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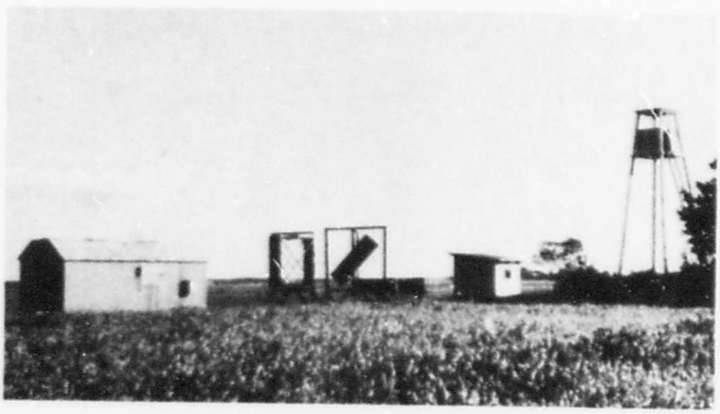
RESEARCH OF LIGHTNING DISCHARGES

Technical ~~Scientific~~ Report ~~No. 2~~



Magnetic Field Variations of Lightning

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Researches of Lightning Discharges

"Magnetic Field Variations of Lightning"

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Abstract.

The variations of the magnetic field from lightning discharges within the vicinity region, up to 20 km from the lightning paths, were investigated during the thunderstorm seasons of 1956-57 at four field stations outside Uppsala.

The stations were equipped with specially constructed recording cathode-ray oscillographs. In 1956 there were eleven cathode-ray oscillographs in operation and in 1957 twelve.

The oscillographs were connected over aperiodic amplifiers and integrating circuits to frame aerials shielded from the electric field components. The frame aerials were placed in horizontal, in forty-five degrees as well as in vertical direction to the earth's surface.

In combination with records from the cathode-ray oscillographs devices for daylight photographs of the lightning paths were simultaneously operated. During the thunderstorm seasons of 1956-57 it was possible to obtain with the new method 146 photographs from lightning paths in daylight.

A description of instrumental equipment, field stations, and investigation methods is given.

A special investigation procedure was developed for analyses of the lightning discharge mechanism in consideration mainly of the change and development of the paths or channels in lightning discharges. In these investigations simultaneous photographs of the lightning paths in combination with oscillograms showed to be of the highest value. An onward development of the new method is considered.

The change in the magnetic field variation with the distance from the lightning path was discussed. The interesting results required a continuation by simultaneous oscillographic analyses from some stations located at greater distances than within the sensitivity range of the network of the stations now used.

A statistical analysis of front variations and time intervals between multiple strokes was carried out. The results were limited to available data for 1956.

Different aspects of daylight photographs were discussed In one case it was possible to obtain a special daylight pho-

tograph of a vertical lightning path in the sensitivity range of the network of the stations. The recorded lightning discharge ignited a cowshed. From simultaneous oscillograms it was possible to analyse the variation feature and value of the igniting current which attained 50 kiloamperes and had a duration of 1000 microseconds.

A survey of the obtained research material and its treatment was presented during the contract period. The 1956 thunderstorm season was characterized by a much smaller number of suitable observations and oscillographic records than the following one. From the accomplishment of the contract at the very end of the thunderstorm season of 1957 followed that the very comprehensive material of this season had not yet been treated. Only some short transitory views and results have been mentioned in this report.

Table of contents.

1. Introduction.

Analysis of the discharge mechanism of lightning can only be carried out in the vicinity region of the lightning paths. From this it follows that investigations must involve considerable experimental difficulties. They require a number of outside arrangements in the form of suitably located field stations, equipped with aerials that capture as exactly as possible the electro-magnetic variations of the lightning discharges. The stations must be equipped with a large number of instruments, in the first place self-recording cathode-ray oscillographs, amplifiers and time circuits. Operation of the stations requires connection to a local electric power supply. The chief purpose of the investigations must be an analysis of the processes of the discharges for lightning in the vicinity of the field stations. It is in the nature of things that the local power supply will often be subjected to surges and interruptions due to the lightning discharges in the vicinity, and therefore provision must also be made for the field stations to receive reserve power from their own gasoline driven AC generators.

One troublesome circumstance is due to the pure chance occurrence of thunderstorms in the measurement areas suitably located for investigation purposes. It is found that the number of lightning discharges especially favourable for analysis may fluctuate considerably from one thunderstorm season to the next. Therefore, in order to ensure the greatest possible results during a thunderstorm season, great demands have to be imposed on the personnel charged with the operating of the field stations. Likewise the instrumental equipment must be kept well trimmed, in view of the fact that the loss of a thunderstorm suitable for measuring represents an appreciable loss of investment as regards both equipment and personnel.

A special difficulty is to be found in the short duration of the thunderstorm seasons. For only a few months, therefore, there must be engaged alongside those permanently employed for the research work a large number of temporary assistants, who have to be quickly trained in the operative work at the field stations.

What is stated above has charecterized the earlier investigations of discharge properties of lightning in the vicinity region that were made possible owing to special support. This was arranged through the European Office, Geophysics Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, United States Air Force, Brussels. A contract No. AF 61(514)-636-C was concluded with the University of Uppsala for these researches. The results of this contract have been set out in an earlier Technical Scientific Report No. 1, see /1/ in the list of referencies. This report is abbreviated below to TSR 1. Here there will be presented a report covering a continuation of the investigations during the thunderstorm seasons of 1956 and 1957, which were supported by contract No. AF 61(514)-943 between the United States Air Force, European Office, Brussels, Air Research and Development Command, and the University of Uppsala.

What is stated as characterizing the earlier investigations also applies to those last carried out, which are covered by the present account.

That the mechanism of lightning discharges was found to be extremely complicated was already apparent from the results given in the earlier account in TSR 1, and this has been confirmed in all respects by the subsequent investigations. From the experience gained in the investigations now reported there likewise stand out the evident advantages of the analysis method for the lightning discharges adapted in the earlier investigations. This consisted of an investigation of the lightning's discharge mechanism by means of the variations produced by the lightning in the magnetic field.

The strength of this method of investigation lay, among other things, in the fact that it was based on the relation between the lightning current's variations and the corresponding variations in the magnetic field generated around the lightning path. If the distance between the lightning path and the place of observation of the magnetic field variations is known, it is found, as may be seen from what follows, to be possible within some distance ranges to determine with good approximation the current intensity in the lightning path.

A particular advantage with the magnetic field measurement method is provided also by its giving field intensities which, because of the frames, are fixed in direction along the plane of the frames. This is not least important in connection with a special extension and improvement of the analysis methods, which has already been announced in TSR 1. The method is based on simultaneous photographing of the variations of the lightning discharges analysed by the cathode-ray oscillographs. This combination of simultaneous photographing and analysing oscillographically the lightning discharges has been found to give valuable results, and efforts have therefore been made to develop and improve this method of analysis still further.

2. Instrumental equipment.

The instrumental equipment employed during the thunderstorm seasons of 1956-57 was more or less the same as that already described in TSR 1, attention to which is directed. In the present work only some extensions and improvements will be described.

In the earlier description of equipment it was stressed that the frequency range for the amplifiers used in the measurements should, if possible, be changed to a lower frequency, and this was done at the beginning of 1956. In this way there was attained full linearity with a lowest frequency of 5 cycles/second. The polarity change previously found, for which correction had to be computed, has entirely disappeared from the records thanks to the alteration of the amplifier.

It was of interest to analyse more closely the rapid variations in both the pre-discharges and the main discharges with a view to comparing the figures with the results obtained earlier. A special cathode-ray modulator, multi-vibrator coupled, which gave a strong intensity on the recording cathode-ray oscillogram for about 50 μsec has been designed and has provided facilities for studies in detail.

In the TSR 1 report referred to above, it was shown that the newly designed device for daylight photography of lightning paths offered great possibilities of development. Right from the first trials a certain amount of experience was gained of the ways in which the release devices for the camera shutters might be improved. It was found in the first trials of the device that some photographs of the lightning were lost. This was due to the operator in some situations finding difficulty in aiming the camera at the region of the thundercloud which was emitting lightning discharges. And this was mainly due to the angle range of the camera being too restricted. The difficulty has been overcome by setting up two cameras at a given angle to each other and with separate releases. In Fig. 1 there may be seen such an arrangement of two cameras with mechanical release devices. Beside the cameras may be seen the thyratron circuit through which the releases of the cameras are triggered. The electronic circuit for triggering was also improved with the object of ensuring greater reliability, simpler adjustment, and quicker mechanical release.

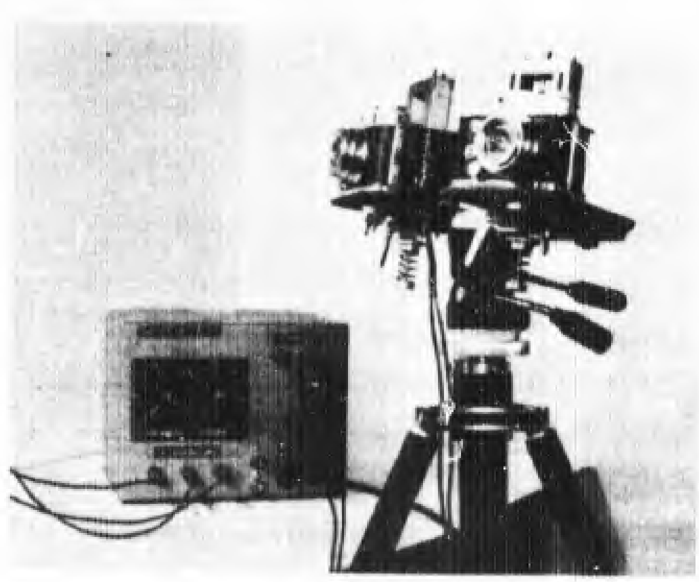


Fig. 1. Improved photographic device with two cameras and electronic circuit constructed at the Institute for daylight photographs of lightning paths.

It was found desirable to achieve the shortest release times possible. On the other hand, it was necessary to compromise between quick release and mechanical stability. If fine adjustment were carried too far it immediately brought about a certain amount of instability. The time delay from the start of the impulse until the camera began to be released amounted to 1-3 milliseconds (msec), and the actual release time for the camera could be brought down to app. 8 msec, that is a total release time of app. 10 msec. This release time was found to be sufficiently short. This was evidenced by a large number of photographs which were taken of lightning paths with pre-discharges and which consisted of only one main discharge. In conjunction with the employment of the photographic method it was found necessary, by marking of time on the oscillograph's moving film, to introduce a time recording controlled by the camera's photographic release.

To facilitate communication regarding time between the outdoor observer and the photographer magnetic tape recorders were introduced during the 1957 thunderstorm season. This method carried with it two other advantages, it was possible to obtain on the magnetic tape both marking of the time difference between lightning discharge and thundering and also the variation forms for the thundering.

In the earlier investigations, the magnetic field variations of the lightning had been measured with both mobile vertical frames and fixed horizontal frames. As the latter were found to be particularly sensitive to horizontal components from streamers, characterized by sloping directions to the earth's surface, there were introduced in 1956 mobile frames at an inclination of 45^o to the horizontal plane. These were set up at the stations at Åkerby and Husbyborg. The special employment of these frames will be referred to in another connection.

3. Field stations.

The same field stations as were used in the investigations of 1955 and which are pictured and described in TSR 1 were also used during the 1956 thunderstorm season. The relative positions may be seen on Fig. 2 of the three stations,

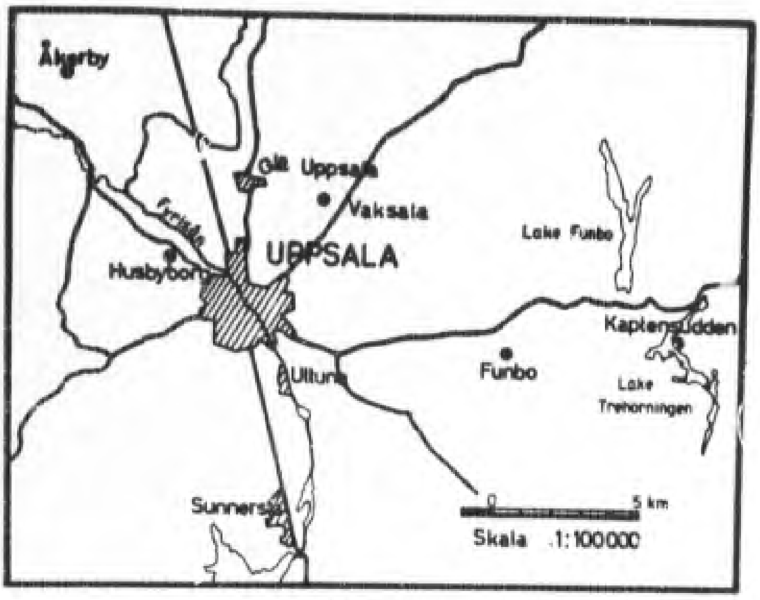


Fig. 2. Sketch map of field stations in the vicinity of Uppsala.

Åkerby, Husbyborg, and Funbo. The great distance between Åkerby and Funbo was in the first place due to a special investigation. The purpose of this was to determine whether the magnetic field intensities from lightning discharges underwent certain changes in variation form with the distance. A number of recordings showing some changes of this kind were made in the 1956 thunderstorm season.

With the object of obtaining if possible simultaneous photographic results of lightning paths from two stations, it was necessary to move the three stations so that they were nearer to each other. With this view the station at Åkerby was moved before the 1957 thunderstorm season to a place named Vaksala, the other two stations were retained, and the network of stations thus consisted of the stations Husbyborg, Vaksala, and Funbo. See Fig. 2.

Fig. 3 shows a picture of the station at Vaksala, which it was possible to locate in a free and open position.

It was desirable to obtain as far as possible free and open fields of vision to provide for photography in daylight of lightning paths. With this object, towers about 10 metres high were constructed for the stations at Funbo and Vaksala. On the upper platforms of these the photographic equipment was placed. To guard against the danger of lightning strokes the towers were furnished with lightning conductors. A tower

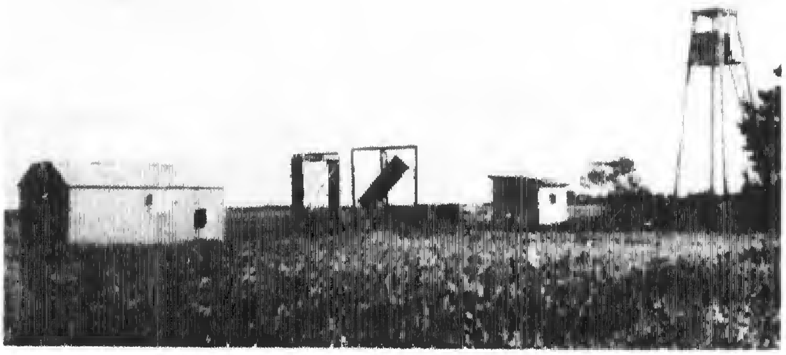


Fig. 3. Field station at Vaksala set up in 1957.

of the type described, that for the Vaksala station, is visible on Fig. 3. It was possible to make use of an existing tower belonging to the Swedish Defence Forces for the Husbyborg station.

4. Investigation methods.

In the investigations of 1956 and 1957, as in earlier investigations, there was employed the specially developed method for measurement of the magnetic field's variations which is designated the H method and by which the field intensity H was measured.

Previously it was the changes in the electro-magnetic field produced by the lightning in the vicinity region that were measured by means of the electric component of the field variation, the E method. The extensive simultaneous measurements /2/ which were made with this method furnished in themselves interesting results as regards field changes, but they had an obvious limitation, especially where the vicinity region was concerned. It turned out that the E method was particularly sensitive to local disturbances. Moreover, the measurement results did not give the explicitness which was desirable. At greater distances from the lightning paths, on the other hand, the E method proved to be especially suitable, in view of the smaller demand in respect of amplification.

The main reason for deciding to employ the H method was, in the first place, as already stressed, the relation between the magnetic field variations and current intensity variations in the lightning path. In this case it was not only the question of the current intensity variations in the main and the partial discharges in the lightning path. It was just as much the question of the current intensity changes in the pre-discharges which were particularly important for estimating the discharge process.

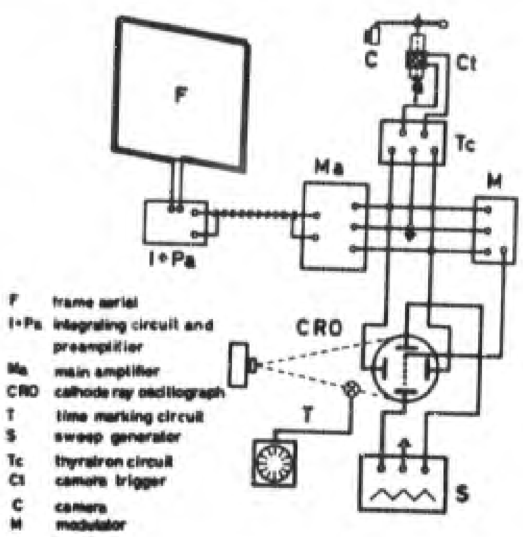


Fig. 4. Measuring principle of frame aerial method in combination with cathode-ray oscillographs, photographic cameras and time-marking system.

The principle of the H method, published earlier /3/, is shown in Fig. 4. The frame aerial F captures the magnetic field variations. Owing to a specially designed screening device the few winding turns of the frame are protected from the action of the electric field components in the discharge process. The magnetic field variations captured in the frame aerial circuit pass through a suitably adapted resistance, and they must consequently represent the first derivative of the magnetic field variation or dH/dt. Where it is a matter of investigation of the variation structure of the rapid field variations a recording by the dH/dt method with cathode-ray oscillographs furnishes very serviceable results. This applies particularly to investigations of variations of the front in the magnetic field intensities. The method has been used with advantage in earlier investigations. It is of course possible though tedious to integrate the recorded dH/dt curves. To avoid this, the frame system has been provided with an integrating circuit, which is strengthened in a pre-amplifier, marked Pa in Fig. 4. This is placed close to the frame aerial. By means of a coaxial cable the integrating tensions are transmitted to the main amplifier, Ma, which is located in the field station building, in which the recording oscillographs and the auxiliary equipment are located. The RC-coupled main amplifier has a frequency response from 5 kc up to 100 kc/sec. The gain is adjusted in five steps from 10^2 to 10^4

The outgoing cable system from the main amplifier steers three circuits: the cathode-ray modulator, M, the deviation plates of the CRO tubes and the thyratron circuit, Tc, of the cameras. The trigger of the cameras, Ct, operates the mechanical release of the cameras for photographic exposures of the lightning paths.

The time-sweeping generator, S, is of triangular, linear type. This is necessary in order to facilitate computing of the recording curves. The generator is common for the cathode-ray oscillographs operating in one and the same station on different frame aerial systems. This procedure is extremely convenient for the analysis of the curves.

The time recording system, T, is common to all the oscillographs which are operating at a field station. The system consists of a clock synchronised by the Swedish 50 cycle AC mains. By employing the same type of synchronous clock at all stations there is ensured a cheap and reliable time synchronisation for all stations operating simultaneously. In the event one of the stations is subjected to interruption of the AC system, the time recording is temporarily ensured by a locally driven emergency clock.

For the computation of current variations in the lightning path it is only possible, as shown in another connection, to make use of magnetic field variations for lightning discharges at distances up to approximately 15 kilometres distance from the recording station. This means a limitation of the material available for current intensity measurements. On the other hand, the recordings outside the limit given are of particular interest in judging the influence of the second term in the expansion equation. With regard to the distance from the lightning this is dealt with more particularly in another connection.

In the course of 1955 there were carried out a few preliminary attempts at photographing the lightning paths in daylight at the same time as an oscillographic analysis of the magnetic field intensity variations of the lightning. Continued experiments with the combined method furnished such valuable results in the 1956 thunderstorm season that the method was further developed and applied in the 1957 thunderstorm season. In 1956 there were 11 cathode-ray oscillographs and two photographic camera equipments in operation, and in 1957 we had 12 cathode-ray oscillographs and 3 photographic camera equipments. The results with the photographic method could be still further improved by means of the above-stated location of the cameras in special towers.

The number of oscillograms for individual lightning discharges recorded by the cathode-ray oscillographs during a thunderstorm season amounts to many thousands. Of these it has been possible to completely analyse only a reduced number. Nevertheless, a large number of the oscillograms excluded from complete analysis may be employed for statistical treatment. In this respect a very large number of recorded curves is available. With the aid of a harmonic analysator procured for the purpose the curve material will be analysed in respect of superposed rapid variations.

The most important reason for a more comprehensive analysis of the oscillograms not being possible was lack of information regarding the distance of the lightning paths from the recording stations. Improvement in this respect has occurred since the photographic method with simultaneous observation from a tower was introduced. By means of magnetic tape recording of the time between the strokes and the following thundering the throwing out of oscillograms suitable for treatment has been still further reduced.

A still further improvement in this respect is both important and necessary. It must be based on entirely new methods which, in the event resources for the experiments are at disposal, should be included in a new and expanded investigation programme.

5. General remarks.

The investigations of the discharge mechanism of lightning continued during the thunderstorm seasons of 1956-57 have shown still more complicated discharge processes than had previously been found. This stands out from different examples given below. It is obvious that the complicated nature of a lightning discharge involves considerable difficulty for an experimental investigation.

Even the initial process of the lightning discharge - the pre-discharge - has been found to be very much more extended in respect of time than was previously found. This is due to the fact that the pre-discharge must mainly take place inside the thundercloud, where one has to reckon on slow ionisation processes. This requires pre-discharge times of hundreds of milliseconds or msec.

After the pre-discharge has left the cloud, durations of some hundreds of msec are reckoned for it. In contrast to these slow times for the pre-discharge processes we have the discharge times for both the first lightning, or the main discharge, and for the succeeding partial discharges or multiple strokes. In these the current attains its maximum or crest value in the course of a few microseconds or µsec while the diminution of the current down to its zero value is a matter of a few hundred µsec as a rule.

The time intervals between the multiple lightning strokes are something between a few tens and a few hundreds milliseconds.

As a rule, the pre-discharge process has very low current values compared with the subsequent main and partial lightning discharges. There are exceptions: cases arise where the current amplitude of the pre-discharges is as high or even higher than the subsequent lightning discharges.

It can easily be realized what experimental difficulties must be involved in reproducing by means of cathode-ray oscillographic measurement methods these processes, which are fluctuating both in respect of time durations and of amplitude figures. It is obvious that a single oscillograph, in view of its restricted sweeping time basis and its limited recording facilities for fluctuating amplitudes, cannot reproduce several phases or even only a few phases in the fluctuating and complicated discharge process.

It is perhaps mainly this difficulty in principle that has so long prevented the discharge phases of the lightning from receiving a complete analysis. Numerous investigators have contented themselves with analysing the lightning discharges by means of one oscillograph only. What the result of such a procedure may be is obvious.

From what has been stated, it follows that an exhaustive analysis of the complicated discharge process requires a number of simultaneously recording oscillographs. These should be installed both for different sweeping times and for different amplitude sensitivities. It is this principle regarding investigation method which prevailed both in our earlier investigations and in that presented here.

One can readily understand that great demands must be imposed on the trimming of the instrumental equipment, it should record perfectly during the brief and valuable opportunities for observation constituted by a lightning discharge. Great demands must also be imposed on the judgment of the field station operators. They must adapt the amplitude sensitivity of the recording cathode-ray oscillograph to the amplitude variations fluctuating from one lightning discharge to the following ones. Poor adaptation may easily lead to over-sensitivity in recording with consequent spoiling of a valuable opportunity for observation.

Experience showed that for the investigations so far carried out it was suitable to work with the following three sweeping times in the cathode-ray oscillographs: 0.2 sec, 1000 μsec, and 50 μsec.

The long sweeping time of 0.2 sec gives both the time intervals and the amplitude sequence. With the 1000 μsec sweeping time there is obtained the field intensity variation in the lightning channel. These two methods were employed in TSR 1. By using 50 μsec with a special circuit there are obtained, as already stated, the values for the rapid fronts. By coordinating the recordings from a discharge when the three sweeping times have been employed it is possible on the whole to arrive at complete reproduction of the entire discharge process.

It was possible by means of the discharge processes in a number of lightning discharges to generalize the mechanism of these. But it should not be forgotten that the lightning discharges are characterized by an extremely fluctuating variation among themselves. For example, there is a noticeably great dispersion that arises in the current intensity of the lightning, in the current's variation form, and in its time duration. One is therefore compelled to reconstruct the variation properties of the separate lightning discharges. With a sufficient extensive experimental material it should be possible to establish a few more common variation types. On the other hand, as regards some details, a well arranged statistical analysis can be of great value.

A complete survey of the extremely fluctuating lightning discharge phenomena can only be attained in the event a comprehensive experimental material is available. It is this principle which has always constituted the basis of the investigations carried out so far and here dealt with.

As was stated earlier, great importance has been attached to taking daylight exposure photographs of the lightning paths simultaneously and side by side with the oscillographic analysis if possible. In the first place, these photographs provide a better documentation than visual observations of a lightning path. It will be seen later that photography of a lightning path that is oscillographically analysed at the same time can furnish supplementary information regarding the extent of the lightning path and its alteration during different phases of the discharge process. In this way it is possible to obtain more comprehensive information concerning the rôle played by the different lightning channels in the discharge process. One may also obtain valuable information concerning the movements of charges inside the discharge region.

One question of interest is the change of the magnetic field intensity variations with the distance from the lightning path. The short distance between the field stations during the observation period was not particularly convenient for such an investigation. Such an investigation must be carried out with different arrangements as regards distance between the stations. Nevertheless, some interesting cases were obtained with the distances used between the stations. Examples of some cases of interest will be given below.

In the two thunderstorm seasons covered by the contract the number of curves particularly suited for treatment amounted during 1956 to about 1900 and during 1957 to about 3000. Of these, the recordings of 1956 have been drawn with magnifying apparatus and are ready for further analysis. The curve material for the 1957 season, owing to the short time available since the termination of the contract, have not yet been made ready. For further information see chapter 13.

The number of photographs of lightning exposed in daylight was in the first contract year 38 with about 250 oscillograms recorded at the same time and in the second year 108 with about 600 simultaneous oscillograms. Besides these combined measurements there is an extensive oscillographic material which is particularly suited for treatment of special details. In general, the available and extensive oscillographic material will require considerable time for a tolerable amount of treatment.

In the course of the contract period four publications, /4, 5, 6, 7/, attached to this report, have been issued. They have all been compiled as a result of the investigations at Uppsala sponsored by the Air Force.

6. Special investigation methods for the channels of lightning.

Some of the oscillograms of lightning discharges with complicated variation forms require special explanation. The first lightning discharge in an active region of the thundercloud has been found to initiate secondary lightning discharges before the discharge has yet terminated. These secondary discharges may have their course in quite a different direction of path from that of the original lightning. This is quite explainable from a physical viewpoint.

It is not very uncommon in the part of the thundercloud that is active for discharges for there to arise assemblies of charges with accompanying field intensities that are high. These regions will lie as often as not on the edge of the start of a discharge - thus they are in a labile state. These charge assemblies with their high field intensities often lie in regions which border on regions where the field current has already attained an intensity high enough for starting the first lightning discharge. In such situations it occurs that the labile regions are momentarily affected by the field change issuing from the first discharge. The result is a momentary release of secondary discharges, which in some cases follow quite a different direction of path than the first discharge which initiated the discharge process. As is known, it is a simple matter to start discharges by means of charged laboratory circuits with a rapid field change momentarily imposed from outside. From the physical viewpoint there is nothing to exclude the supposition that similar processes must take place inside regions of the thundercloud that are active and labile for discharges. From what has been stated in this connection it is easy to realize what complicated problems arise when it is a matter of investigating in a thundercloud region active for discharges the various charge movements and the directions of path caused by them.

All the same, it has been found that simultaneous measurements of the magnetic field current variations of the lightning discharges in three planes in which frame aerials are set up provide possibilities for a method of analysis for determination of the direction of lightning paths. The method is explained by means of Fig. 5. According to this the frames are set up in the following three planes in relation to the earth's surface: in the vertical (v), at 45° (v45), in the horizontal (h). According to what has been stated in another connection induction from a lightning discharge generates field intensity variations in the three frames. Owing to the arrangement of the frames, it is possible to utilise the figures for the field intensity in the different frames for determination of the direction of the lightning path which generates the induction.

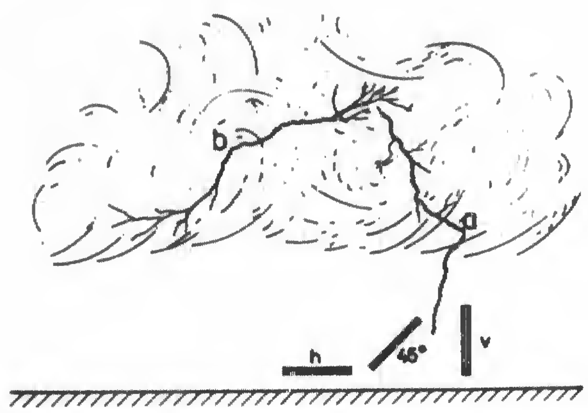


Fig. 5. Frame aerials in three angles to earth's surface used in orientation of lightning channels.

A lightning discharge, for instance that designated by a in Fig. 5, induces the highest field intensity in the vertical frame (v), lower in 45° frame (v45), and lowest in the horizontal frame (h). A subsequent lightning discharge in the same path - e.g. a partial discharge or a multiple stroke - should if it has the same direction as the first discharge, give the same relation conditions for the different field intensities in the frames. In that way it is possible to check the direction of path for multiple discharges coming one after the other. If suddenly there occurs a different direction of path, for instance the path b in Fig. 5, the relative figures between the field intensities are changed in the different frames.

An alteration of current direction in the path, thus from cloud to earth or the reverse, makes itself apparent by different polarity in the field intensities recorded.

The cases stated deal with the discharges in lightning paths, the first discharge or the main discharge and the following partial discharges or, as they are sometimes denoted, the multiple strokes. The method of analysis may also be employed for the current paths which characterize pre-discharges. In this there appears an experimental difficulty due to the current values of the pre-discharges being most often appreciably weaker than for main and partial discharges.

In these cases the difficulty may be avoided by recording the pre-discharges with oscillographs having greater sensitivity than for the main discharges. On the other hand, this most often means that the subsequent main and partial discharges are spoiled by over-sensitivity in recording. In such cases the only solution is for the latter discharges to be recorded with separate oscillographs set for lower amplitude sensitivity. The investigations so far carried out have not permitted such doubling of recording cathode-ray oscillographs. Consequently it is only in a small number of cases that, in spite of only one cathode-ray oscillograph being connected to each frame, there have nevertheless been obtained simultaneous recordings for both the pre-discharges and subsequent discharges in the main lightning path.

In order to utilise to the full the above-described method of analysis it is necessary to study by a special method the series sequence of discharges following one on the other in the same lightning path. This applies both to the intervals of time between the partial strokes and to their amplitude. Results obtained with such a method have been published /5/.

The special analysis method described above does not necessarily require that the lightning paths should be accompanied by daylight photographs. But on the other hand, these considerably facilitate the analysis and at the same time constitute a much-needed documentation. None the less it is worth mentioning that not all photographs of lightning discharges with associated oscillograms are suitable for treatment according to the special analysis method described. The method is for treating and analysing cases where several discharges occur in the lightning paths. Moreover the method requires that the oscillograms are taken at such a distance from the lightning paths that the oscillograms have not gone over to the changed variation form which is typical for atmospherics. Consequently one must count on a certain amount of loss of lightning discharges particularly suited for treatment according to the method described. But even a small number of cases furnish valuable information and perspectives about the complicated nature of a lightning discharge.

7. Special analyses of the lightning discharge mechanism.

The special analysis method described in the preceding chapter has been applied to a number of lightning discharges recorded by both the photographic and the oscillographic method. The results given here are only from the thunderstorm season of 1956. In all probability the material from the 1957 thunderstorm season comprises very many more cases than those which were found analysable during 1956. This is due to the greater number of daylight photographs and the simultaneous oscillograms that were yielded by the 1957 thunderstorm season. As stated in another connection, it has not yet been possible to treat this extensive material.

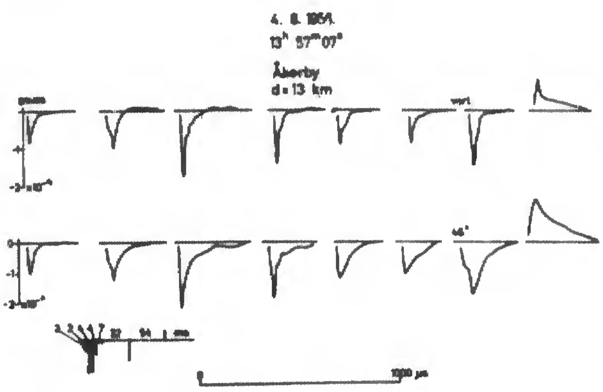


Fig. 6. Oscillograms from two frame aerials showing 8 partial discharges with corresponding time intervals. The last discharge with reversed polarity.

In Fig. 6 there are reproduced oscillograms of a lightning discharge which consists of 8 partial discharges, of which the 7 first have negative polarity. This means, therefore, transfer of negative charge downwards to earth. The last discharge, on the contrary, shows positive polarity, and the current proceeds in the opposite direction. The times between the discharges are shown at the bottom left of Fig. 6. All the discharges have the same type of variation with steep fronts and comparatively slow return to their lowest values. The variation form belongs to a common type and is characterized by great regularity. In Fig. 7 there is given a daylight photograph of the discharge. The picture shows a long lightning path at approximately 45° to the horizontal. The join in the middle is due to the lightning having been taken in both cameras of the photographic device.

Fig. 7. Daylight photograph of lightning, oscillograms given in Fig. 6.

The oscillograms according to Fig. 6 were made simultaneously on both a vertical and a 45° frame. The amplitude relations are given in the table of Fig. 8. From this it may be seen that the 7 first discharges followed the channel

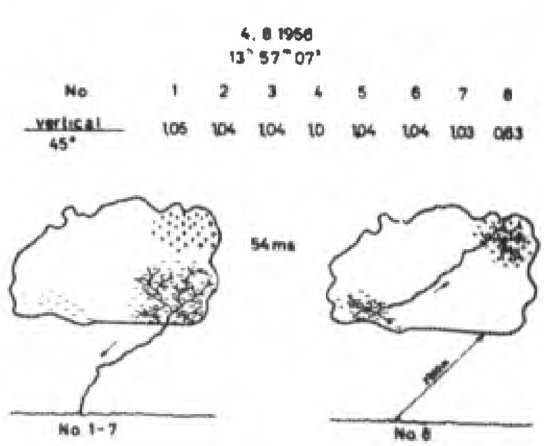


Fig. 8. Amplitude relations and lightning paths located from lightning in Fig. 7.

which is given by the photograph in Fig. 7, whereas the last, coming 54 msec later, proceeded in another direction up into the cloud, as is illustrated in Fig. 8. This must be taken as a consequence of a disturbance of the charge balance and thereby an alteration in the field current distribution in the cloud.

The intervals of time between the partial discharges amount to 3, 1.5, 4, 11, and 37 msec. The first are unusually short, whereas the two last are of more common type. What appears to be special for this lightning according to the photograph in Fig. 7 is its long length, which is uncommon for lightning discharges between cloud and earth. A noteworthy feature is also the short duration of the partial discharges.

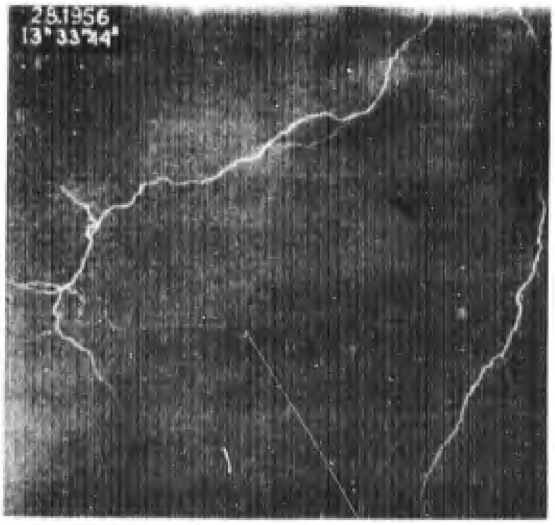


Fig. 9. Daylight photograph of lightning containing two channels.

In Fig. 9 there is given a lightning photograph showing two channels, one running between cloud and earth and the other between different parts of the cloud. The corresponding oscillograms may be seen on Fig. 10, from which it may be concluded that three discharges followed one on the other. The first is of the usual type with characteristic steep front, whereas the other two are characterized by the charges being pumped into the channel in jerks. Compared with

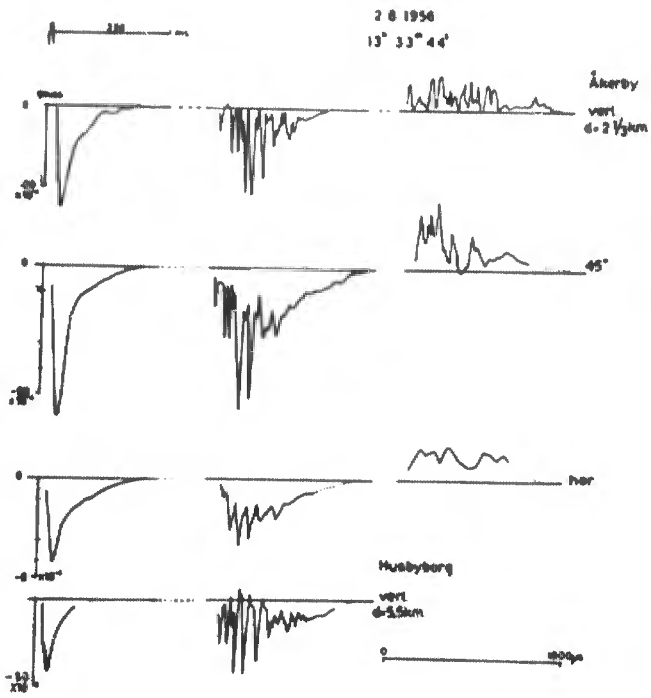


Fig. 10. Oscillograms of 3 discharges in lightning of Fig. 9.

the discharges according to Fig. 6 the difference is very striking. The case shows what extremely variable discharge processes we have to deal with from case to case. The oscillograms made comprise recordings on vertical frame (v), 45° frame (v45) and horizontal frame (h) at the Åkerby station. At the Husbyborg station the recording comprises the vertical frame (v). The last partial discharge is lacking for this frame, owing to the cathode-ray oscillograph being set for too low sensitivity. The intervals of time between the discharges amounted to 8 and 228 msec.

As there is simultaneous recording on several frames in different planes it is possible to decide which discharges followed the different channels. The amplitude relations between the frames, vertical/horizontal and vertical/45° respectively, are given in the table in Fig. 11. It is obvious that the first and second partial discharges follow the same channel, that at the right of the photograph. Further evidence that these two first discharges followed the same channel is provided by the relation between the field intensity figures of the vertical and the horizontal frames being about double compared with corresponding figures for the

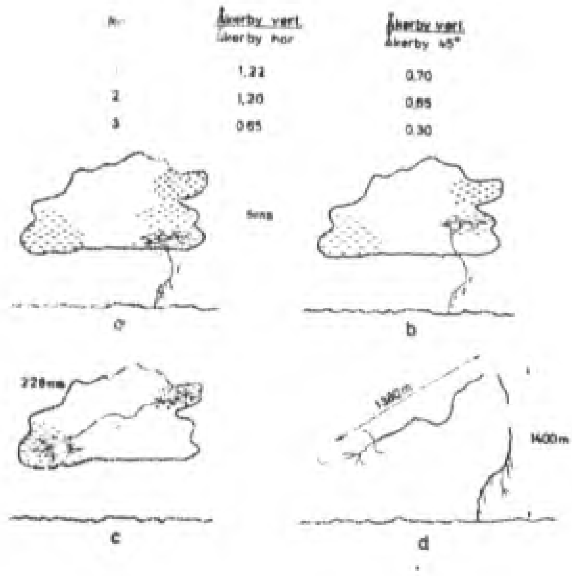


Fig. 11. Field force relations between frames as caused by lightning of Fig. 9. Estimated direction of paths.

last partial discharge. Even the polarity change in the last discharge indicates that this is bound to another channel.

The discharge process may be conceived as having the course shown in Fig. 11. With an interval of 8 msec, two discharges pass according to a and b in Fig. 11. By this the field distribution is altered in such a way that after 228 msec there occurs a discharge solely in the cloud according to sketch c in Fig. 11.

Fig. 12. Daylight photograph of vertical lightning path.

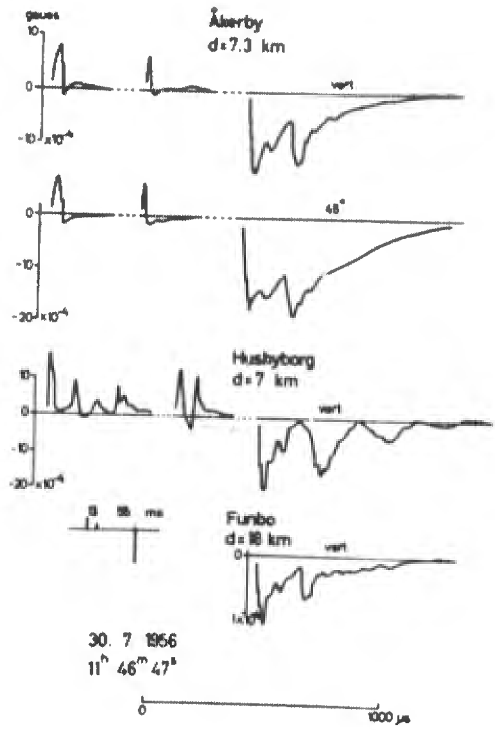


Fig. 13. Oscillograms from
the lightning in Fig. 12.

In Fig. 12 there is shown a channel the visible length of which amounts only to about 1000 metres. In Fig. 13 a survey is given of the oscillographic field variations caused by this lightning discharge. The discharge opens with two positive pre-discharges with 13 msec difference of time. After 55 msec a main discharge starts, consisting of two current impulses one after the other, with a difference of 175 µsec between them. The recordings for the Åkerby station are best adapted for taking out the relation figure vert/45° and it is found from these that the pre-discharges and the first part of the main discharge, Ha, followed the same channel. With the development of the second part of the main discharge, Hb, a change in the relation figure sets in, which indicates a change in direction of channel. From the polarity it is seen that it is a matter of a negative charge which is being moved from cloud to earth.

The discharge may thus be conceived as proceeding in the way outlined in Fig. 14. Two negative charge volumes are located as shown by the sketch, and the main discharge starts from the region a. After the main discharge has been

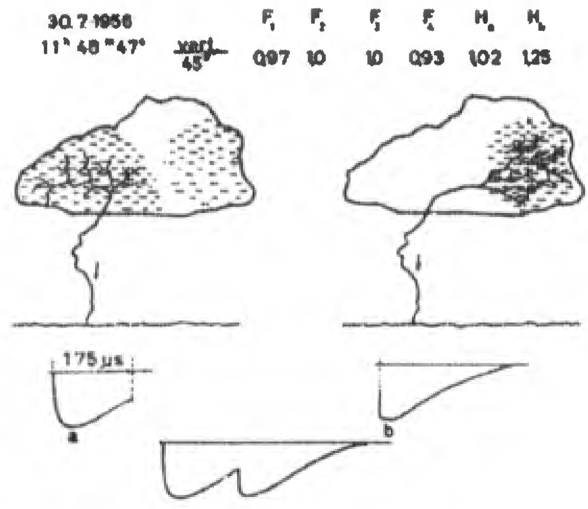


Fig. 14. Oscillogram of lightning
in Fig. 12 outlined with paths.

proceeding for 175 µsec the pre-discharges from the charge at b have reached the channel already completely formed and a lengthened channel partly in the same direction is formed. The difference in the relation figures indicates the change in direction.

Fig. 15. Daylight photograph of
typical horizontal lightning.

