker parts of the recorded field force in the oscillographs are to some extent hidden by the zero-band of the instruments (ref. [4]). The most frequently occuring duration values are from 100 to 200 μsec. This is in full accordance with duration values that have been measured by quite another method (see fig. 2—6). In this case atmospherics were taken up by open antenna circuits. The duration of the rapid main and partial discharges was of the same order of magnitude in fig. 9. Duration values of up to 1000 μsec. are, as may be seen from fig. 9, very rare. It is of importance to keep the quoted duration values in mind when we have to deal with the problem of the total duration of lightning strokes.

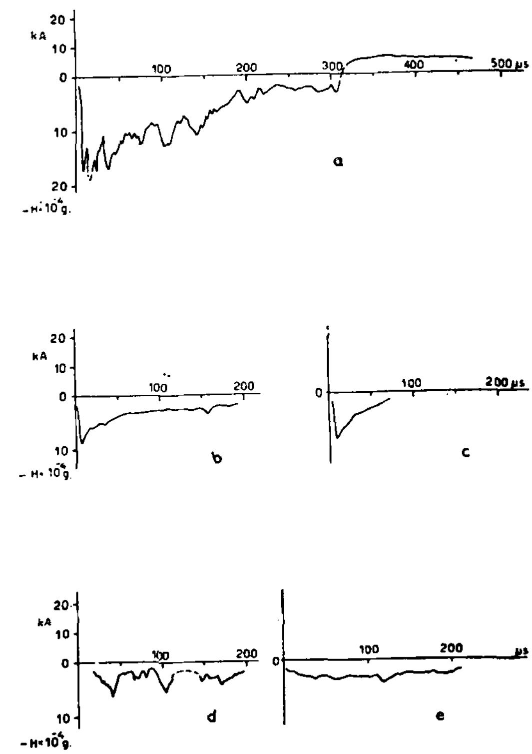

Fig. 8. Current variation diagrams of concecutive lightning strokes in same path. Typical diminuation of current amplitudes from first occurring discharge.

Investigations of Radiated Electromagnetic Field of Lightning as Necessary for Study of Variability of Discharges

The very pronounced variableness, which appears to be characteristic of lightning discharges, requires special precautions if we are trying to carry out a reliable statistical investigation. This must .be considered with regard as well to the duration of the discharges, as to the intervals between them and the total duration of lightning strokes. Evidently the primary condition must be to analyse by cathode ray oscillographic recording methods a sufficiently great number of individual lightning strokes. As we shall observe further on it is rather an easy task to obtain extended observations, especially if the researches are extended to include lightning discharges between clouds, and thus not only limited to vertical ones against the earth. In this connection we are able to use extensive experiences from another recent investigation not yet published. This one deals with thousands of oscillographic records of atmospherics taken during the thunderstorm season of 1949. The atmospherics were recorded simultaneously in Sweden with the aid of two stations at a distance of 576 kilometres apart. From this extended accumulation of recorded lightning discharges we are able to conclude that there is no pronounced difference in character, either with regard to duration of individua consecutive discharges in the lightning strokes, or with respect to time intervals between the discharges.

Some examples of typical consecutive lightning discharges recorded from separate lightning paths at one of the two mentioned stations at a distance of 576 km apart, are reproduced in fig. 10—11. In these cases the lightning discharges were located at a considerable distance from the recording station. This must to some extent have influenced the records by reflection effects from ionospheric layers. Such special influences will no tbe discussed in this article. From fig. 10—11, follows that consecutive discharges in the paths of the examples chosen do not show any appreciable differences in their variation character.

We therefore decided to carry out, during the latter part of the recent thunderstorm season of 1949 in Sweden, an extended analysis of the number of strokes, their total duration and the time interval between multiple discharges in the lightning strokes. For this pur-

