New results of lightning observations

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Key words

Downward stroke
Upward stroke
Connecting streamer
Field measurement

Summary

From the results of lightning research on Monte San Salvatore near Lugano in Switzerland, the formation of charged lightning channels is examined in detail. The numerous upward strokes, growing from the top of the measuring tower towards the clouds, enable the evolution of the streamer to be traced from the very start, the currents and charges flowing into it being measurable. Photographic records on moving film prove that there are fundamental differences between positively and negatively charged channels. Upward connection streamers are discharges growing from the top of the tower towards a lightning stroke coming downwards from a cloud. With downward strokes from positive clouds, which often carry very heavy charges, extremely long connecting streamers have been observed. Quite new is the oscillographic recording of the electric field distribution near the point struck by the lightning, before and during the instant of discharge. For this, a device known as a "field mill" with high speed of rotation was designed. Some oscillograms obtained by this method are reproduced and discussed.

INTRODUCTION

SINCE 1943, A lightning observation station has been maintained on Monte San Salvatore near Lugano by the Swiss High-Voltage Research Commission. The station has been progressively expanded and many results have been gained. The present report concerns part of the field only, i.e. observations relating to the formation of the discharge channels of lightning strokes.

A brief review is given here on the equipment at present available. To intercept the lightning on the summit of Monte San Salvatore, which rises 640 m above the water level of Lake Lugano, there are two towers with a height of 70 m, the steel needle at the top included. One of them is the transmitting tower of the PTT and is erected only a few meters below the summit. The other, which has been built especially for lightning measurements, is situated on a rock outcrop some 400 m away. The currents of all lightning strokes picked up by the steel needle are conducted to earth through a measuring shunt. The voltage drop across the shunt is transmitted to the oscillograph by a coaxial well screened cable. All measuring instruments are situated in a Faraday cage in a building at the foot of the PTT tower. Actually, two oscillographs are provided; the magnetic one is used to record the relatively long, weak current components of the lightning current, while the other, a cathode-ray oscillograph, traces the wave shapes of the current impulses. In addition, the corona currents produced by the electric field in the vicinity of the towers during thunderstorms, of the order of 10^{-4} to 10^{-3} A are continuously recorded. During the past summer, a special equipment for measuring the electric field near the tower before and during lightning strokes was used for the first time. There will be said more about this equipment in the last section of the chapter.

On the summit of Monte San Salvatore there is a pilgrim church with a terrace from which the panorama view is excellent. Below this terrace, a photographic laboratory has been installed which allows a view in all directions. During night time, all lightning strokes in the neighbourhood are photographed by means of 8 normal cameras. Other cameras with fast moving film (Boys cameras) are used to record the progression of the charged lightning channel before the main discharge. Pictures of strokes to the measuring towers are of special interest when the shape of the current curve and its direction are known at the same time. From the photographic laboratory only the tower in a distance of 400 m can be photographed, the PTT tower being too near. Therefore, a second laboratory was set up in Breganzona about 3 km to the north of Monte San Salvatore, from where the entire summit of the mountain, with the two towers, is visible. Because of the delay time of the shutter, camera control by the strokes of lightning which will have to be recorded is not useful. Therefore, photographic lightning observations can only be carried out at night, when the shutters can be left open during many minutes.

UPWARD STROKES

Ordinary lightning experienced in flat country consists of *downward* strokes. Their discharge begins very probably between the different charge zones within a cloud, when one branch grows towards earth. They are therefore nothing else than leaders from cloud lightning, growing towards earth. *Upward*-growing strokes, on the other hand, begin at special points on the earth's surface where there is a highly concentrated electrical field. They are dealt with separately in this report because they are frequently esperienced at the measuring towers and because they allow the formation of the lightning channel to be traced from the very start and the current flowing into the channel to be measured.