Fig. 15 shows the photograph of a horizontal lightning path, which owing to its great length has not all come into the camera's field of vision. The outdoor observer has only noted a horizontal channel for this lightning discharge. It may therefore be taken that the lightning lacks branches to earth. The lightning channel's length on the photograph amounts to about 2.5 kilometres, too low a figure, seeing that the lightning is at an inclination in relation to the camera's plane. There is another possibility of determining the length of the lightning discharge, by means of distance determinations from the three stations, which amounted to 8 km for Funbo, 1 km for Husbyborg, and 6.5 km for Åkerby. On the basis of these particulars the length, which must be at least 5 km, has been drawn in on the map in Fig. 16. The height of the lightning above the ground is about 1.2 km.

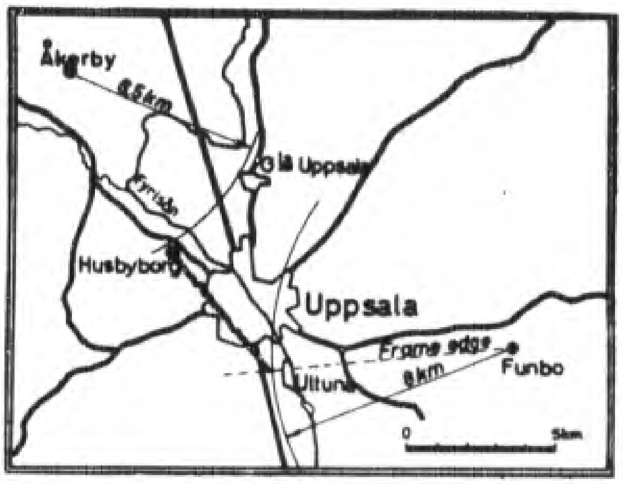


Fig. 16. Length of horizontal lightning in Fig. 15 as calculated by distance observations.

Here we have a typical horizontal lightning discharge and the simultaneous oscillographic recordings for the lightning are given in Fig. 17. It is found that it consisted of 7 partial discharges, of which 3 have positive polarity and 4 negative. The polarity changes are very pronounced on all the recordings. The oscillograms show very regular variation forms throughout for the partial discharges coming one after the other, with steep fronts and therefore slowly diminishing values.

To provide further check of the discharge process, a

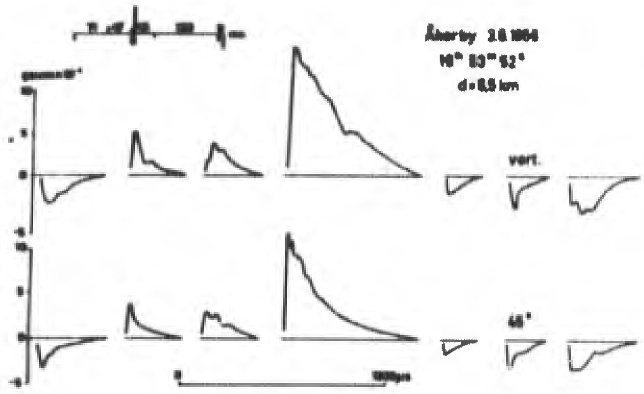


Fig. 17. Oscillograms of horizontal lightning reproduced in Fig. 15.

Disch no.	Åkerby vert. Max. ampl.	Åkerby vert. Curve form	Åkerby 45° Max. ampl.	Åkerby 45° Curve form
1	1,1		0,9	
2	3,2		2,6	
3	2,2		1,8	
4	8,4		7,3	
5	1,1		0,9	
6	1,6		1,4	
7	2,3		1,9	

Disch no.	1	2	3	4	5	6	7
vert./45°	1,22	1,23	1,22	1,15	1,22	1,14	1,21

Fig. 18. Survey and curve forms from lightning in Fig. 15 with evidence that partial discharges have passed in the same channel.

survey of curve forms and amplitudes is given in Fig. 18. In this there is also given the relation figure for the frames vert/45° and, within the limit of accuracy applicable in this case, the figures are equal, which is evidence that the partial discharges have passed in the same channel - the horizontal lightning path.

Particularly noteworthy is the polarity fluctuation for the different partial discharges. Further the discharge occurring after 126 msec, with steep front and greater duration than the other partial discharges, is especially striking. One gets the impression that the partial discharges with the lower amplitudes may rather be looked upon as pre-discharges.

This is the first time opportunity has been available to investigate oscillographically a typical horizontal lightning discharge, and the result proves the great value as regards analysis of having at disposal at the same time both simultaneous oscillographic recordings and documentation by photographic exposure. The result of detailed analysis of a typical horizontal lightning discharge is unique in the highest degree, and future analyses of similar discharge processes are awaited with interest.

The examples given in this chapter show that there has been found a supplementary method for the study of the mechanism of lightning discharges. With this method it has been possible to follow some phases of development in a lightning discharge, which were not previously known. There is good reason for applying and developing the analysis method on a more comprehensive material than has hitherto been available. It may be supposed that the extensive material not yet treated from the 1957 thunderstorm season will furnish extensive and supplementary results.

8. Oscillographic records of special interest.

As will have been seen from the above, it is only for a limited number of lightning discharges that it has been possible to apply the analysis method according to chapter 6. In the other plentiful material from the 1956 investigations there are numerous lightning discharges, the analysis of which is of interest from other points of view. It has been found advisable to give examples of such lightning discharges as special cases.

Fig. 19. Daylight photograph of a lightning between cloud and earth with branches running laterally.

In Fig. 19 there is reproduced a photograph of a lightning discharge between cloud and earth with pronounced horizontal branchings running laterally. The length of the lightning path, following a curved direction down to earth measured in the photograph's plane, is about 1700 metres. The distance between the two extreme points of the branches going horizontally and laterally has been measured as about 2400 metres, a figure that is too low, as the branches form angles to the plane of the photograph. A stereoscopic picture by photography from two stations would have been desirable in this case. It appears that the stretch in horizontal lateral directions is considerably greater than the more vertical part of the lightning path.

In Fig. 20 there is given an oscillogram of the lightning discharge, which was taken at 20 km distance from the lightning path. According to the oscillogram the lightning discharge consisted of two discharges in the same path with a 36 msec difference of time between them. Comparison of the two discharges shows the most striking difference in variation type.

The first discharge was initiated by a very pronounced pre-discharge process in some parts with marked superpositions of a more rapid variation type, with forms such as have been described earlier /4/. What is remarkable is the

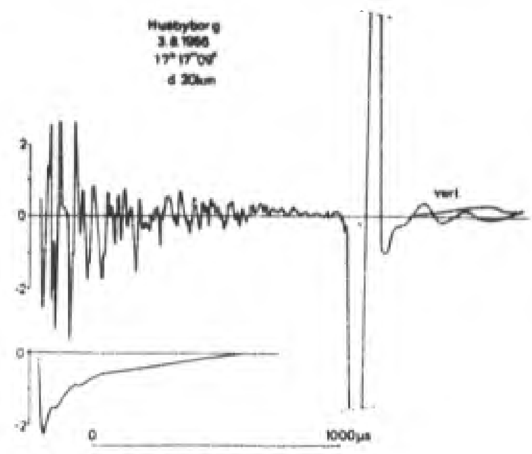


Fig. 20. Oscillogram of lightning in Fig. 19 with pronounced pre-discharges and bipolar variation feature of main discharge.

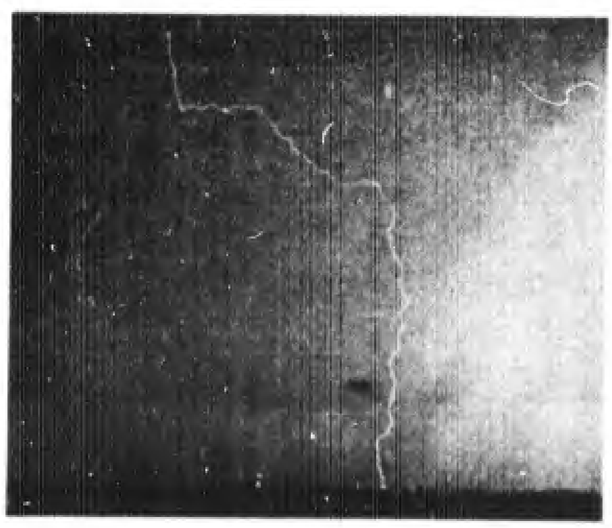


Fig. 21. Daylight photograph of curved lightning with its lower part vertical.

high amplitudes at the beginning of the pre-discharge. This is followed by a strong, partly over-sensitive main discharge. This is succeeded by another discharge with much lower amplitude and of ordinary aperiodic variation type.

The main discharge is of a pronounced bipolar type, characteristic of an aperiodic lightning discharge transformation to bipolar type with the distance from the lightning path, a question that will be referred to later. There is reason to ask why the second discharge s aperiodic variation form has not been influenced to anything like the same extent.

Fig. 21 shows a photograph of a very simple discharge between cloud and earth. In this case also the sole main discharge passing in the lightning path is preceded by a characteristic pre-discharge with comparatively high amplitude. The interesting feature in this case, see Fig. 22, is

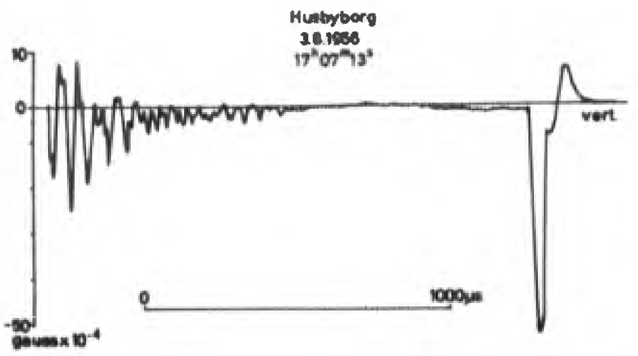


Fig. 22. Oscillogram of lightning in Fig. 21 with pronounced pre-discharges, its main discharge with disposition to polarity change.

that the main discharge shows a disposition to polarity change, in spite of the fact that the distance between the measuring point and the lightning path was 9 km. In the case treated in Fig. 20 the distance between the lightning path and the observation point was more than double, or 20 km. In the region where the amplitude of the discharge diminishes there may be seen a slight tendency to superposed variation. This also occurs in the other weaker discharge in Fig. 20.

Besides the recordings where at the same time as the oscillograms daylight photographs were successfully exposed, there was obtained in the 1956 thunderstorm season a very extensive and interesting observation material consisting solely of oscillograms. As in earlier investigations of which examples are given in TSR 1, this new material presents interesting aspects as regards the extremely fluctuating variation properties of the lightning discharges. Some few cases from this extensive material will be given here.

Particularly interesting are the oscillographic investigations comprising time sequence for multiple strokes and the simultaneously analysed variation structure of the individual discharges.

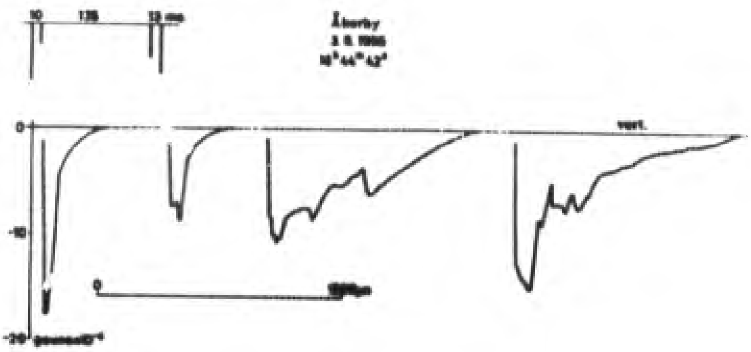


Fig. 23. Oscillograms of four multiple discharges, the two last with long duration.

Fig. 23 gives a case with multiple strokes, four discharges being developed in the same lightning path. The two first discharges follow on each other with a difference in time of only 10 msec. Characteristic of these two first discharges is their regular variation form and their short duration of about 100 µsec. After a comparatively long interval of 135 msec come two discharges with long duration of 900 and 1000 µsec respectively. These two partial discharges have quite a different variation structure from the first two. Their irregular variation form shows that during the actual discharge process considerable fluctuations in field intensity occur, in other words in the current course. This may be explained to some extent by the resistance for some reason being momentarily increased in some part of the discharge channel. Another explanation assumes a constant resistance in the channel the whole time and that the increases have their cause in current impacts which from time to time are fed into the channel from adjacent charge accumulations.

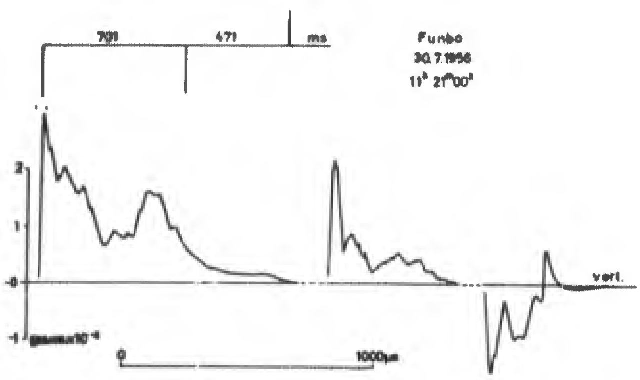


Fig. 24. Oscillograms of three multiple discharges, the last passed in a different channel.

Another case with three multiple strokes is given in Fig. 24. In this case the intervals of time between the partial discharges are of such long duration as 700 and 470 msec respectively. Characteristic for all the three discharges are the steep fronts and the irregular variation forms in general. By means of the analysis method used in chapter 6 it has been possible to establish that in this case the third discharge has, like the two first, passed in a different channel. Inadequate daylight photography at the same time prevented decision as to the positions of the channels.

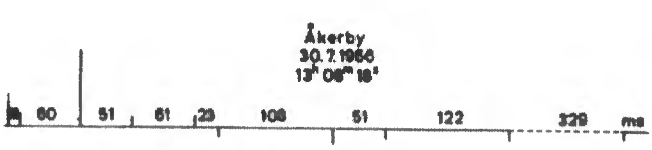


Fig. 25. Time intervals of ten multiple lightning discharges with extremely long total duration, explained by discharges in different channels.

In exceptional cases the lightning discharges may extend over a second or a little longer time. An example of such a prolonged discharge time is furnished by the time sequence in Fig. 25. In a case like this the discharge mechanism is extremely complicated and probably made up of several channels, which have among themselves many partial discharges. The superposition of discharges in the cathode-ray oscillograph's oscillograms has made it impossible to follow the discharges with certainty.

The examples treated in this chapter represent merely a small part of the cases which may be picked out for more thorough treatment from the extensive material acquired during the 1956 thunderstorm season.

9. Changes in magnetic field variations with distance.

From many points of view it is of interest to investigate the field intensity variations with distance from the lightning path. As stated in another connection, the short distances between the field stations made them not particularly well suited for such an investigation. A different distribution between the stations would be required for this. All the same, some cases of interest were obtained. These, which will be described in some detail below, were all obtained by recording with vertical frames.

It may be of interest to consider in this report two cases where the distance to the lightning path from the two stations was practically the same. These cases are reproduced in Fig. 26 and Fig. 27. For one of the stations, Husbyborg, the distance to the lightning path was 4 km and for the other, Åkerby, it was 6 km. The curves given in Fig. 26 represent a typical pre-discharge process - the succeeding main discharge was found to be quite over-deviated in recording and could not therefore be reproduced. On the whole, the two pre-discharges show agreement between the stations as regards variation structure. On the other hand, the amplitude is lowered where the distance to the lightning path is greater. In Fig. 27 there is given another lightning discharge which occurred during the same thunderstorm, a little later and with the same distances from the two sta-

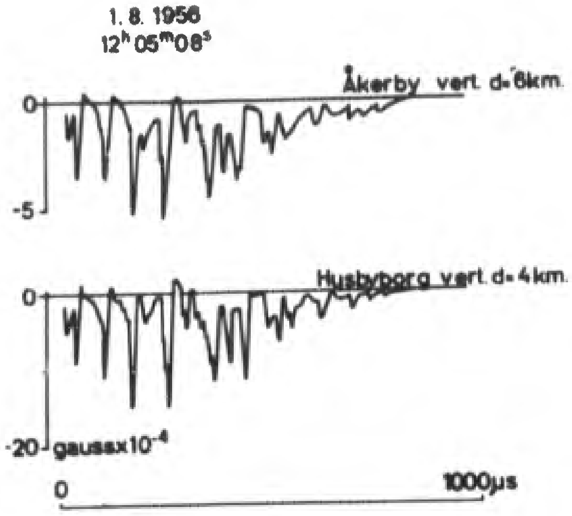


Fig. 26. Oscillograms of typical pre-discharges from lightning with practically the same distance to recording stations.

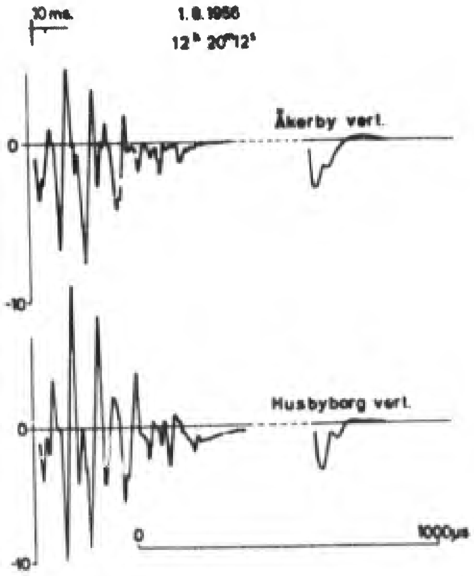


Fig. 27. Oscillograms of typical pre-discharges with high amplitudes followed by main discharge with low amplitude. Distance to stations the same as in Fig. 26.

tions. In this case also pronounced pre-discharges took place with on the whole good agreement between them. The main discharge coming afterwards has strikingly low amplitude and only a slight tendency to change in quasi-periodical direction.

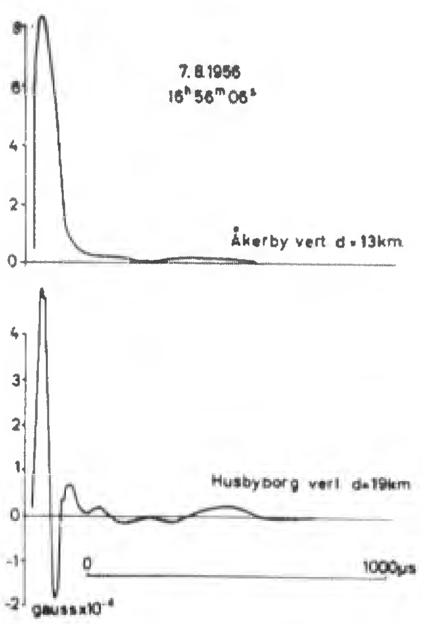


Fig. 28. Oscillograms from two stations showing transition with distance to bipolar type.

In Fig. 28 there is shown a simultaneous recording from the Åkerby and Funbo stations, with distances between the lightning path and the stations of 13 km and 19 km respectively. The station nearest the lightning path, Åkerby, shows a typical unipolar ordinary variation type, while the greater distance to the lightning path for the Funbo station gave rise to a pronounced bipolar quasi-periodical variation form.

An example, consisting of three multiple discharges recorded at the Husbyborg and Funbo stations is given in Fig. 29. The difference in time between the two discharges following the first discharge are 93 and 77 msec respectively. In this case it was not possible to measure the distances to the lightning path but judging from the field intensity variations the Funbo station had the shortest distance. In

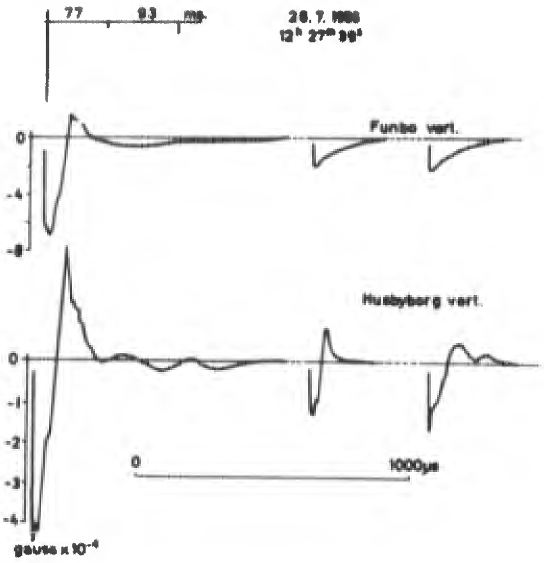


Fig. 29. Oscillograms from two stations, three multiple lightning discharges, all at the most distant station, with marked transition to bipolar variation.

the first discharge, which has the highest amplitude, the transformation to bipolar variation type has already set in at the Funbo station, whereas the two succeeding discharges are still aperiodical. At the Husbyborg station, which has the greater distance to the lightning path, a transformation to bipolar variation has already set in for all three discharges.

Transformation with distance in a case where it was possible to follow the change at three stations and for which the distances to the lightning path were known is exemplified by Fig. 30. For the Åkerby station the discharge variation is of a type common to lightning discharges. On account of the short distance of 6 km to the lightning path the field intensity happened to be over-recorded. Even at 11 km distance, that applying to the Husbyborg station, the discharge has been transformed to bipolar type. This has still further gone over to a marked quasi-periodical variation type with the discharge reaching the distance of the Funbo station, 25 km from the lightning path. The magnetic

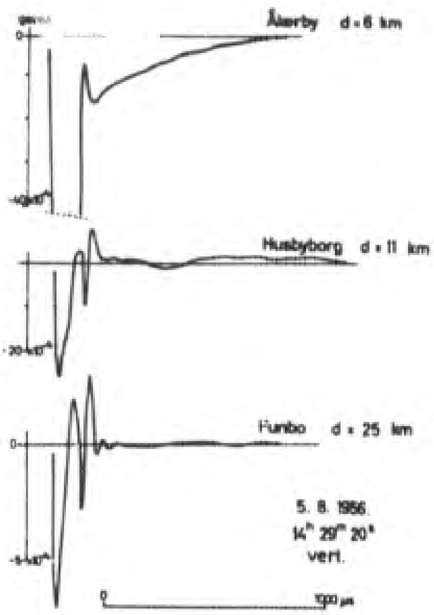


Fig. 30. Oscillograms of lightning from three stations with marked transition to bipolar variation with increasing distance.

field intensity variation has therefore at this last distance gone over to the variation form which as regards lightning discharges goes under the general designation of atmospherics, or in its abbreviation spherics.

When dealing with the transformation with the distance of lightning discharges, which are typically aperiodic at the source, we must obviously consider the influence on the variation forms of reflections by ionospheric layers. Here it has not been discussed to what extent this effect has influenced on the transformations exemplified in the preceding figures. Such an investigation will be carried out in detail when a more extended amount of oscillograms will be available for analysis.

It is well-known that the variations of lightning in the form of atmospherics have been subjected to a great deal of research in various quarters. The more or less marked transition of the lightning discharges to quasi-periodical courses with distance has, in the treatment of such investigations, led to the atmospherics being given the generally accepted designation of wave forms of atmospherics.

In some quarters, on the basis of the variation forms of atmospherics it is a question in some cases of distances up to thousands of kilometres from the source of disturbance. Attempts have been made to draw conclusions regarding the variation forms of the lightning discharges developed at the source. In view of the fluctuating aspect of the transition forms, of which only a few examples have been given above, it may be seen how indefinite such a method of arriving at conclusions may be.

In this connection it may be stated that there exists in Sweden an investigation that has been carried out /8/ in which with the aid of two stations at 570 km distance and using simultaneous oscillograms the forms of variation for atmospherics were investigated. In that case it was a question of atmospherics at both small and great distances. The investigation furnished more than clear evidence of the difficulties of attempts at estimating the variation forms of the lightning at the actual source, on the basis of corresponding variation forms in atmospherics at a great distance.

As is known, there are possibilities of computing theoretically, by means of the variations of the magnetic field from a lightning path, the changes with the distance from the source. Examples of the method have been given in two publications /8/, /2/, the first of which is included in TSR 1. The simplest case is represented by a straight vertical lightning path. There is an observation point at the distance d from the lightning path; this distance must be greater than the length of the lightning path. If c designates the velocity of light for the magnetic field force H in C.G.S. units, we get the equation:

$$H = \frac{2h}{d^2} I + \frac{1}{c} \frac{2h}{d} \frac{dI}{dt} \quad (1).$$

In respect of the varying values applying both to the lightning current I and to its first derivative with time, the equation (1) should rather be considered as a guide.

According to the experimental experience assembled, which has already been documented in TSR 1, the variation aspects which the lightning discharges are found to possess in the vicinity region are extremely fluctuating. It appears therefore that it is not possible at present to penetrate further into the problem of variation with distance by means of theoretical computations. Consequently it is still necessary to continue with experimental investigations of the variation changes of the lightning discharges with distance. It will only be after such are available in sufficient numbers that quite another background for a theoretical analysis will have been obtained.

10. Statistical analysis.

The great dispersion in the various measurement figures which have come out in investigations of the variation properties of the lightning discharges makes a statistical analysis a necessity. As the oscillographic material for 1956 is ready for statistical analysis, while the corresponding oscillographic material for 1957 is not yet in the state required for treatment, a really extensive statistical treatment must be deferred to a later date. For this reason, there have only been included in this report some few statistical results from 1956 that are of special interest.

a. Front variations.

As has been stated, there was designed for the study of the fronts of lightning discharges a special device especially adapted for analysis of the fronts of the discharges. The method was intended in the first place for study of the fronts of main and partial discharges together - that is multiple strokes. It was found that, besides this purpose, the method enabled recording of the fronts of predischarges to be made. No fewer than about 100 such have been analysed. As regards front variation for multiple strokes the extensive material was also examined in respect of the special variation forms of the front. It should be stated that the frontal time comprised in the analysis covers the time from the start of the current right up to the moment when its maximum value was reached.

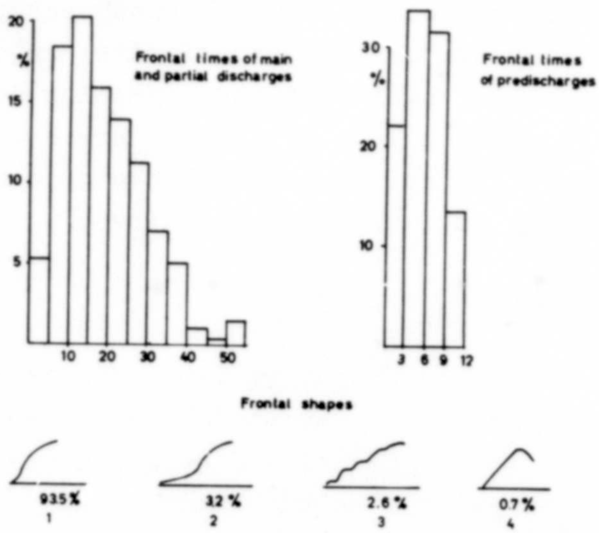


Fig. 31. Statistical analysis of frontal times.

In Fig. 31 there is given the statistical result of the front analysis. According to Fig. 31 the most frequently occurring frontal times for main and partial discharges amount to times varying between 5 μsec and 20 μsec. The agreement must be considered as very good when compared with the results published in TSR 1 and in another work /9/. The more so as the results were obtained by a different method. In such a comparison, there must always be expected some differences due to the great dispersion in the variability of the lightning discharges. It will be seen from Fig. 31 that the frontal times for pre-discharges are shorter all the way through than for multiple strokes. This is related to the fact that the pre-discharges are made up of considerably shorter spark lengths than the long spark paths that characterize main and partial discharges in the lightning paths.

At the bottom of Fig. 31 a statistical distribution is given of the different types characterizing the frontal variation. It is the type 1 far to the left that is predominant, and the others are mainly to be regarded as variants of it. This applies especially to type 2, for which the clear inflexion at the beginning of the discharge is explained by the fact that it always takes some time for the break through, initiated by the pre-discharge for the main channel, to reach its final stage. To a smaller extent the inflexion may also be detected for type 1. In calculating the frontal times for the two first types of variations the weaker rise in the current at the start of the front has been included in the total frontal time. Thereby the time has been lengthened a little, and this must be considered when comparing it with the frontal times stated in earlier works.

The third variation type with jerky rises in the current to the highest value is very interesting but uncommon. The fourth uncommon type with a straight rise of the front requires a very extensive ionisation in the lightning s channel region.

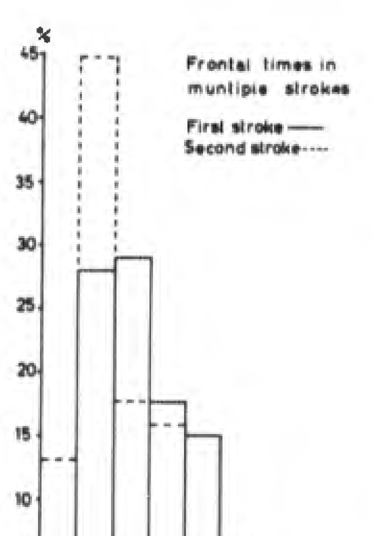


Fig. 32. Difference in frontal times between first and second discharge in lightning.

It is of interest to investigate whether there is in a lightning discharge a tendency for the first discharge in the path to show longer frontal time than that immediately following. An example of the result of such an investigation is shown in Fig. 32. It will be seen from this that the first discharge has a longer frontal time than that coming next in order in the lightning path. The physical explanation of the difference is evident. The first discharge must build up ionisation in the channel. After the first lightning has passed the channel the ionisation persists for a certain time, in some cases one must count on so long a recombination time in the channel as many msec. In addition, there is the well-known fact that the pre-discharge process with subsequent discharges is quite different in comparison with the first discharge in the channel.

b. Time intervals between multiple discharges.

In the earlier report, TSR 1, there was described a new method for determining the time intervals between discharges following one on the other in the lightning channel. Owing to the small number of suitable thunderstorms the measurements first carried out were few in number. A supplement has therefore been made with the aid of the more plentiful material obtained in 1956. The statistical compilation of this is given in Fig. 33. On the whole the agreement is good compared with the distribution of the intervals as given in TSR 1. It should however be noted that the number of intervals of shorter duration is appreciably greater in Fig. 33 than appeared from the earlier material. The longest time intervals, though rare, lie around 250 msec in the new material.

When investigating time intervals for multiple strokes care must be taken that the measurements really do comprise lightning discharges which passed in the same channel. If such a check is not made, quite misleading results may be obtained. For checking that the lightning discharges according to Fig. 33 did follow the same channel, the method stated in chapter 7 was used with advantage. On going through the whole material of discharges suited for analysis it was found that one obtained a number of cases with lightning dis-

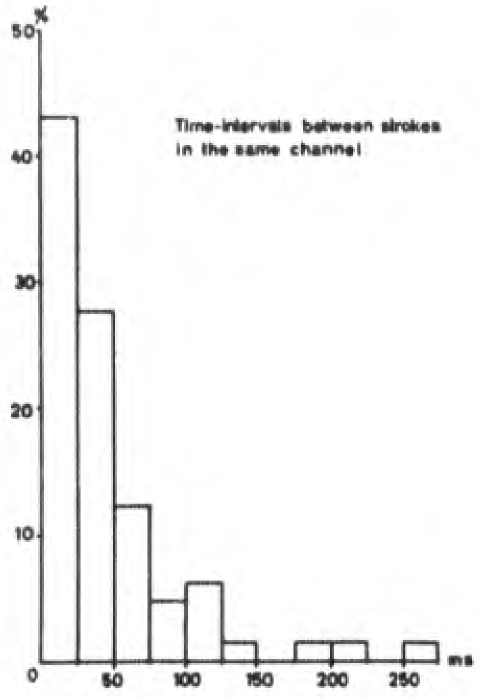


Fig. 33. Statistical analysis of time intervals between discharges in the same channel.

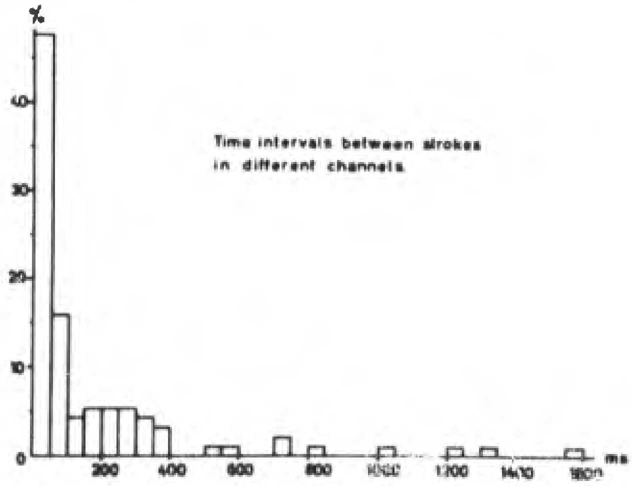


Fig. 34. Statistical analysis of time intervals between discharges in different channels.

charges in different channels. These discharges were built up, as stated earlier in another connection, by a lightning discharge initiating secondary discharges in its immediate surroundings in the thundercloud. In such cases, the discharges proceed in separate channels, but arise in comparatively short time intervals.

The method stated in chapter 7 has also been employed for analysis of the time intervals for such lightning discharges in separate channels and in Fig. 34 the result will be found. It appears that the longest intervals measured amount to 1.6 msec. Values greater than 500 msec are comparatively rare. Most striking is the large number of short time intervals around 50 to 100 msec, which is evidence that a rapid initiating of secondary lightning discharges often occurs.

11. Interesting daylight photographs of lightning discharges.

In the thunderstorm season of 1957 it was possible to photograph 108 lightning discharges in daylight at the field stations. Interesting results are anticipated among these when the treatment is available of the oscillographic results for the same times. It is considered of interest, however, to reproduce here a small number of these recordings. In Fig. 35-38 four photographs are given. The first, Fig. 35, shows a lightning with several branches. This type is not uncommon in the extensive material. In passing, it may be mentioned that this lightning was accompanied by typical whistlers. The second, Fig. 36, shows a lightning with no branches whatever. It may be seen that this lightning alternately comes out from and disappears behind cloud formations. In some cases, therefore, the photographic method has its limitations; in this case the oscillographic method is superior.

The two lightning discharges in Fig. 37 and 38 resemble each other very much. The difference in time between them is only one minute and both are characterized by two vertical discharge paths alongside each other. In comparisons made with the aid of oscillographic recordings there has been observed in a number of cases a striking agreement of variation structure between lightning discharges following one on the other, in spite of the difference in time between them amounting to several minutes. This is evidence that adjacent

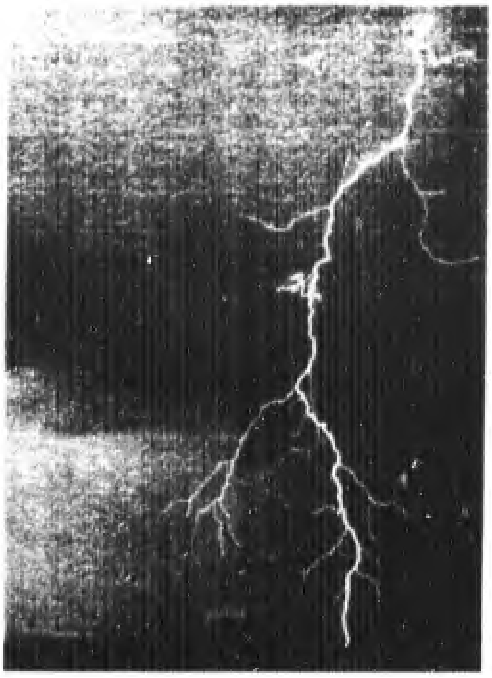
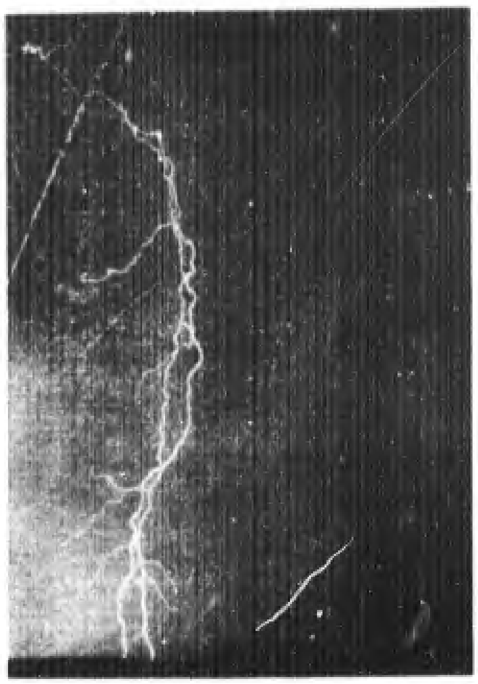


Fig. 35. Daylight photograph of lightning with typical branches and followed by pronounced whistlers.

Fig. 36. Daylight photograph of lightning penetrating cloud formations.



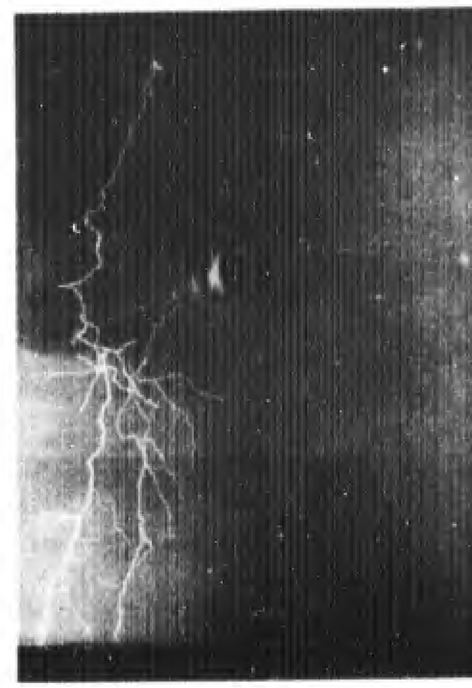


Fig. 37-38. Two daylight photographs of lightning discharges of similar features from the same emission centre of a thundercloud taken within a time difference of one minute.

regions in a thundercloud may for a considerable time generate lightning discharges with strikingly similar discharge properties. Simultaneous recording by both oscillographic and photographic methods should furnish valuable information in this respect. These will be of increased value if they allow of stereoscopic reproduction.

A strikingly complicated lightning is shown by Fig.39. It appears as if in this case there has been photographed a lightning discharge between different cloud parts, with branches to earth missing. Whether the lightning channel forms a closed circuit cannot be decided. The strange appearance of the path may also be due to an unfavourable position for the plane in which the lightning was photographed. In this case also, a stereoscopic reproduction would be of the greatest value. More information concerning the lightning path in Fig. 39 will probably be yielded when the oscillogram for this lightning has been treated.

Fig. 39. Daylight photograph of lightning strikingly complicated.

12. Simultaneous photographs of a lightning discharge from two stations.

In ten separate cases, success was achieved in photographing a lightning simultaneously from two stations with the object of obtaining, if possible, information regarding the position of the lightning path in space. In Fig. 40 there is presented a photograph taken at the Husbyborg station with a distance to the lightning path of 1.7 km, and in Fig. 41 the same lightning is photographed at the Funbo station at a distance of 13 km from the lightning path. If the presence of streamers on the two photographs is taken as basis, it appears hardly credible that they originate from the same lightning path. All the definite streamers occurring on the photograph from the Husbyborg station are practically invisible on the photograph from the Funbo station. The reason for the difference is a great absorption due to water drops in the photographing from the greater distance. In all probability a photographic exposure of a lightning path like that exposed in Fig. 40 at a still shorter distance from the chan-

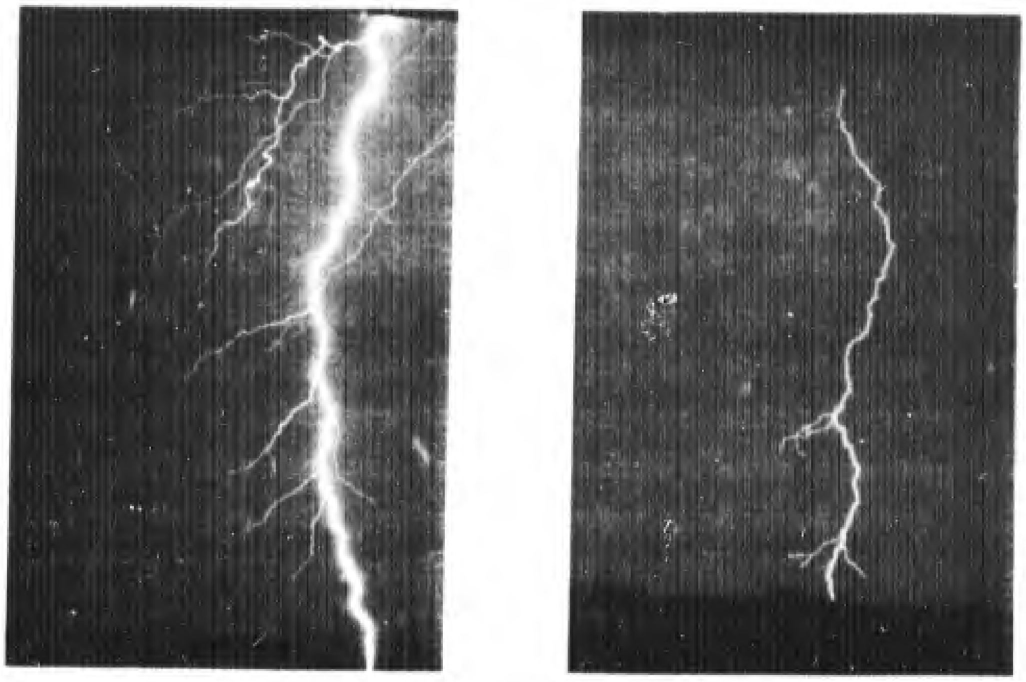


Fig. 40-41. Two daylight photographs of the same lightning taken at two stations. Distances to the path 1.7 km and 13 km respectively.

nel and under more favourable conditions as regards absorption would furnish still further interesting details in respect of streamers. From the example presented, there can be realized the great difficulty that must always be present in photographing streamers of feeble brilliancy. Where the discussion of streamers is concerned, therefore, one must take into consideration the limitations involved in the photographic method. There may belong to a lightning channel an immense number of streamers of small brilliancy, which simply do not get recorded, because both optics, film type and extra light disturbances stand in the way of exact reproduction of these phenomena of feeble brilliancy.