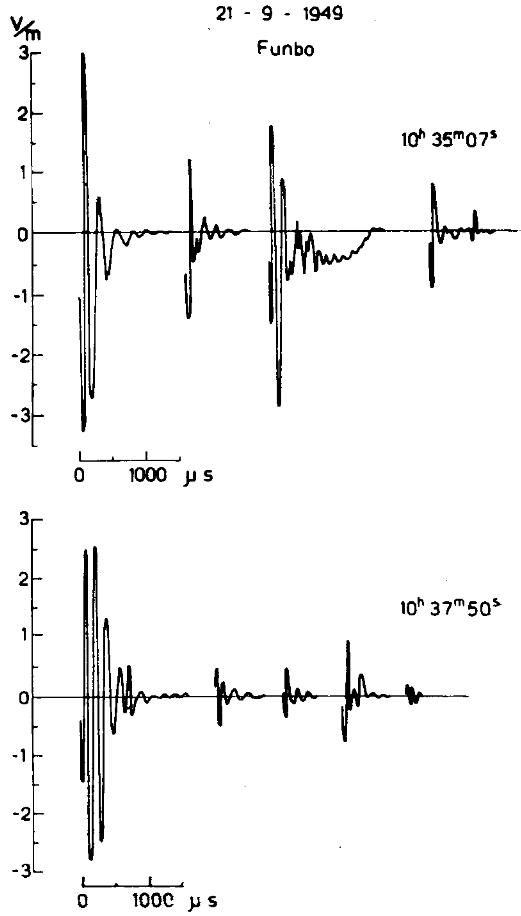

Fig. 10. Consecutive discharges in distant lightning channels recorded at the Institute's field station.

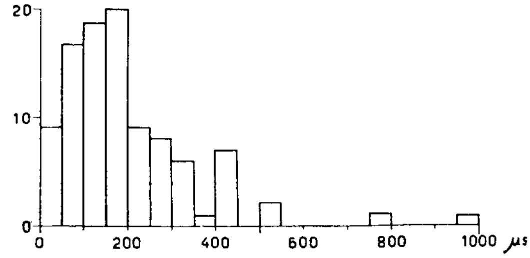

Fig. 9. Duration of currents of individual discharges of 106 vertical lightning discharges recorded at the Institute.

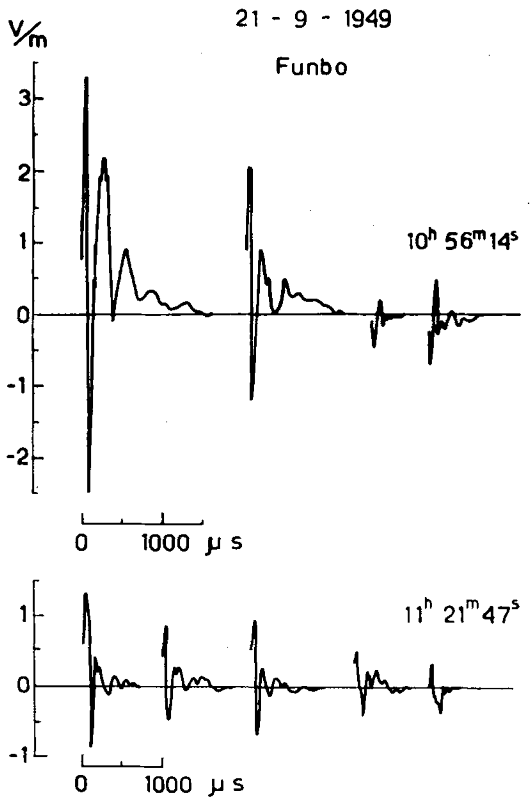

Fig. 11. Consecutive discharges in distant lightning channels recorded at the Institute's field station.

pose we chose a certain day, Oct. 20th 1949, when we had reason to expect only two regions of lightning storms in Sweden. They were situated at such great distances apart that the measurements did not become affected by local disturbances in the vicinity of the thunderstorm centres. The map of fig. 12 illustrates these centres where the filled circles represent damages by strokes to earth-connected structures, such as buildings, telephone lines or electric lines.

In order to measure the lightning discharges from the centres mentioned, an open antenna circuit in combination with a cathode ray oscillograph was used [2]. The method allowed records of the rapid variations of the vertical field force as produced by the lightning strokes from the thunderstorm centres. If the time-base circuit of the oscillograph was adjusted to a suitable time scale we could thus record that each rapid discharge in a lightning stroke — thus the consecutive multiple strokes — appeared as rapid vertical deviations from the zero line of the oscillograph. These vertical deviations were followed by traces of a damped after-variation with a gradually diminishing amplitude. The direction of decrease of this after-variation enabled us to determine the number of multiple strokes and the sequence of them. The records are of a similar type as the ones reproduced in fig. 10—11. From the above mentioned investigation of records of lightning discharges, simultaneously made at two stations far apart, followed that all lightning discharges of appreciable intensity passing in the channel of a lightning stroke, can be recorded provided the amplification of the oscillograph is increased to a sufficiently high level.