The first observations of such lightning strokes were made on the Empire State Building by McEachron. Information relating to the observations at the measuring towers on Mount San Salvatore is given in Table 1. All strokes recorded in the past 10 years (1957–1966) are arranged according to the direction of growth and the polarity of the current. Only discharges with a charge of at least 1 C were recorded as strokes. The large proportion of upward strokes is remarkable. Taken over the last 10 years, the average is about 83%. During the last two years, they represent over 90% of all strokes. Since all lightning strokes occurring at night are photographed, it has been possible to record upward strokes at other places in the surrounding area. Most of them start at aerial installations on mountain tops, on buildings fitted with a rod lightning conductor, or on flagpoles. On the ridge at the top of Monte Generoso, an upward stroke was observed which started from a rock outcrop. There is also a photograph of an upward stroke from a church-tower situated in a relatively unexposed position on the ridge of quite a flat hill, only 200 m above the Lake Lugano. Since the branches of the streamer always point in the direction of growth, upward strokes can be recognized in the pictures (Figures 1 and 2) by the branches spreading upwards.

Upward strokes allow to measure the currents and charges occurring during the build-up of a streamer. The discharges always begin with a relatively low current (in the order of 10 to 10^3 A) of relatively long duration (10^{-2} to 10^{-1} s). Figures 12–15 reproduce typical examples of such current curves. These curves are reproduced in relation to the field oscillograms, so that they appear in part 5 of this report. The upward strokes, therefore, are in contrast to the downward strokes in which the previously charged channel is discharged to earth, resulting in current impulses up to 2×10^5 A with

TABLE 1 Number of recorded strokes during the 10 years' period from 1957 to 1966, arranged according to progressing direction and current polarity

	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	total 10 yrs
Number of evaluated oscillograms	28	9	46	37	18	36	92	45	90	133	534
Simultaneous strokes on the two towers	2	1	14	5	0	5	26	13	32	25	123
Evaluated strokes	30	10	60	42	18	41	118	58	122	158	657
Downward strokes											
total	7	2	12	8	9	17	25	10	5	13	108
from negative clouds	3	2	10	5	9	15	21	7	3	7	82
from positive clouds	4	0	2	3	0	2	4	3	2	6	26
Upward strokes											
total	23	8	48	34	9	24	93	48	117	145	549
to negative clouds	13	7	44	29	9	22	83	38	93	121	459
to positive clouds	8	0	2	5	0	2	6	4	13	16	56
with both polarities	2	1	2	0	0	0	4	6	11	8	34