13. Igniting lightning discharge with simultaneous daylight photograph.

Once previously in the history of the Institute /3/ there has been successfully analysed oscillographically a vertical lightning discharge out on the open plain region at 4.5 km distance from the Husbyborg station. The outstanding feature of this lightning was that it both ignited a load of hay and killed a farmer standing on the load. Oscillograms of this lightning are reproduced in Fig. 42. and it

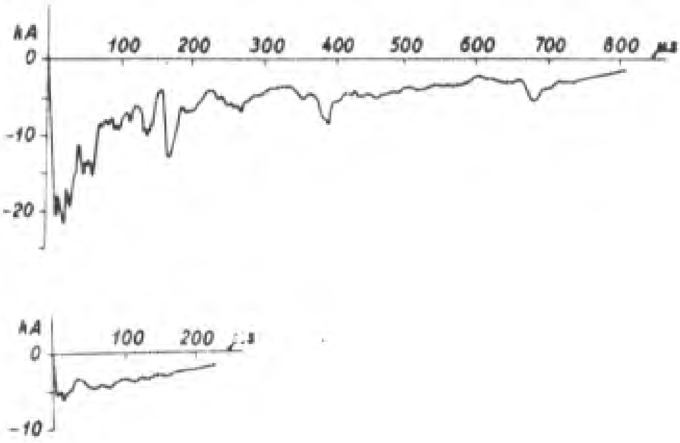


Fig. 42. Oscillogram of igniting and killing lightning.

may be seen that two discharges passed in the path one after the other. The first of these had a maximum current of 22 kiloampere and a duration of nearly 1000 µsec. The computation of the current intensity I in this lightning discharge was done according to an approximation formula, in which are included the maximum field intensity H, the horizontal distance r along the earth's surface between the vertical lightning and the observation point and the height h of the lightning path. Here r and h are expressed in kilometres, H in 10^{-3} Gauss and I in kiloamperes. The formula is as follows:

$$I = \frac{rH}{2} \frac{\sqrt{r^2+h^2}}{h} \qquad (2).$$

Strangely enough it happened that during the 1957 thunderstorm season a lightning ignited a cowshed in the sensitivity range of the network of stations. It was possible both to photograph this lightning and to obtain oscillograms of it. The daylight photograph of the lightning is reproduced in Fig. 43 and it was taken at the Funbo station

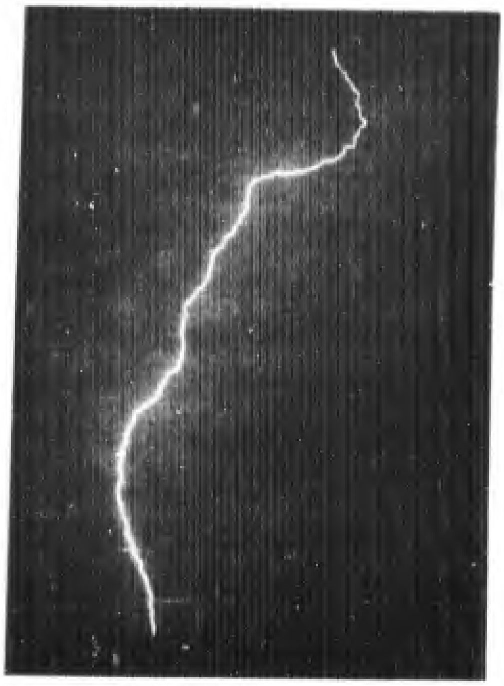


Fig. 43. Daylight photograph of lightning which ignited a cowshed situated in the sensitivity range of the network of stations.

at a distance of 3.8 kilometres. The lightning discharge belongs to the vertical type, and the oscillograms on a vertical frame at the Husbyberg station at a distance of 12 km are given in Fig. 44. The lightning discharge consists of

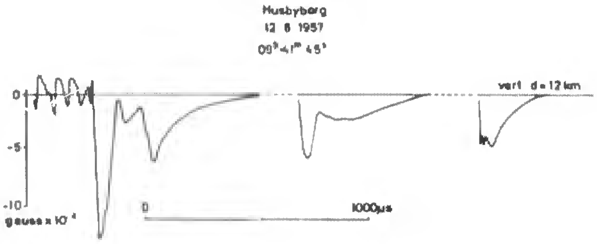


Fig. 44. Oscillograms of igniting lightning in Fig. 43 with duration of main discharge of 800 µsec and maximal current amplitude of 50 kiloamperes.

three partial discharges one of them of high amplitude and the great duration of 800 usec.

The general and necessary condition for a lightning discharge to have the ability to ignite, and thus constitute what is called a "gangster" in the diversified crowd of lightning discharges, is that it shall have high current intensity as well as long duration. This condition applied for the lightning discharge first mentioned, which both ignited and killed. The decisive question now is whether the lightning discharges according to Fig. 43 and Fig. 44 have the same properties. As regards the lightning's long duration this does apply for the discharge with the highest amplitude in the oscillogram of Fig. 44 with a magnetic field force value $H = 1.25 \times 10^{-3}$ Gauss. The photograph of Fig. 43, on the basis of knowledge of the camera's focal distance enlargement and its distance from the lightning path, allows of an estimate of the lightning path's length h. This was 1.8 km. The mentioned magnetic field intensity's maximum value H in Gauss 10^{-3} was 1.25 and according to the formula the maximum current intensity is calculated to 50 kiloamperes.

There are very distinct similarities between this igniting lightning discharge and that reproduced in Fig. 42. The duration of both of them has the length necessary for igniting and both are likewise characterized by sufficiently high current intensity. The variation type shows in both cases that new charges are pumped into the channel during the time discharging is proceeding. Another similarity is that the lightning discharge in both cases was multiple, consisting of one or two weaker partial discharges. The presence of these has nothing to do with the igniting actions, which are wholly determined by the discharges showing high current intensity combined with long duration.

... rvey of investigation material, its obtainment and ...atment.

It seems advisable to include in this report a general survey of the recording and observation material that has been assembled during the period of the contract. It has already been stated that the treatment of the investigation material for the last thunderstorm season, 1957, has not yet been completed at all. This is partly due to the extensive treatment which the recorded material must always undergo before it can be employed as basis for an analysis. It has, therefore, been considered advisable, pending the final treatment of the whole of the vast material - this applies both to the 1956 and to the 1957 thunderstorm seasons - to submit now an account of how the material is being progressively treated, together with a general survey.

The recorded material obtained at the close of each thunderstorm is collected immediately from the different field stations. The films are developed and subjected to a first examination to ascertain how the recordings have come out. There is then carried out a coordination between the time markings on the recordings and the reports made out at the field stations concerned. This first treatment procedure is designed to make sure of the film material for future treatment, which goes on in the period of waiting between thunderstorms. Later detailed examination, with the aid of magnifying apparatus, is put in hand of the films which are suitable for further treatment. It is always found that only a certain percentage of all the recorded oscillograms can be utilised for analysis of the field intensity variations. This is because it is not possible to avoid a considerable number of field intensity variations being recorded, which lie outside the borders of the measurement area for which the field stations are specially installed. These oscillograms are kept for separate examination.

Thus the preliminary examination proceeds even during the thunderstorm itself. After this there follows a detailed examination of the oscillograms by means of the magnifying apparatus and notes are made of the oscillograms which, in view of the different kinds of analysis, are especially suited for further treatment. After that, preparation of the oscillograms by drawing them on a suitable scale is put in hand. This procedure is necessary but takes up time. In this way the oscillograms are given a form which can constitute a basis for analyses of the mechanism of the lightning discharges. It is against the background of this comprehensive method of treatment that the survey now given should be considered.

The 1956 thunderstorm season was characterized by a very much smaller number of suitable occasions for observation of lightning discharges than the season of 1957. This is clearly evident when making comparisons between the two seasons. The number of curves plotted during 1956 amounted to 1890. Simultaneous recordings at 3 stations comprised 41 lightning discharges and the corresponding figures for 2 stations were 194 lightning discharges and 772 curves. Single lightning discharges recorded at one station amounted to 240 with 832 curves belonging to them. The number of multiple strokes amounted to 198, distributed over 798 curves. The number of lightning paths that were observed was 125 and the associated curves numbered 633. Lightning paths photographed in daylight constituted 38 and they were accompanied by 250 curves.

As regards the 1957 material for observations not yet finally treated the following may be stated. The number of lightning paths amounted to 108 and associated curves to about 600. Regarding the number of lightning discharges observed and simultaneously recorded these amounted to 750, with associated curves estimated at about 3000. For purpose of comparison it may be mentioned that the total number of recorded oscillograms during this thunderstorm season was between 25 000 and 30 000, which illustrates the exclusion, stated earlier, of lightning discharges the recordings of which will not be treated.

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ARKIV FÖR GEOFYSIK

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Band 2 nr 23

OLOV NORINDER and EDGAR KNUDSEN

A new method of measuring rapid magnetic field variations from atmospheric electric discharges by using a loop system on the earth's surface

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By OLOV NORINDER and EDGAR KNUDSEN

With 22 figures in the text

Contents

1. Introduction

In thunderstorm researches the electromagnetic variation properties of the lightning discharges constitute a fundamental research object. In investigation of these there have been used in most cases open antennae connected over amplifiers to cathode-ray oscillographs. By this method there are obtained values for the variation structure of the electric field from the lightning discharges. On this subject there exists an extensive investigation material, mainly dealing with the electric field variations from lightning discharges at a great distance from the lightning paths, and in exceptional cases disturbances in the vicinity region. Two recently completed works at the Institute for High Tension Research ([1], [2]) may be cited as examples. In these publications aperiodic amplifiers have been used.

In the vicinity region of the lightning discharges the open antenna method has shown some drawbacks, it is sensitive to disturbances from rainfall discharges and from local disturbance fields. At the Institute a method has been developed [3, 4] which enables the variations in the magnetic field caused by the lightning to be measured. The advantage with this magnetic method is chiefly found in the close relation prevailing between the magnetic field's variations and the current intensity variations in the lightning discharges. In measuring the magnetic field variations use has been made of frame aerials with small number of turns and protected against the effects of the electric field's variations by suitably arranged screening by non-magnetic metal netting. For measurement of the different field components the frames are set up in the vertical plane, horizontal magnetic field measured, and in the horizontal plane, vertical magnetic field measured. In the case of a vertical frame it is possible by rotating in relation to the lightning path to obtain the maximum values of the magnetic field.

As will be seen from the publications cited and from what follows, the variations of the induced magnetic field are measured over amplifiers and integrating circuit connected to a recording cathode-ray oscillograph. On comparative investigations of the magnetic field force measured by both vertical and horizontal frame systems it was found that the amplitudes generated by the lightning discharges in the magnetic field in the horizontal frame attained as a rule only $\frac{1}{3}$ of the corresponding amplitude variations measured by vertical frame [5]. Increasing the horizontal frame system's electronic amplification factor beyond the sensitivity limit already attained was found to lead to appreciable disturbances in respect of the electronic integration circuit coupled into the frame system. One way of increasing the sensitivity might be to increase the number of ampère turns in the horizontal frame. In view of the fact that to avoid self oscillation in the frame system great distances must be maintained between the turns, the arrangement would involve considerable cost and would limit the sensitivity of the frame system all the same. It therefore seemed advisable to the authors to adopt a single turn loop system in place of the horizontal frame system. This loop system consists of a single turn of insulated copper wire buried in the top layer of the earth's ground surface. The loop may even consist of several turns, by which means space is saved. In that case, care must be taken that each turn is kept sufficiently apart from the other turns, to avoid self oscillation. The limit for this can easily be tried out experimentally. The method allowed of easily increasing the ampere turn surface without any great cost. The ampere turn surface thus increased provided considerably greater measuring sensitivity. The result was, as will be seen below, that the magnetic field variations could be investigated at very great distances from the source.

2. Description of the loop measuring method

a. *Measuring circuit diagram*

Fig. 1 shows the block diagram for the measuring circuit, with L designating the loop laid down in one turn of insulated copper wire. The integrating RC circuit is designated by I and is connected to the pre-amplifier Pa and the main amplifier Ma. The amplification in the latter may be varied in steps by means of a switch. The cathode-ray oscillograph with anode voltage circuit and the modulator M connected to the grid of the CRO tube form one unit. The modulator allows a suitable sensitivity level to be set on the CRO. The recording time base arrangement allows of regulation for different linear time base sweeps.

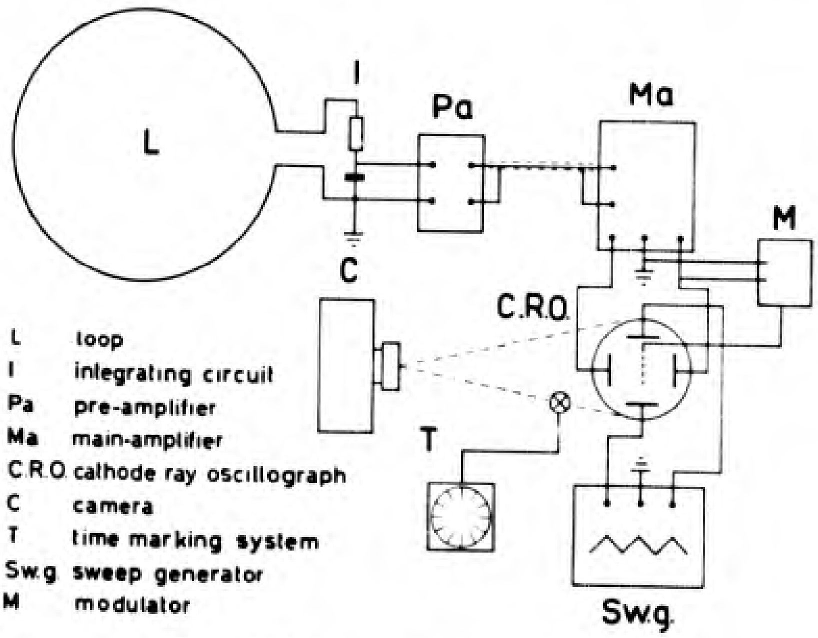

Fig. 1. Diagram of measuring circuit.

In the camera C, the shutter of which is open during recording periods, the film moves at a constant velocity of 2.5 mm/sec. The time markings on the oscillograms are produced by the light from a small lamp operated by a synchronous clock movement connected to the Swedish interconnected 50 cycle power system.

b. *Theoretical bases for the measuring method*

It is well known that the changes caused in the electromagnetic field by ligtning discharges are such that in the first place measuring devices with an upper cut-off frequency of 100 kc/sec are sufficient. The frequency spectrum is therefore such that we can consider it as quasi-stationary for loops of the sizes employed in the following investigations—e.g. as if the induction is constant in the loop's area.

We introduce the following magnitudes:

S = area of the loop in square metres.
R = resistance in ohms in the integrating circuit.
C = the capacitance in Farads in the integrating circuit.
k = the absoute value of the ratio between the outgoing tension from the main amplifier and the ingoing tension to the pre-amplifier.
B = the vertical component in Gauss of induction in the loop area.
V = output tension from the main amplifier.

It has been found by measurement that the amplifying arrangement has negligible distortion for the frequency range in question, this being tested among other things by feeding different curve forms from a test generator. The resistance and leakage capacitance may be ignored and there is therefore obtained, when the time constant of the integrating circuit is selected sufficiently large, the relation:

$$V \approx -\frac{k\,S\cdot 10^4}{R\,C}\int_0^t \frac{d\,B(\tau)}{d\,\tau}\,d\,\tau = -\frac{k\,S\cdot 10^4}{R\,C}\,[B(t)-B(t_0)]. \qquad (1)$$

3. Measurement stations and local interferences

The loop method was tried out for the first time in 1954 at one of the Institute's field stations at Funbo-Löfsta. At a depth of 10 cm there was laid a loop of 5500 m^2 area, consisting of a lead-sheated telephone cable with two parallel insulated copper wires 0.6 mm diameter inside the cable. These were linked to the measurements and in the vicinity of thunderstorm weather showed that the measuring method was quite serviceable. The magnetic field variations were obtained both for the main strokes of the lightning and for superimposed rapid field variations. The results showed good agreement with corresponding measurement results on screened frame aerials.

With the object of also measuring the magnetic field variations for electrical atmospheric discharges at great distances, further trials were put in hand at the Institute's field station at Åkerby. At this station the outer field conditions were not interfered with, owing to a large level open plain around the station. On the open ground surface, which consisted of homogeneous clay-mixed arable land, a loop of 1 mm^2 copper wire with plastic insulation was laid about 10 cm deep in the ground. The single turn loop had an area of 20,100 m^2. For checking purposes, a special screened frame aerial of 20 turns sufficiently far apart to avoid self oscillations in the frame was put up. The total area of the frame turns amounted to 2000 m^2.

As stated, the experiments were designed for atmospheric discharges at lengthy distances. This required that the measurements should be made with the greatest possible amplification. It was found that both the frame and the loop gave evidence of strong local interference, which obviously emanated from the ground surface lying beneath the measuring devices. Oscillographic analysis showed that the main interference came from the ground and from the 50 cycle alternating current power system. This main interference was accompanied by a superimposed 150 cycle interference, which obviously increased with the load in the 50 cycle AC system.

Interferences of equivalent type with superimposition of 150 cycles had not arisen even with great amplification at the earlier station at Funbo. Closer investigation

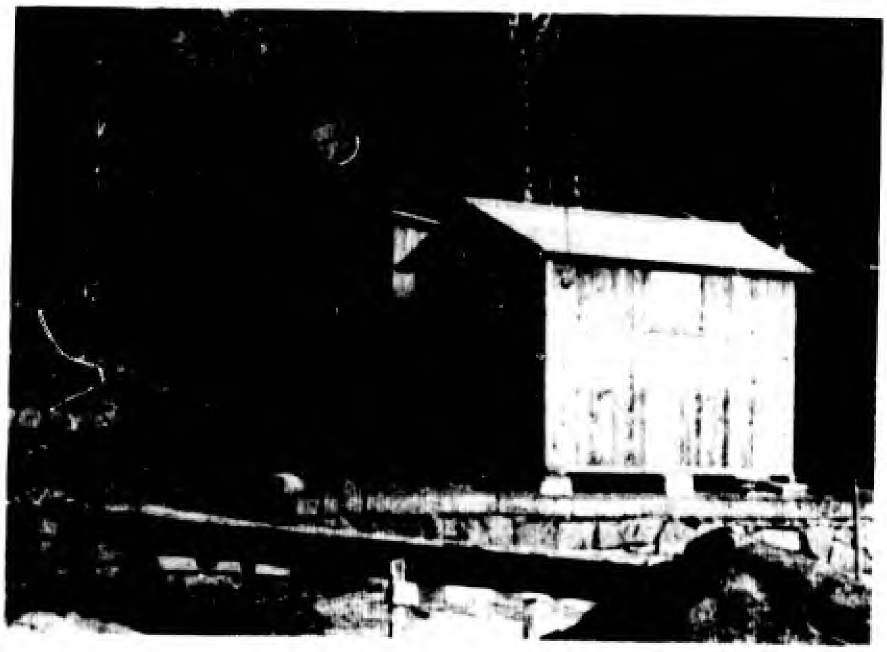

Fig. 2. Field station Kaptensudden, Funbo.

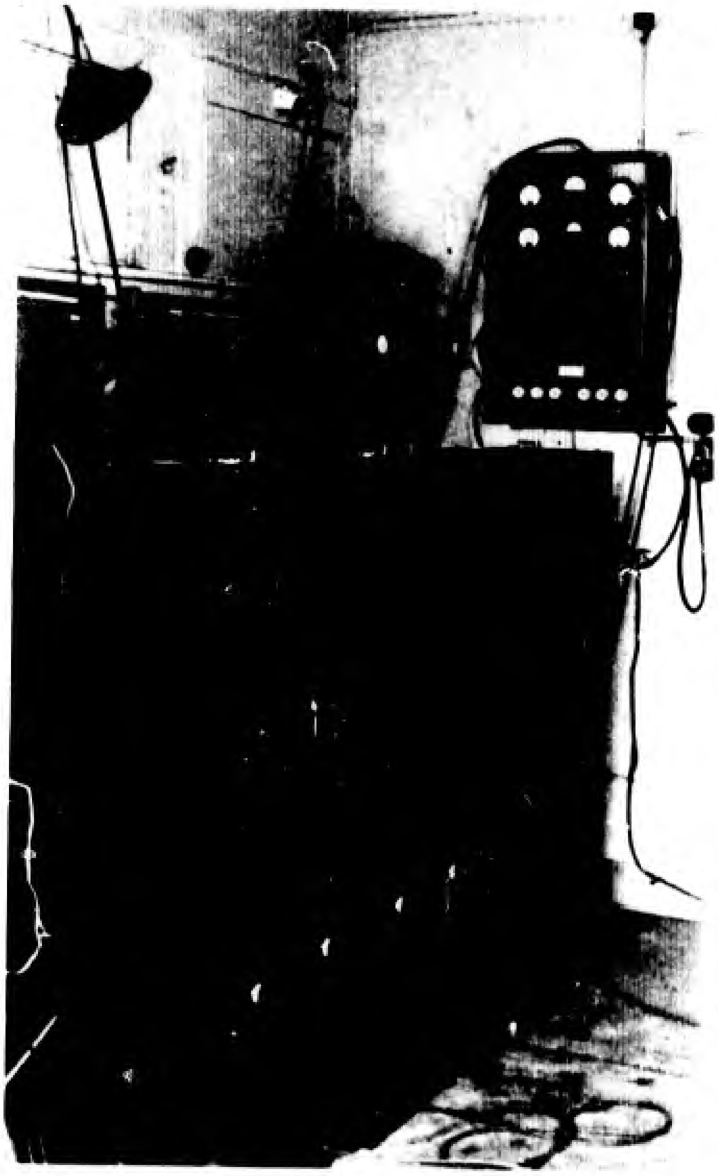

Fig. 3. Recording cathode-ray oscillographs used in investigations.

showed that the interference in the station at Åkerby had a special cause. Because of the adjacent airfield, all electric power aerial lines supplying the farms of the region had been removed and all electric power distribution in the region had been laid in underground cables. It was this underground cable system in the ground area that produced both the 50 and the 150 cycle interferences. As the latter interferences varied with the load in the power system, it was not found possible to work out simple compensation circuits. However, it was found that for measurement of lightning discharges during nearby thunderstorms in the areas up to 60–70 km distance the magnetic field components have amplitudes that are large in comparison with the local interferences. In these cases the interferences can therefore be ignored. However, it was found that for measurement at lengthy distances with great amplification the station at Åkerby was not suitable.

Consequently it was necessary locate further investigations on the loop method at other measuring places. One trial consisted of a small single turn loop with an area of 314 m², which was located at a field station at the Institute. It was found,

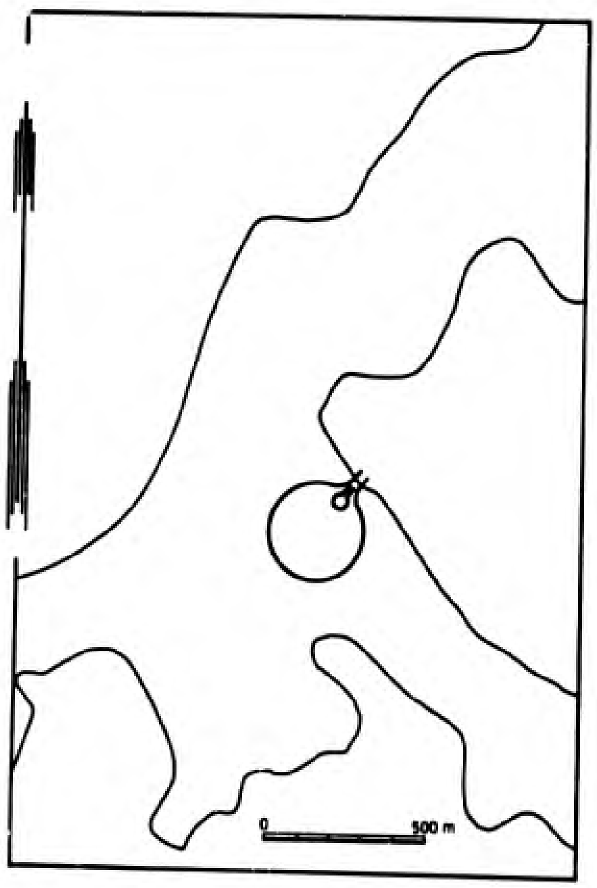

Fig. 4. Map of lake Trehörningen with measuring loops.

as expected, that a large transformer station in the vicinity produced considerable 50 cycle interference. Nevertheless this did not prevent measurements of the magnetic field variations from lightning strokes at distances up to 20–30 km from the measuring loop.

It proved necessary still further to increase the sensitivity range for the loop method and a region must be sought where the interference level for 50 cycle interference was low. For this reason the further measurements on the loop method were arranged at a measuring station specially established for the purpose, Kaptensudden, Funbo, see Fig. 2. The station was provided with 3 recording cathode-ray oscillographs (see Fig. 3) and it was also provided with a direction finder of the cathode-ray oscillograph type [6]. The station was situated on the shores of a lake—Trehörningen—a circumstance which made it possible to lay suitable loops on the lake bed at a depth below the surface of the water of 3–4 metres. The bed consisted of a thin layer of ooze on a deeper layer of blue clay, and this bed must be regarded as very homogeneous and suited to the measurements.

As shown on the map of Trehörningen Lake in Fig. 4, there were laid at the measuring station on the lake bed two loops of 150 m and 80 m radius respectively, the areas being 70,600 m² and 20,100 m² respectively. By laying the loops on the lake bed very low interference levels were assured, enabling measurements with very considerable amplification to be made.

Calculations made of the magnetic variation forms coming into the loops from lightning discharges and also for other and weaker electrical discharges in the atmosphere showed that attenuation due to the water could be entirely neglected. The fact that the loop was laid on the lake bed made it possible to carry out an important check of the measuring method, by measuring in winter the magnetic variations from a loop placed on the lake's ice surface. It was a matter of deciding in particular whether the loop method really did measure the components of the magnetic field without any disturbing action of the components arising at the same time from the electric field.

The loop recording method had earlier been checked by comparisons with simultaneously recorded oscillograms from the loop and from the horizontal frame aerial as already tried out and extensively employed. This check showed good agreement. It was also a question of deciding whether a loop laid either on ordinary ground or on an ice surface was affected by the electric field's component, particularly where measurements from interference sources at a great distance were concerned. The loop was laid for this purpose in a circle, either on the ground or on the ice surface, being then extended to form two parallel conductors. The deflection for magnetic field values diminished progressively as the loop extended to the two conductors growing more and more parallel. This was found to apply also for the perturbation forms referred to as due to the 50 cycle power system. A particular advantage of the method using the loop system is that the measuring device can easily be concealed in the ground or the water, so that it is not subjected to outside damage.

4. The field force variations measured — their relation to the distance from the lightning paths

As stated earlier, the measurement with the loop represents a purely magnetic measuring method. The results were obtained at varying distances from the lightning paths. It has long been known that the magnetic field is subject to pronounced change in amplitude with varying distance from the discharge centre. In the vicinity of the lightning path the field force is dominated by the current intensity I of the lightning, but even at a distance of 10 kilometres the influence of the lightning stroke's first derivate dI/dt will be nearly equal to the influence of the current I. At a greater distance the influence of the dI/dt term becomes dominant. As long ago as 1925 Lejay [7], basing on Maxwell's fundamental equations, could calculate how the magnetic field force changed with the distance from the lightning path. The calculations are on the assumption that the lightning paths are straight, but the direction in relation to the earth's surface is arbitrary. The simplest case refers to a vertical lightning path of height h with current intensity I and the first derivate dI/dt. For an observation point on the earth's surface at a distance d greater than h, and where c designates the velocity of light for the magnetic field force H in C.G.S. units, there is valid the equation:

$$H = \frac{2h}{d^2} I + \frac{1}{c} \frac{2h}{d} \frac{dI}{dt}. \tag{2}$$

By aid of the equation (2) it is possible, on the basis of the ranges of distance from the lightning path, to divide the magnetic field force variations into three main groups: (1) The vicinity region where the field force is entirely dominated by the I term with typical aperiod variation forms in the magnetic field force. (2) The transition region, where dI/dt begins to make its influence felt and the aperiodic variation form begins to show a quasi-periodic tendency. (3) The long-distance region, where the variation form goes over to typically quasi-periodic.

In respect of the varying values applying both to the lightning current I and to its first derivate dI/dt, it is possible in some cases to measure extremely fluctuating values as regards both amplitudes and variation forms in the magnetic field. From this point of view the equation (2) should rather be considered as a guide for orientation in the subject. In this connection it should be borne in mind that the magnetic field variations of the lightning stroke are almost invariably accompanied by rapid superimposed variations of a quasi-periodic character. As is known, they give rise at long distances to the groups of quasi-periodic variations which accompany lightning strokes.

5. Magnetic field force variations in the vicinity region

As stated in another connection, simultaneous recordings have been made in the vicinity region on a horizontal frame and on loop. The purpose was to check whether there was agreement between the two methods of measurement as regards both amplitude and variation form. In Fig. 5 oscillograms are given for two lightning strokes, that to the left in Fig. 5 consisting of one stroke in the path and that to the right showing two consecutive strokes in the same lightning path. As may be seen, the agreement between the two methods is good. Nevertheless a slight difference in the amplitude values is apparent, depending on the difference in sensitivity of the circuits used.

As has been stated, the magnetic field from lightning discharges can in some cases be characterised by rapid superimposed variations which extend over considerable

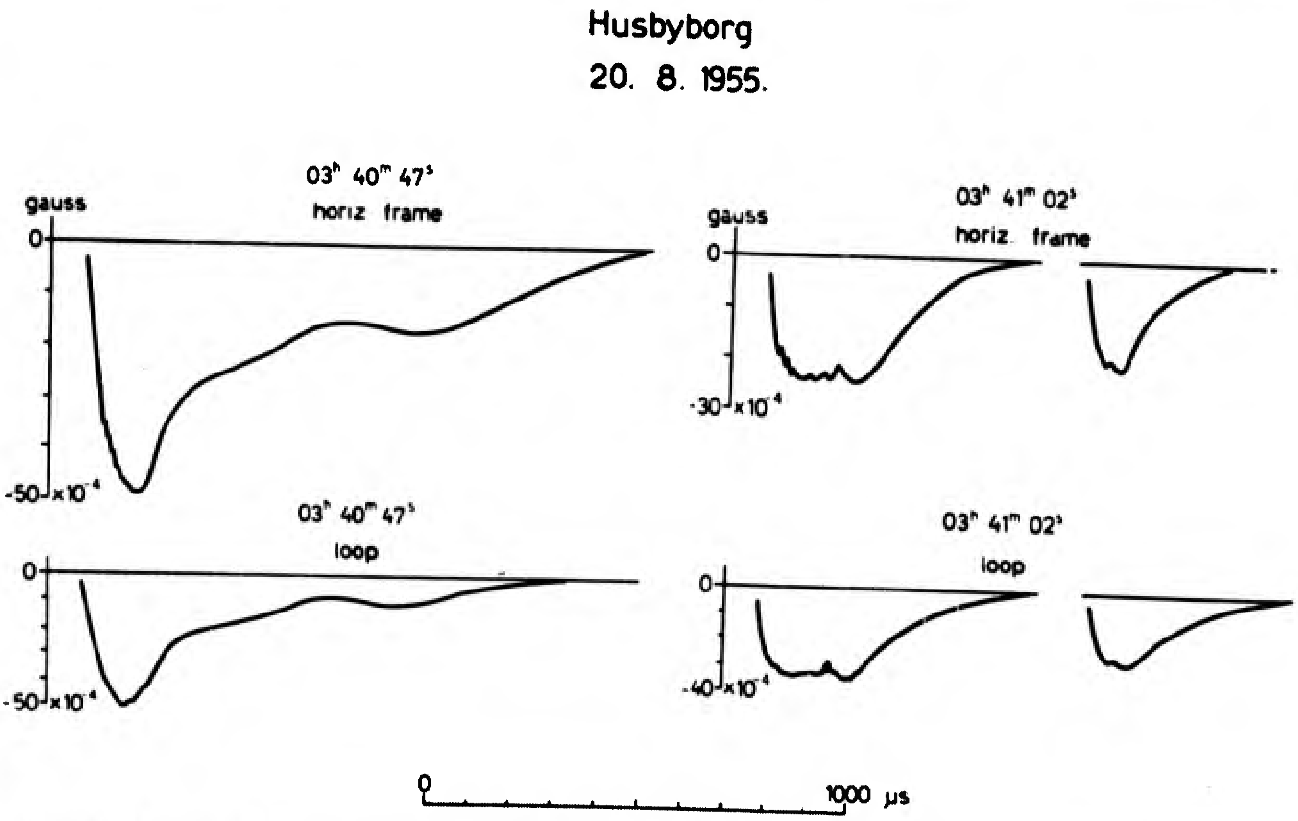

Fig. 5. Oscillograms of lightning strokes with comparison between frame aerial and loop method.

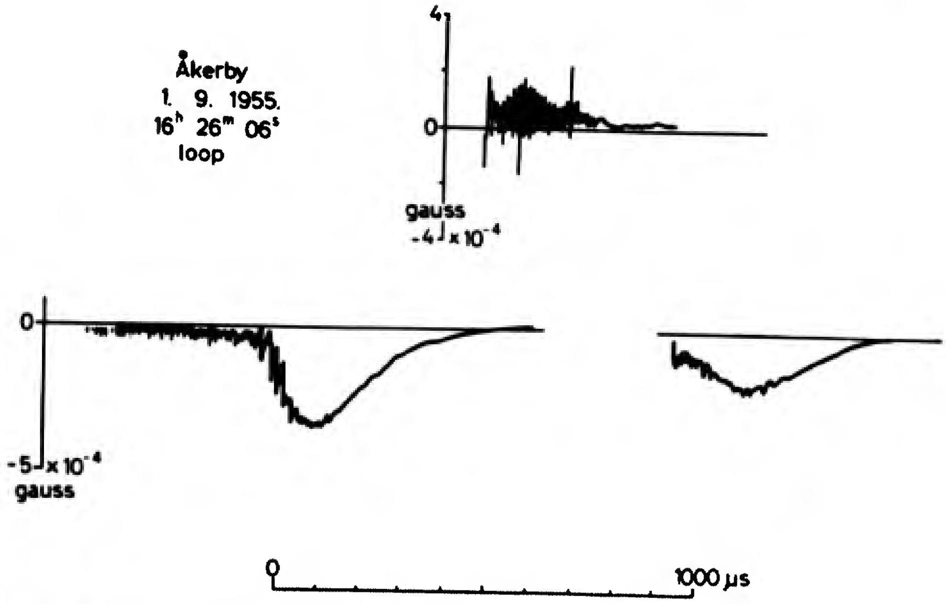

Fig. 6. Three consecutive strokes in same lightning path recorded with loop method showing superimposed variations.

Fig. 7. Photograph of lightning path of Fig. 6 taken in full daylight with electronic device.

portions of the discharge process. An example of this is given in Fig. 6, where a lightning discharge consisting of three consecutive strokes in the same path shows greater assemblies of superimposed rapid variations in the oscillograms taken with the loop system. For this discharge there is available a photograph taken in daylight at the same measuring station, Åkerby, see Fig. 7. In this case the camera shutter was actuated via a thyratron circuit connected to an electronic relay which reacted for the pre-discharge associated with the lightning.

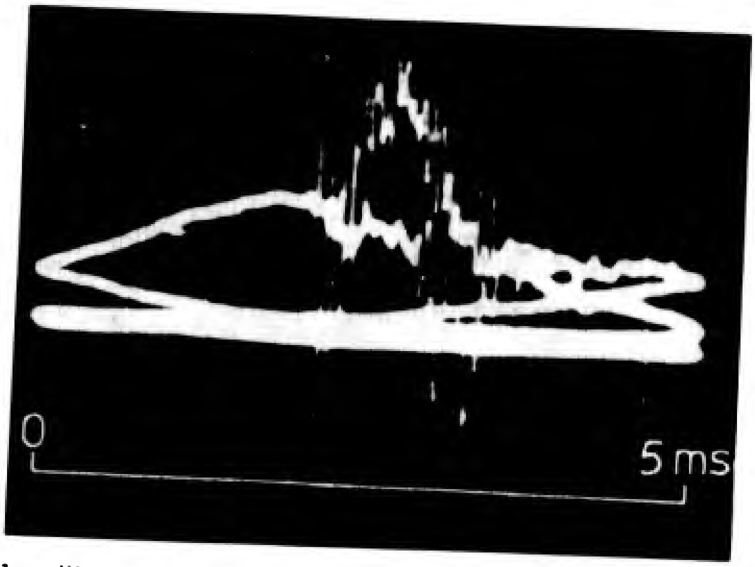

Fig. 8. Original oscillogram showing rapid superimposed variations taken with loop system.

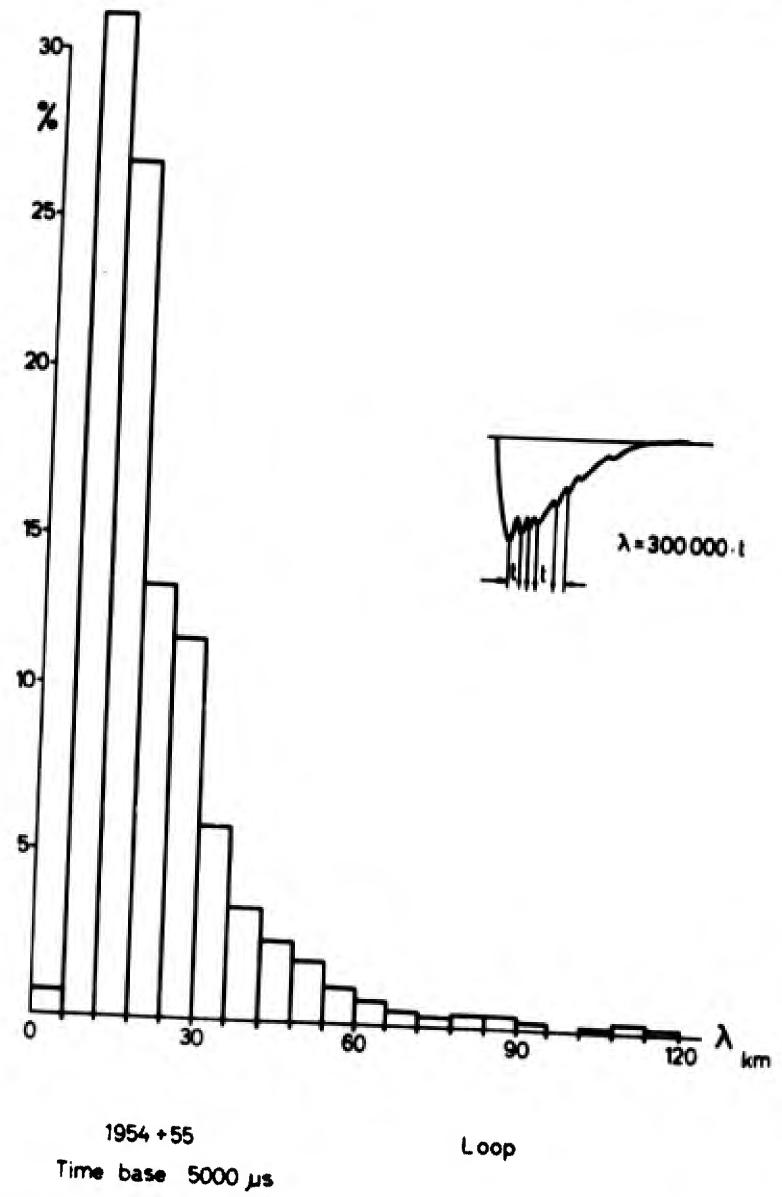

Fig. 9. Wave-length ranges of superimposed rapid variations from loop system.

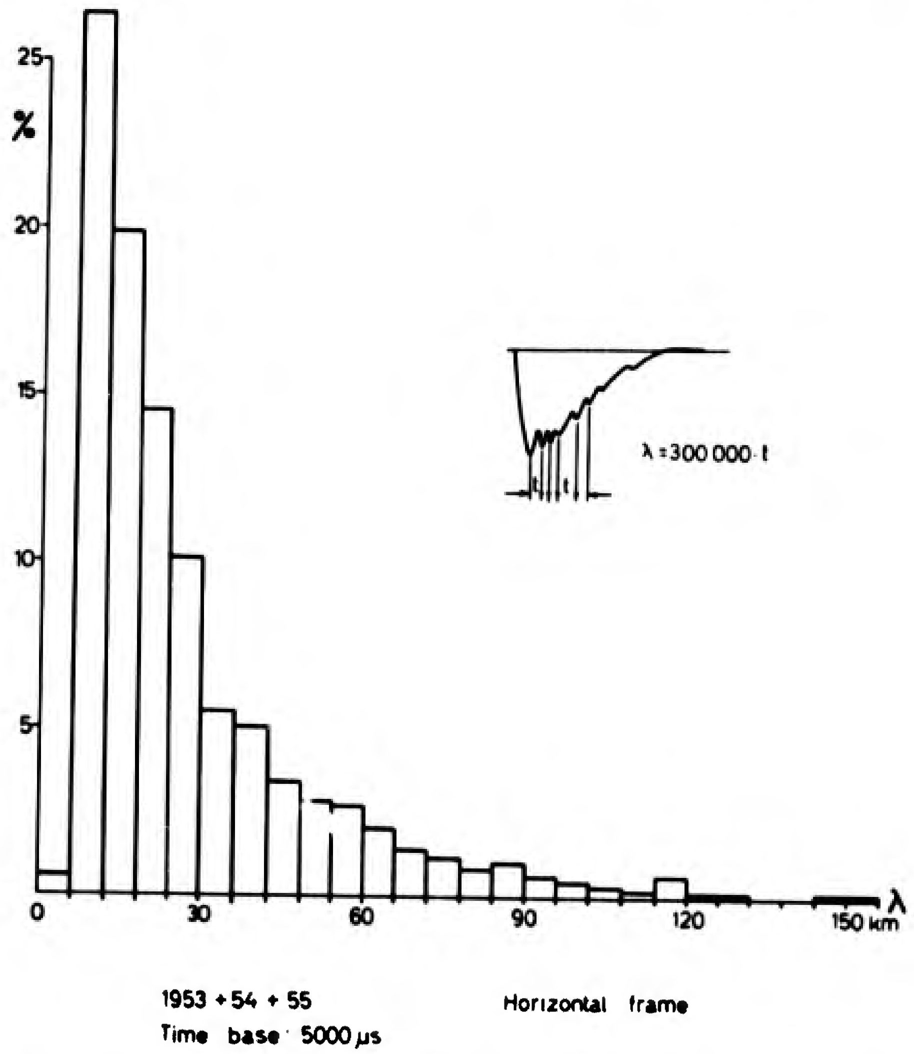

Fig. 10. Wave-length ranges of superimposed rapid variations from frame aerial system.

In the years 1954 and 1955 a large number of oscillograms were taken in the vicinity region, both on the frame method and on the loop method. These have often shown a number of typical superimposed variations similar to what appears on the above-cited Fig. 6. In Fig. 8 there is given an example of an original oscillogram of rapid superimposed variations recorded with the loop system.

It is of great interest to compare by means of statistical analysis the distribution in the wave-length ranges of superimposed rapid variations for the two measuring methods. The result of such an analysis may be seen in Figs. 9 and 10, which display an unusually good agreement in the wave-length distribution between the two methods. The statistic analysis shows for the two methods the greatest accumulation of wave-lengths in the 5–10 km interval and the 10–15 km interval respectively. In these ranges is to be found the wave-length of 11 km recommended at several of the General Assemblies of the International Union for Scientific Radio (URSI) as suitable for direction finders operating with tuned circuits. Thus it has been found that the magnetic field in lightning discharges has its maximum occurrence of quasi-periodic wave-lengths in the said wave-length band. These wave-lengths have their origin in rapid superimposed variations on the main lightning discharge curve at the source. It is probable that the same wave-length distribution will also hold good for pre-

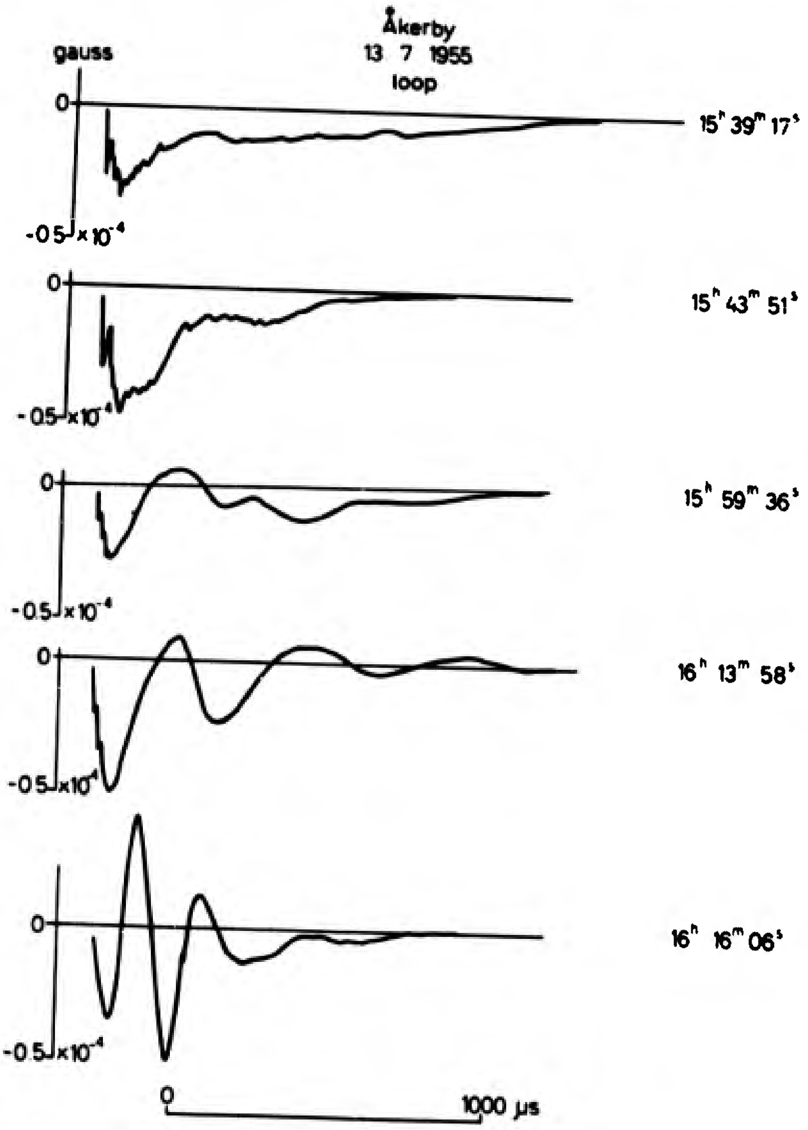

Fig. 11. Transition with distance of variation form of lightning discharges recorded by loop system.

discharges to lightning strokes. The material has not yet been completely treated in this respect.