Hence, the described method should result in an extended analysis of the number of discharges in lightning strokes. It was also

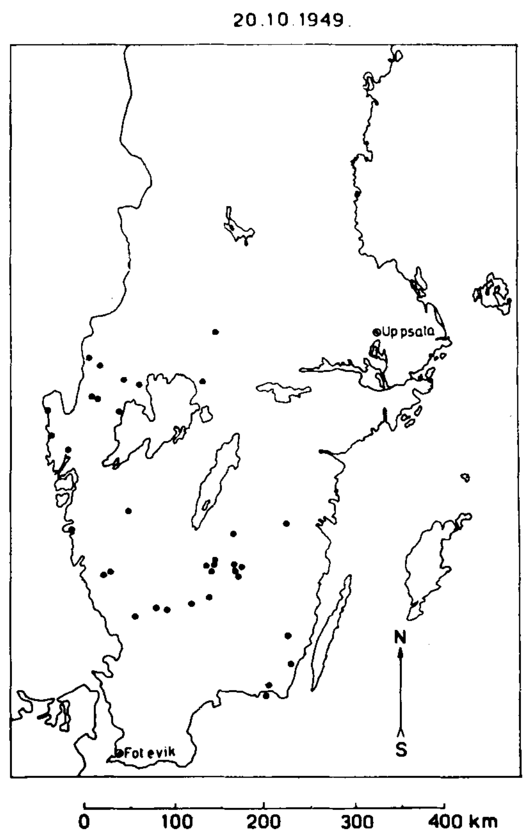

Fig. 12. Map of distant lightning discharges. Filled circles indicate damages of strokes to ground.

possible to analyse the time intervals between the multiple strokes and the total duration of lightning discharges. The total amount of separate lightning paths, recorded in the investigation, was 257. Of these only 57 consisted of one discharge in the path, 200 carried two or several discharges of which it was possible to measure 686. With the aid of these it was possible to determine 629 intervals.

The collected and analysed records allowed a calculation of the percentage number of multiple strokes reproduced in fig. 13. Evidently, the number carrying only one lightning discharge in the channel must in such a distribution become somewhat preponderant. In this connection it will be of special interest to compare the distribution with the number of strokes in 138 vertical lightning paths see

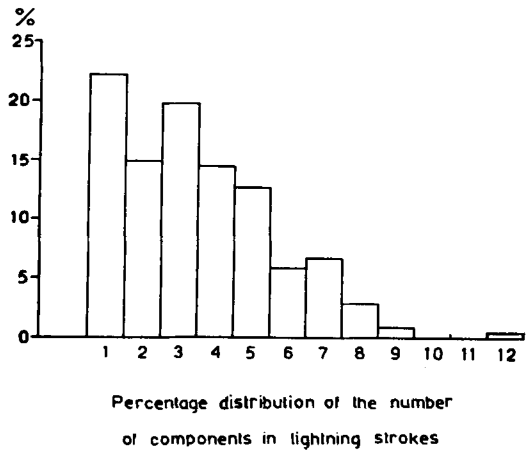

Fig. 13. Percentage distribution of number of components recorded from 257 separate lightning paths.

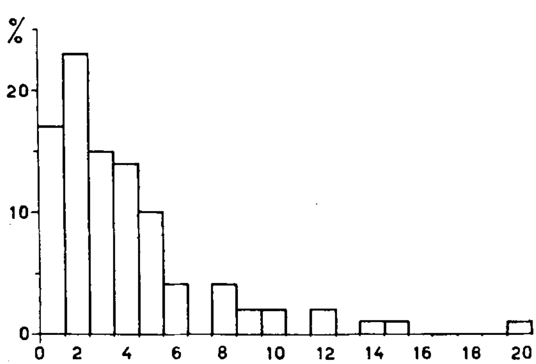

Fig. 14. Percentage distribution of number of components of 138 vertical lightning paths.

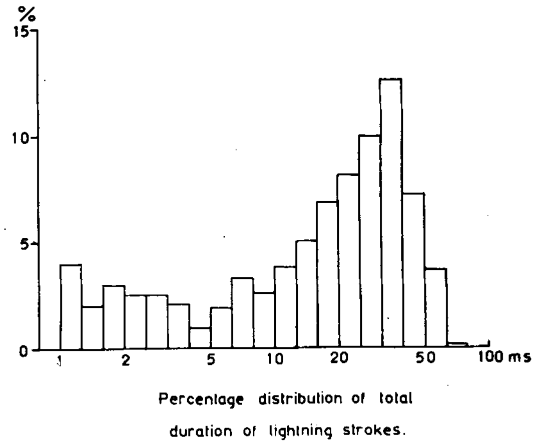

Fig. 15. Percentage distribution of total duration of 250 lightning strokes.