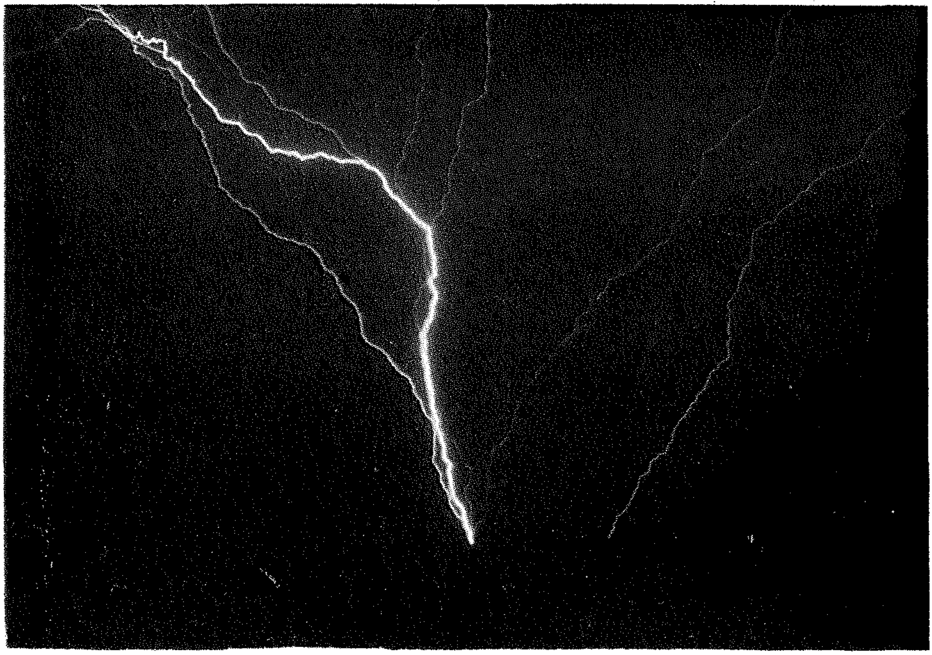


FIGURE 1 Upward strokes, simultaneous from both towers

FIGURE 2 Upward strokes from both towers (right) and from Monte Sighignola (left)

times to half va ue of about 10^{-4} s for lightning strokes from negatively charged clouds and about 10^{-3} s for strokes from positive clouds. Impulse currents are often observed in *upward* flashes in the form of consecutive strokes occurring when the current needed to build up the channel has decayed. These impulse currents are obtained when the channel which has grown upward has been encountered by charged channels from cloud lightning. Consecutive strokes could be regarded as independent downward strokes, which follow the channel still charged of the previous, usually decayed, upward discharge.

It is not rare for positive and negative upward strokes to attain charges in the order of magnitude of 100 C and, in extreme cases, 300 C. These figures are remarkably high, when compared with the surge charges liberated by the impulse discharge of a channel in the downward direction. For downward strokes the highest impulse charges measured where 15 C from negative clouds, add 50 to 100 C from positive clouds. By comparison with 100 or 300 C it may be concluded that when a lightning channel discharges, only part of the charge required to build up the streamer comes out. The rest is probably dissipated by diffusion in the atmosphere, or is compensated by existing charge carriers of the opposite polarity. The bigger discharges are usually considerably ramified (see Figure 1). They exceed the visible height of 1 km above the tip of the towers, corresponding to the field of view of the camera 3 km away. Its charge may therefore be distributed over a cloud several square kilometers in area.

RECORDS OF STREAMER FORMATION ON MOVING FILM

Most knowledge of the formation of streamers has been gained from moving films. The well-known progression of the "leader" in regular, sharp steps (Schonland, Malan) is confined to the formation of the *negatively* charged channel. Figures 3 and 4 show examples of such photographs; Figure 3 is a downward stroke from a negative cloud, Figure 4 shows the upward discharge from a negative tower to a positive cloud. The progression of *positively* charged streamers takes place at roughly the same speed, but they are usually much less luminous. On only about 15% of the photographs of such discharges is the streamer visible, and not until 1964 was it possible to prove their existence on the measuring towers. The progression of the positive streamers is in most cases continuous, i.e. without steps; at most the intensity may fluctuate periodically (Figure 5). Only in the case of upward strokes in the region between 40 and 150 m above the top of the tower weak steps are visible; below 40 m from the top the growth was never recorded. The values measured for velocity of progression, length of steps and duraction of steps (or periodicity in the case of positive streamers) are summarized in Figure 6.

A particularly good picture of the formation of a *negative* streamer from the top of a tower can be seen in Figure 4. In the original picture a fine corona discharge at the end of the bright head of each step is well visible. The picture shows that the corona discharge does not develop continuously between two steps. The duration of development and luminosity of the corona is so short that they appear to be instantaneous on the moving film (i.e. less than 5 μs). The shooting out of a new corona discharge seems to go hand in hand with the change from a poorly conducting string within the preceding corona shell to a conducting streamer channel, giving rise to the brightly luminous head. In Figure 4(b) the initial steps of this development are represented schematically. The individual steps are drawn apart—without paying attention to the true time intervals—so that they do not overlap.