6. Transition region for quasi-periodic variation

It is particularly interesting to investigate the range of distance from lightning paths where the magnetic field force changes from aperiodic to quasi-periodic variations form due to the influence of both I and dI/dt in equation (2). The most convenient method for such an investigation is constituted by simultaneous recording of the lightning strokes. These should be located at considerably greater distances apart than the distances of 7.0, 11.7 and 17.0 km, representing the distances from the Institute to the field stations at present in use.

Nevertheless, it is possible to make an orientating investigation for the transformation of the variation forms by systematic recording for some hours of the field changes for a thunderstorm. This should be restricted and be moving away from the recording station, which should be furnished with a direction finder for keeping track of the lightning paths in the thunderstorm as it draws away. In the

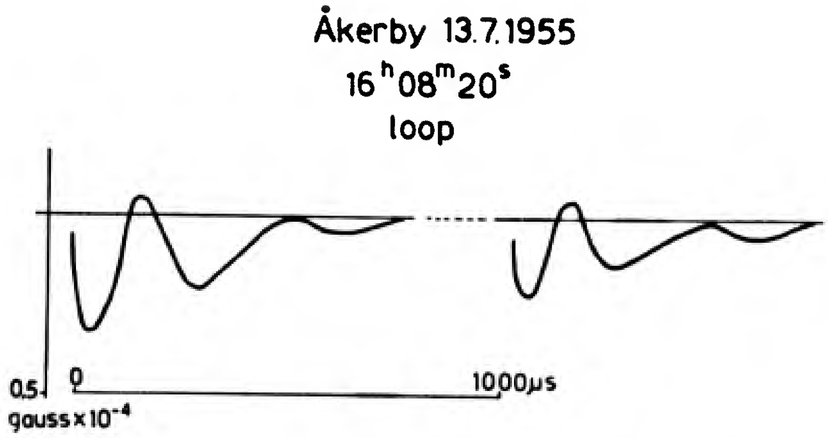

Fig. 12. Two multiple strokes in same lightning path.

1955 thunderstorm season two such thunderstorms were found, which progressively moved away from a measuring station, while at the same time it was possible continuously to record the magnetic field variations oscillographically by a loop system.

An example of magnetic field variations for a thunderstorm centre moving away during a given time from a field station is given in Fig. 11, where the field force values recorded follow one upon the other in respect of time. It is found that the typical aperiodic variation form for the top curve progressively changes to an ever more pronounced quasi-periodic variation form as the thunderstorm draws away. During the time the thunderstorm was moving away, multiple strokes were recorded in some cases and an example of two such strokes in the same lightning path may be seen in Fig. 12. Both of these display great resemblance in variation form to the lightning stroke which came 5 minutes later. The transformation in variation form for the consecutive lightning strokes in the same path has clearly proceeded equally far.

Another example of field variations in a thunderstorm drawing away are given in Fig. 13. In this case the recordings were made by means of the loop laid in Lake Trehörningen. The magnetic field variations in this case are arranged in 5 types, following on each other with growing distance from the thunderstorm's centre. The thunderstorm was moving away in a southerly direction from the measuring station and for curve No. 1 the distance had already reached 25 km. It is clearly seen how the curve form changes with the distance, which for the lowest curves in Fig. 13 was estimated at 70 to 80 km.

In this connection it should be observed that the magnetic field's amplitude change with distance cannot be judged by the method used in Fig. 13 with selected variation curves. This is owing to the great dispersion in the current intensity values for the lightning. From this it follows that lightning strokes at long distances may show almost the same amplitude maximum as those in the vicinity, due to changes in current intensity for the different lightning strokes. It is only possible by simultaneous measuring of the magnetic field at a number of stations suitably placed over an area that the field's variation with distance can be found.

Another measure of the progressive transformation undergone by the magnetic field's variation form as the thunderstorm draws away may be obtained by examination of the curve forms recorded during the time coinciding with the recording time according to Fig. 13. During that time there were taken 110 oscillograms altogether. It was found that during the first 20-minute period types 1–2 predominate and in the following 20-minute periods the types 2–3, 3–4 and 4–5 predominate.

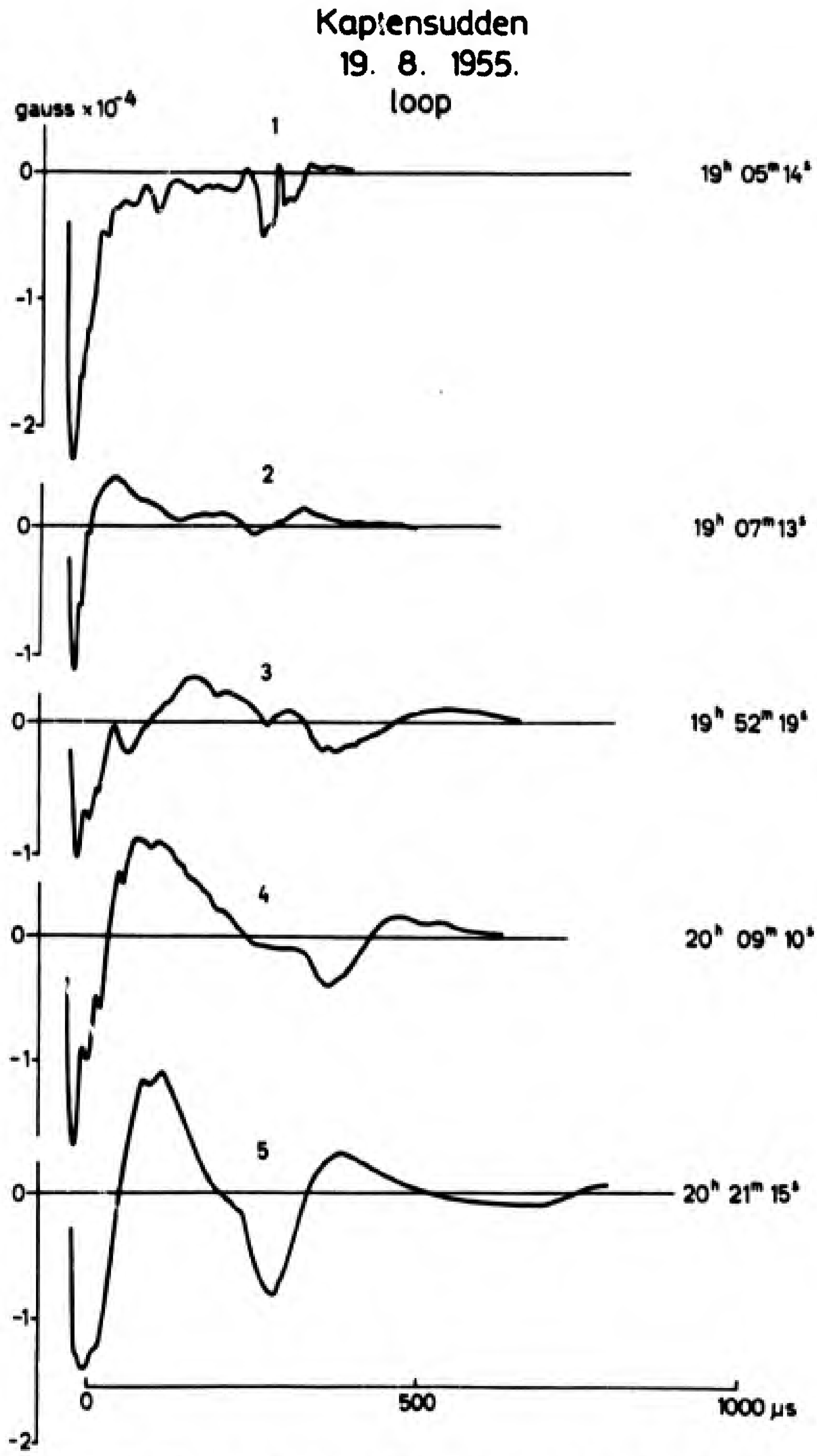

Fig. 13. Field variations of thunderstorm moving away.

In the two recording occasions reported here, we did not have the opportunity to determine the distance to the lightning path exactly. For a completely exact investigation of the extremely interesting transformation problem the field variations from the same lightning stroke should be measured for different distances and with exact determination of distance and observation of the lightning path for each measuring place. Such an investigation would require a larger staff and more instruments than were available to the Institute.

7. Variation forms at long distances

At distances greater than 100 kilometres from the lightning paths the dI/dt term dominates as per equation (2) the magnetic field force's variation form. For distances of this magnitude or greater the magnetic and the electric fields should according to theoretical computations give the same variation form. For closer investigation of these conditions, there were carried out during the late summer, autumn and early winter of 1955–56 a number of measurements at the station at Kaptensudden. Measurement was done simultaneously by cathode-ray oscillograph of the electric component with open antenna and the magnetic component with the loop method. The time circuits of the two oscillographic systems were operated with the same time sweep generator. It is possible with this method to judge exactly how the variation processes for the two measuring methods agree as regards time.

The investigation was chiefly designed to find for the great distances dealt with in this connection the agreement in variation form measured according to the two methods. In this preliminary investigation therefore it was not considered necessary in connection with what was referred to earlier to state the field force values, the more so as the distances from the centres for the electric discharges were not stated exactly but only apply to large areas. In determining the distance of the area there was observed by means of direction finders, at the same time as the taking of the oscillogram, the direction to the discharge recorded. By comparison with synoptic maps and by means of direct observations in the region of the discharges it was possible to determine approximately the distance of the disturbance sources for the curves reproduced later.

During the situation of 22.8.55 there was carried out simultaneously with oscillographic recording a determination by direction finder of the disturbance source. According to meteorological reports there existed at the time a cold front stretching

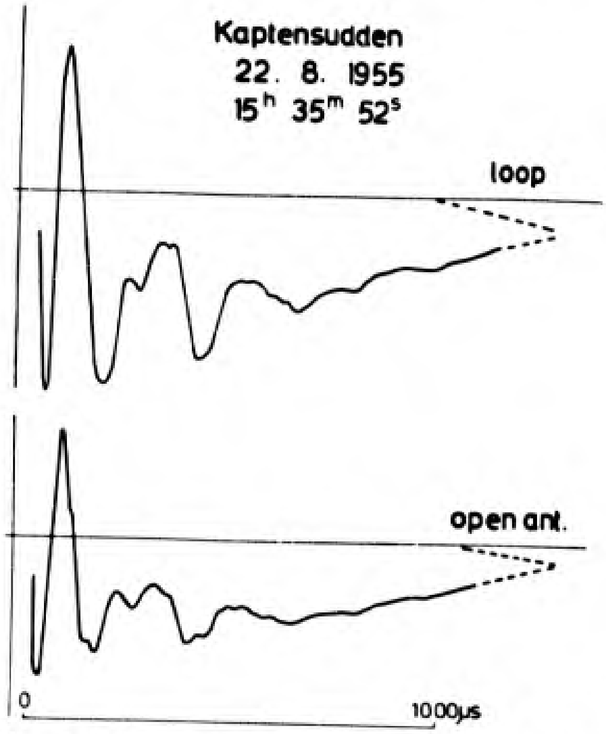

Fig. 14. Comparison between loop and open antenna method for long distant lightning strokes of irregular variation forms.

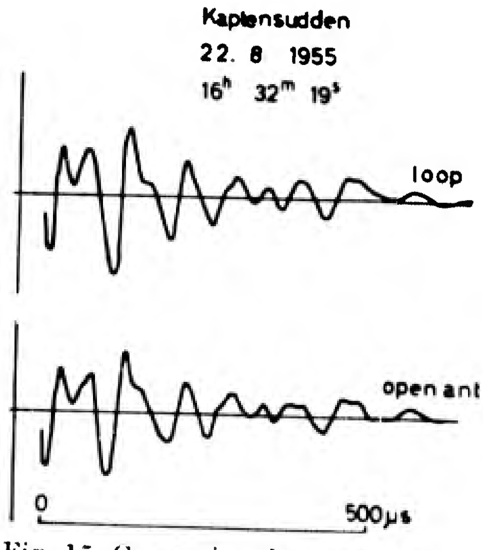

Fig. 15. Comparison between loop and open antenna method for long distant lightning strokes of irregular variation forms.

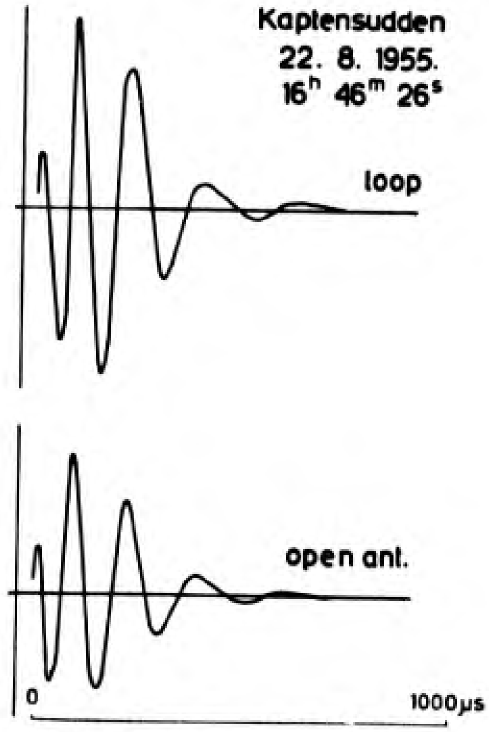

Fig. 16. Comparison between loop and open antenna method for long distant lightning discharges showing regular quasi-periodic variation forms.

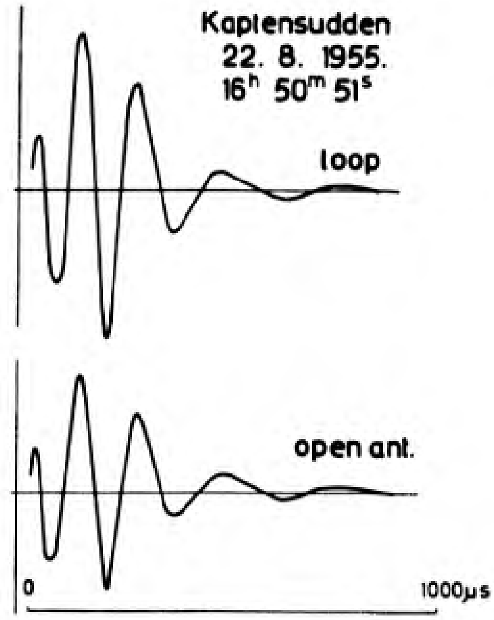

Fig. 17. Comparison between loop and open antenna method for long distant lightning discharges showing regular quasi-periodic variation forms.

from the Swedish town of Kalmar over the southern part of the Island of Gotland in the Baltic and up towards the southern part of Finland. This front was accompanied by thunder activity. The recordings are particularly interesting, seeing that for the most part they passed over a sea region. The distances from the discharges amounted to 300–500 km.

The two first recordings, Fig. 14 and Fig. 15, show a fairly irregular variation form, but despite this the agreement in the field variations between the oscillograms taken with the loop system and the open antenna system was strikingly good. The two later recordings, Fig. 16 and Fig. 17, show discharge forms of the typical quasi-periodic variation form which characterises common atmospherics. In this case, too, the agreement was very good.

During the thunder situation on 9.9.55 deflections were observed on the direction finder only in north-westerly directions. In this case the meteorological reports gave information of thunderstorms in south-west Lappland. The distances for the discharges amounted to 600–700 km.

The two first recordings, Figs. 18–19, are characteristic for quasi-periodic variation forms and the agreement between the loop system and the open antenna system is very good. In the two subsequent recordings, Fig. 20 and Fig. 21, the lightning strokes are characterised by much more irregular variation forms. In these cases as well there is agreement between the oscillograms obtained by the two measuring systems.

It was discovered some years ago at the Institute that electric discharges, distinguished from lightning discharges in their proper sense, arise during certain weather situations in snowclouds and especially in snow-squalls [8]. These discharge forms

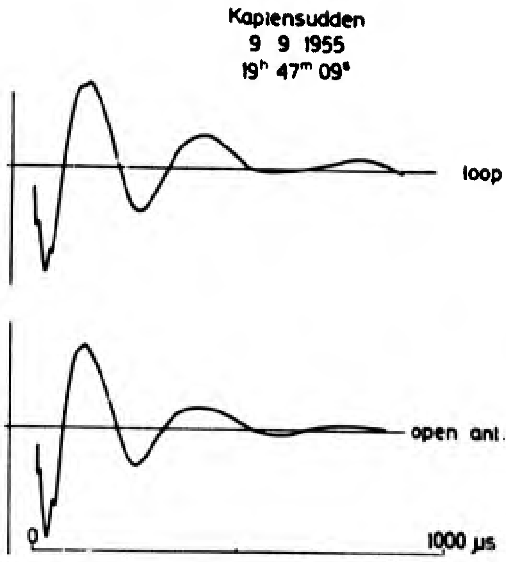

Fig. 18. Records of lightning strokes of quasi-periodic variation form obtained at distances of 600–700 km showing agreement between loop and open antenna system.

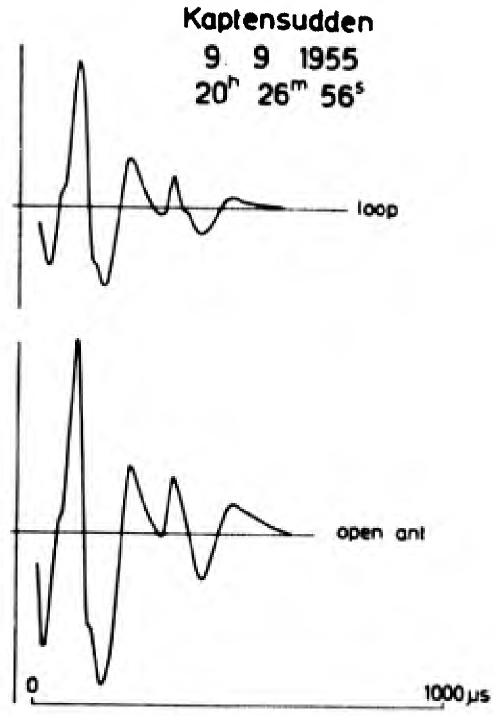

Fig. 19. Records of lightning strokes of quasi-periodic variation form obtained at distances of 600–700 km showing agreement between loop and open antenna system.

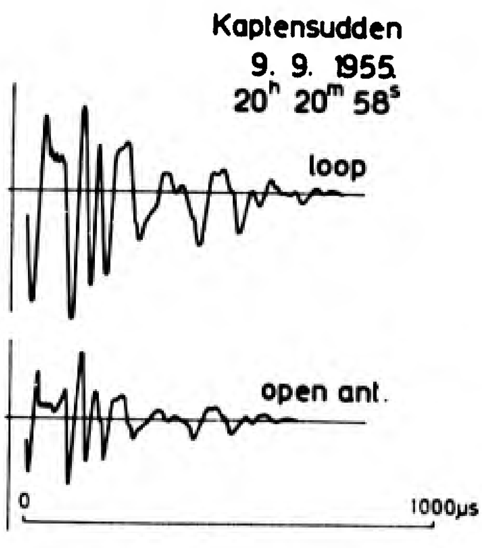

Fig. 20. Records of lightning strokes of irregular variation form obtained at distances of 600–700 km showing agreement between loop and open antenna method.

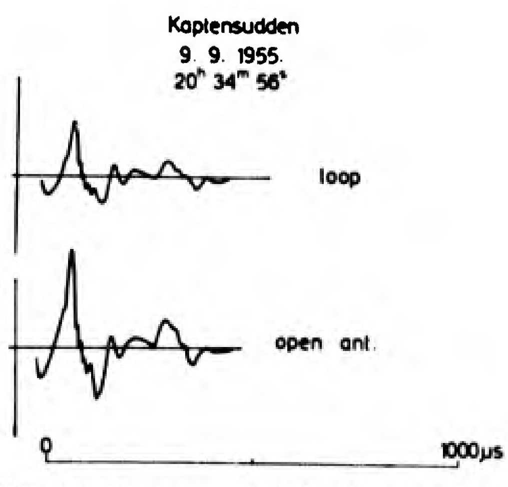

Fig. 21. Records of lightning strokes of irregular variation form obtained at distances of 600–700 km showing agreement between loop and open antenna method.

are characterised as a separate form of atmospherics with very mild variation forms. These were analysed on a number of occasions during the winters of 1954 and 1955–56 by oscillographic recording by means of the open antenna method with the direction of the regions where the discharges occurred determined at the same time by means

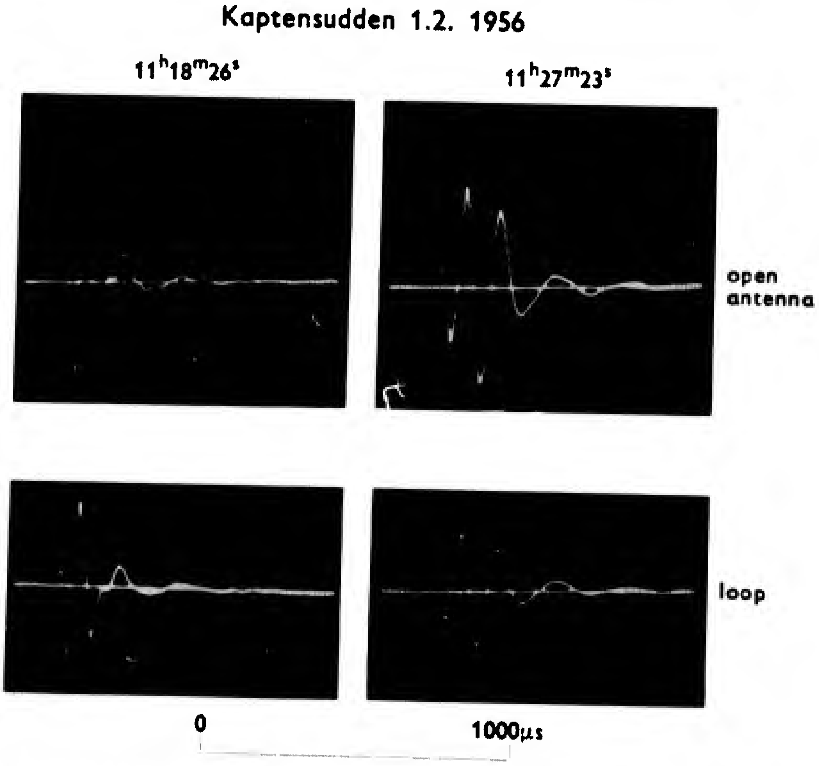

Fig. 22. Copies of original oscillograms of electric discharges emitted by snow-squalls from distance of 300 km taken with open antenna and loop method.

of direction finders. The electric discharge processes which cause this special form of atmospherics are undoubtedly much weaker than those applying to lightning discharges. None the less it is of special interest to investigate more closely whether it is possible to analyse them with the loop system. In the winter of 1955–56 there arose a number of weather situations in which the special form of atmospherics was emitted from snowclouds. Such a situation developed, for example, on 1.2.56 and in this case the source of the disturbances was localised to a distance of 300 km from the observing station, Kaptensudden. The disturbances were recorded simultaneously by the open antenna and the loop, and in Fig. 22 some examples are given in the form of copies of original oscillograms. The agreement between the two methods is very evident.

By means of the examples given it has been shown for the first time that the loop system can very well be employed for analysis of magnetic field variations emanating from sources of electric discharges in the atmosphere, whether these have the character of lightning discharge in its proper sense or of discharge forms with lower intensity, emanating from snow-squalls.

8. Summary

A new method for the measurement of rapid variations in the magnetic field generated by electric discharges in the atmosphere is described. The theoretical bases for the measurements are treated.

The new measuring method presents advantages over the oscillographic method using frame aerials previously employed by the Institute for High Tension Research, mainly in being less expensive and allowing of much greater sensitivity.

Systematic experimental comparisons with the frame aerial method have been made. The new measuring method permits of an analysis of the characteristic slow discharge variations in lightning strokes. The loop method also allows in the vicinity regions of the source of the disturbances the analysis of the rapid magnetic field variations accompanying the lightning discharges. These constitute sources of origin for the quasi-periodic wave-forms accompanying the lightning discharges, which have been analysed extensively by other authors at great distances from the disturbance sources.

Systematic oscillographic investigations were made of the magnetic field's variations from the disturbance regions with lightning strokes at distances varying between 300 and 700 kilometres. At the same time the electric field's variations were measured by the open antenna method. As might have been expected from the theoretical grounds, the two methods displayed good agreement.

ACKNOWLEDGEMENTS

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The Institute for High Tension Research, Uppsala University, May, 1956.

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HARALD NORINDER and BURGHARDT VOLLMER

Variation forms and time sequence of multiple lightning strokes

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Variation forms and time sequence of multiple lightning strokes

By Harald Norinder and Burghardt Vollmer

With 22 figures in the text

1. Introduction

For more than half a century it has been known, thanks to photographic methods with movable cameras [1], that lightning discharges consist as a rule of several strokes succeeding each other in the same path as the flash. As lightning represents an extremely complicated electro-magnetic discharge process in the atmosphere, investigations by optical means can only be employed to a limited extent for study of the course of the phenomenon in lightning and, in any case, not at all as regards the electromagnetic components.

It was only with the employment of cathode-ray oscillographs as measuring instruments for the analysis of lightning discharges that research respecting the electromagnetic variation forms of lightning discharges could be directed on quite another plane. This was done in Sweden towards the beginning of the 1920's [2] and it was not long before researches with the same methods, in the following 25 years, attained very rapid development, especially in the United States.

In the course of that investigation work the existence of multiple strokes in the lightning paths was once again discovered. On account of certain practical interests it was considered imperative, for the investigation of such multiple strokes, to develop a simple but robust measuring device: the fulchronograph [3]. The instrument constituted an interesting modification of the much-used method with magnetic links [4] for the measurement of peak values in the lightning current when earth-connected objects were struck. In the fulchronograph, use was made of magnetic links placed on a highly rotating wheel. The small speed of rotation of the instrument where the recording of the rapid variations in the lightning current was concerned did, indeed, enable the peak current values of passing multiple strokes in a lightning channel to be obtained, but on the other hand it was not possible to study either the variation form of the discharges or the interval of time between the discharges, which is so important from many points of view. This constitutes a definite limitation in the measurement method, as closer analysis of both the lightning current's variation form and the interval in time between multiple strokes is of consequence in various respects for the application of the research results.

For instance, in dealing with the noise level from atmospherics due to lightning discharges it is important to know both the variation structure and the intervals between the partial discharges. This is not least important when it is a question of investigating the distribution of atmospherics, also called sferics, on certain regions of the earth's surface. Even when it is a matter of investigation of the variation form of sferics, the question of multiple strokes is important. As a rule when measuring one can only record the sferics occurring with the strongest amplitudes, the others are concealed below the lower limit of the sensitivity level.

In consideration of the above viewpoints the definite conclusion has been reached in the Institute for High Tension Research that it must be necessary where multiple strokes are concerned to develop and apply a measurement method based on analysis with cathode-ray oscillographs. In this connection, both the variation form of the current and the time sequences between multiple strokes are of essential importance.

2. Analysis of lightning current variation forms

In Sweden at the Institute for High Tension Research there is used since many years a quite special investigation method in respect of the current variation of lightning. We have made use of the variations produced in the magnetic field in the vicinity area of the lightning discharges. The measurements have been carried out with the aid of frame aerials set up in vertically or sometimes in other planes to the earth's surface. Tension variations from the frame aerials have been recorded over amplifiers by means of cathode-ray oscillographs. In this way it has been possible to measure the variations in the magnetic field caused by currents in the lightning discharges. Details and results of this investigation method will be found in earlier publications [5], [6]. Already in these publications it was, as will be discussed further on, possible to measure the variation forms of currents in multiple strokes. By the method it was also possible to obtain an insight into the time sequences of multiple strokes.

At the Institute for High Tension Research the investigations of lightning discharges in their vicinity areas by means of the frame aerial method have been taken up again in a far reaching way during the thunderstorm season of 1953 and fulfilled during the following seasons of 1954–56. The new investigations have been concentrated to the simultaneous variations of the magnetic field from lightning strokes as obtained at two or three field stations in the vicinity regions of lightning discharges. Measuring methods and results from the first season, mentioned above, are published [6].

The advantages of the frame aerial method for investigations of the variation features of lightning currents are quite obvious. Hence it must be considered as a matter of course that the method should also initiate the following application for investigations of variation forms and time sequence of multiple lightning strokes.

3. Variation forms of magnetic fields and currents in multiple strokes

The first results in respect of measurements of the variation forms in multiple strokes have been treated in the work cited above [5]. The original oscillograms of two utmost remarkable multiple strokes from the above-mentioned publication are reproduced in Fig. 1. These oscillograms were obtained by a very speedily recording cold cathode-ray oscillograph [7]. That the lightning discharge consisted of two strokes in the same path follows from Fig. 2 where the two strokes have been recorded by another oscillograph with a slow time variation.

The lay out of the two strokes is given in Fig. 3 where also the corresponding calculated current variations in the discharges are given. This calculation was possible

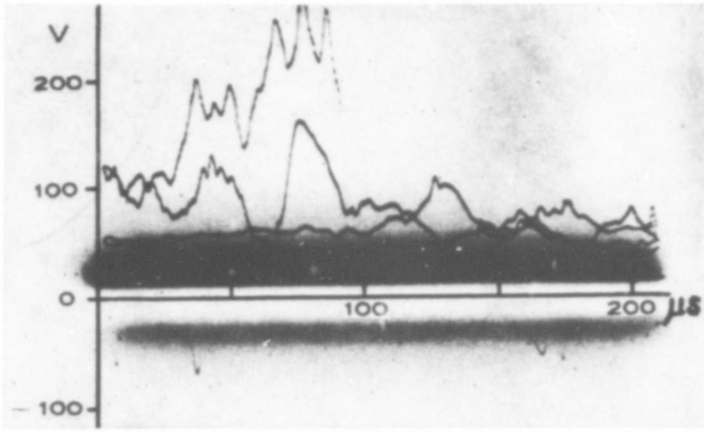

Fig. 1. Oscillogram with high-speed variation of igniting and killing flash.

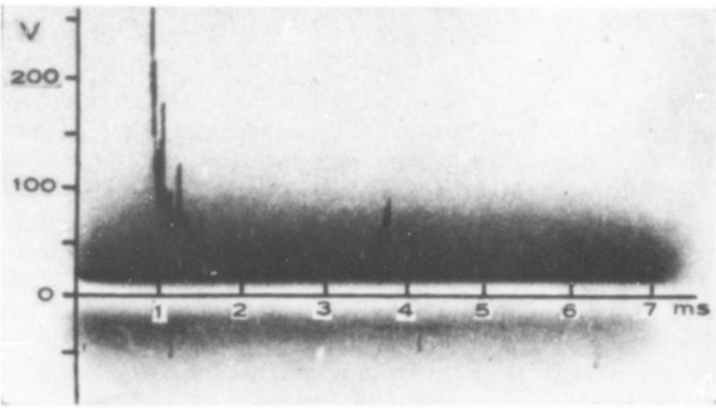

Fig. 2. Oscillogram with slow-speed variation of lightning flash of Fig. 1.

thanks to the known distance from the stroke to the cathode-ray oscillographic station. This distance was 4.5 kilometres. The lightning path was strictly vertical against the earth's surface as observed directly by one of the authors (N.). The length above soil of the lightning path, obtained by angular measurements by two observers, was 0.9 kilometre. From the front times of the discharges and with a penetrating velocity of the tip of the lightning of 100 metres/µsec the length was calculated to be 1 kilometre.

The vertical lightning hit the ground in an open field where a farmer with a hay-cart, a horse and a helpmate represented the highest object within at least 300 metres around. The ground was very homogeneous at the point of the stroke and consisted of a thin layer of cultivated soil on a very deep layer of clay.

The lightning flash had a very tragic consequence. The farmer was hit by the stroke, his dress and the hay were set on fire. The helpmate became unconscious. The farmer's watch stopped at the exact time of the stroke and both the watch and its chain showed typical melting traces. By laboratory experiments the same melting effects were

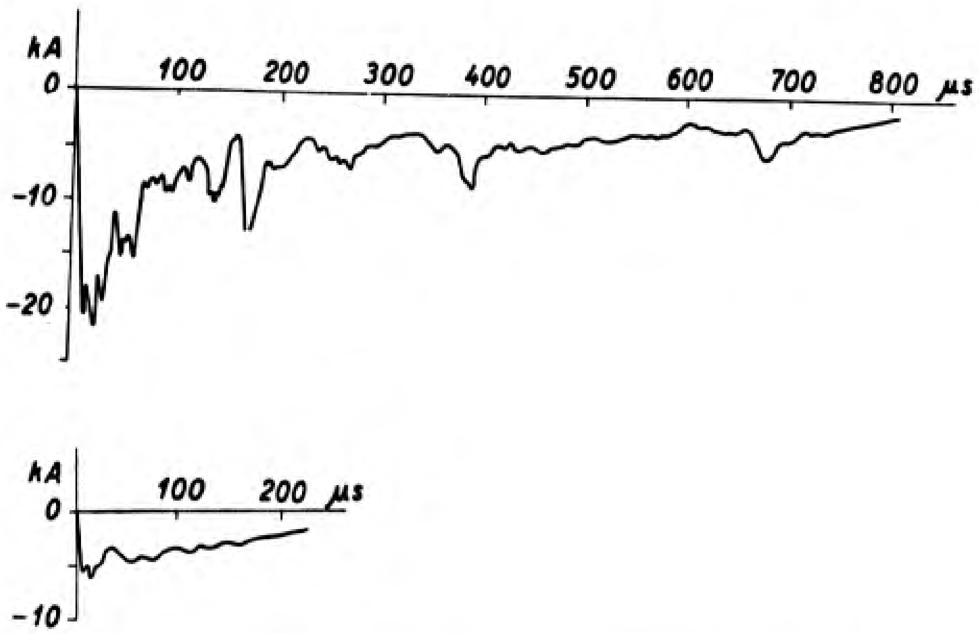

Fig. 3. Current variations in igniting and killing lightning flash.

obtained on a similar chain as the one attached to the watch when applying a current of the same variation structure as that of the severe lightning stroke—viz. a peak value of the current of 22.5 kiloampères and a duration of 1000 μsec. The behaviour of the horse in the front of the cart was quite peculiar. The horse which had fallen down on his knees at the stroke was taken out of the shafts and raised itself after a shout. He walked some steps and began to eat, but fell down dead after a little while.

Another interesting example of the variations of multiple strokes, taken from the quoted work [5], is reproduced in Fig. 4. From this it will be seen that the current intensity variations are characterised by superimposed rapid variations and in some cases of rapidly growing rises in the initial current intensities.

It should be stated that the individual curves exemplified in Figs. 1–4 for multiple strokes are taken from investigations at the Institute carried out so long ago as the thunderstorm seasons of 1940–41. They were recorded with a cold-cathode-ray oscillograph [7] in which a special relay device was employed. This screens off the slow after variations in the discharges, so that the duration for the current curves recorded cannot be fully reproduced. The curves dealt with below, however, were recorded with sealed off cathode-ray oscillographs and with these there are also reproduced lower amplitudes of the slow after variations in the current.

It is worth noting that the measurements of the magnetic field in Figs. 1–4 were made with vertical frame aerials. The same method was employed during the 1953–55 thunderstorm seasons for the measurements which will be dealt with in this work.

An original oscillogram taken from the investigation material produced from the measurements during the 1953–56 thunderstorm seasons, is reproduced in Fig. 5. Oscillograms of this kind have enabled analysis to be made of the variation forms in individual multiple strokes. With such an analysis it was not possible to establish the sequence of time of strokes coming one after the other in the flash. It was not until the 1955 thunderstorm season that a special device tried out in experiments was available, which enabled investigations to be made of the time sequence of the strokes.

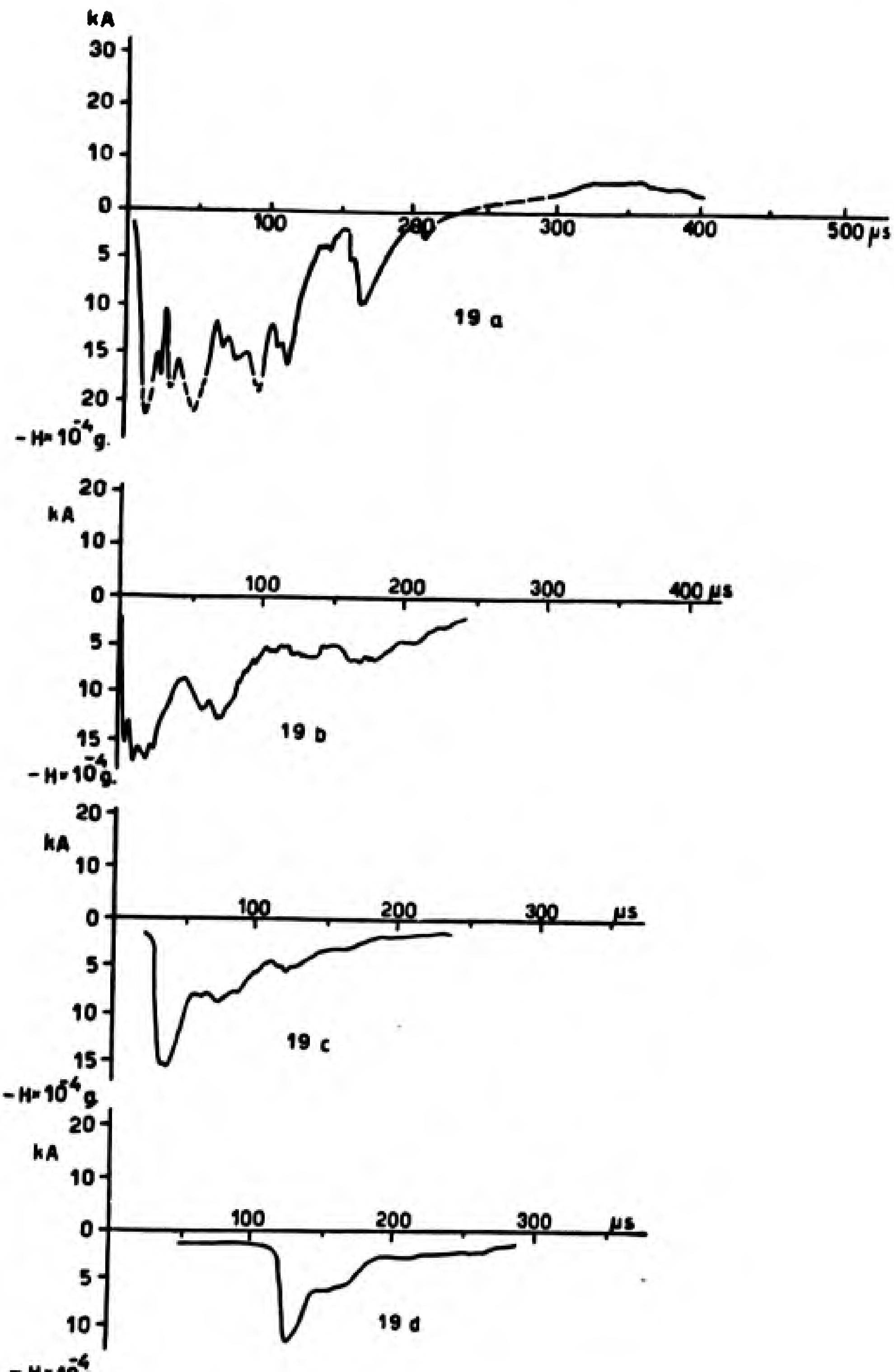

Fig. 4. Oscillogram with high-speed variation of multiple strokes.

Even in 1955 it was possible to analyse the variation form in multiple strokes recorded simultaneously at two stations, Husbyborg and Åkerby, with a distance of 7 km between them. Two examples of these recordings are given in Figs. 6–7. The distances in these figures represent the respective distances between the stations and the lightning paths. It was then found that the variation forms agreed surprisingly

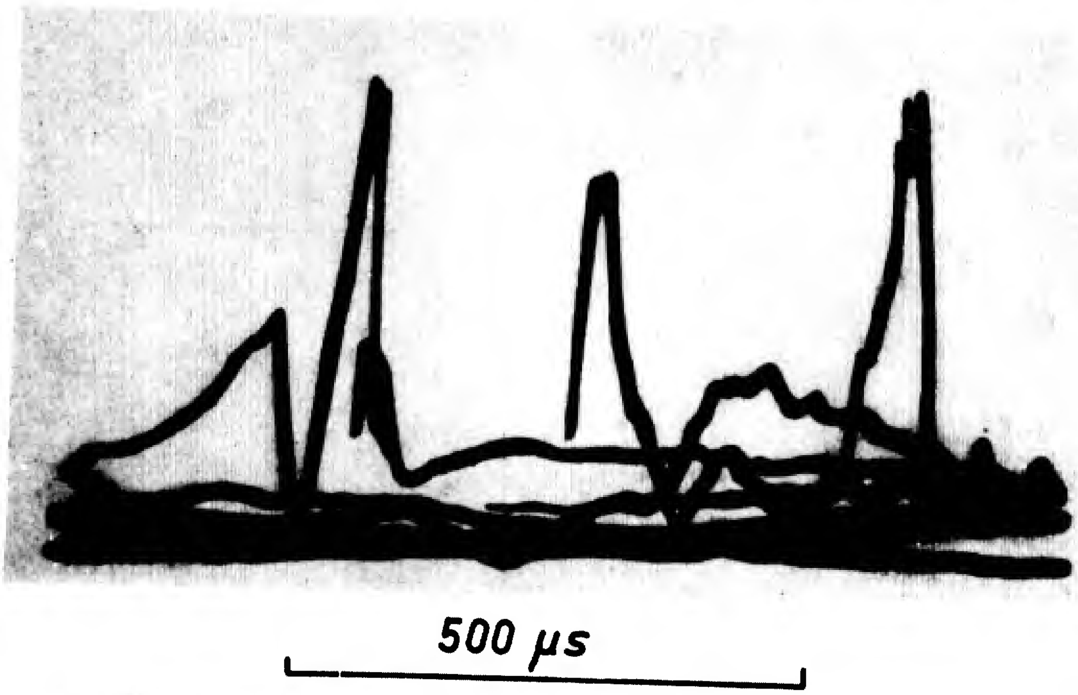

Fig. 5. Original oscillogram of magnetic field variation in multiple strokes.

well between the two stations, an extremely important result with a view to calculation of current intensities. As may be seen, the amplitudes are different, this being due to the distance of 7 km between the two stations and to the respective distances to the lightning channel being different in the two cases.

The data obtained for the variation forms for multiple strokes from one of the three stations employed in the investigations are extremely comprehensive. For the most part there have appeared essentially different variation types. One of these, which is very common, is characterised by a typical steep front. In respect of the steep fronts reproduced, it is worth noting that the long time axis sweeps of 1000 μsec and in exceptional cases 5000 μsec do not allow of exact reproduction of the front slopes in μsec. Up to now it has not been found practical within the scope of the investigation programme in this paper to include an accurate measurement of the front slopes. Such an investigation demands a special equipment and operation in respect of cathode-ray oscillographs. Work in this direction has been put in hand and will be published in another connection.