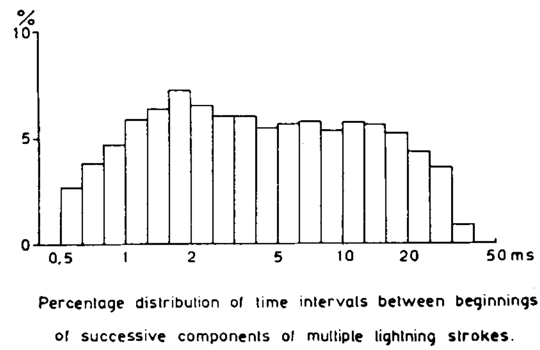

Fig. 16. Distribution of time intervals of successive components of multiple lightning strokes.

fig. 14. This distribution has been taken from an earlier investigation (ref. [3]). When we are considering the shifting variation features of lightning discharges in total we must accept that the distributions in the two cases show a surprisingly good conformity.

Multiple strokes in excess of four are less frequent than the range on four. This is easily accounted for, the more so as the charges of a thunderstorm cloud must be distinguished by a certain limitation. The active charges within the cloud transported by a lightning, can in some cases be diminished to an insignificent value by merely one or a few discharges. From this point of view it will indeed be of a special interest to compare the number of discharges in different types of thunderstorms. Especially a comparison of the conditions within thunderstorms in the temperate zones

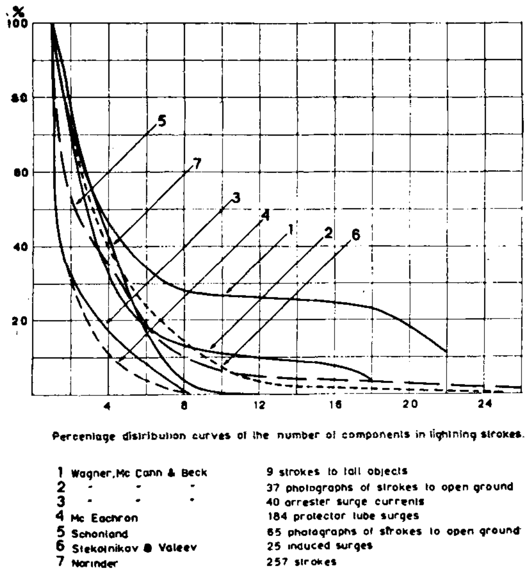

Fig. 17. Distribution of number of components in lightning strokes.

with those in the subtropical zones should be of great interest.

The percentage distribution of the total duration of the multiple discharges, carried out in a logarithmic scale, are reproduced in fig. 15. The most frequently occuring values are varying between 20—40 msec. A percentage comparison, of the durations of the intervals between multiple strokes in the same channel is reproduced in fig. 16. Evidently the duration of the intervals is evenly distributed on a logarithmic calc.

Comparison with Results concerning Duration and Variability of Lightning Discharges in Low Latitude Countries

It is of special interest to compare the results obtained by the investigation of the above mentioned 257 lightning strokes with values obtained by other methods and under different climatic conditions. In this respect it is simple to try a comparison with the data compiled by Wagner and Mc Cann [1]. There are several reasons for such a comparison. The compiled values have been gathered from ob-·ervations from different countries in the ·ld, all of them situated at much lower ·itudes than Sweden.

In order to carry out such a comparison the curves in the paper by Wagner and Mc Cann dealing with the number of multiple strokes, the percentage distribution of time intervals between strokes and the total durations have been redrawn and the recent swedish results have been entered in the redrawn curves. In the original curve systems the authors included some measurements from Sweden taken from my first observations of magnetic field variations from lightning strokes. In this case a differential method was used, which did not allow of a record of the slow moving after-variations of the current pulses. This outcome is quite contrary to the integral methods introduced in a later publication ref. [3]. The quoted older data do not quite correctly reproduce the time intervals between subsequent current pulses and hence they have been excluded from the new curve system of time intervals.