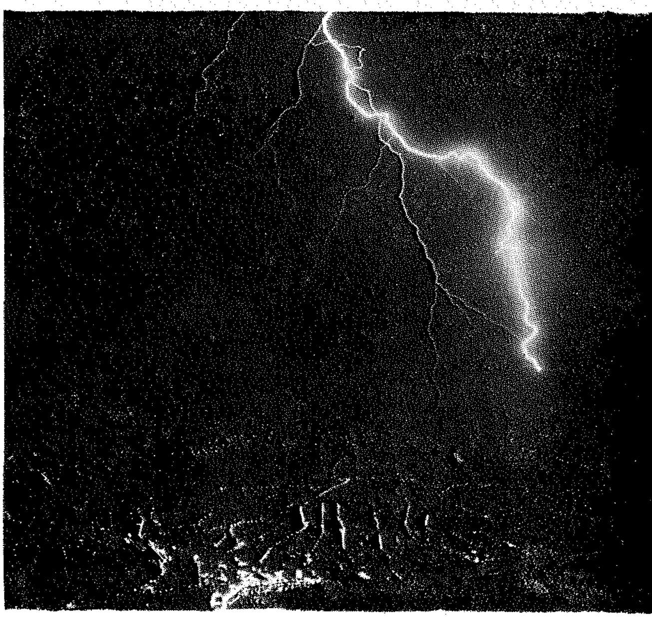


FIGURE 3 Downward stroke from a negative cloud, striking, the tower 400 m away

a) Recorded on stationary film