A couple of typical examples of variation forms with steep fronts are shown by Figs. 8–9. The magnetic field is characterised, particularly in Fig. 9, by pulsing variations which arise after the front has passed and which change in time to corresponding variations of the current in the lightning channel. From the curves in Figs. 9–10 it appears that one may not at all regard variation curves with a smoothed out course as typical of current variations in lightning discharges. Similar variations in the magnetic field of the lightning current were discovered in the investigations some ten years ago and they are seen in Fig. 4.

A type of variation where the fronts almost without exception are flat is exemplified by Figs. 11 and 12. Particularly characteristic is the stepwise developed ascent in the first curve of Fig. 11 and Fig. 12.

In connection with what was stated previously, an analysis of the variation forms of the magnetic field as they have appeared from the material presented must

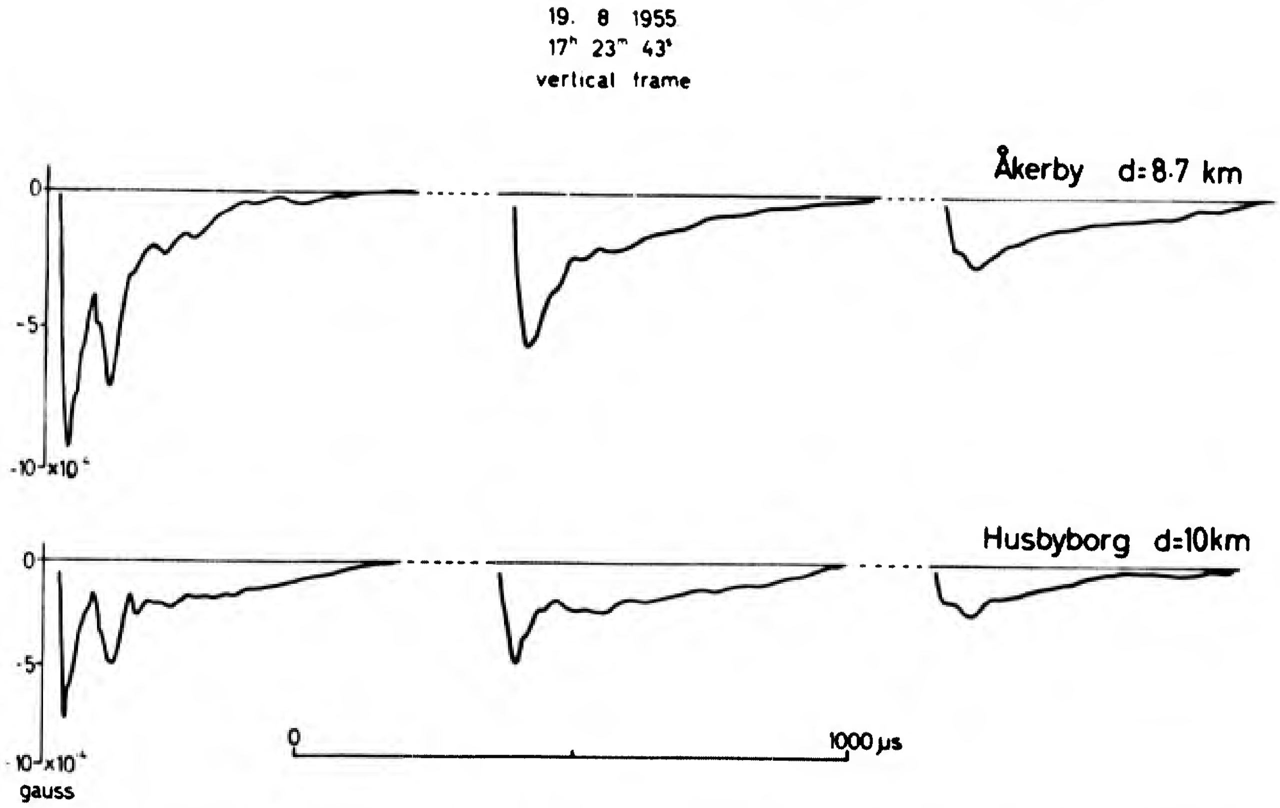

Fig. 6. Multiple strokes with distances to source recorded simultaneously at two field stations.

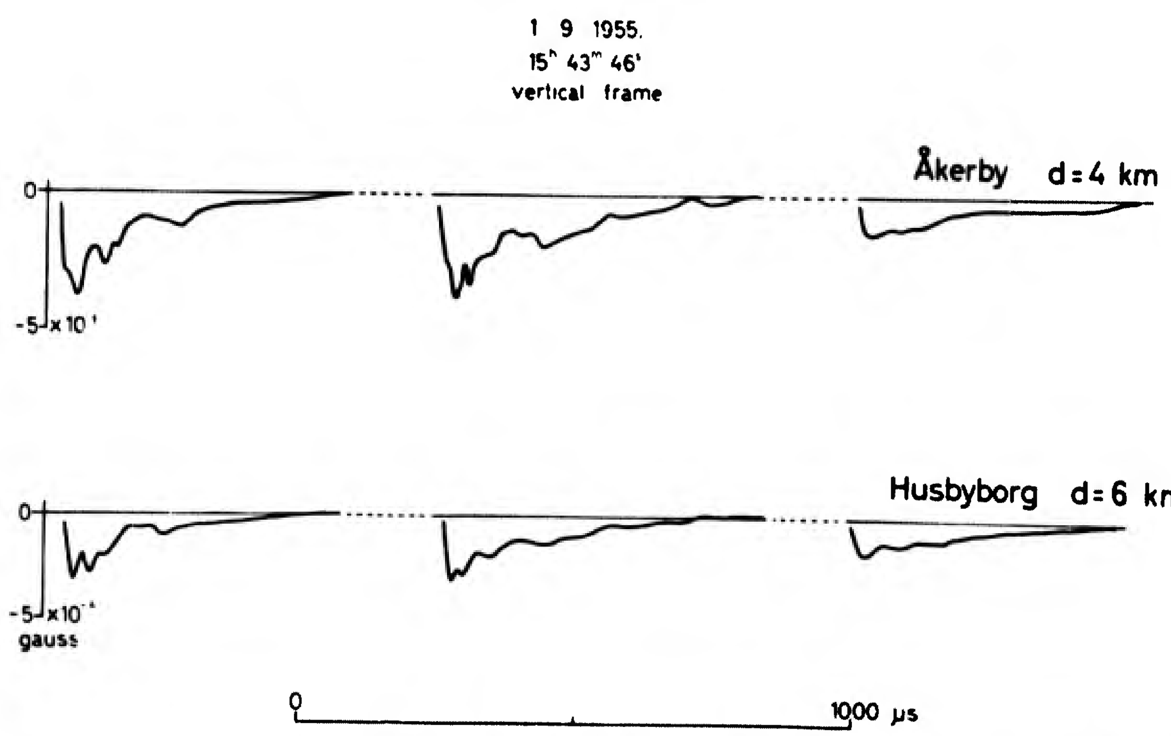

Fig. 7. Multiple strokes with distances to source recorded simultaneously at two field stations.

represent the variation forms of the lightning currents in multiple strokes. The material presented shows with all necessary clearness that most often it is very complicated courses which characterise the variations in the region nearest the lightning

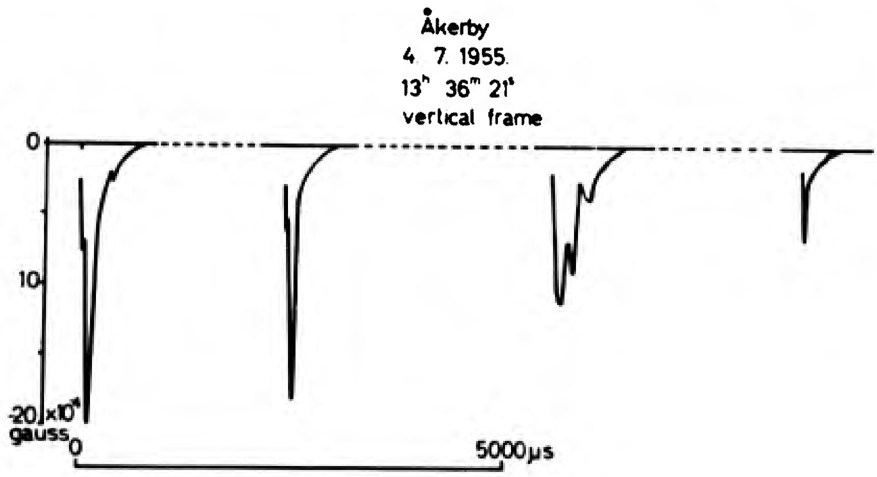

Fig. 8. Multiple strokes with steep fronts.

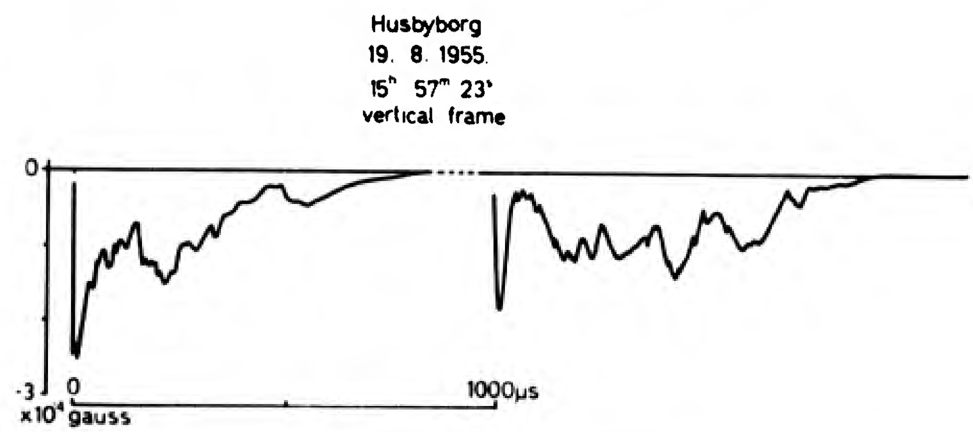

Fig. 9. Multiple strokes with steep fronts superimposed by after-variations.

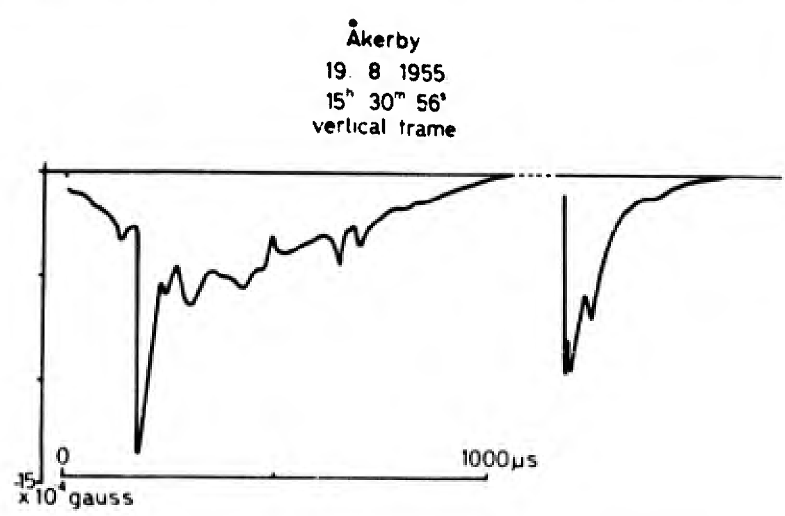

Fig. 10. Multiple strokes where front of first one starts slowly.

channel. In the variation curves of multiple strokes in the same lightning path as exemplified in Figs. 8–12 the recording methods have not allowed a determination of the time difference between the multiple strokes. In conjunction with the material presented respecting the lightning current it must be of the greatest interest to go

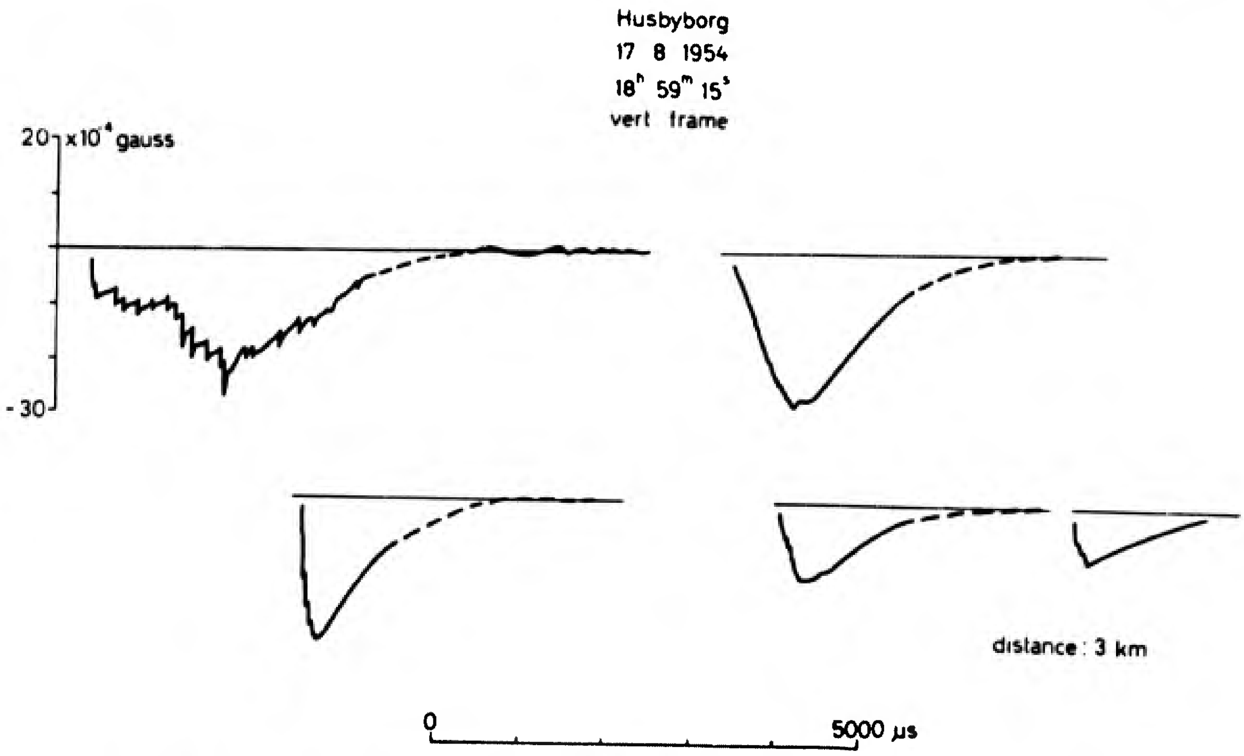

Fig. 11. Multiple strokes with flat fronts, some with rapid superimposed variations.

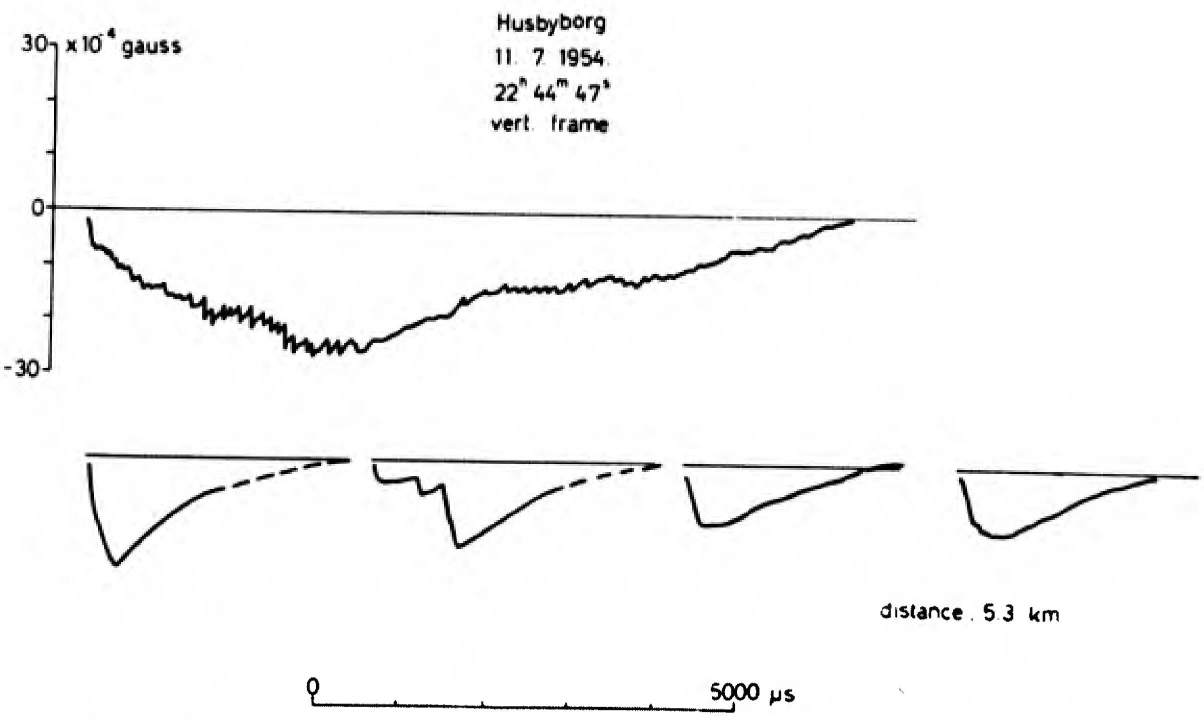

Fig. 12. Multiple strokes with flat fronts, some with rapid superimposed variations.

a step further in order to study the time difference between the multiple strokes—a problem of greatest interest with regard to the discharge mechanism of lightning strokes. This has been made possible by the following method recently introduced.

4. Analytic method for time sequence of multiple strokes and total duration of lightning discharges

It has been shown above that the variation form of multiple strokes can very well be obtained by a rapid recording arrangement with cathode-ray oscillographs. With later experiments it was found that recordings of this nature could be combined with simultaneous recordings of the multiple strokes, where a sweep time so slow as 0.2 sec. was employed. This slow variation time had the effect that multiple strokes appeared in the recordings as vertical lines, the position and amplitude of which could be utilised for orientation in time for the respective multiple strokes. The sweep generator for this purpose was of a saw-tooth linear form, enabling the time differences of the multiple strokes to be distinguished as regards their time sequence. The return of the sweep time was arranged to be so rapid that it could be ignored. See Fig. 13. The records were taken up on a film with a rapid linear time velocity. In this manner multiple strokes following one on the other could be determined in respect of their time sequence and on the recording films one can clearly see the multiple strokes following one on the other with their different amplitudes. Thus the method provides very good possibility of determining the time sequence for discharges following one on the other.

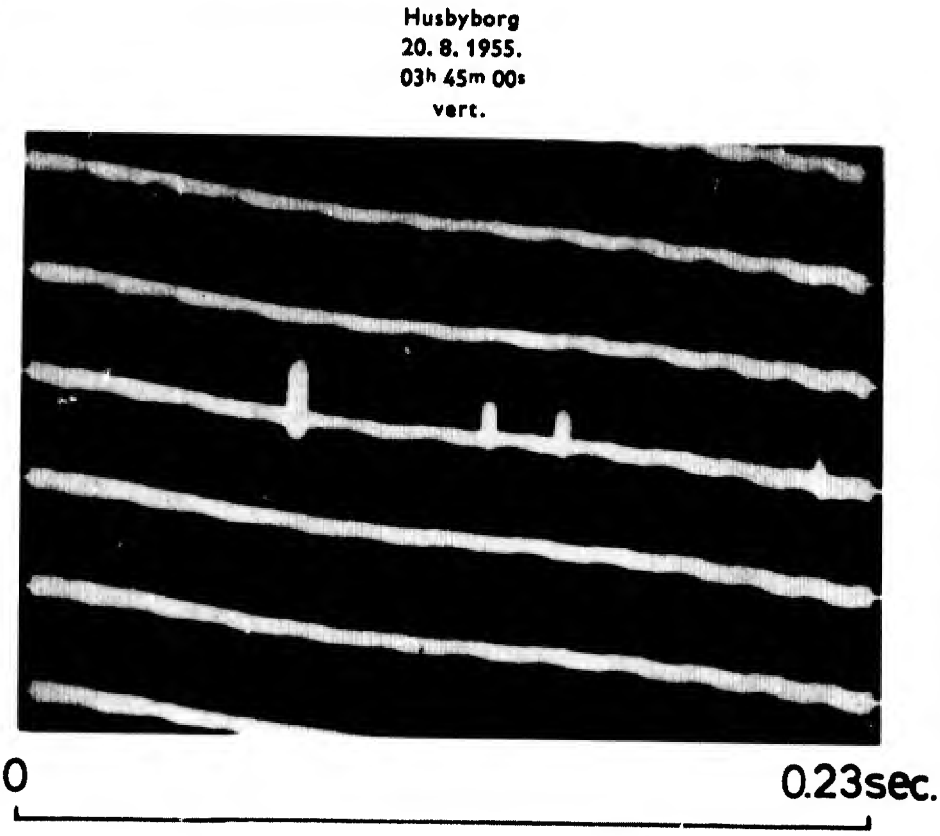

Fig. 13. Slow-speed oscillogram for recording of time intervals of multiple strokes.

5. Variation forms of multiple strokes in time sequence

Seeing that it is the first time that by means of recording with cathode-ray oscillographs details have been brought out of the variation form in multiple strokes, it may be worth while exemplifying these. Not the least reason is because the lightning

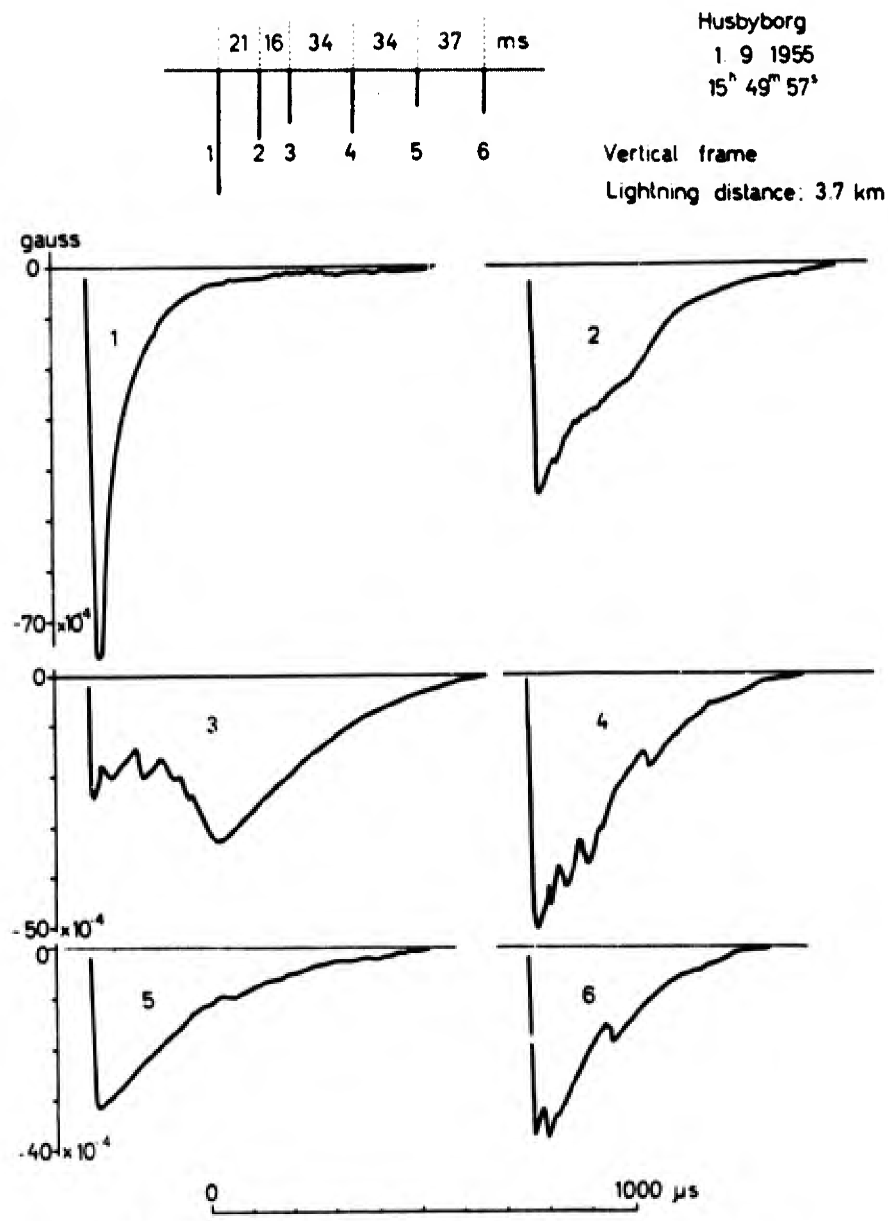

Fig. 14. Multiple strokes and their time intervals.

discharges following one on the other illustrate, as already pointed out in another connection, in a surveyable manner the mechanism of lightning discharge and in particular the transformation which the variation form of the lightning discharge undergoes in the discharges coming one after the other. In this way it is possible to distinguish different variation types, which makes clear the basically complicated discharge process, which comes out when it is a matter of the genesis and continued development of a lightning flash.

In Fig. 14 there is given a discharge type which is very remarkable because it differs in marked manner from other variation forms of multiple strokes in the extensive material. The six discharges in this lightning flash are all characterised by overlappings, which clearly appear in Nos. 3, 4 and 6 particularly. The occurrence of these overlappings is connected with the fact that the lightning path is strongly ionised up by the first discharge, and in the channel there then come in stepwise discharges from sub-branches coming out of the charging region from which the lightning current

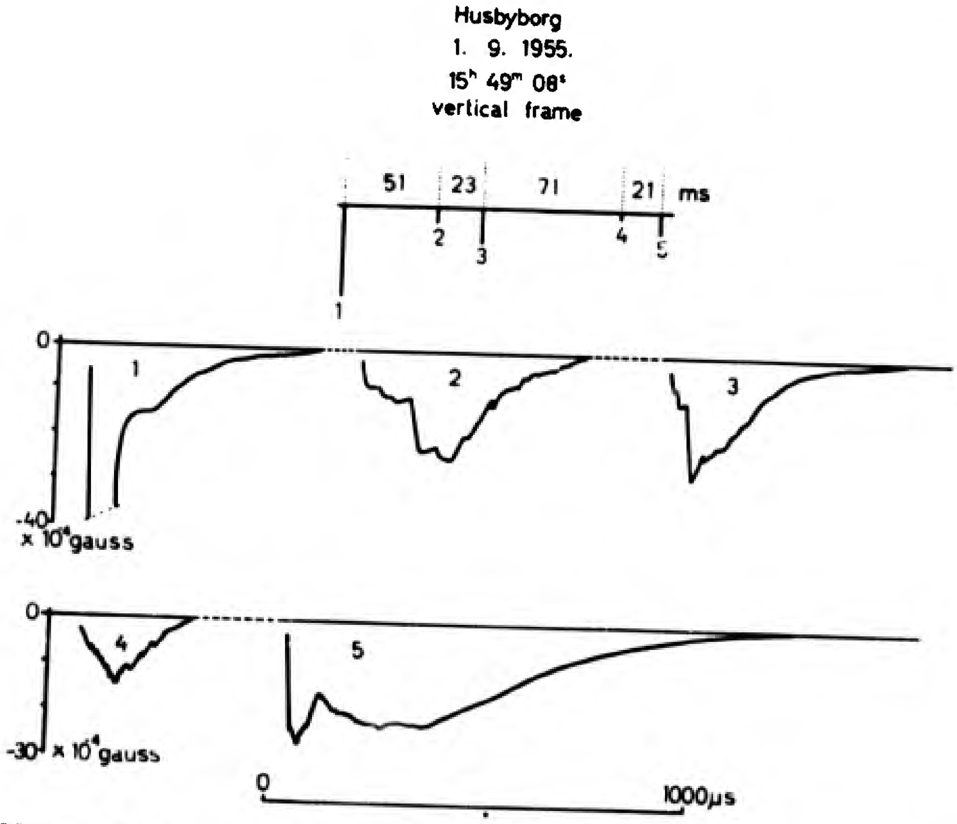

Fig. 15. Multiple strokes with distance 3.3 km to source. Only first one with steep front.

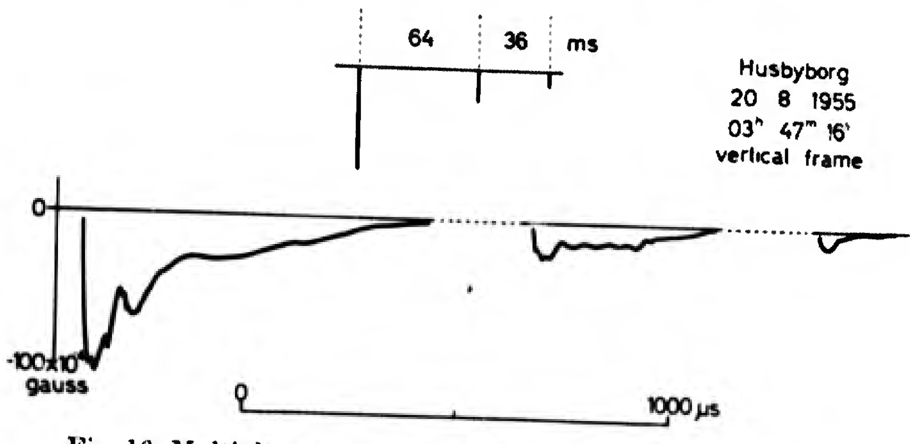

Fig. 16. Multiple strokes with decreasing fronts from first one.

is fed. In this connection it may be interesting to refer to the foregoing typical case, Figs. 8–9, where time sequence and distance were lacking but where all discharges have steep fronts. There are numerous such cases in the extensive material.

As regards Fig. 14 it may be observed that the repeated steep fronts may possibly be explained by the lightning path's distance from the observation point having so low a value as 3.7 km. This is contradicted by the discharge process according to Fig. 15, with a distance to the observation point of 3.3 km. In this case the first discharge appears with very steep front and is followed by three discharges, 2, 3, and 4, where the fronts have become flatter and at the same time quasi-periodic overlappings have come into the course. In the lightning path, the resistance has in

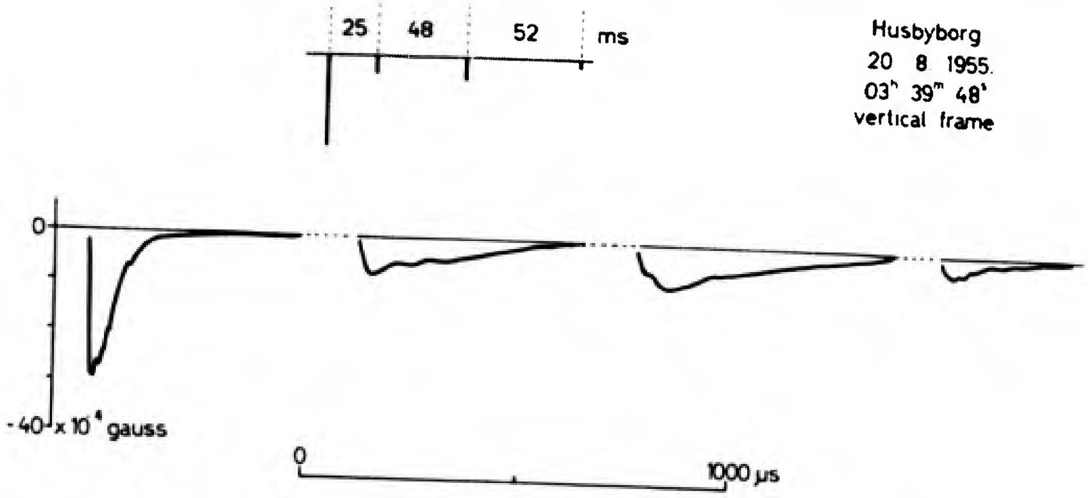

Fig. 17. Multiple strokes with decreasing fronts from first one.

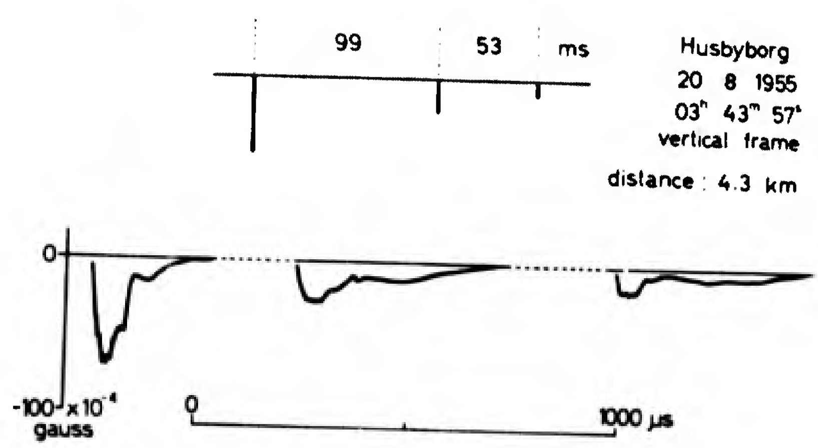

Fig. 18. Multiple strokes with decreasing fronts from first one.

this case evidently increased, a circumstance which is considered as constituting a valid explanation of the flattening of the front. In the last discharge, 5, the resistance has clearly diminished once more and this finds expression in a steeper front for this discharge. A typical decrease in front steepness beginning with the second discharge in the channel may also be seen in Figs. 16 and 17, two lightning flashes for which distance determination was lacking, but where owing to the high values of amplitude for the magnetic field intensity of Fig. 16 it is known for certain that the distance is of the order of 5 km. Similar typical decrease in front steepness appears for the variation forms in Figs. 18 and 19. In these two cases the first discharge is succeeded by clear decrease in front steepness for the subsequent discharges. It must be remarked that the lightning flashes in Figs. 16–19 are originating from the same thunderstorm.

It may be stated that the progressive decrease in maximal amplitudes for subsequent discharges in the lightning path in comparison with the first discharge should be regarded as a quite natural development—the lightning discharge comes to lower current amplitudes with subsequent strokes, because the charge available from the region which maintains the discharge process is successively diminishing.

The fact that the front steepness in general is decreasing for subsequent discharges is related to special ionisation conditions in the lightning path. The remaining ionisation in the channel between the strokes will obviously diminish the tendency of

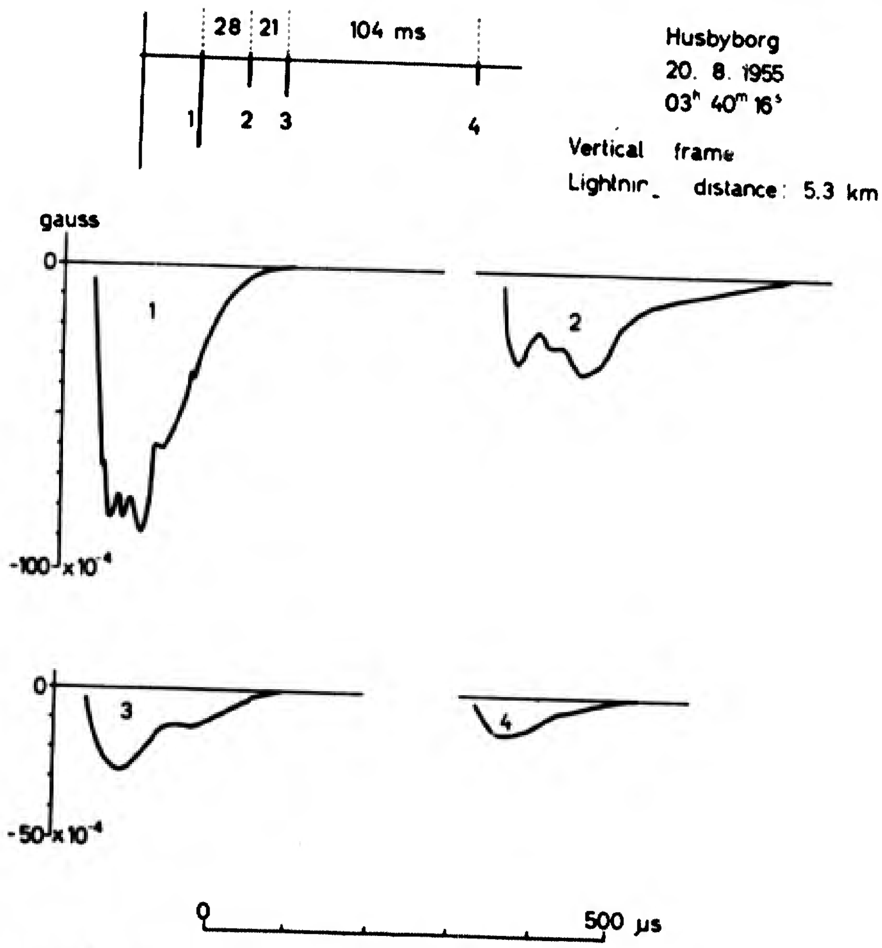

Fig. 19. Multiple strokes with decreasing fronts of first one accentuated in succeeding.

disruptive discharges—thus diminishing the steepness of the fronts. But we have very evident exceptions, exemplified for instance in Fig. 14, where all multiple strokes are characterised by steep fronts. This indicates a persistent high resistance in the lightning path [8]. How such a high resistance can be developed and maintained is a very intricate experimental problem not yet ripe for solution.

6. Statistical outline related to time sequence of multiple strokes

The total number of multiple strokes which were analysed by the method described for time sequence in the thunderstorm season treated in this work amounted to 50, all recorded by the vertical frame method. The method has been still further developed during the 1956 thunderstorm season and there is available a more comprehensive material, which has not yet been fully treated. As far as can be judged from the nature of the new material it agrees to a large extent with the results presented in this work. The modifications are small and are mainly due to the larger number of observations available.

In view of the fact that the investigations of multiple strokes dealt with in this work, as stated earlier, have not previously been undertaken in other quarters and also that a comparatively large number of lightning flashes could be analysed, it has been considered advisable to subject the results to statistical summary.

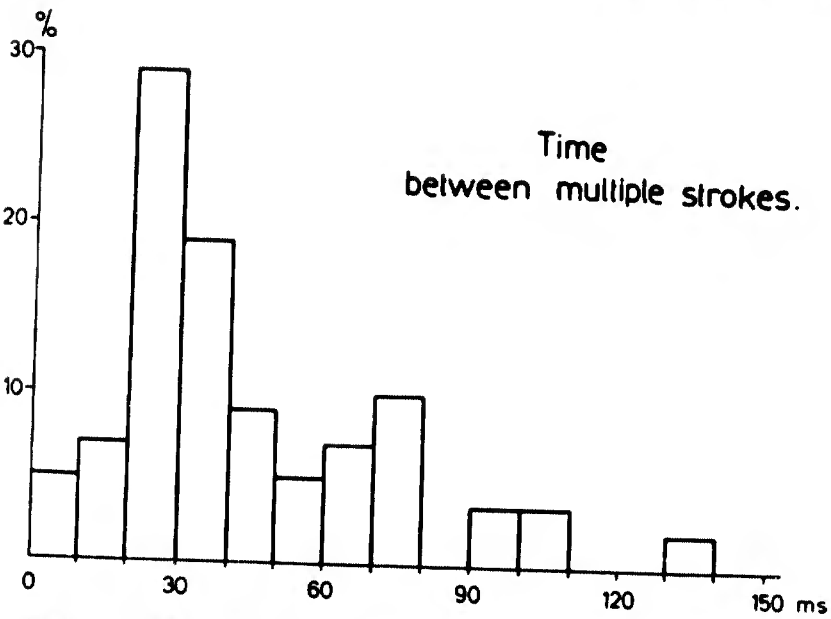

Fig. 20. Percentage of difference of time intervals in multiple strokes.

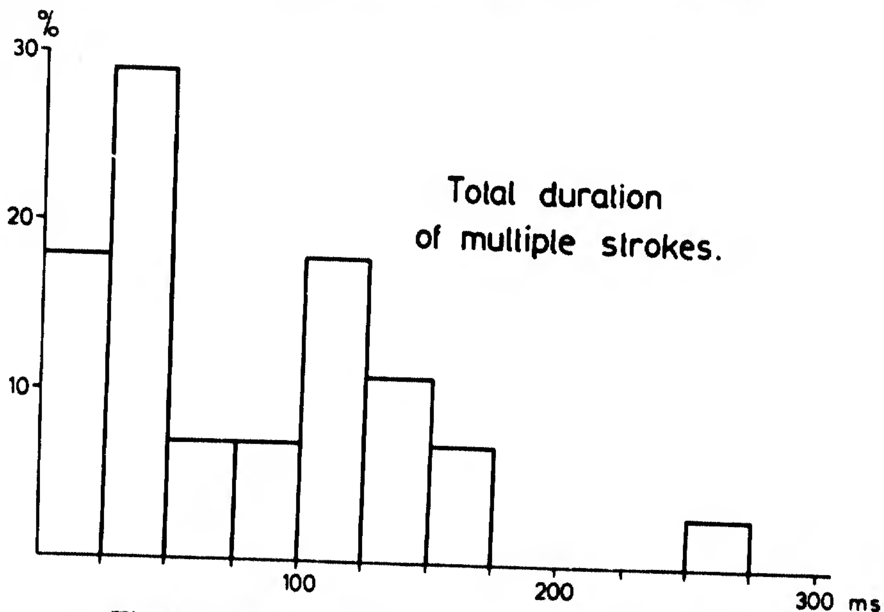

Fig. 21. Percentage of duration in multiple strokes.

In Fig. 20 there is given in percentage the time difference between multiple strokes, from which it follows that the frequently recurring time difference varies around 30 milliseconds, with exceptionally longer differences of the order of 150 milliseconds.

The total duration is evidently a distribution of special interest, as it can be calculated from the data accumulated. The distribution in percentage of this duration is given in Fig. 21. In exceptional cases this duration attained values between 200 and 300 milliseconds. Most of the numbers are dispersed below 100 milliseconds.

Another problem of interest is the scattering of amplitudes in multiple strokes. For an earlier publication [5] it was possible to obtain information on the same problem by using a method more simplified than that used here. This earlier investigation was based on 125 vertical lightning flashes in the vicinity region. It was found that in a lightning flash with two multiple strokes, the one occurring first had the highest field intensity in 83 % of cases, and when there occurred three multiples in 56 %.

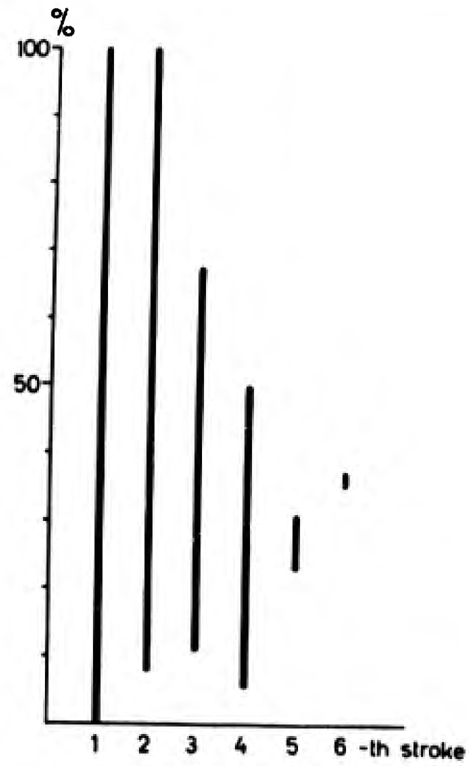

Fig. 22. Amplitude scattering of multiple strokes.

In lightning flashes with 4–7 multiple strokes, the 2nd and 3rd strokes had the highest field intensity.

The amplitude scattering of multiple strokes as obtained during the thunderstorm season of 1955 is given in Fig. 22, resulting in a typical predominance of amplitudes of the field intensity for the strokes occurring earlier in the flash. This must be considered as quite reasonable, the more so as a lightning flash must exceed itself in intensity with increasing strokes in the channel.

SUMMARY

In the analysis of atmospherics from lightning discharges the time sequence and variation forms of multiple strokes have earlier been neglected. This problem is important from several points of view. It is stressed when the noise level from lightning strokes is carried out by counting the number of strokes over a given land region.