In fig. 17 the percentage number of components in lightning strokes is reproduced. The number of strokes from the Swedish material does not result in a distribution curve with such high values as are valid for strokes to tall objects. The curve obtained from our great number of observations represents a typical average picture and an extension of the obser-

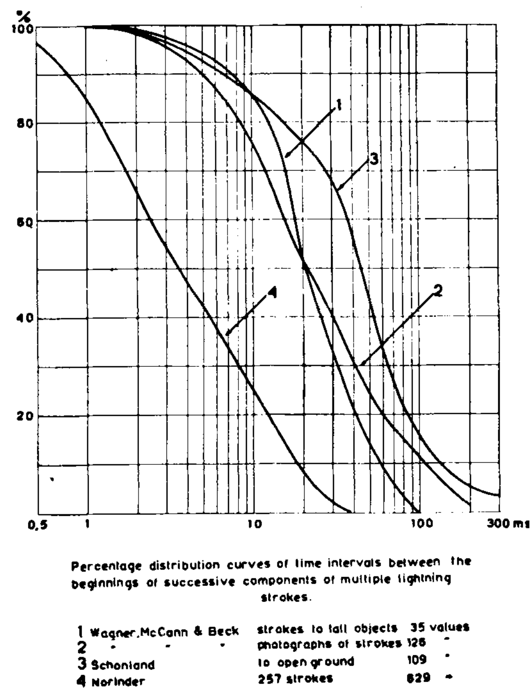

Fig. 18. Time intervals between successive components of multiple strokes.

vations will probably not alter this general character.

In fig. 18 is reproduced the percentage distribution curves of time intervals between the beginning of successive components. In this distribution the Swedish values [4] are of a pronounced shorter time variation type, and mostly approach to the curves 1 and 2. The values of 3, taken in South Africa, have pronounced time intervals of longer durations.

In fig. 19 the percentage distribution of durations of lightning strokes is reproduced. Also in this case there is a pronounced difference between the durations as measured in Sweden compared with those in countries situated at lower latitudes.

There is no doubt that the influence of the tall objects upon the results cannot be neglected when the lightning mechanism and especially the time variation character of lightning discharges are considered. The differences in the curves of fig. 19 are pronounced also when we are dealing with measurements where strokes to open ground are analysed. These differences must have another explanation. I am inclined to ascribe the differences to a certain extent to latitude effects, as indicated previously. I have not personally been in a position to investigate lightning discharges in countries situated at a more southerly latitude, but I have had many opportunities to observe thunderstorms visually in southern countries, both in Europe, Africa and North America. My personal impression is that the intensity of such thunderstorms at lower latitudes in most cases is at a much higher level than in Sweden.

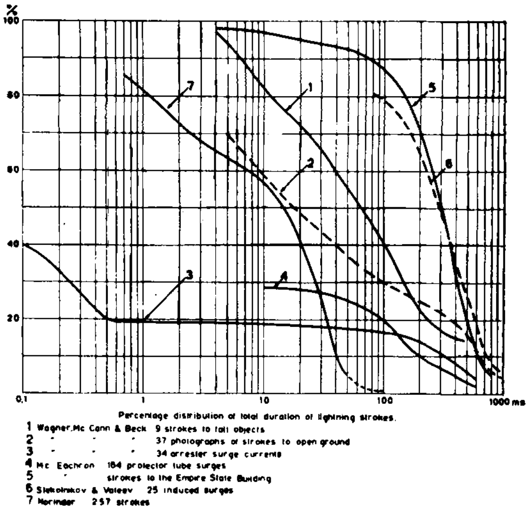

Fig. 19. Distribution of total duration of lightning strokes.

Characteristics of Lightning Discharges as Influenced by Latitude Differences of Thunderstorm Intensity

There are several groups of observations which in an evident way manifest that the thermodynamic intensity within thunderstorm clouds very often must be remarkably higher in low latitudes. From this it must follow that the amount of energy transformed into electic charges within the thunderstorms also must attain a higher intensity level. There is no doubt that this quality to some extent must guide to the physical explanation as to why both the lightning current intensity, the length of the intervals between multiple strokes and the total duration of the lightning strokes will sometimes result in marked differences when thunderstorms in higher and lower latitudes are compared. Obviously it should be of special interest to undertake a thorough investigation of this problem. The problem is of importance with regard to the propagation and transformation of atmospherics at long distances. Another aspect must be to what extent lightning currents to the earth are contributing to the maintenance of the negative charge of the earth.

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