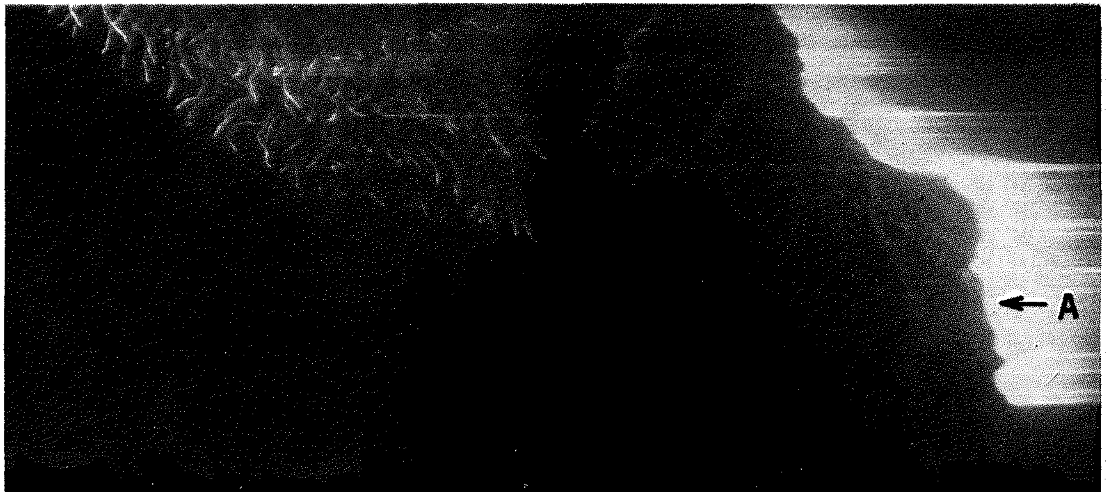
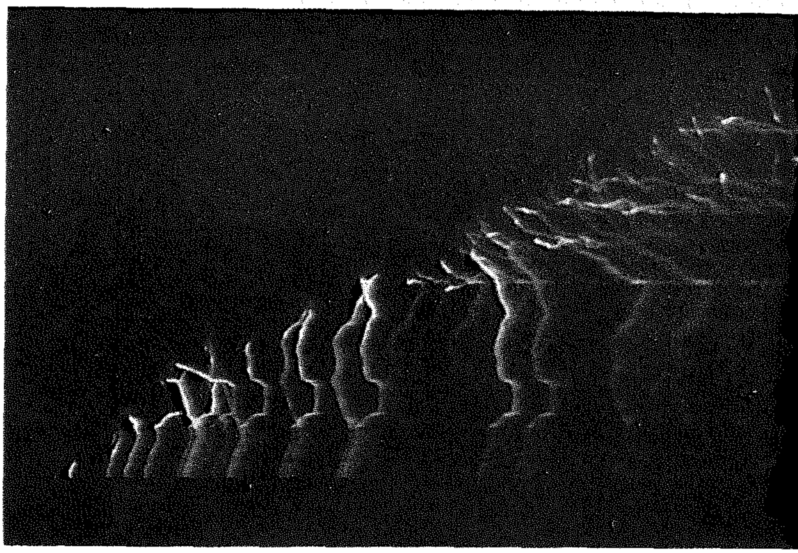
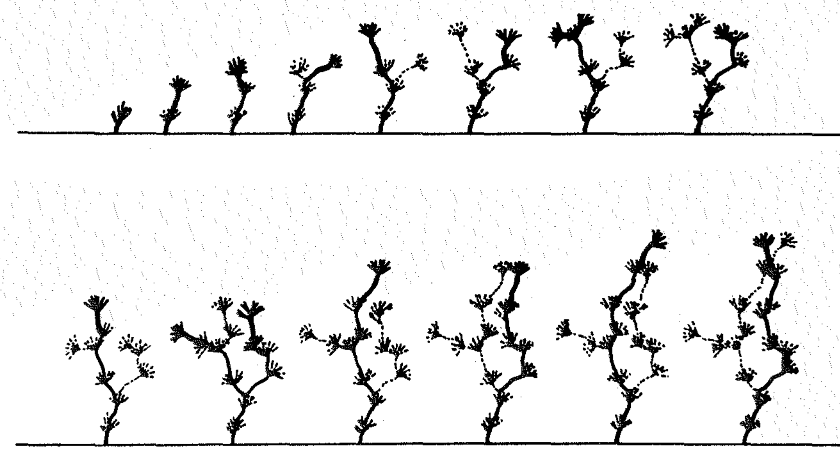