By a special sweep recording circuit the variations and the time sequence of multiple lightning strokes have been analysed at the Institute during the thunderstorm seasons of 1953–55. The results were obtained by using movable vertical frame aerials in combination with amplifiers and cathode-ray oscillographs. The method allowed an analysis of the magnetic field components of multiple lightning strokes.

ACKNOWLEDGEMENTS

The authors wish to thank those members of the staff of the Institute of High Tension Research who, along with physics students of the Institute of Physics, Uppsala University, afforded all valuable help in the carrying out of the observations at the field stations. For the computing of the records, the authors are especially indebted to Mr. Z. Graufelds at the Institute.

Special cathode-ray oscillographs and direction finders were used in this investigation. The instruments were constructed at the Institute with the help of grants made by *Statens naturvetenskapliga forskningsråd* (The Swedish Natural Science Research Council) and *Statens tekniska forskningsråd* (The State Council of Technical Research). The authors are extremely grateful for this help in connection with the necessary instrumental equipment.

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HARALD NORINDER and EDGAR KNUDSEN

Atmospheric electric discharges from distant snow squalls and occlusion fronts

ALMQVIST & WIKSELL / STOCKHOLM

1957

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Read 6 June 1956

Atmospheric electric discharges from distant snow squalls and occlusion fronts

By Harald Norinder and Edgar Knudsen

With 17 figures in the text

1. Introduction

An entirely new type of atmospherics or spherics, which emanate from snow squalls and similar sources, was noticed for the first time in Sweden in 1949 [1]. Since then these spherics have been investigated in Japan [2].

The very first investigations with cathode-ray oscillographs showed that the new spherics had unusually regular forms of field intensity variation compared with spherics from lightning discharges. Moreover, the former from the same distance showed lower field intensities throughout than did spherics from lightning discharges.

As Sweden's geographical situation is particularly favourable as regards the occurrence of the new spherics, it has been considered advisable to carry out an orientation investigation, with the idea of finding the relation between the occurrence of the new spherics and various meteorological weather situations. The investigation also comprised a closer examination of the forms of variation in the new spherics, particularly as compared with the spherics emanating from lightning discharges.

2. Investigation method and equipment

Thunderstorms rarely occur in Sweden in the winter season November-April. The indications recorded by the Institute's cathode-ray direction finders during the winter, therefore, as localised with their small deflections to thunderstorm centres, far outside Sweden as a rule. It has been found that alongside these deflections there occur in certain periods of the winter comparatively large deviations on the direction finders. These spherics have been localised to centres inside the country and the meteorological conditions have been such that there was no probability that the new spherics had their cause in lightning discharges.

With a view to learning more about the occurrence of this new type of spherics, observations were carried out in 1954–55 with a direction finder set up at the Institute's field station located at Husbyborg outside Uppsala. The experience gained was such that during the 1955–56 winter season there was put in hand as a trial an experimental programme, including provisional direction finding by means of two direction finding stations, one in Upsala and one in Kalmar. For practical reasons, the distance of 370 km between stations was chosen. The geographical location of the stations may be seen on the maps shown later. During the period of investigation,

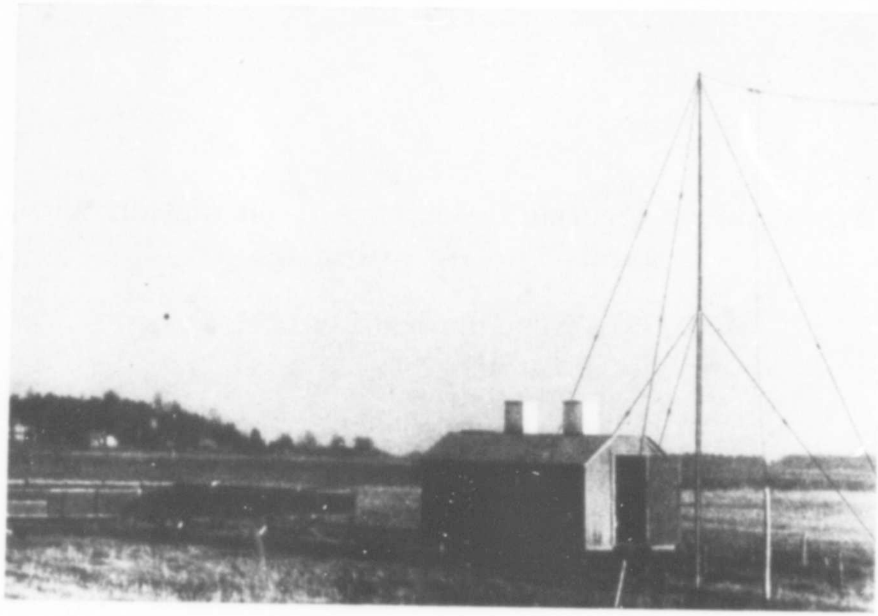

Fig. 1. Field station at Åkerby.

control direction finding was carried out at the Institute's direction finding station at Husbyborg. The other direction findings for the Upsala-Kalmar base line were carried out at the Royal Swedish Air Force's military air fields in the vicinity of Uppsala and Kalmar respectively. The Swedish Air Force placed personnel at disposal for the direction finding work.

On account of the local interference at the Institute for High Tension Research it was not possible to perform cathode-ray oscillograph measurements of the electric field force variations from the new spherics. For the measurements, there was employed a field station, Åkerby, Fig. 1, at a distance of 7 km from the Institute. At the times when, in the daily control observations on a direction finder mounted at the Institute, it was suspected that the new spherics were present, simultaneous recordings were made on the three direction finders and the cathode-ray oscillographs at the Åkerby station. Owing partly to shortage of personnel and partly to the distance between the field stations it was not possible on all occasions to carry out these observations simultaneously by the direction finders and the cathode-ray oscillographs. On those occasions when simultaneous recording could not be done with cathode-ray oscillographs and direction finders, it was possible on the basis of experience to determine approximately the distance to the source of disturbance by means of the appearance of the deflection on the direction finder. In such cases, no difficulty was experienced as a rule in finding the actual disturbance area by comparison with the weather maps.

For a period of 14 days the Swedish Air Force extended its assistance with the recording to comprise half an hour every four hours throughout the 24 hours. Unfortunately, it happened that this was done in a period with particularly stable weather conditions, when disturbance sources for the new spherics were entirely lacking throughout Scandinavia, with the consequence that serviceable results were

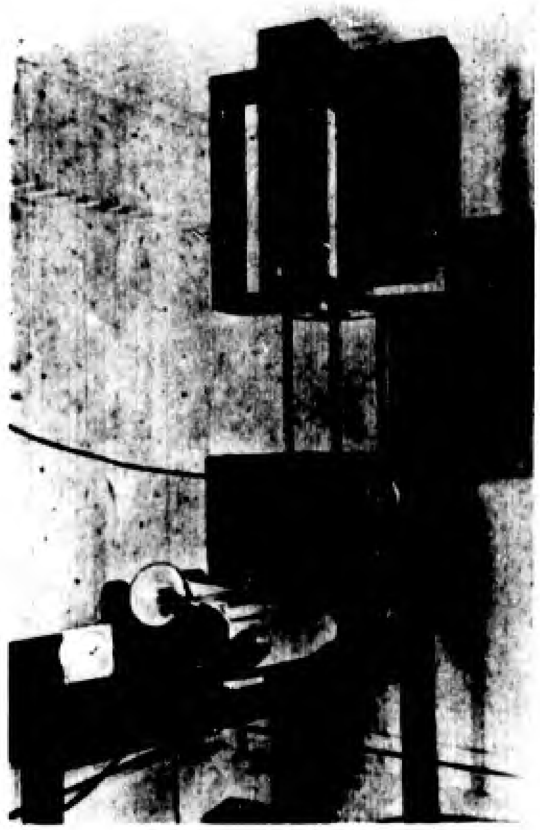

Fig. 2. Direction finder with mechanically recording system.

comparatively few. Nevertheless, this series of observations was of great value as regards experience, with a view to arranging trials with direction finders on a larger scale.

As stated, owing to interference conditions, the oscillograph recording of electric field variations due to atmospheric discharges had to be located at the field station in Åkerby, which was selected both because it was comparatively close (7 km) and because it provided good antenna conditions. The station was equipped with the Institute's specially designed cathode-ray oscillographs, with accessory amplifier and sweep generator. A detailed description of the instrumental equipment will be found in an earlier publication [3]. The aerial equipment was coupled on the well-known E-method and its data approximated the values stated in the first publication on the subject [1]. The recording times for the cathode-ray oscillograph were limited as a rule to ½ hour, as in that way a sufficient number of field variations for analyses was obtained for the situation in question.

The direction finders are of the cathode-ray tube type and combined with a sense aerial, providing the great advantage that by means of a direction finder there is obtained the bearing to the disturbance source. The direction finders were designed at the Institute for High Tension Research [4], and Fig. 2 shows a direction finder with recording device and a special recording synchronous clock set up at a station.

The direction finders were in charge of an operator who was responsible for control and adjustment. The recording device was attached to the direction finder and may be seen in more detail on Fig. 3. It consists of a mobile ring A fixed in front of the oscillograph's screen and provided with a thin wire B along its diameter. For measurement, the observer has to turn the ring rapidly so that the wire covers the direction of flection of the disturbance on the screen. The turning movement is transmitted

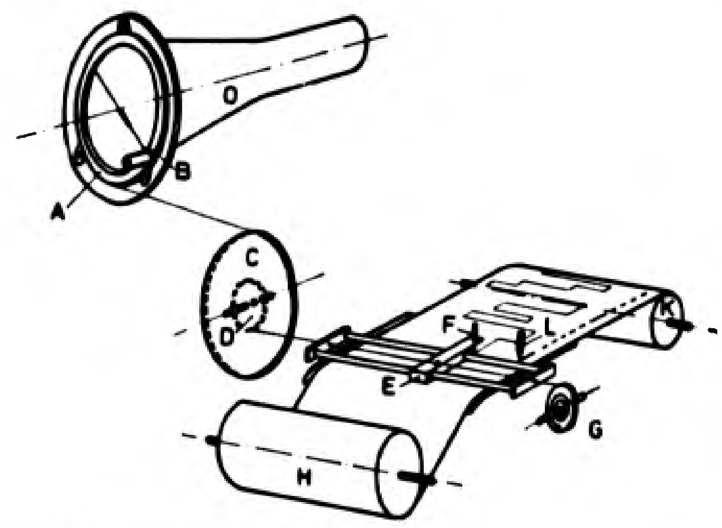

Fig. 3. Mechanical arrangement for recording of oscillographic deviations of direction finder.

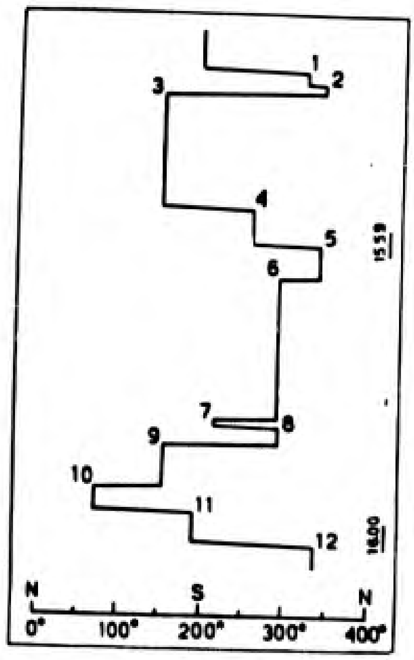

Fig. 4. Exemplified recorded atmospherics at Institute's field station.

to the recording apparatus set up beside the direction finder of Fig. 2. This apparatus, see Fig. 3, consists of two rollers *H* and *K*, which feed forward a wide paper tape. A trolley *E* provided with recording pen *F* runs on this tape. By means of a thin steel wire and a gear for the movement *C*, *D* and the tension device *G*, the movement of the trolley is coupled to the movement the ring describes for settings on the oscillograph screen. A special writing pen *L* moved by an electro-magnet provides the time markings. It is possible in this manner to record the directions of deflections at low cost, and Fig. 4 gives an example of recording made at a field station in thunder weather during a period of a little more than 1½ minutes. Azimuths for the recorded disturbances are given by the figures 1–12. To the left in the corner of the recording tape the time markings may be seen. By coupling the pen, the above-stated *L*, for time markings to a relay connected to the synchronous clock, it is possible to obtain synchronous time marking for simultaneously operating direction finders over practically the whole country. Of course, there is nothing to prevent the connection for time marking being made to time controlled pendulum clocks. Similar synchronous marking for photographic signals may be used for oscillographs simultaneously recording the variation forms of disturbances.

Simultaneous recording between two or more stations requires an absolutely reliable system of time synchronisation between the stations. This problem has been settled in the manner explained above and could be adopted without extra expense, owing to the fact that the Swedish State Power Board has introduced synchronisation of the whole Swedish distribution system of 50 cycles. Two synchronous clocks started simultaneously at two field stations will therefore owing to the signal arrangements keep on giving the same time markings. The system has previously been used with great advantage in the Institute's earlier investigations using direction finders and with simultaneous records of distant atmospherics from lightning sources at two distant stations.

3. Individual comparison of direction-finding results and maps

As has been stated, special meteorological situations are characterised by electrical accumulations in the atmosphere, which under certain conditions are sufficiently intensive to generate spherics of the new type. A question of the utmost interest has been, therefore, to localise the areas from which the discharges come. The method meant that, with the aid of weather maps related as near as possible in respect of time with the observation occasions, efforts were made to examine the weather conditions in the area where indications of the new spherics made themselves apparent. To make this more clear a number of cases will be dealt with below, in which the discharges were localised. The weather map situations have been compared with observations of spherics of the new type.

On 19.12.1955 recording was started at 10.55 a.m. All observations on the direction finder showed deflections in a straight easterly direction, corresponding distance about 250–300 km. Deflections came at the rate of 2 to 3 per minute, and this happened to be the only direction. Fig. 5 shows the meteorological conditions over the area in question. The map applies to 1 p.m. and shows that an occlusion front stretching from Åland to the south-east through Esthonia is moving slowly to the north and north-east. South and west of the front cumulo-nimbus clouds are reported with snow squalls both from the region of the Gulf of Riga and south of it and further over

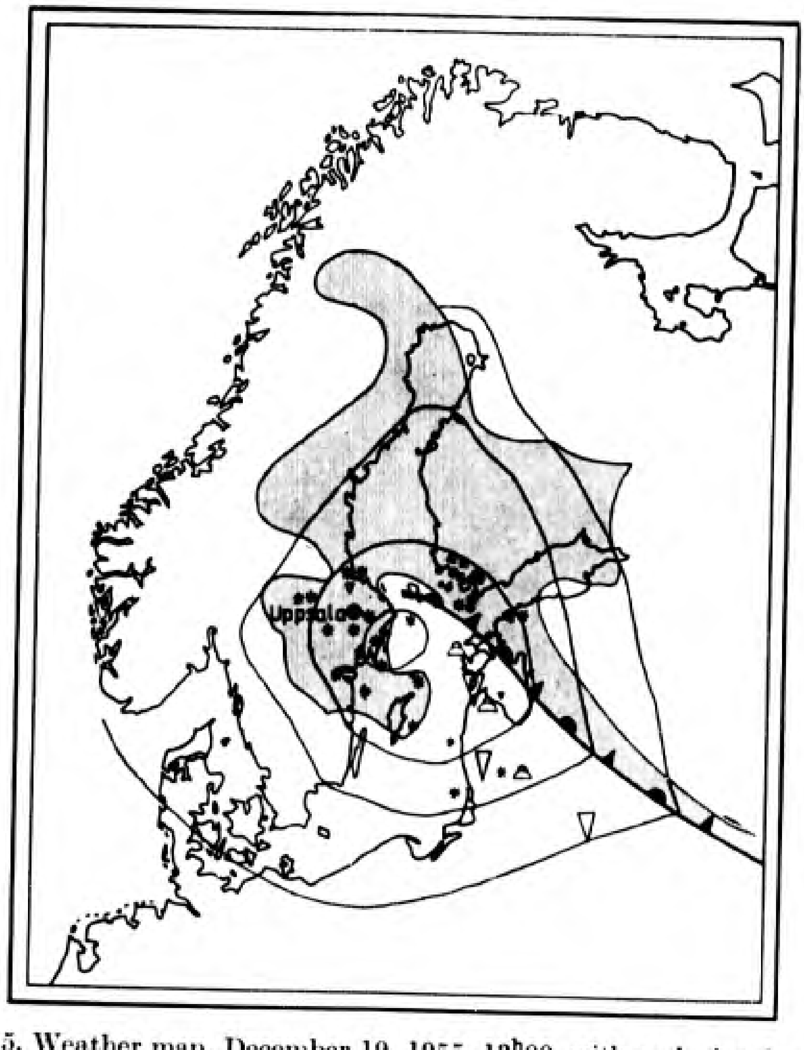

Fig. 5. Weather map, December 19, 1955, 13^h00, with occlusion front.

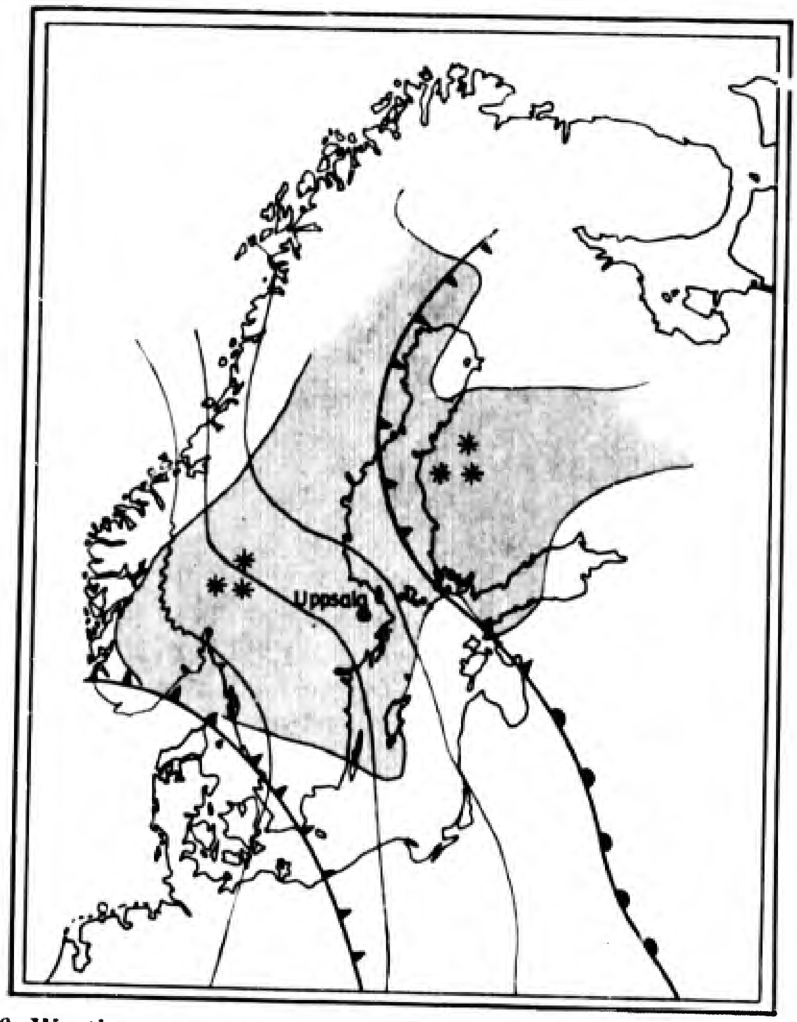

Fig. 6. Weather map, January 10, 1956, $13^{h}00$, with a weak cold front.

parts of north and central Baltic. From the area in the Gulf of Finland in advance of the front and in conjunction with the snowfall there are reported cloud strata but not cumulo-nimbus. These clouds appear therefore chiefly in an east-south-east direction and south-east from Uppsala. No thunderstorm reports have come in from this area. In direct easterly direction, as the direction finder indicated, there lies an occlusion front with snowfall on the front and it is probably this which is related to the discharges.

On 10.1.1956 recordings began at 2.30 p.m. Direction-finding observations showed deflection in the sector west to south-west with a distance for the spherics of 400–500 km. The deflections were at the rate of 1 to 2 per minute. Fig. 6 shows the weather situation at 1 p.m. where a rather weak cold front begins about 12 o'clock to make its way over the Swedish south coast and west coast area. In the neighbourhood of and along the front there are reported mostly cloud strata during the early hours of the afternoon. A question of the greatest interest is whether cloud strata give rise in certain cases to discharges. It is not inconceivable that the discharges in such cases take place between strata located one over the other or from a charged stratum out into the surroundings. From northernmost Denmark and from the Skagerack area there are reports of clouds of cumulus type. In this case it is probably the cold front that causes the discharges. This was found also to be the case with a similar situation not published.

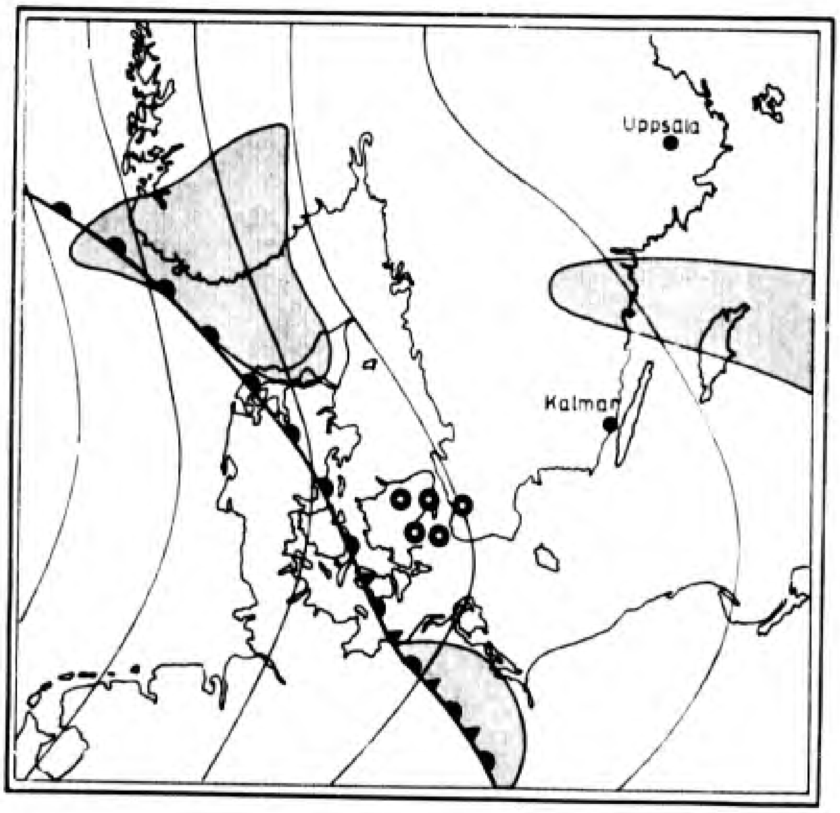

Fig. 7. Weather map, January 11, 1956, 10^h00, with occlusion front. Round points marking intersections of direction finders.

On 11.1.1956 recordings were started of the field intensity variations from spherics at 10.30 a.m. and recordings with direction finders were made between 11.15 a.m. and 11.25 a.m. The map of Fig. 7 gives the situation at 10 a.m. The round points in south Sweden and east Denmark represent the points of intersection obtained in the 10 minute period during which recording with direction finder proceeded. The map shows that an occlusion front is beginning in the forenoon to come in from the south-west and chiefly over south-west Sweden. At 10 o'clock there are only reported cloud strata from these areas and adjoining waters and from Denmark. This case constitutes still further evidence that cloud strata give rise to discharges. No thunder reports are present. In this case it is probably in the occlusion front that the discharges are generated. In this connection it should be noted that the synoptic map applies to the time about one hour before the recording with direction finders. At the time of recording with direction finders the front has moved to the north-east. Recordings with cathode-ray oscillographs were made on that day and these will be dealt with in another connection.

On 13.1.1956 recordings with direction finders were made between 11.15 a.m. and 11.30 a.m. The weather map, Fig. 8, applies to 10 a.m. On the figure, the points of intersection are indicated in the same manner as for Fig. 7 and it will be seen that they lie very well located in the area with cumulo-nimbus clouds accompanied by squalls of rain and sleet which were reported at 10 a.m. from south and central Denmark. No thunder was reported from the area concerned. This case shows very strikingly that discharges may occur in areas with snow squalls, as was stated in the first publication [1]. Records with the direction finders in this situation resulted in several points

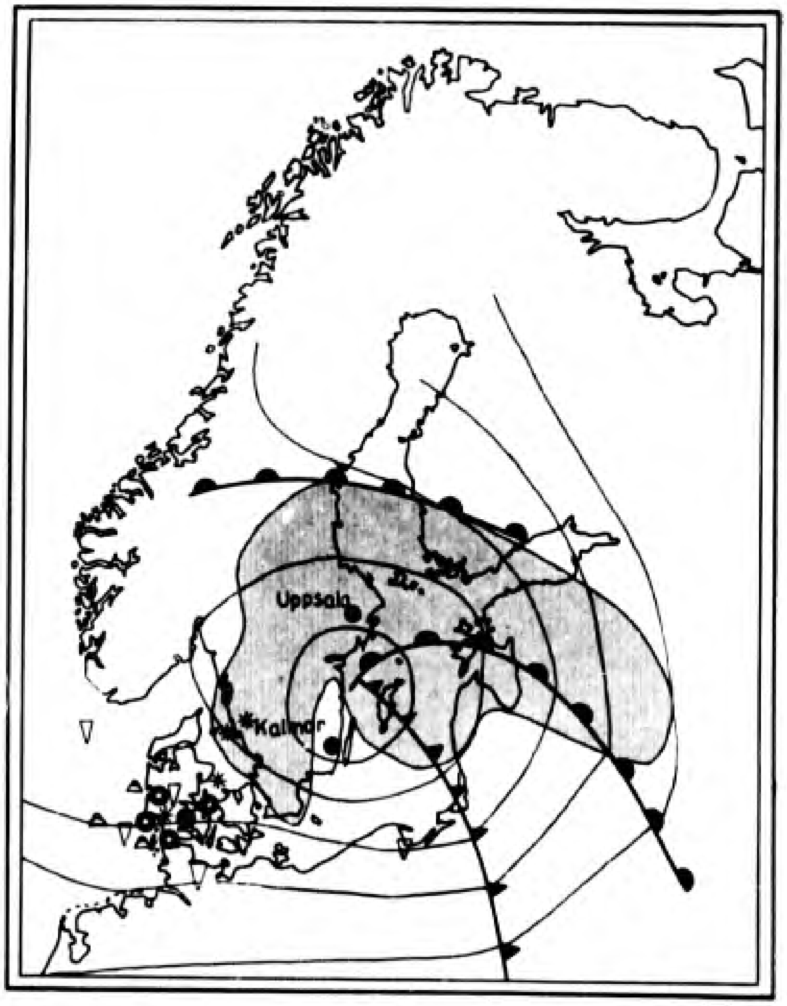

Fig. 8. Weather map, January 13, 1956, 10^h00, with cumulo-nimbus clouds accompanied with squalls of rain and sleet. Round points marking intersections of direction finders.

of intersection over central Poland. The observation material from this area is very scanty and it has therefore been omitted.

On 18.1.1956 at 9.55 a.m. recording was begun with cathode-ray oscillographs and simultaneous observations of the direction finder showed deflection in a very narrow sector right to the west. The deflections corresponded to a distance of about 600–800 km. The spherics this time came rather closer together than usual, about 1 every 10–20 sec. No difficulty was encountered in finding the region concerned on the synoptic map, Fig. 9, from 10 a.m. Cumulo-nimbus clouds with heavy snow and rain squalls were reported generally from south Norway, but chiefly from the regions west of the watershed from southernmost Norway northwards. No thunder was reported. Any possibility that the disturbances could come from areas in central Sweden are excluded, as the deflection in such case would have been considerably greater.

On 1.2.1956 recordings with the cathode-ray oscillograph were started at 11.10 a.m. Simultaneous observations on the direction finder showed deflections of very varying amplitudes in the sector south $\pm 20°$. Thus it was in an extensive area that the sources of the disturbances had to be sought. This is confirmed in striking manner by the map in Fig. 10, which is for the same day at 10 a.m. Cumulo-nimbus clouds with snow squalls were found to be occurring over the whole of south-west Sweden and the south

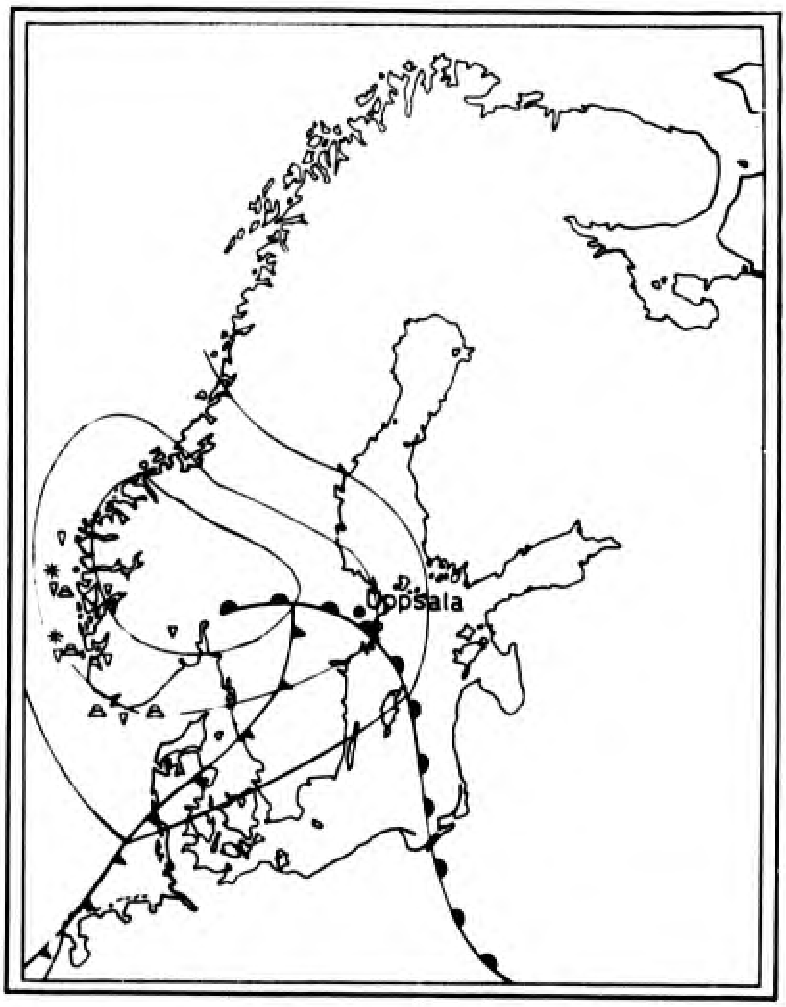

Fig. 9. Weather map, January 18, 1956, 10^h00, with snow squalls on west coast of Norway.

Baltic. The disturbance sources were geographically established and they extended over a comparatively large area. No thunder was reported. The dotted lines in Fig. 10 indicate the sector in which deflections occurred and it may be noted how this agrees with the area of snow squalls and cumulo-nimbus clouds observed.

In the individual treatments carried out above only 6 cases with accompanying maps and description have been examined. During the period of observation a comprehensive material was obtained. As regards this the necessary particulars are uncertain, chiefly owing to the far too scanty observation data. The far too short and not always suitably located base line between the stations, moreover, restricted the possibilities of further treatment. Of course, it would have been possible to select another and more suitable base system for the direction finders. As this work was mainly concerned with preliminary experiments, account was taken, as stated, of the practical points of view in the selection of base line. This meant that several cases occurred where the points of intersection lay on the prolongation of the base line between the stations or very near it, which involved uncertainty.

With definite experiments, at least three and preferably four stations with direction finders should be set up in Sweden. Another limitation lies in the fact that the area for analysis was limited to distances up to 700–800 km. This was done with the object of obtaining cases which were free from the influence of thunderstorms located at

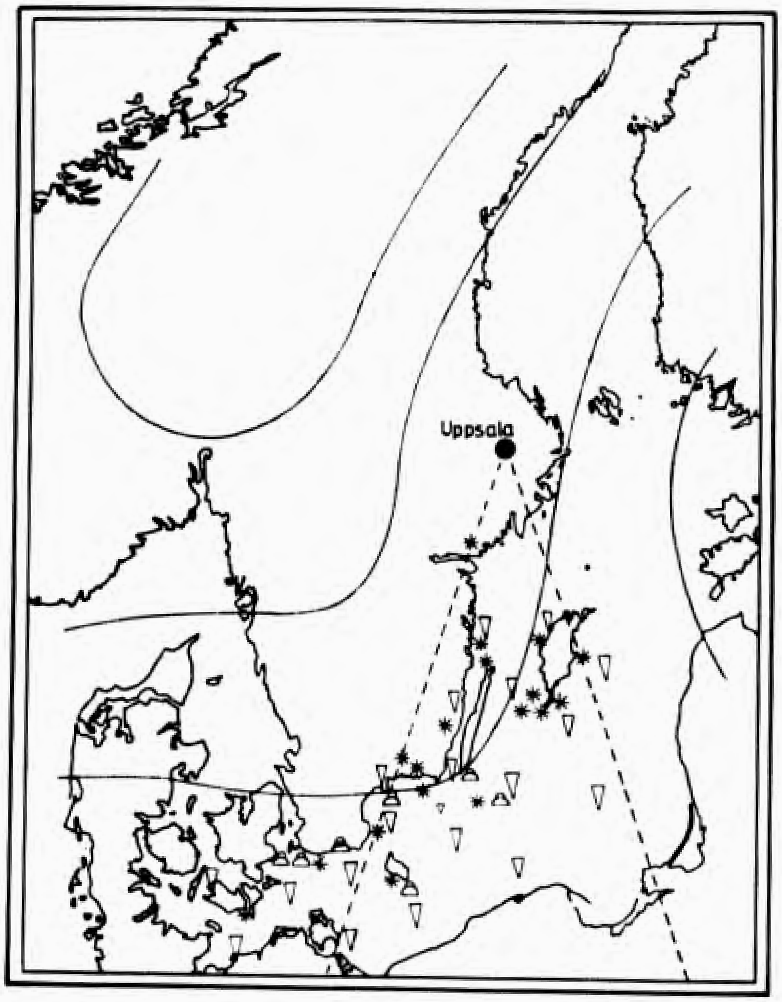

Fig. 10. Weather map, February 1, 1956, 10^h00, snow squalls registered by direction finder within da hed lines.

greater distances. In this way it was sought to establish the relation between meteorological situations and the occurrence of discharge masses in the atmosphere of sufficiently high intensity to give rise to electrical discharges of a type different from lightning discharges in the proper sense.

It is particularly interesting that in no case during the period of observation did the meteorological observation stations report thunder or lightning in the areas concerned. In the cases which were closely examined the meteorological observation places are comparatively closely situated and a thunderstorm in these localities would hardly escape the notice of the observers.

From the material presented it is seen that in winter over Sweden there occur atmospheric discharges which give rise to spherics of a new type. These are of a different character from the spherics which have their origin in lightning discharges. From what has been shown it may be taken that the discharge courses are linked with certain meteorological situations. From the discussion above in connection with Fig. 8–10 it is clear that electrical discharges can occur in snow squalls. This provides further confirmation of what was pointed out in 1949 [1] and later in 1955 [2]. In connection with Fig. 7 the discharges are linked with an occlusion front and according to Fig. 5 it is either an occlusion front or snow squalls which emit the spherics. According to Fig. 6 spherics arise also in cold fronts. The fact that these under certain conditions are accompanied by charges sufficiently intensive to generate electrical discharges of the type dealt with is in good agreement with earlier observations carried out by one of the authors 40 years ago [5]. In measurements of the electrical potential gradient in the lowest air strata, in some cases with very cold weather there occurred rapid variations in the potential gradient with the dropping of ice particles in the form of ice needles. The electro-static charges of the ice clouds and the electrical discharges produced by them are little known up to the present. It is obvious that the charges play a not inconsiderable role in the occurrence of spherics of the new type and this question will be dealt with again later.

The results so far produced are based on a limited material. The investigations should be extended in many respects and particularly by employing three suitably located stations for direction finders and cathode-ray oscillographs. The chief aim of the authors has been to show an interesting new object of research, where future investigations must be arranged on a broader basis than resources have hitherto permitted. No doubt prevails that the meteorologists, by employing electronic means in the direction indicated by us, can obtain a valuable complement for the observation at great distances of certain weather situations.

4. Variations of electric field intensity in the new types of spherics and comparison with variation forms emitted by lightning discharges

As stated earlier, on days when the direction finder indicated activity of the new spherics records were made of the electric field force by cathode-ray oscillographs for about half an hour. In this way some 500 oscillograms of spherics were obtained on different days and in various situations.

As early as 1949, it was stated in the previous publication [1] that the electric field changes which characterise the new type of spherics show very soft and regular forms in comparison with spherics from lightning discharges. On the latter there often occur superpositions of rapider courses, but these are entirely lacking with the new spherics, an observation which is supported by another investigation [2]. The results obtained in the investigation here reported have therefore still further confirmed earlier observations.

In respect of spherics emitted by lightning discharges and variation forms with distances from the disturbance source (forms varying with the distances from the disturbance source), numerous efforts have been made to make a classification. There have been brought out a number of differing variation forms. It is not surprising that this should be the case if one examines the highly differing variation forms applying to lightning discharges in the proximity region [6], [3].

Thus, contrary to what has been brought out for spherics from lightning discharges. the new spherics display very regular variation forms, even at short distance from the disturbance sources. This is illustrated characteristically by the two original oscillograms given in Fig. 11 which were taken with open aerial at the Institute's field station Funbo 2 (Kaptensudden). From Fig. 11 it may be seen without trouble that the type of variation agrees well with those given in the earliest publication [1]. In exceptional cases there occur small deviations from the regular form, examples of which will be found in Fig. 12 on original oscillograms from the Åkerby station. In this case the superpositions are in all probability caused by a remote lightning discharge.

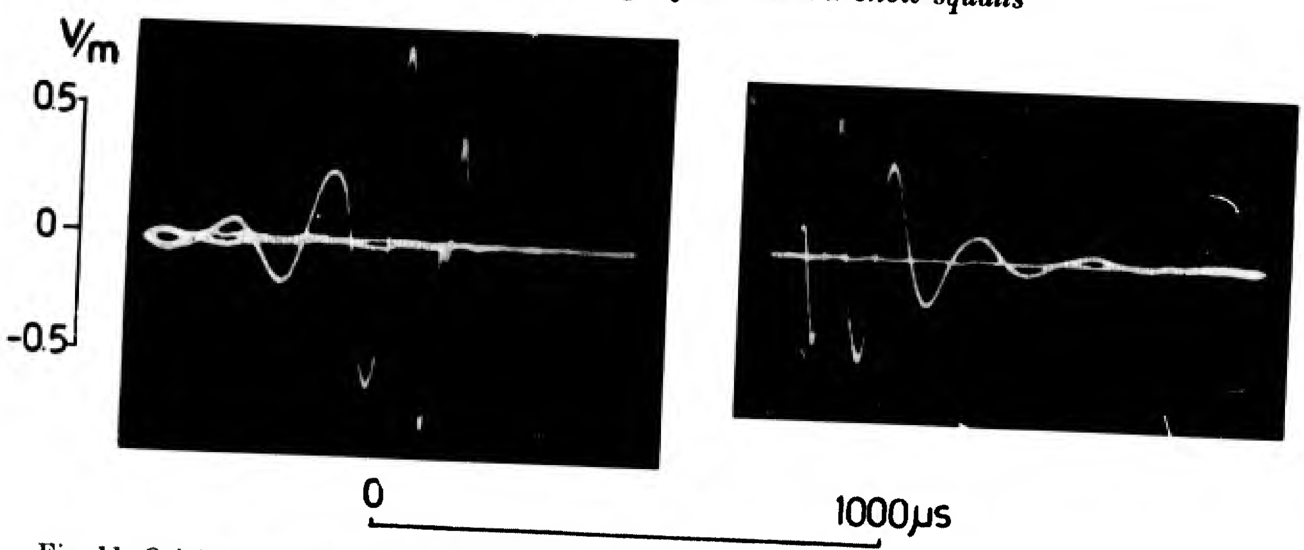

Fig. 11. Original oscillograms of snow squall atmospherics lacking small superimposed variations recorded at station Funbo 2.

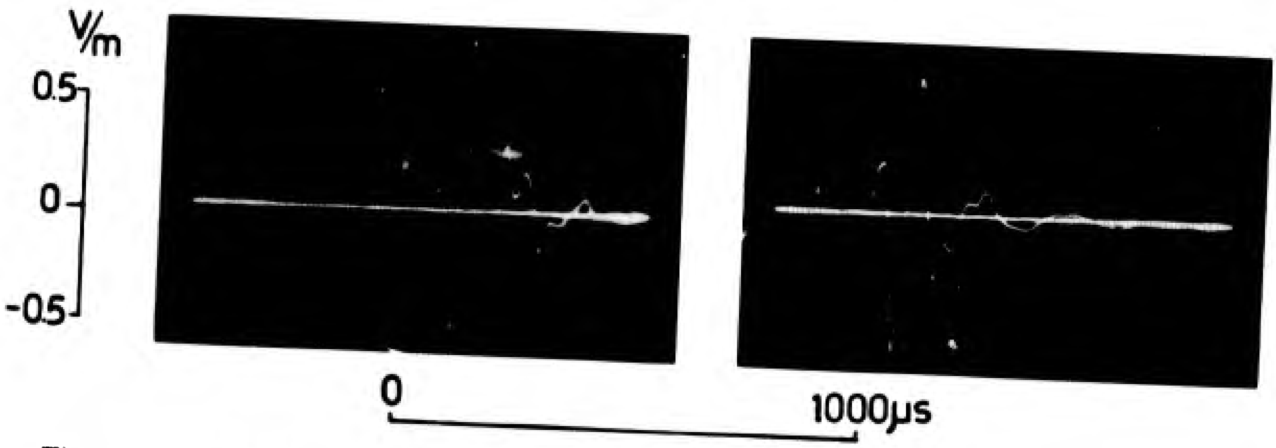

Fig. 12. Original oscillograms of snow squall atmospherics with superimposed rapid variations caused by remote lightning discharges recorded at station Åkerby.

In this connection it is of course particularly interesting to compare the results with the variation forms found in a comprehensive investigation [7], in which a very large number of atmospherics from remote lightning discharges were investigated simultaneously at two Swedish stations. One of the stations was at Funbo in the vicinity of Uppsala and the other one at Fotevik on the Falsterbo Cape at the southern tip of the Scandinavian Peninsula. The distance between the stations was 570 km. The total sample of analysed simultaneous oscillograms was about 1000.

With only a few exceptions the simultaneous oscillograms were characterised by very typical superimposed rapid variations, of which Fig. 13 is a representative example. Only in extremely few exceptional cases did the investigation with the two stations give variation forms of the regular type which characterises the new spherics type, and Fig. 14 constitutes an example of such a rarely occurring regular variation form.

To make a classification of the variation forms in atmospherics such as they develop from lightning discharges has its obvious limitations, not least owing to the varying factors which influence the changes in the variation forms. It is only on condition that the change is systematically followed and one has its causes under control from

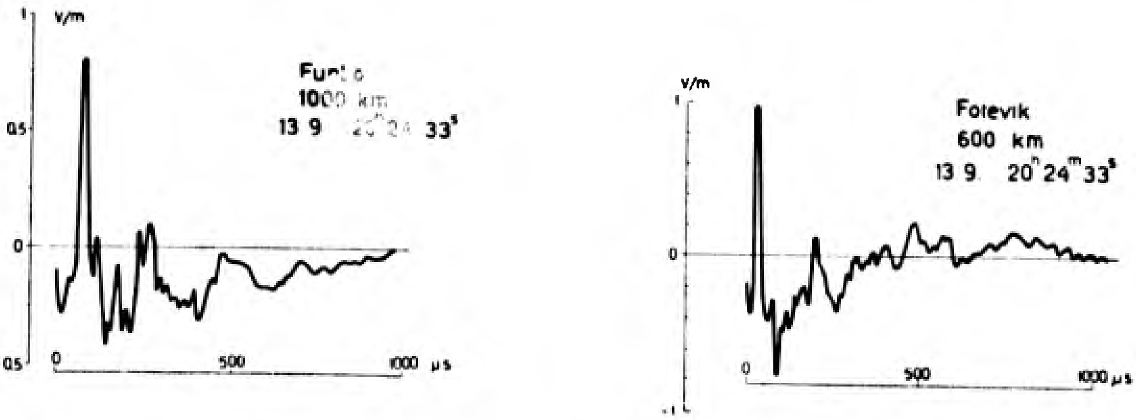

Fig. 13. Atmospherics with irregular superimposed variations recorded simultaneously at two distant stations in Sweden.