FIGURE 3 Downward stroke from a negative cloud, striking the tower 400 m away

b) Recorded on moving film



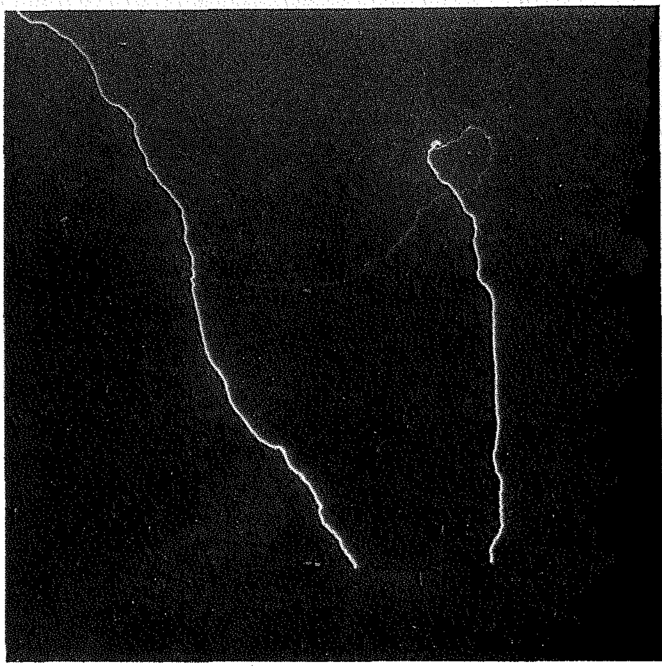
a) Recorded on moving film



b) Initial stages drawn schematically

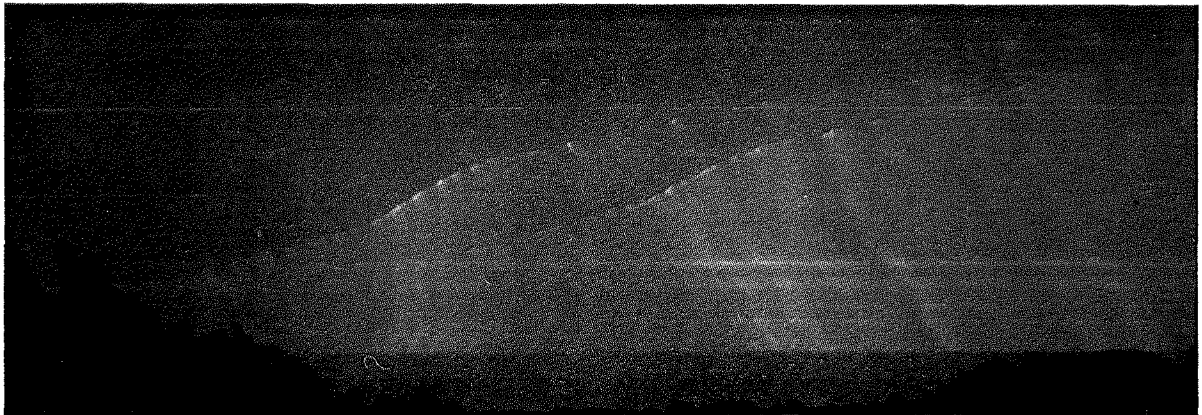
FIGURE 4 Upward stroke from the negative top of the tower towards a positive cloud

Moreover, for each step, the path of the preceding dark steps is indicated by dotted lines. From this diagram of progression it can be seen that the lightning channel must consist of two parts. One is the luminous, inner core which is probably only a few millimeters in diameter or less, and which carries the current. The other part builds the outer envelope which carries the charge. From the corona visible in the picture it follows that the diameter of this envelope is about 6 m at least, though it is probably larger because the fine ends of the corona brushes are not visible.



a) Recorded on stationary film

FIGURE 5 Upward strokes from both towers, from positive top of the tower to negative cloud



b) Recorded on moving film

FIGURE 5 Upward strokes from both towers, from positive top of the tower to negative cloud

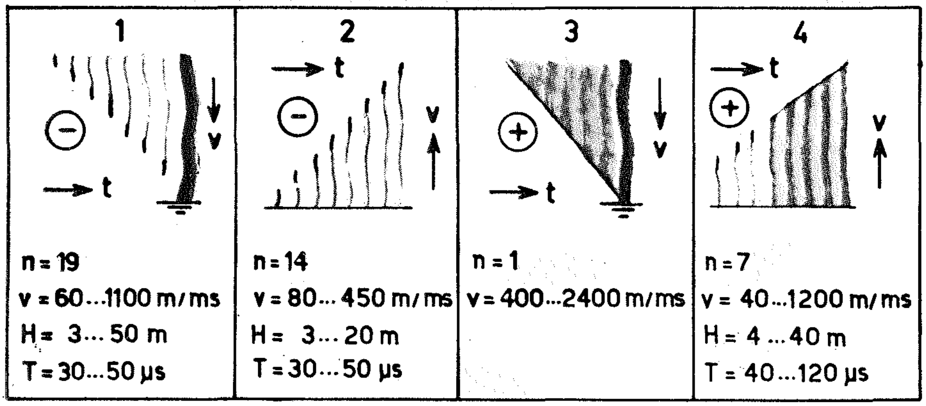


FIGURE 6 The growth of negative and positive streamers

a) Downward stroke from a negative cloud

b) Upward stroke from a negative tower top

c) Downward stroke from positive cloud

d) Upward stroke from positive tower top

n = number of discharges evaluated; v = velocity of progression; H = Average step length; T = mean time interval between steps