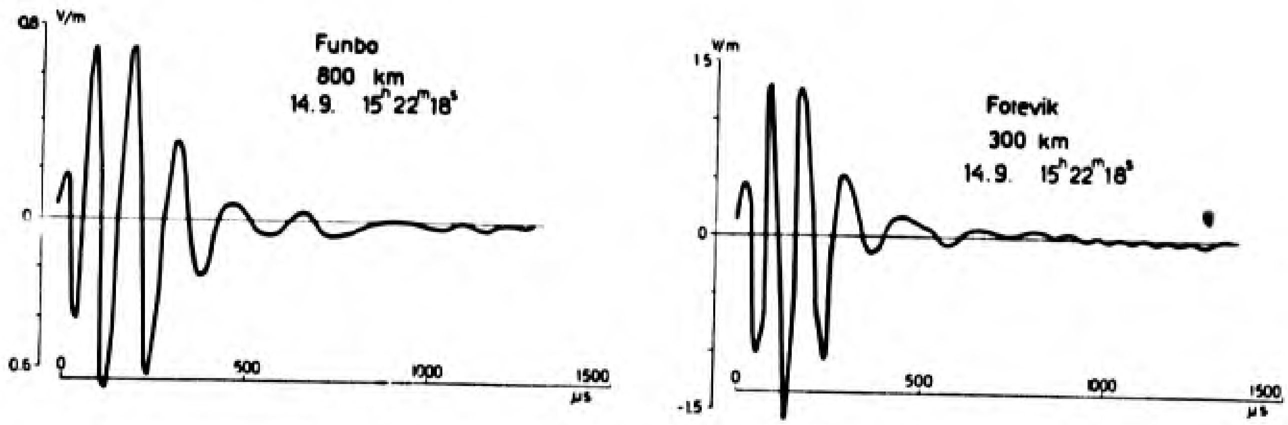

Fig. 14. Atmospherics of regular quasi-periodic variation type recorded simultaneously at two distant stations in Sweden.

the disturbance source and outwards that a classification can be worth while and be of any interest.

Despite the pronounced alteration in variation forms and the extent of the superimpositions in spherics generated by lightning discharges, a large number of the oscillograms enable calculation of a characteristic mean variation curve to be made. Such a curve from the work previously mentioned [7] is shown in Fig. 15 and applies for distances to the lightning discharges of less than 1000 km.

The regular variation form in the new spherics enables the construction with ease, and without great deviations from the individual variation forms, of a mean variation curve of the same type as shown in Fig. 15. This is given in Fig. 16 and is based on 150 separate oscillograms.

Comparison of the properties of the two mean curves shows a striking agreement in general variation structure. One difference is evident—the quasi-periods for the new spherics according to Fig. 16 are appreciably more regular than the equivalent quasi-periods according to Fig. 15, based on spherics emitted by lightning discharges. This is quite explainable, as the latter are founded on a basic material of spherics with pronounced individual irregularities, whereas spherics of the new type, as stated, show good agreement in variation forms among themselves.

In Table 1 on the basis of Fig. 16 the times for successive quasi-periodical semi-periods have been given and by doubling the semi-periods obtained the equivalent

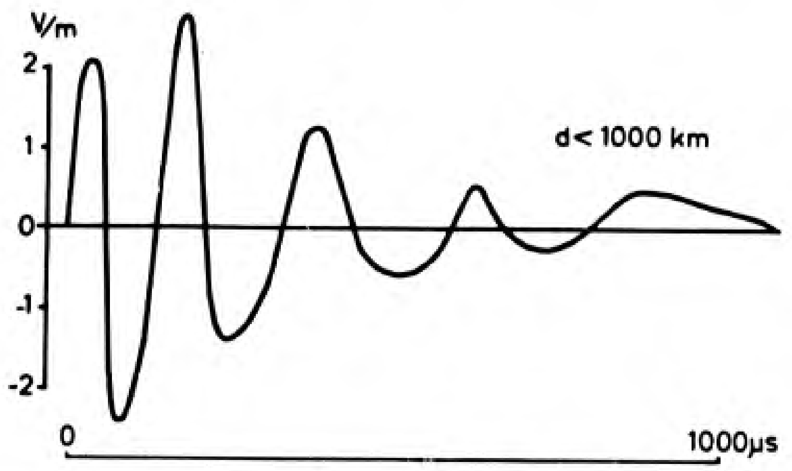

Fig. 15. Mean variation curve of atmospherics from distant lightning discharges.

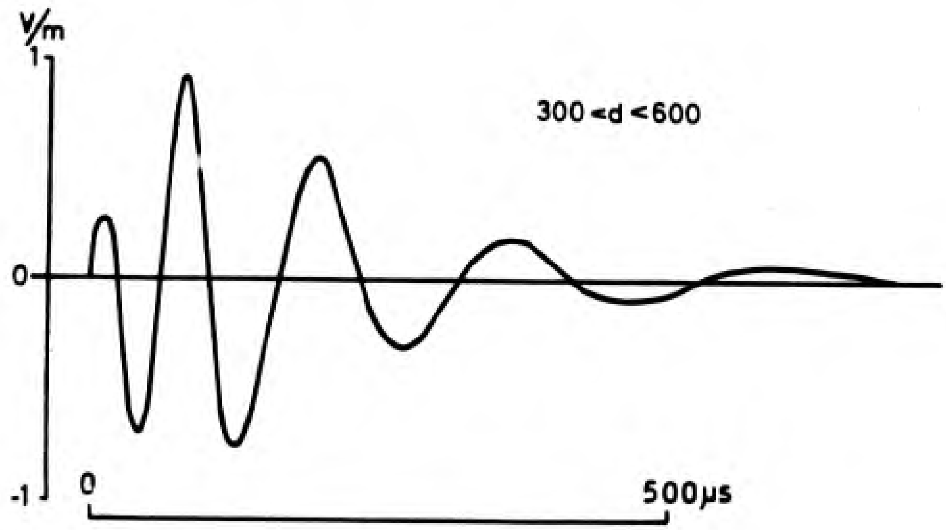

Fig. 16. Mean variation curve of distant atmospherics from snow squalls.

frequency has been obtained. The same procedure has been carried out in reference to Fig. 15 for Table 2.

A comparison of the figures in the two tables for the frequency of consecutive quasi-periods indicates that for Table 2 the duration of the semi-period is considerably longer than the corresponding figure for Table 1. For the former the semi-periods are not so regular as for the new spherics, the explanation of which is to be found in the fact that the curves for Table 2 are computed from atmospherics from lightning discharges. It is also particularly noticeable that the total mean duration for the new spherics only amounts to 650 μsec, which is considerably shorter than for spherics from lightning discharges, these durations having the ratio 1:2.

As regards field intensity values for the new spherics it is not possible at the present stage of the investigations to present any extensive statistical material. At a distance from the disturbance centre of about 300 km the field intensities for 150 separate observations with slight deviations between them amount to a mean value of 0.25 Volt/metre, which constitutes about one fourth of the values which apply for the same distance for spherics generated by lightning discharges.

As regards the important problem of long wave propagation the regular variation

Table 1.

Semi-period No.	1	2	3	4	5	6	7	8	9
Time in μs	25.2	36	46	56.8	70.6	82.6	93.1	114.3	151
Frequency in kc/s	19.9	13.9	10.8	8.8	7.1	6.1	5.4	4.4	3.3

Table 2.

Semi-period No.	1	2	3	4	5	6	7	8	9
Time in μs	59	79	71	112	104	147	83	135	140
Frequency in kc/s	8.5	6.3	7.1	4.5	4.8	3.4	6.0	3.7	2.1

forms in the new spherics should be particularly adapted to an analysis. In this respect the spherics generated by lightning discharges must be treated with greater caution owing to their greater dispersion of variation next to the disturbance source.

5. Sources of new spherics

Up to now in investigations of the new spherics there has been no occasion to investigate them in the vicinity region of the disturbance source, a method which has been used, however, for lightning discharges [6]. The discharges which generate the new spherics are in all probability very weak, taking into consideration the light and sound effects generated by them—a weakness which is lacking as a rule with lightning discharges. As regards the variation forms of the new spherics at the disturbance sources we must await results which can only be obtained by a combined investigation with direction finders for localisation of the disturbance sources and simultaneous recording of the field intensity variations in the vicinity of the disturbance sources by means of cathode-ray oscillographic methods.

No doubt exists that the new spherics are generated by discharges from charge accumulations in clouds with particles of snow and ice crystals suspended in them. Without a doubt the cloud accumulation which characterise snow squalls constitute sources for electrical discharges which give rise to the new spherics. Moreover, as stated earlier, it is not excluded that ice clouds with more even stratification may bear charge accumulations sufficiently intensive to generate discharges in them or towards the surrounding air regions free from clouds.

The occurrence of electrical charge accumulations in snow and ice clouds is confirmed by observations from aircraft. In some cases the charge accumulations from snow and ice particles are of such an extent that their effects are evident close to the earth's surface and not least over sea surfaces.

At some time the intensively charged precipitation particles from a snow squall cloud must be distributed, e.g., in a volume extending from the cloud and down to the earth. If, as a first approximation, we assume this volume to have the form of a

Fig. 17. Fishing boat 11 metres long on which intense St. Elmo's fire occurred during heavy snow fall.

cylinder and the volume charge distribution to be homogeneous, it is easy to calculate by means of the potential theory the field force intensity along the axis of the charged cylindrical volume. This field intensity may be considerable if the cylinder is high enough, as in a snow squall cloud, for instance. On the other hand, in ordinary thin snow clouds the electric field intensity will not be very great.

One of the authors (N.) personally observed such a case during a voyage to the United States in November 1926 on the Swedish liner Gripsholm. On a dark afternoon the ship was passing through a heavy snow squall, and on the masts and other pointed high parts of the ship he observed very pronounced St. Elmo's fire phenomena. This was typical evidence of the strong electrical field through which the liner was passing. There are many other indications of heavily charged particles in snow squalls.

Another interesting case of luminous discharges, St. Elmo's fire (corposant), occurred on 8.12.1954 in the Baltic Sea in the vicinity of the town of Västervik. A fisherman on his fishing boat, 11 metres long, see Fig. 17, lying about 16°69′ E, 57°39′ N. was engaged in taking up his nets, and at a little distance from him lay another boat doing the same. On the second boat also the following phenomenon occurred, but not so strongly. Around 21.45 hours the fisherman on the firstnamed boat observed luminous discharge from a large iron shackle in the bows, attached to the stem band. Before the luminous discharge appeared there was heard a sizzling noise. The light extended for a decimetre from various iron parts and was violet green. The light had an inside chalk-white core the size of a pea. A Nife accumulator lamp of iron also emitted flames of the same length. When the fisherman tried to extinguish the light on the lamp with his hand, decimetre-long luminous discharges came from the hand. Decimetre-long glow-light also came from a nail in the mast. When the anchor was drawn up from the water, glow-light appeared on it as well. When asked about the meteorological conditions at the time of observation, the fisherman said that intensive snow-fall prevailed with big flakes. After the snow had been falling for a time it went over to snow in grains, and the electrical phenomenon diminished more and more until it gradually ceased. It is noteworthy that on the same evening there had been observed in the Institute's direction finder very strong spherics which were localised to the region around Västervik.

Yet another case supports our assumption that snow squalls are sometimes accompanied by strong field intensities even out at sea. In *Pilot Charge*, May 1950, the following was reported: "Second Officer B. V. Campbell of the American S.S. American Manufacturer, Captain R. O. Patterson, Master, reports as follows: On December 17, 1949, at 2300 G.C.T., in lat. 50°20′ N., Lon. 43°28′ W., en route from Belfast to Boston, an unusual display of St. Elmo's fire was observed during frequent passing snow squalls. It would begin with the topmast trucks, gradually lighting the entire topmast, antennas and shrouds. At times the king posts appeared to glow. The barometer was 29.96 inches, rising; wind NW., force 6, rough sea; air temperature, 34° F,; sky, overcast."

The examples stated furnish evidence that such big charges in some cases are accumulated in snow squalls that they generate luminous discharges, even on such a low object on the even sea surface as the little fishing boat at Västervik.

There is nothing to contradict that the new spherics are emanated from spark discharges within the area for electrically charged particles of snow and ice. From what we have observed the course of variations for the new spherics at distances so short as 120–150 km is very regular in their variation form, which suggests that they are generated by small spark and luminous discharges within the cloud parts. In this connection, one cannot overlook that a lightning discharge constitutes the final phase of a discharge process which passed through successive stages until in its final stage it is characterised by the disruptive lightning discharge. This final phase is preceded by successive pre-discharge courses and it is probable that the new spherics from the electro-physical standpoint are closely related to these pre-discharges.

SUMMARY

Atmospherics or spherics of a new type emanating from electric discharges in clouds containing snow and ice particles discovered at the Institute for High Tension Research some years ago have been investigated with regard to their sources and variation forms. The sources were located by two direction finders placed on a base line. The variation forms were analysed by cathode-ray oscillographic records. They showed quite another regularity than spherics from lightning strokes and were lacking superimposed rapid variations. At distances of 300 kilometres the field forces of the new spherics attained 25 % of the corresponding values of spherics from lightning discharges.

ACKNOWLEDGMENTS

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The authors are indebted to the Swedish Air Force for valuable help with operation of two direction finders placed on the air fields in Uppsala and Kalmar.

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ARKIV FÖR GEOFYSIK

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Pre-discharges in relation to subsequent lightning strokes

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Read 6 June 1956

Pre-discharges in relation to subsequent lightning strokes

By Harald Norinder and Edgar Knudsen

With 22 figures in the text

1. Introduction

The complicated nature of a lightning stroke involves great difficulty for experimental investigation. As is known, an individual lightning discharge consists of the following main phases: (1) the pre-discharge stage, when the channel is formed through the ionisation with a total duration of up to tens of milliseconds (msec) and in some cases even longer; (2) the front, which is characterised by the current rush proper with durations of some few microseconds (μsec) up to some tens of μsec and in exceptional cases appreciably longer times; (3) the after-variation, when the current falls from an amplitude maximum back to nil, with a duration often of some hundreds of μsec, in some cases many msec. The total duration of a lightning stroke may vary very appreciably.

Further, in the lightning path there occurs most often after the first lightning stroke—the main discharge or the main stroke—a number of partial strokes following one after the other—partial discharges or multiple strokes. Up to about 40 of these in the same lightning have been recorded in the U.S.A. In measurements of multiple lightning strokes carried out at the Institute for High Tension Research up to around 20 have been recorded. The intervals between the successive discharges amount as a rule to some tens of msec, though these intervals may vary considerably. The multiple lightning strokes are chiefly characterised by the above-stated development forms (2) and (3). The total duration of a lightning stroke may thus extend over considerably varying sections of time—from a few milliseconds and up to, in extreme cases, full seconds. In view of these fluctuations in time variation it is obvious that a complete recording of all phases in the course presents appreciable experimental difficulty.

The chief instrument for investigation of the properties of the electro-magnetic variations has been for 35 years the cathode-ray oscillograph. Measurements of lightning discharges with this instrument connected to an open aerial for recording the variations in the electric field intensity were carried out in 1921 by one of the authors [1].

It has been found that special experimental difficulties arise when employing cathode-ray oscillographs for the study of lightning discharges. The restricted sweep length in a cathode-ray oscillograph makes it possible with one instrument only to analyse in detail one or at most a few of the time-varying stages in the lightning discharge. This difficulty has often been overlooked in earlier investigations, with the result that many of the variation properties of the lightning discharges have been ignored.

The stage in the discharge mechanism which presents particular recording difficulty is without a doubt constituted by the pre-discharge processes, both because of their small amplitudes and also owing to their long duration. This has been the reason why closer analysis of the pre-discharge mechanism has so far been neglected. It is in the nature of things that the pre-discharge mechanism is of the utmost interest chiefly from the physical standpoint. But there is also a purely practical demand for investigation in this field. This applies not least to the noise level, which is associated with the mechanism of lightning discharges and is of present interest for radio communication problems. The variation structures of the pre-discharges are also of great significance for a general analysis of atmospherics. The above-stated circumstances constituted very good reasons for us at the Institute for High Tension Research taking up the electric and magnetic variation properties of the pre-discharges for closer investigation in the last few years.

One of the present authors has previously investigated the electric field variations in pre-discharges in the vicinity regions of the lightning discharges [2]. In those investigations there were used simultaneously two cathode-ray oscillographs of different sweep time and sensitivity. These investigations were later taken up in other quarters [3] and the electric field variations of the pre-discharges in the vicinity region were then also investigated.

In other investigations carried out earlier by the Institute of the discharge mechanism of the lightning, one of the authors instead of analysis of the variations generated in the electric field by the lightning applied quite a different method for the analysis of the lightning's discharge mechanism. This new method is characterised by the variations in the magnetic field generated by the lightning discharges being analysed [4, 5]. The method is based on the intimate relation between the variations in the magnetic field and corresponding variations in the current in the lightning path. Experience gained in experiments over a considerable period has unmistakably shown that the method with measurement of the magnetic field variations from lightning discharges furnishes quite a different and appreciably better survey of the discharge mechanism in the lightning path than is obtained when the electric field components in the lightning discharge are used for analysis. This applies not least when one considers the complicated mechanism in the pre-discharges. It was these circumstances in the first place which were the reason that in the present work it was decided only to make use of the variations generated by the pre-discharges in the magnetic field.

Extensive investigations of magnetic field variations due to lightning discharges were made at the Institute during the thunderstorm seasons of 1953–56. Description of the investigation method and theoretical commentary are available in a previous work [5]. The investigations of 1953–56 have been published in part [6] and the present work gives the method, the apparatus equipment and the results.

One object in the investigations comprised the magnetic field variations of the pre-discharges and their relation to lightning discharges. This aspect of the lightning discharge process was only given passing attention in the earlier publication. In view of the fact that the object constitutes a separate aspect of the discharge mechanism, it was considered advisable to deal with this aspect in the work now presented.

2. Equipment and working method

The difficulty involved in experimental investigation of the pre-discharges has been avoided by setting the sensitivity of the cathode-ray oscillographs and amplifiers during the recording periods at particularly suitable sensitivity level, so that the main discharge appears with appropriate amplitude on the screen of the oscillograph. All the same, it is not always possible to obtain a detailed analysable oscillogram of the pre-discharge. This applies particularly when lightning discharges are formed at very small distances from the observation station. In such situations the consequence is that in view of the greater amplitude of the subsequent main discharge the oscillograms will be spoiled. In some cases the recording will moreover be complicated but, despite this, oscillograms of this type are particularly valuable for an analysis, chiefly because the pre-discharges in these cases usually appear with all the clearness desirable. Even in cases where the main discharge has a simple variation structure the result will be that the pre-discharge can be analysed.

Another matter is of importance in this connection. On the recording films of the field stations there appear in many cases oscillograms of discharges in nearby thunderstorms, where outdoor observers did not observe any lightning discharges, either in the form of light phenomenon or subsequent sound. In such cases, however, it is not out of the question that the discharges were accompanied by weak light phenomena. Seeing that the investigations at the Institute only proceeded in summertime and in strong daylight, the observers did not have any possibility in any case of observing such light phenomena. The question is whether such light phenomena associated with the pre-discharges would in general have such an intensity that they could be observed with the naked eye other than in complete darkness. On the other hand, the oscillograms on the said observation occasions have without exception the variation structure as regards field variations that applies to pre-discharges. It was therefore considered fully advisable to treat them separately under the designation of pre-discharges without subsequent main or partial discharges.

In this connection it should be stressed that a lightning stroke in the proper sense with its either disruptive or more slowly developed discharge constitutes the final phase in a progressive discharge process and from the physical point of view there is nothing against this process being in many cases arrested at an early stage—in other words, stopping at a pre-discharge stage. Such cases have been analysed by one of the authors [2] by means of the lightning stroke's variation in the electric field in the vicinity regions.

Survey of the oscillograms for the three years shows that there is a comprehensive material which is particularly suitable for analysis of the variation properties of the pre-discharges. This material comprises more than 500 separate oscillograms of pre-discharges and some 200 of these represent pre-discharges without subsequent main or partial discharges. The oscillograms were recorded by means of two sweep times, usually 1000 μsec and in exceptional cases 5000 μsec. In the analysis of the slower variation regions of the pre-discharges, these slow sweep times were especially suitable. For regions in the pre-discharges with the fastest variation types there was obviously required a different and specially rapid oscillographical measurement technique. As will be seen, it was possible despite this to analyse to a certain extent even the more rapid variation forms of pre-discharges.

3. Variation types and their features

On examination of the material it was found that it was possible in the first place to distinguish three different variation types. Two of them occur both in discharges with main and partial discharges and in those where the latter were lacking. The third variation type is characterised by very rapid field changes and it appears during the period of the pre-discharge just preceding the main discharge. Owing to the slow sweep time, as already stated, this more rapid discharge form could only be analysed

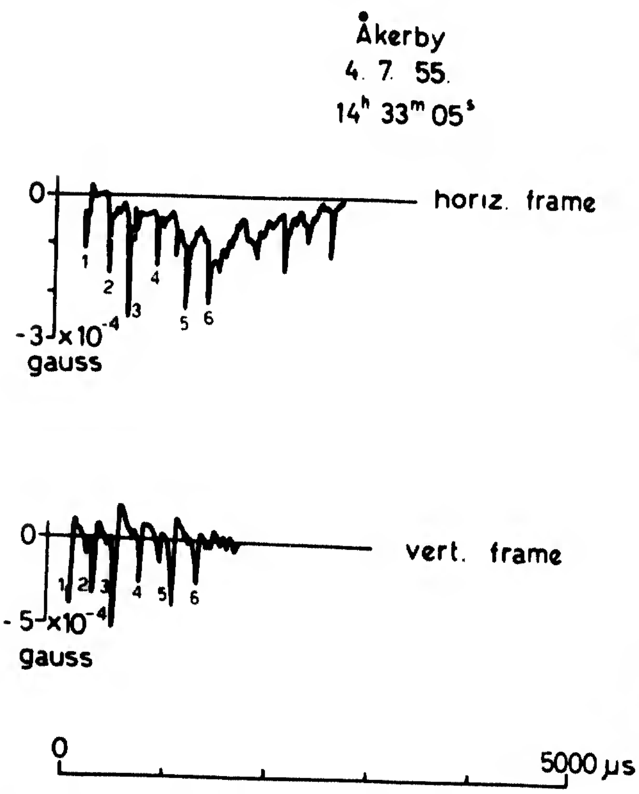


Fig. 1. Pre-discharges of type 1 recorded simultaneously on horizontal and vertical frames.

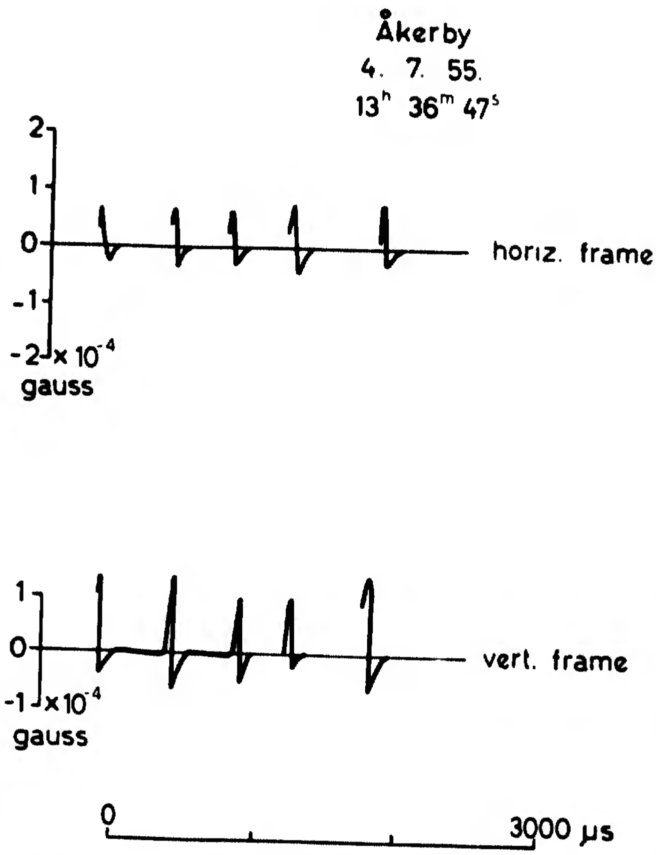


Fig. 2. Pre-discharges of type 2 recorded simultaneously on horizontal and vertical frames.

to a limited extent by means of the oscillograms available. An analysis of these rapid field variations of type 3, as suggested, calls for a special recording method, and this is being worked out. These rapid field variations could, nevertheless, be analysed on broad lines by statistical analysis.

In the first place we deal here with field variations from those pre-discharges which are not followed by main discharges. Examples of simultaneous recording of the two types occurring in such cases and designated by 1 and 2 may be seen in Fig. 1 and Fig. 2. The variations were recorded on both vertical and horizontal frames. The characteristic feature of type 1, see Fig. 1, is that distinct strong rapid impacts occur at intervals of some hundreds of μsec. Between these there arise rapid variations in the field intensity, characterised by low amplitude. From Fig. 1 it will be seen that the agreement with simultaneous recording between the vertical and the horizontal frame aerials is very good. In connection with Fig. 1 the rapidly developed simultaneous impacts are numbered from 1 to 6 for the two oscillograms. With this type of recording it is in most cases possible to determine which impacts belong to the vertical and the horizontal frames, owing to a common sweep generator giving the same variation in time for the two oscillographs. From Fig. 1 it will be seen that after impact No. 6 the vertical frame's field intensities return to low values. On the other hand the field intensities from the horizontal frame, which has greater sensitivity for horizontal components, continue to show rather higher values. As the horizontal frame aerial is sensitive for the lightning path's location in space, this may explain the unipolar component which in this case appears on the horizontal frame's oscillogram.

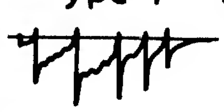
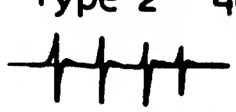
The other from of pre-discharges, type 2, is shown in Fig. 2. This form is characterised by rapid rises in the field intensity, separated by intervals of some hundreds of μsec. The field intensity after such a rise returns rapidly to zero and remains there until the next impact begins. Even in Fig. 2 it is seen that the agreement in time between the field intensity recordings of the vertical and the horizontal frames is very good. Comparing the two main types it is found that both are characterised by the powerful impacts, in other words by the rapid increases in the field intensity, with the intervals consisting of some hundreds of μsec. The essential difference between the two types is that between the big impacts type 1 shows rapid superimpositions on the aperiodically diminishing branches whereas type 2 does not have these.

From the purely discharge point of view, type 1 may be explained by saying that the forward rush in the channel proceeds the impacts, causing considerable field intensity variations at intervals of some hundreds of μsec. Alongside these impacts there arises in the same channel a series of streamers from the surrounding, is of very brief duration and with small current. These cause the small rapid superimpositions. We shall return to this question later. In contrast to this variation form, type 2 consists of isolated impact rushes at intervals of a few hundred μsec. Between these rushes the channel is at rest.

The possibility that type 1 might arise from several simultaneous discharges superimposed on each other is very small, as type 1 occurs in 60 % and type 2 in 40 % of all the oscillograms. This may be seen in Table 1, which gives a survey of the polarity of the vertical and horizontal frames. From Table 1 it may be seen that the negative polarity predominates in both type 1 and type 2.

The field intensity variations discussed so far have been assumed to be caused by the process applying to pre-discharges without subsequent main or partial dis-

Table 1.

		Positiv	Negativ
Type 1 60 % 	vert.	5	36
	hor.	14	30
	tot.	19	66
Type 2 40 % 	vert.	17	24
	hor.	14	47
	tot.	31	71

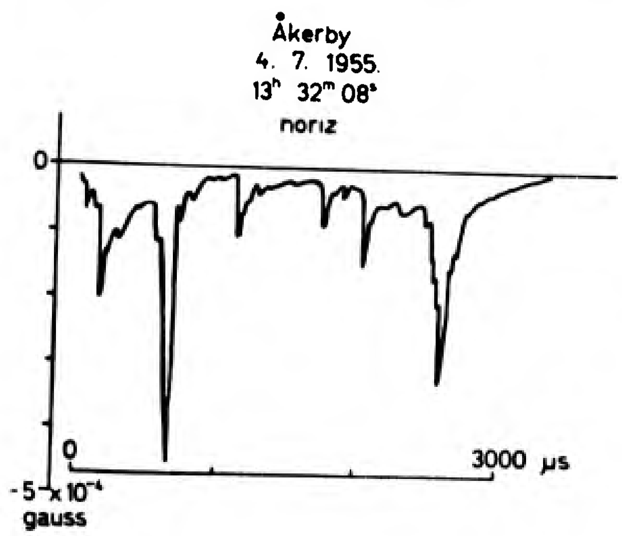


Fig. 3. Pre-discharges of type 1 from horizontal frame.

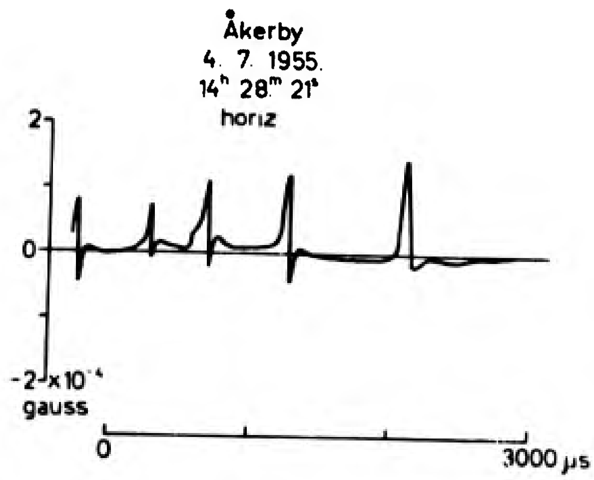


Fig. 4. Pre-discharges of type 2 from vertical frame.

charges. They refer therefore to the situations, of which the existence has previously been pointed out, where the lighting discharge has been arrested in the pre-discharge stage.

In this connection, it is particularly interesting to go closer into the similarity between pre-discharges with and without main and partial discharges. Figs. 3 and 4 show examples taken direct from oscillograms of field intensity variations from pre-discharges which were accompanied by main and partial discharges. The field intensity variations of the latter are not plotted on the figures. A number of examples of pre-discharges with subsequent main discharges are given later in another connection. It may be seen from the oscillogram in Fig. 3 that the pre-discharge agrees with type 1, and in Fig. 4 with type 2. This agreement in the types of pre-discharges, both lacking and accompanied by main and partial discharges, is not peculiar to the examples given but is found to apply throughout.

The variations of the pre-discharges have so far been grouped around the two types 1 and 2. This is based on the standpoint that all recorded oscillograms up to now of pre-discharges can be arranged under these types. They are evidently expressions of separate courses in the pre-discharge process.

4. Statistical treatment

The statistical distribution of the time intervals between field intensity variations is of special interest and the oscillograms from the pre-discharges have for that reason been treated on the basis of the intervals of time between the impacts.

Fig. 5 gives a general survey of the impact intervals for pre-discharges with accompanying main and partial discharges. This survey comprises both type 1 and type 2 recorded on vertical frame aerial. The reason for bringing them together statistically is that their time differences do not display any difference in tendency. From the survey it may be noted that the dispersion of the intervals is very great, from 50 to 500 μsec. This great dispersion is worthy of note, as measurements with rotary lens systems [7] show that the impact intervals from cloud to earth hold themselves to a restricted area between 50 and 90 μsec. According to Fig. 5 there are 60–

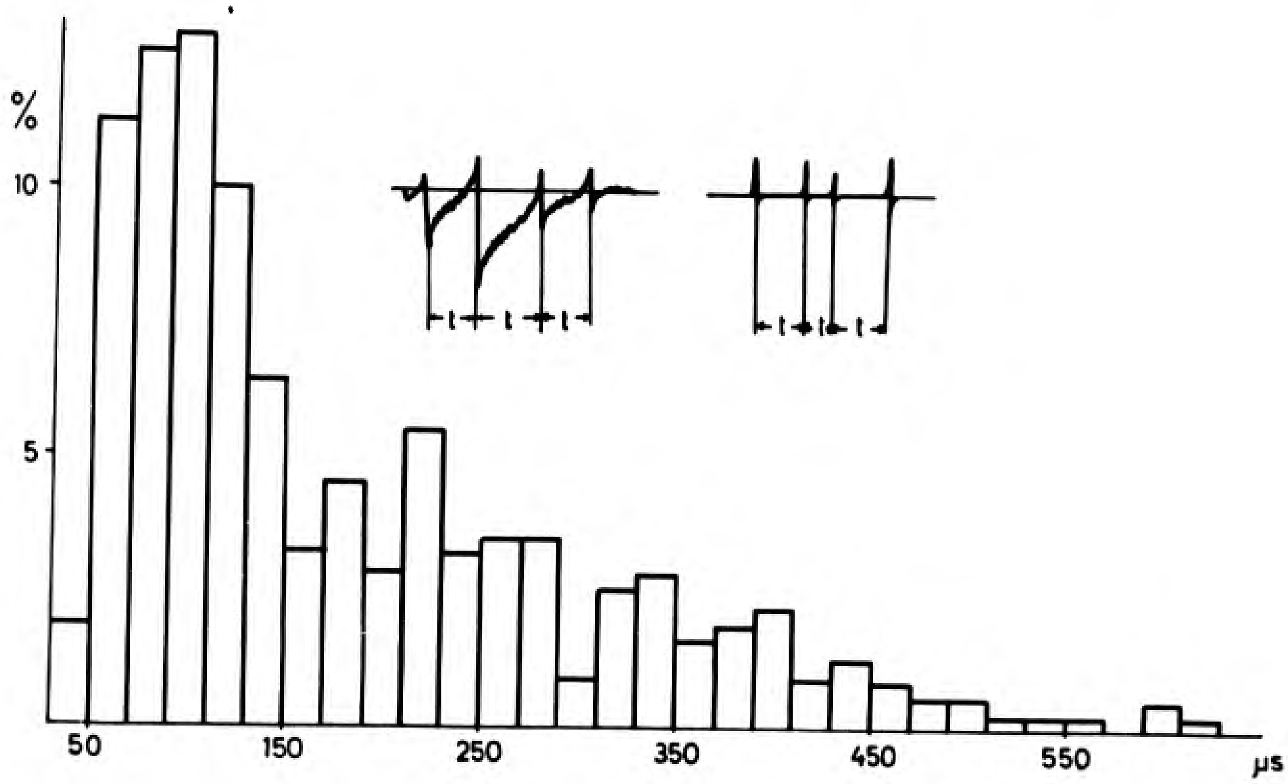


Fig. 5. Analysis of time intervals of rapid impacts in pre-discharges of type 1 and type 2.

70 % with longer times than what has been obtained in some optical investigations in other quarters with rotary lens systems. The results obtained according to Fig. 5 agree with what was obtained in another investigation [3] of pre-discharge intervals with the E-method. Thus it is evident that a definite difference is obtained according to whether the recording method is optical or electro-magnetic. It has been suggested by another author [3] that the cause of this difference is simply that with a rotary lens system that part of the pre-discharge process that lies inside the cloud is lost. There is nothing to prevent this part of the discharge process having a different character, which should be brought out by a further statistical treatment. The difference in the results shows clearly that it is not possible with purely optical methods to draw too far-reaching conclusions regarding the electro-magnetic variation structure of the lightning discharges. It is more a statistical treatment of same which must be designed to throw light on the difference in the duration of the intervals. For such a treatment one may on the basis of extensive experimental experience of lightning discharges in the vicinity region start out in the first place from the fact that the discharges comprised in the category of pre-discharges without subsequent main or partial discharges almost without exception belong to discharges in the thunder-cloud itself. Figs. 6 and 7 give the statistical distribution of the rapid field intensity variations for pre-discharges without accompanying main and partial discharges. The treatment applies to field intensities both for vertical and for horizontal frame aerials. In this case too the pre-discharge types 1 and 2 are combined in the survey. It will be seen that the agreement for the two frame aerial systems is very good. The intervals between the rapid field intensity variations are mainly between 100 μsec and 800 μsec, or outside the area recorded with rotary lens systems. For further investigation as to whether the intermediate pauses for the impacts inside and outside the cloud are different, we have made a statistical treatment of the

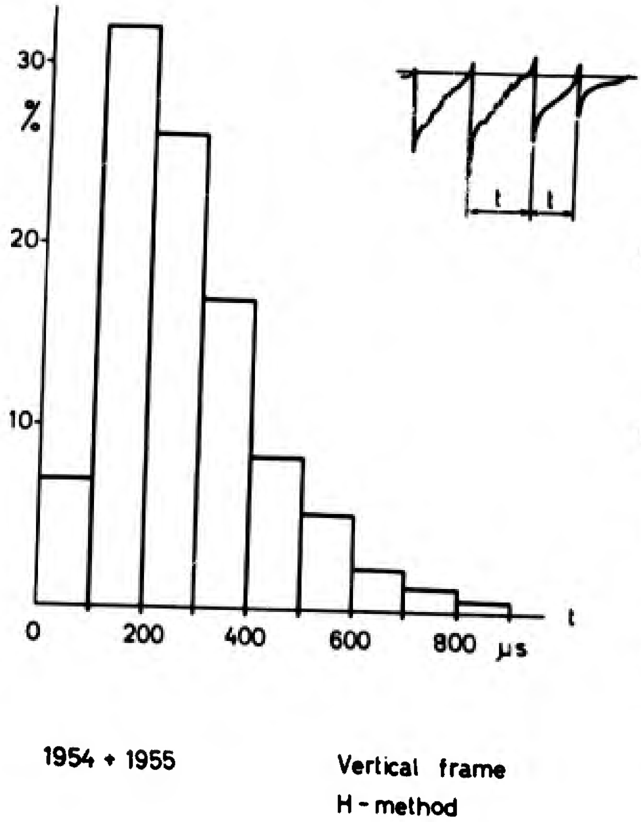


Fig. 6. Analysis of time intervals from vertical frame of rapid impacts in pre-discharges lacking main and partial lightning strokes.

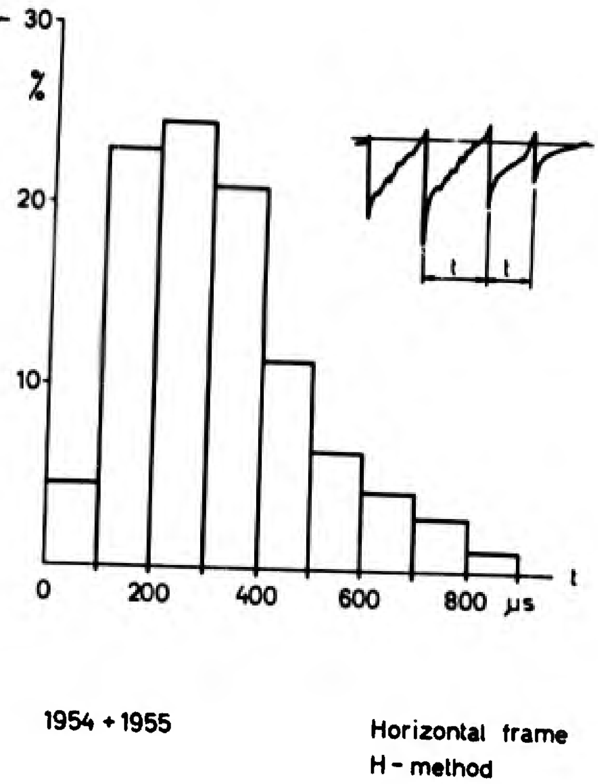


Fig. 7. Analysis of time intervals from horizontal frame of rapid impacts in pre-discharges lacking main and partial lightning strokes.

time intervals between the impacts for the period of the pre-discharge which, in point of time, come next before the main discharge. This period comprises the variation area for the pre-discharge which is usually recorded by rotary lens systems. This period of the pre-discharge comprises the pre-discharge form previously mentioned as type 3, with time intervals at or below 100 μsec. We have confined the statistical analysis to oscillograms from vertical frame aerials. The result is given in Fig. 8, which shows that 80–90 % of the pauses between impacts lie between 0 and 100 μsec. These figures for the pauses show very good agreement with the figures obtained with rotary lens systems. The great number of intervals of brief duration show clearly that the dominating values in the statistical analysis are based on the third type previously mentioned in the pre-discharge process.

A very clear example of the change in the discharge process is furnished by the oscillogram in Fig. 9, which was recorded with horizontal frame aerial. In this case, *a* represents the impact-like rush of the charge inside the cloud. This part, as already stated, must be concealed by the cloud, so that it cannot be photographed. Another part of the discharge process, designated by *b*, however, shows that the impacts follow very closely one after the other. This part of the discharge has been developed outside the cloud and represents the third type in the pre-discharge process. This cannot begin until the ionisation inside the cloud has attained a given intensity due to the pre-discharges. This later part outside the cloud can be photographed with a high-speed rotary system. With reference to Fig. 9, the part *a* represents the type 1, previously mentioned, with long intervals between the big impacts.

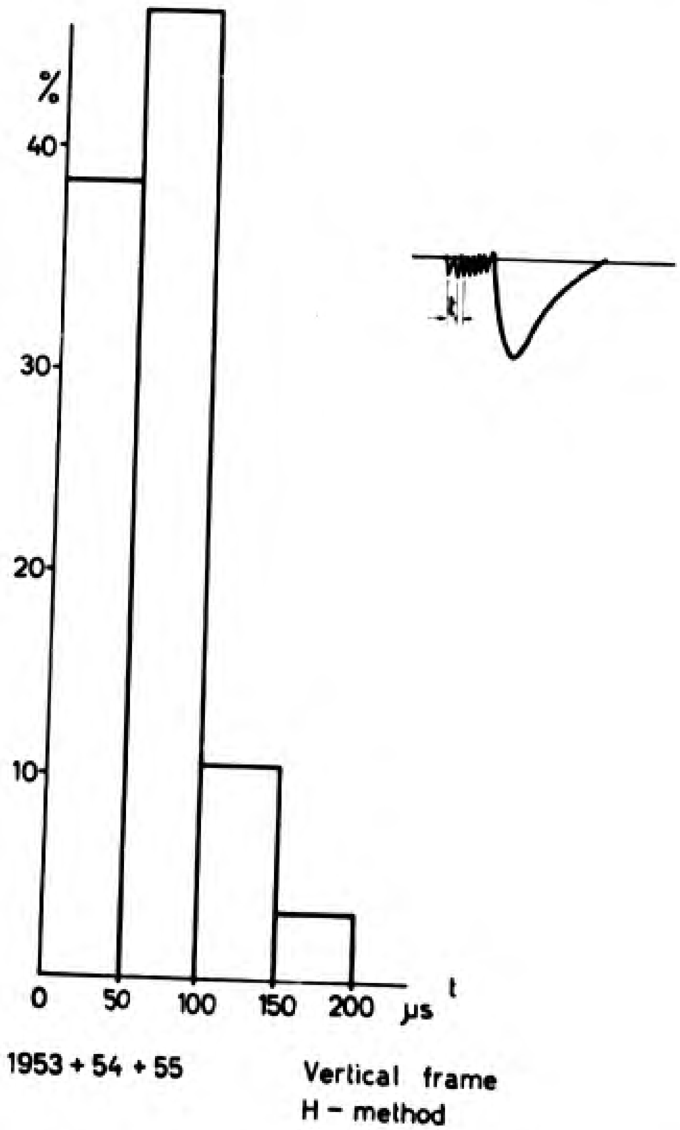


Fig. 8. Analysis of time intervals of rapid pre-discharges of type 3.