UPWARD CONNECTING STREAMERS

A special kind of upward discharge is the connecting streamer. If the charged channel of a downward lightning stroke progresses towards the top of the tower, the electric field strength grows there, with the result that an upward-progressing discharge rises to meet the downward-progressing streamer from the cloud. In the case of lightning strokes from negatively charged clouds connecting streamers 20 to 70 m in length were observed. Figure 3(b) shows an example. The stroke in question has numerous branches, each of which exhibits the stepped progression of the negatively charged channel. One branch will reach the top of the tower and form the main discharge. It is well visible that this leader changes to the bright principal discharge already at point A, some 35 m above the top of the tower. Up to this point an upward connecting streamer has obviously come towards it. The development of the latter, however, is not visible on the picture. Since the build-up of a positive channel is involved, its luminosity is only weak, according to the previons section. It cannot be expected to be visible on the film which is also exposed to the very bright principal discharge. According to Figure 6, the upward connecting streamer must have developed within 1/3 ms. Only when the two approaching streamers are sufficiently close and the corona at their tips interleave, does the current with the characteristic concave wavefront shown in the curve 3 in Figure 10 and 11 begin to flow.

Of particular interest is the corresponding phenomena with lightning strokes from *positive* clouds. In this case upward connecting streamers of great length appear. The visible phenomenon begins as an upward-growing discharge which, after a few milliseconds, changes from the positive current of a few hundred amperes to a powerful impulse. This impulse proves that a channel with a high positive charge (up to 100 C) was present in the cloud, that it was reached by the upward-growing negatively charged channel, and that it was discharged to earth through the latter. On account of the high charge of the channel in the cloud, it is an obvious step to assume that it produced the necessary field strength at the top of the tower which gave rise to the upward discharge. The latter is then merely an upward connecting streamer to the more powerful downward discharge. The point where the two discharges meet is generally outside the field of view of the cameras 3 km away. However, if the progressing velocity of the upward discharge is assumed as being constant, heights of up to 2 km above the top of the tower are obtained. Thus the interesting phenomenon appears, that positive downward lightning strokes may have very long upward connecting streamers from the negative top of the tower.

These long connecting streamers explain another observation: The impulse currents of positive strokes generally have a much flatter wavefront than those of negative strokes. If the discharge wave of the positive streamer approaches the tower through the channel of a long upward connecting streamer, its wavefront is damped and thus becomes flatter. In this connection, it is interesting to note that a positive lightning stroke was observed that evidently struck the needle from the side without any connecting streamer. The impulse current of this stroke exhibits almost the same steepness of the wavefront as a negative downward stroke (Figure 7).

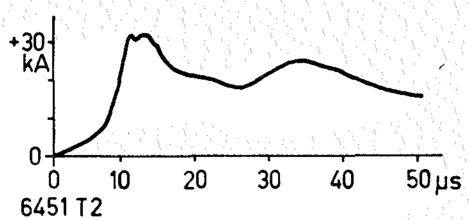


FIGURE 7 Impulse current of a downward stroke from a positive cloud, which struck the tower needle at the side and did not produce any upward connecting streamer

TABLE 2 Characteristic data* of the connecting streamers to the more important downward strokes from positive clouds

Oscillogr. no.	T (ms)	H (m)	Q (C)	i (kA)	$(di/dt)_{max}$ (kA/us)
6451	0	0	30	32	17
6015	0		45	180	9
6572	0		60	77	4
66113	1.0		120	150	20
6527	3.0	500	12	22	4.5
6572	6.1	1000	62	77	3
6675	7.0		30	110	2
6678	7.0		15	55	5
6232	8.7	1200	65	56	2
6520	11.6	1150	35	27	1
6674	12.7		30	30	0.6
66100	12.7		50	65	2
6016	13.0		70	87	2.4
6422	14	1800	130	106	2
6017	15.5		55	46	1.7
6677	19		80	68	1.1

* $T=$ time from the start of the upward progressing discharge until the beginning of the impulse current

$H=$ Vertical length of the upward streamer until its meeting with the channel which has been built up in the clouds (with unchanging progressing speed extrapolated)

$Q=$ Impulse charge (during the first 2 ms after the start of the impulse)

$i=$ Impulse current (peak value)

$(di/dt)_{max}$ greatest steepness of current front (steepest tangent).