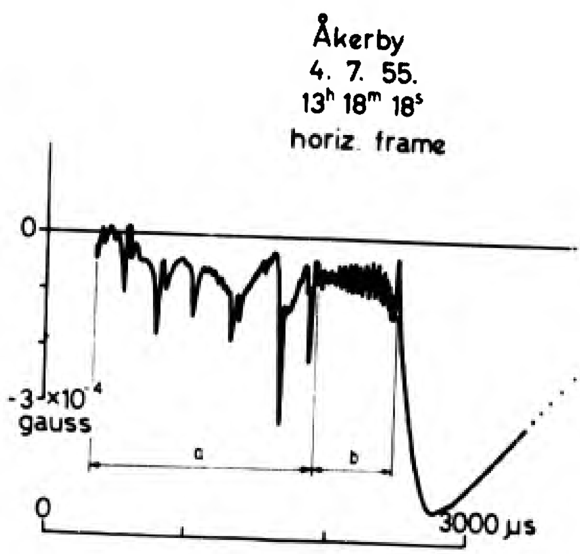


Fig. 9. Oscillogram from horizontal frame showing pre-discharges of type 1 passing over to rapid variation of type 3 before main lightning stroke starts.

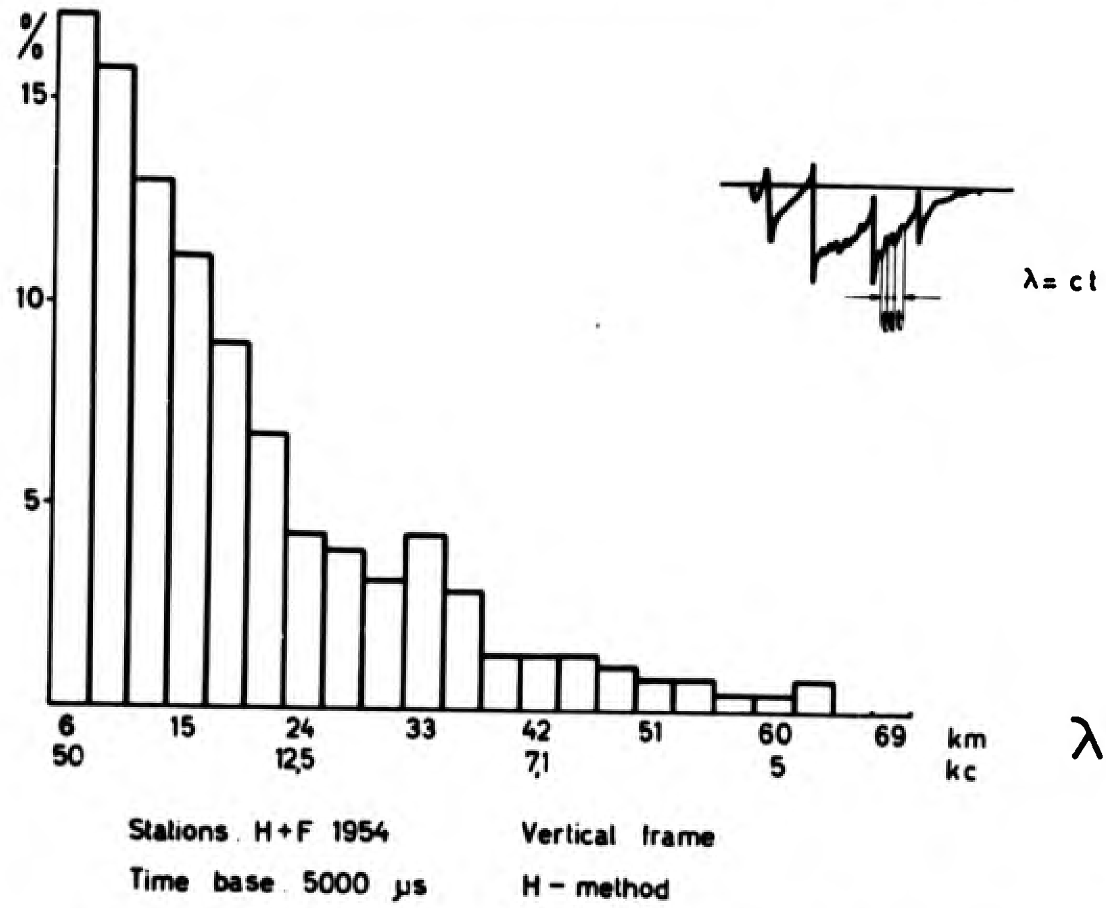


Fig. 10. Statistical survey of quasi-periods of superimposed rapid variations between intervals of impacts in pre-discharges.

The sweep times for the oscillographic recording have made it possible to reproduce clearly the slow variation types 1 and 2 in the oscillograms. On the other hand, the high-speed pre-discharges of variation type 3 most often appear crowded, rendering a time analysis of the discharge form difficult. This time analysis must be performed after enlargement direct from the oscillograms. The interval of time in which this high-speed pre-discharge type arises has therefore been indicated in the oscillograms which follow as an estimate by dotted lines.

In variation type 1 of the pre-discharges, there are found, according to the oscillograms, in the pauses between the impacts, a number of superimposed rapid variations. These have been found to appear sufficiently clearly to allow of a quasi-periodical frequency analysis. Thus, for example, in Fig. 9, we see during the discharge period *a* with its pre-discharge type 1, that there are distinct superimpositions between the impacts, which even increase in number as the impacts approach the area *b* for the rapid variation type 3. It is possible, therefore, that we have to consider two processes which partially coincide as regards time. These processes would consist both of the rapid variations in the field intensity in the area *a* in Fig. 9, and of the rapid field variations of the type 3 in the area *b*. These changes dominate in the latter area, but it is possible that rapid variations from the area designated *b* have made their way even earlier in between the high-speed impacts. They make their presence known there by rapid superimpositions. Still further special oscillographical investigations are required to provide a definite answer regarding the relation and time sequence of these variation properties.

A statistical analysis, which is of interest from a special point of view, is shown in Fig. 10. This figure gives a survey of the distribution of the time intervals for the rapid superimpositions between the high-speed impacts in the field intensity values in accordance with type 1 of the pre-discharges discussed earlier. The analysis has been performed from the recordings with vertical frame aerial and to facilitate survey has been converted to quasi-periodical wave forms. It will be seen from the survey that dominating accumulations of existing wave forms lie in the region up to 15–20 km. One of the authors has already shown in two earlier investigations [2, 6] that the accumulation of such variations lies in the quasi-periodical wave length region which has been on many occasions recommended by the General Assemblies of URSI [8] for the tuning in of direction finder systems for atmospherics. The selection of such a tuning frequency was probably dictated by practical experience of observations with direction finder systems and without the support of investigations as to whether the frequency range is associated with lightning discharges or with their pre-processes. In view of what is demonstrated in Fig. 10 it must involve an appreciable uncertainty to employ tuned circuits on aperiodical or quasi-periodical processes in the direction finding of lightning discharges, especially as the tuning frequency is directed to the pre-discharge process of the lightning. In the present publication, it has been shown in various connections that pre-discharges are not always accompanied by lightning discharges. In this case, direction finders with wide band circuits give more reliable results.

5. Analysis of a special thunderstorm situation

On 4.7.1955 there occurred an interesting thunderstorm situation, which on account of its location could be analysed from one of the Institute's field stations, Åkerby. In two passing thunderstorms there occurred a large number of pre-discharges without subsequent main and partial discharges. An example of the large number of pre-discharges that characterised the two thunderstorms is given in Fig. 11 and is clearly of type 1.

Owing to the occurrence at the same time of visible lightning discharges it was possible for the observers to establish the distance between the station and the dis-

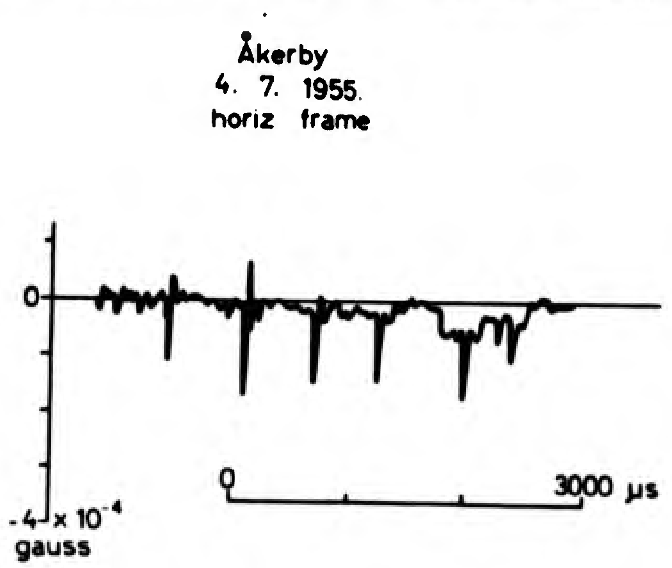


Fig. 11. Typical pre-discharges of type 1 lacking main and partial lightning strokes.

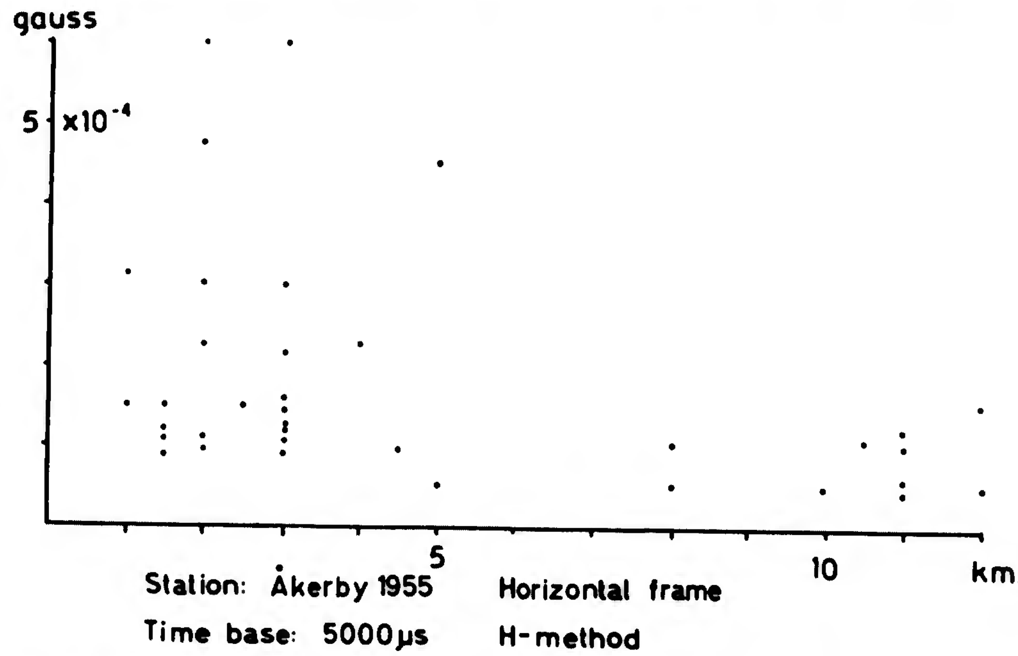


Fig. 12. Peak values in relation to distance from source of magnetic field force in pre-discharges lacking main and partial lightning strokes.

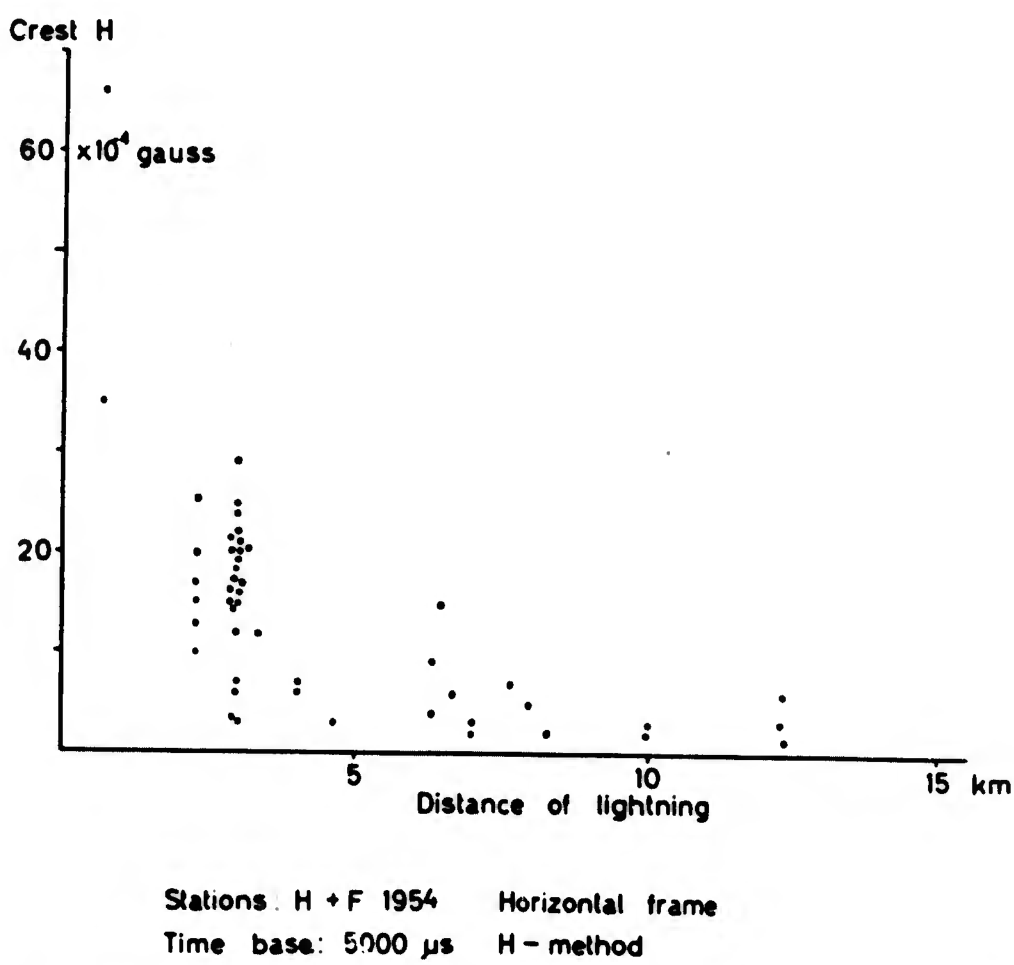


Fig. 13. Peak values in relation to distance from source of magnetic field force in main and partial lightning strokes.

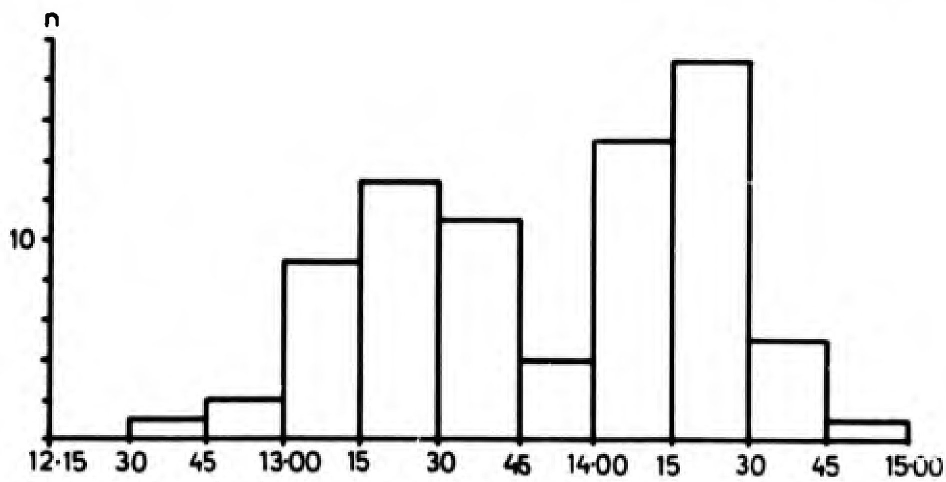


Fig. 14. Variation with time of number of consecutive pre-discharges within two passing thunderstorms.

charge centres of the two passing thunderstorms. These distance determinations also enabled corresponding determination to be made during the passage of the thunderstorms of the distances respecting pre-discharges without subsequent main and partial discharges. These discharges occurred, according to our experience and according to what has already been stated, chiefly inside the thunderclouds. They were therefore most often characterised not by vertical components but by components oblique or horizontal to the ground. The measurement sensitivity for these field intensity variations will then be greatest when a horizontal frame aerial is employed.

With a view to investigating these conditions more closely oscillograms were taken therefore by means of a horizontal frame aerial during these two passing thunderstorms. The analysis was then limited to a number of pre-discharges without main and partial discharges. By means of these oscillograms, the maximum field intensity variations in relation to the discharge region inside the thunder cloud were measured and the result is given in Fig. 12. In this case, it was of particular interest to compare the amplitudes with the maximum field intensity values in thunderstorm situations coming from main and partial discharges, also taken with horizontal frame aerials. This field intensity distribution is given in Fig. 13. In the investigation of the cases treated it is evident that the great dispersion between individual values for the same distance cannot be avoided. This dispersion is due to fluctuating intensity in the current force of the individual discharges. On the basis of the dispersion in Figs. 12 and 13, it is found that the maximum field intensity for a pre-discharge without subsequent main and partial discharge amounts approximately to about 15 % of the corresponding field intensity values for main and partial discharges measured at the same distance from the discharge centre. This relation agrees very well, as will be seen in what follows, with the corresponding relation for pre-discharges followed by main and partial discharges.

The question whether the variation in time sequence for the number of pre-discharges without subsequent main and partial discharges could also be investigated in the two thunderstorms. The variation of the number of pre-discharges with the time has been given graphically with this object in Fig. 14. The outdoor observer noted his first visible lightning stroke at 12.30 and in the next hour the number of visible lightning strokes became increasingly greater, after which it diminished

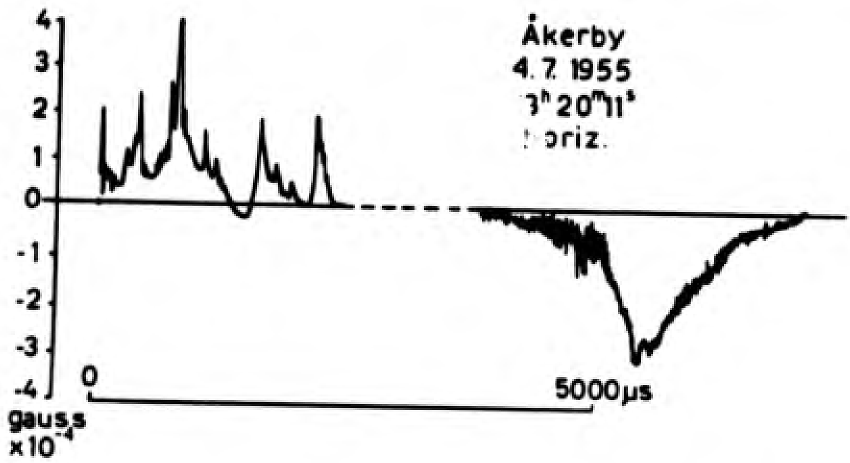


Fig. 15. Pre-discharges of type 1 from horizontal frame followed by main lightning stroke with slooping front.

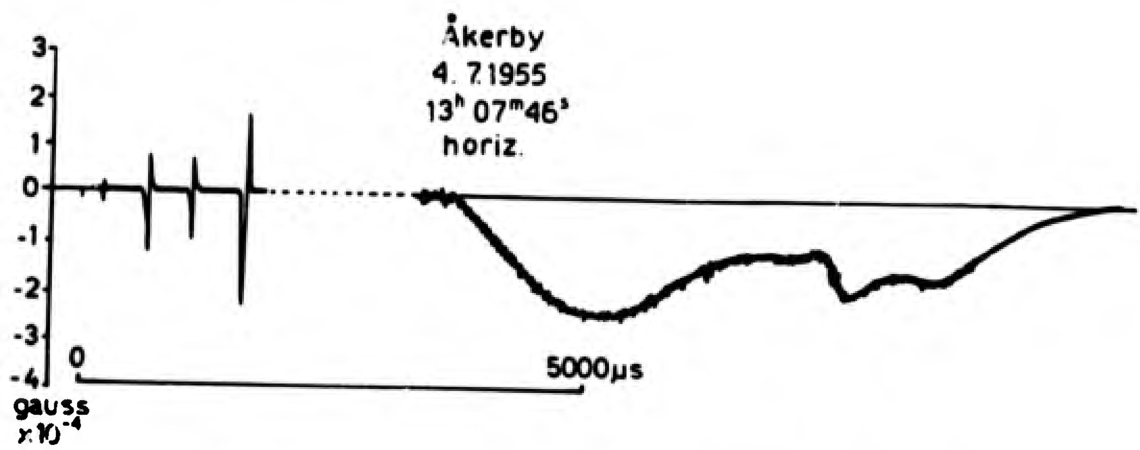


Fig. 16. Pre-discharges of type 2 from horizontal frame followed by main lightning stroke with very slooping front.

during the next half hour. Similar variation also occurred in the number of oscillographed pre-discharges without subsequent main and partial discharges of the subsequent thunderstorm.

The fact that pre-discharges occur without subsequent main and partial discharges has its evident physical reason. In some cases the charge concentrations for the volume charges inside the thundercloud that are active in a discharge are not of sufficiently high intensity to maintain subsequent main and partial discharges. The whole phenomenon stops at one or in some cases repeated pre-discharge processes. On the other hand, in some cases a number of such pre-discharges may on account of the accompanying ionisation prepare the development of a pre-discharge which is followed by main and in some cases partial discharges. In cases where these are typically disruptive they are characterised by steep front slopes. But there may also occur an intermediate form, where the pre-discharges are not accompanied by a spark discharge in the proper sense. The pre-discharges have only sufficient intensity to start a glow discharge, while the volumes participating in the discharge process do not have sufficient intensity as regards field force to maintain a disruptive discharge. The main discharge simply stops at a glow discharge. In such cases, the final process must be characterised by very weak front slopes. Main discharges of this type are not uncommon in the extensive material covering front slopes of main discharges, collected at the Institute's field stations. A couple of interesting cases of such main discharges are given in Figs. 15 and 16, both recorded from a horizontal frame aerial system and characterised by fronts with small slope. In Fig. 15 the main discharge is preceded by pre-discharges of type 1. A feature of utmost interest is that in this case the subsequent main discharge starts with very rapid variations, probably of the same type as that shown as pre-discharge type 3 according to Fig. 9. In Fig. 16, on the other hand, the main discharge is preceded by a pre-discharge of type 2. The subsequent main discharge with extremely little front slope is almost entirely superimposed by rapid variations, and contrary to what is characteristic for Fig. 15 there occur in this case superimpositions of rapid variations with remarkably small amplitudes. The examples show with all clearness how varying and complicated the lightning discharge process can be.

There may also occur thunderstorm situations where the discharge process is simply arrested, and, for lack of volume charges of sufficient intensity as regards field force and charge to establish and maintain a disruptive discharge, there are only pre-discharges. Situations of this type are referred to above. One of the authors, as stated earlier [2], has demonstrated the existence of such cases in conjunction with measurements of the variations of the electrical field in the vicinity region of lightning discharges.

6. Pre-discharges in their relation regarding amplitude to subsequent main discharges

In connection with Figs. 12 and 13, it has been stated that the maximum field intensity for pre-discharges without subsequent main and partial discharges amounts approximately to 15 % of the maximum amplitude of the latter. The field intensities obtained constitute mean cases. It may be of interest to compare this ratio with the ratio obtained in statistical analysis of the maximum magnetic field intensity amplitudes for pre-discharges and main discharges. This statistical comparison based on 330 observations is given in Fig. 17. As may be seen, the same ratio also dominates here—in other words the maximum amplitude of the pre-discharges amounts of 15 % of that of the main discharges. It may be seen from Fig. 17 that the amplitude for the pre-discharges may even be higher as compared with the main discharge, which appears from the fact that the figures exceed the ratio 100. It may therefore be of particular interest to illustrate this more closely by some individual cases. In this connection there is one question applicable, whether the pre-discharges come through with simultaneous recording at two stations. An example of this is given in Fig. 18. In this case the lightning discharge was recorded simultaneously at two field stations 17 km distant from each other. The agreement in variation form between the two stations is strikingly good despite the great distance between them. The part of the oscillogram designated by A coincides with a pre-discharge form of type 1.

Especially interesting is the relation between the prevailing polarity of the pre-discharges and the polarity of the subsequent main discharges. Where recording with a horizontal frame aerial is concerned it may happen that the prevailing polarity for the pre-discharge does not need to be the same as for the main discharge. This is related to the position of the lightning path in space. A typical example of such a

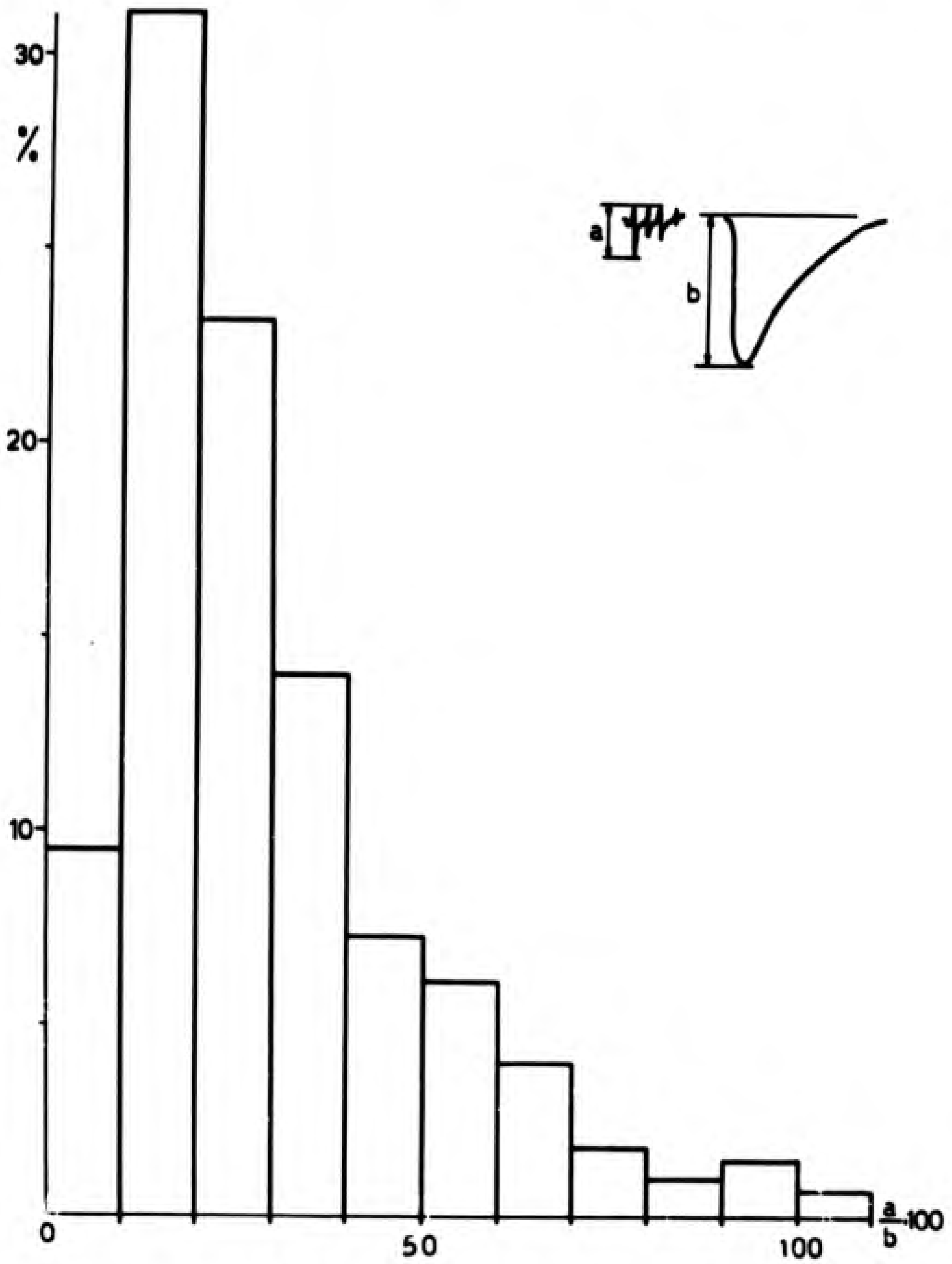


Fig. 17. Peak values of magnetic field force of pre-discharges in relation to peak values of main and partial lightning strokes.

contrary was given in Fig. 15. Even in recording with horizontal frame aerials the relation regarding positions of the aerial and the lightning path often happens to be such that the polarities between the pre-discharge and the subsequent main discharge entirely agree. An example of this is given in Fig. 19, where the pre-discharge amplitudes are as high as the highest amplitude of the main discharge.

In the event the recording are made with a vertical frame aerial mobile in respect of the lightning path the position conditions of the lightning path has no influence, as vertical components are recorded. This applies throughout and is exemplified by Fig. 20. In these three cases the subsequent main discharges are distinguished by characteristic steep fronts. Even in the case where the subsequent main discharge

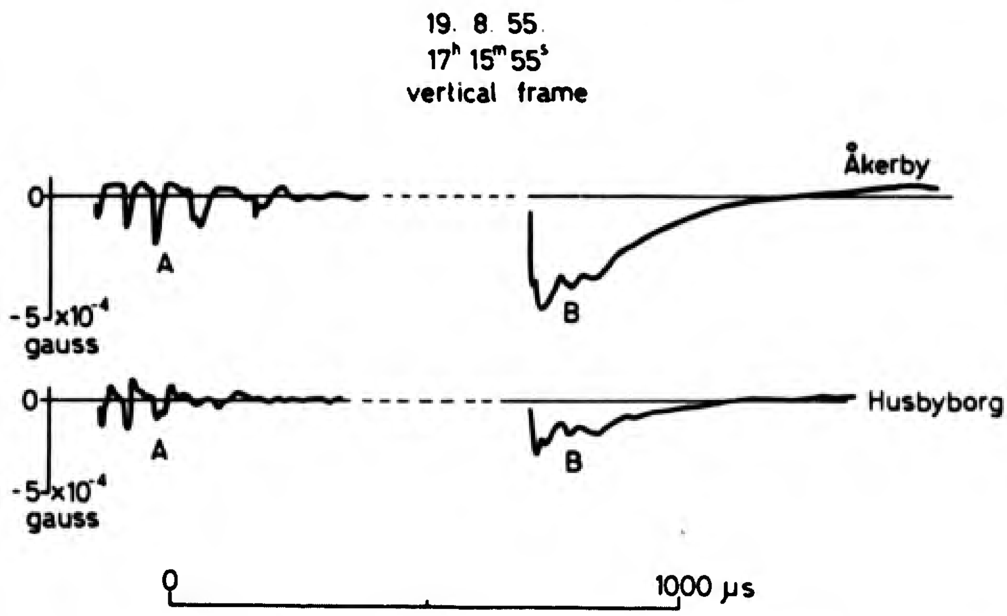


Fig. 18. Simultaneous records of pre-discharges and main lightning strokes from two field stations at distance of 17 kilometres.

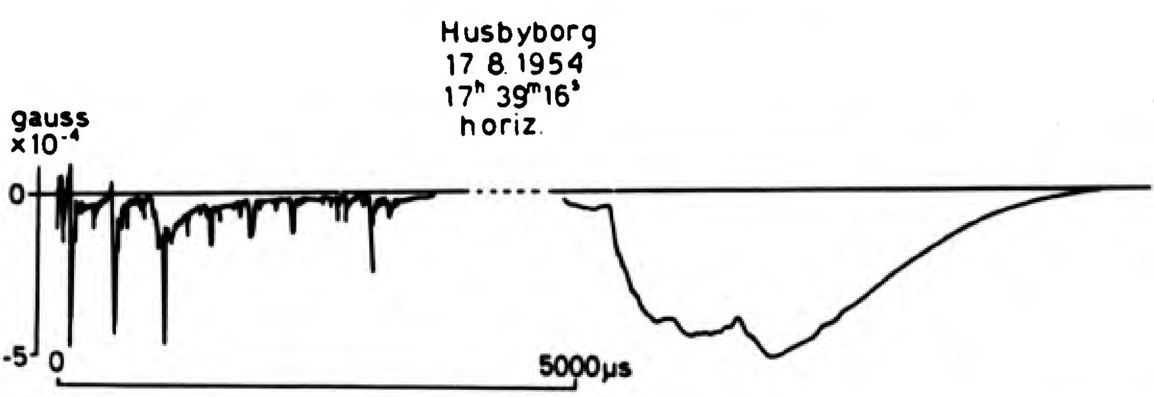


Fig. 19. Pre-discharges with peak magnetic field force of same magnitude as following main lightning stroke with slooping front.

has a steeply sloping front the same condition applies, as may be seen in Fig. 21. In this case the amplitude of the pre-discharges reaches about 75 % of that of the main discharge.

7. Relation between pre-discharges and noise level

The investigation carried out has shown that the pre-discharges are extremely complicated in their different phases of development. There have been found three distinct variation forms, all of which are characterised by rapid changes in the magnetic field intensities measured. The fact that the pre-discharges are made up of such rapid field changes should not in itself be surprising. Their general variation structure is, to a large extent, closely related to the different forms of streamers which precede the formation of long electric sparks produced in some works at the Institute [9–11]. The fact that the discharge in the thunder atmosphere works its way forward between volumes with suspended electrically charged particles or from

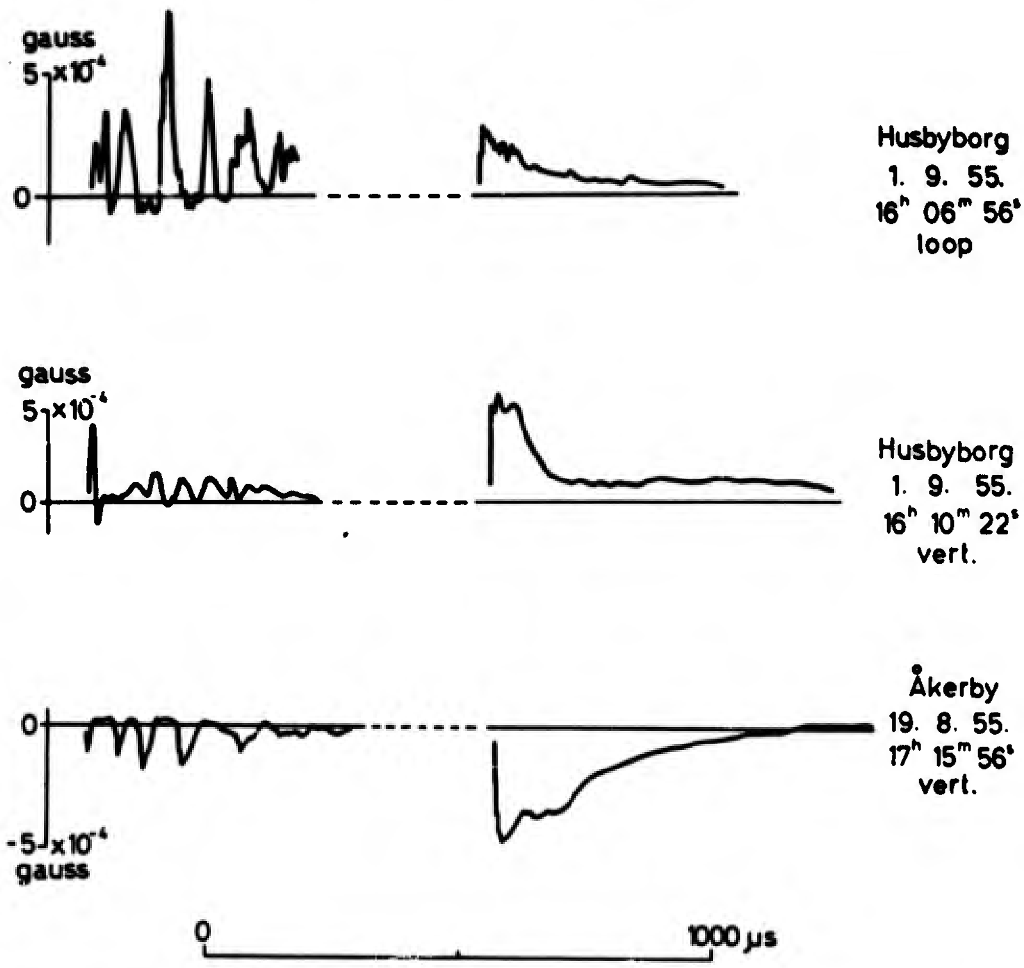


Fig. 20. Pre-discharges of type 1 followed by main lightning strokes with steep fronts.

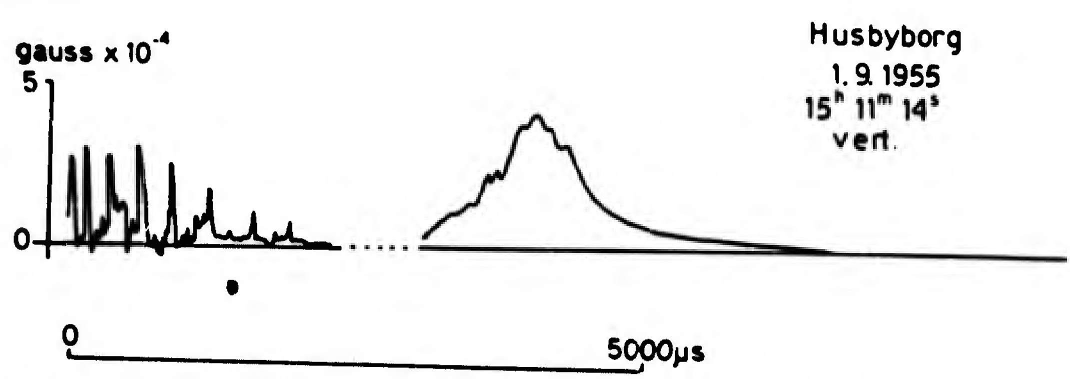


Fig. 21. Pre-discharges of type 1 followed by main lightning stroke with slooping front.

such volumes outwards from an electrically neutral region cannot from the physical point of view involve limitations of the rapid time variations of the pre-discharges.

On taking the mean of a large number of pre-discharges, according to the investigations performed in this work, the maximum field intensity variations stand at about 15 % of those of the main discharges. In isolated cases, as shown, the field intensity figures of the pre-discharges are of the same magnitude as those of the main discharges and in a very few cases higher than those of both the main discharges and the subsequent partial cischarges, see Fig. 20. These properties of the pre-discharges

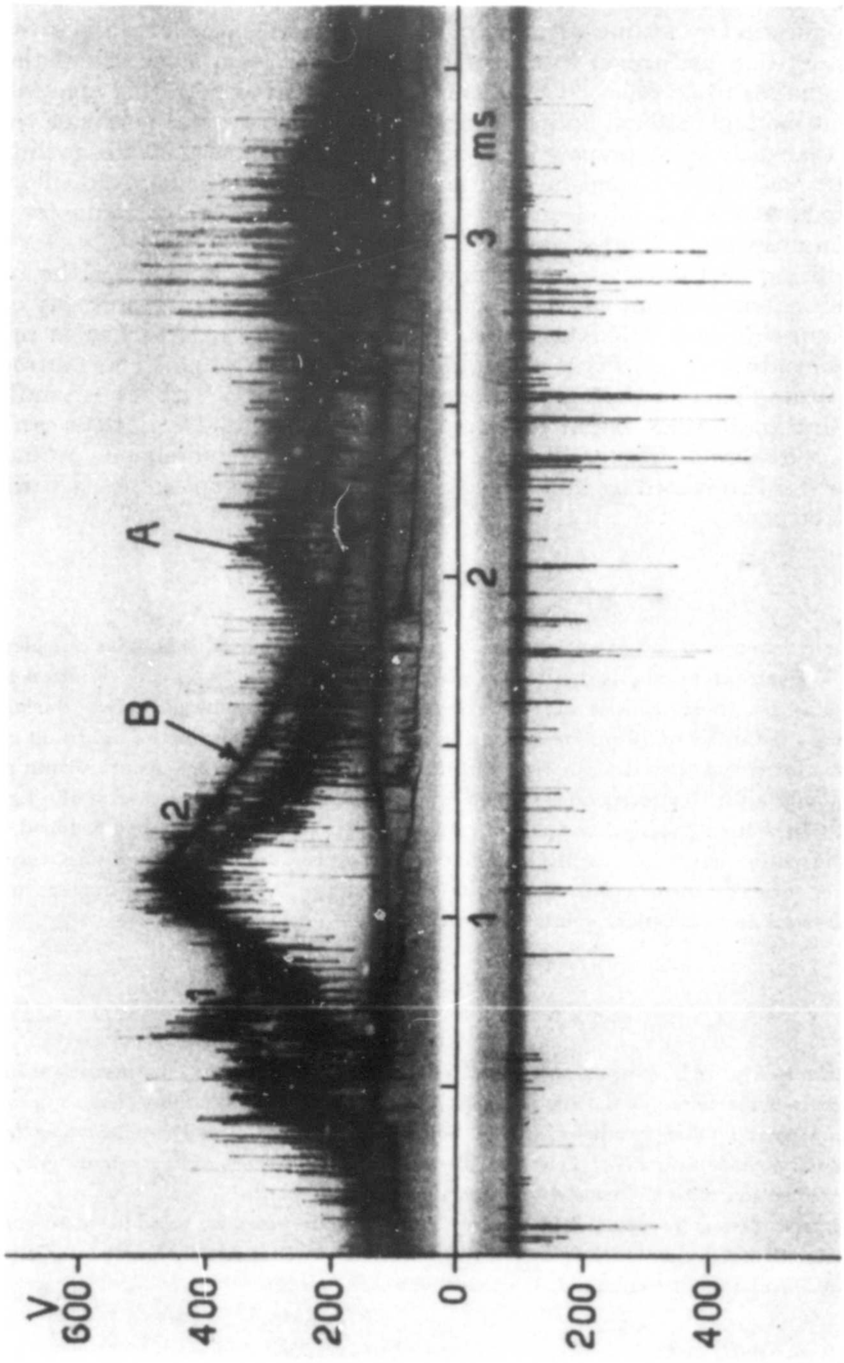


Fig. 22. Cathode-ray oscillograms of lightning discharges taken at Uppsala in 1929 with open antenna circuit. On curve *A* superimposed rapid field variations all over, on curve *B* most at beginning 1 and later on at 2, 3.

and their previously mentioned rapid variation structure must lead to one conclusion: the pre-discharges and their closer analysis are of the greatest importance when it is a question of dealing with the radio-atmospheric noise level and its causes.

The investigation performed in this work of the variation structure of the pre-discharges requires to be followed by a more detailed and penetrating analysis with measurement methods altered and specially adapted from several points of view—a task which is already being prepared. Basing on the experience gained in preliminary trials, there should be included in such an analysis cold cathode-ray oscillographs [12] provided with a special electron beam relay. This entirely eliminates interference when ultra-rapid courses are to be recorded.

Already during the thunderstorm seasons of 1927–29 in Uppsala one of the authors used an open antenna circuit to record with the mentioned open cathode-ray oscillograph the superimposed rapid variations caused by lightning discharges in their vicinity regions. In such records as exemplified in Fig. 22 no amplifier was introduced into the recording circuit, and the oscillograms show directly without any influence from amplification to what extent superimposed and very rapid variations can occur in a lightning discharge. The oscillogram shows also what requirements are necessitated with regard to recording in detailed analysis of rapid superimposed variations of lightning strokes.

SUMMARY

The variation features of pre-discharges in lightning strokes have up to now been neglected in research. To a great extent this is due to the complicated and very extended variation time of lightning discharges. These consist of three stages: (1) the pre-discharges when during time periods of up to the order of 10 milliseconds, the ionisation is starting in the lightning channel regions; (2) the main and partial discharges with their rapid increase of the fronts within periods of sometimes only a few microseconds; (3) the after-variations with a decrease of the lightning currents sometimes during many hundreds of microseconds. The authors have developed special methods for investigation of the variation features of the pre-discharges. They discovered that three different variation forms occur. The variation features of the pre-dischargers were analysed both from physical and statistical points of view.

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