Table 2 gives some of the data of the most powerful *positive* downward strokes measured during the past few years. When the vertical length (H) of the connecting streamer is given, there is also a record on the moving film. It can be seen that, on the average, the longer the connecting streamer is, the flatter the wavefront of the surge becomes. Two strokes are listed, for which there are no records on moving film (they occurred during daytime and could not be photographed), and which do not exhibit any recognizable upward connecting streamers in the current oscillogram, yet nevertheless exhibit a relatively flat wavefront. It may be suspected that there was a connecting streamer with these strokes, which was not shown by the oscillograph because this did not come into action until triggered by the steep impulse current.

MEASURING THE ELECTRIC FIELD

A question which is not yet answered concerns the mean electric field strength between cloud and earth, needed to permit a lightning channel to progress, or an upward streamer to start at the top of the tower. With the upward strokes another question arises: The necessary field, does it build-up in the cloud slowly or rapidly? The latter case may occur when there is a charge transposition due to lightning between clouds. In order to tackle this question, a field measuring equipment was taken into action for the first time on Monte San Salvatore during the 1967 thunderstorm season, and the variation of the field strength was recorded oscillographically.

The actual measuring element is known as a "field mill". It consists of a pair of plates with radial slits. The outer plate, directed towards the field, is earthed and rotated, while the resultant displacement current is measured on the inner plate. The device is illustrated schematically in Figure 8. Whilst

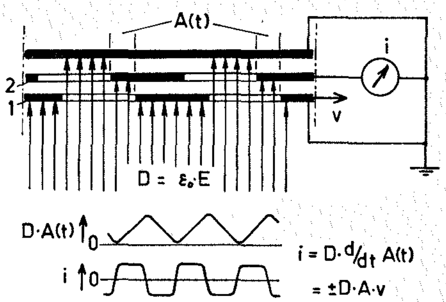


FIGURE 8 Schematic representation of the "field mill" to explain the method of measurement (see text)
1 = moving plate; 2 = measuring plate; A = operative area of the measuring plate; $A(t)$ = uncovered part of A at time t; v = Velocity of the moving plate; E = electric field strength; D = electric displacement; i = displacement current

plate 1 rotates in the direction of the arrow, the lines of the external field penetrating its slits strike either the measuring plate 2 or the earthed background. A pulsating displacement current, proportional to the field strength, flows from plate 2 to earth and can be measured by means of an amplifier. The pulsation frequency governs the possible time resolution. This is given by

$$f = Sn$$

where S is the number of slits and n the speed of rotation of the disc. With the "mill" in question $S = 24$ and $n = 48$ per second, so that $f = 1150$ c/s. Therefore, the limit of time resolution is about 1 ms.

Since it is the intention to follow the variation of the field with time, from a relatively low steady-state value until an upward lightning stroke is initiated, and since no criterion exists to trigger the oscillograph before the stroke, the results of measurement must be permanently stored on magnetic tape and called off when lightning strikes. Figure 9 schematically illustrates the whole set op equipment. The "field mill" is mounted on the PTT tower, some 50 m above the ground, its measuring surface pointing downwards so that no rain can enter. The voltage drop caused across resistor 4 by the displacement current flowing on the measuring plate 2, is amplified for two measuring sensitivities by the amplifiers 5 or 5 and 6, and conveyed by cable to the measuring cabin at the foot of the tower. There, the signals are feed through input amplifier 8 to the constantly running tape recorder 9, where they are stored for 4 s. At the end of this period, just before they are erased by the erasing head 12, they are picked off by the reader head 11 and fed through output amplifier 13 to the measuring system of the magnetic oscillograph 14.

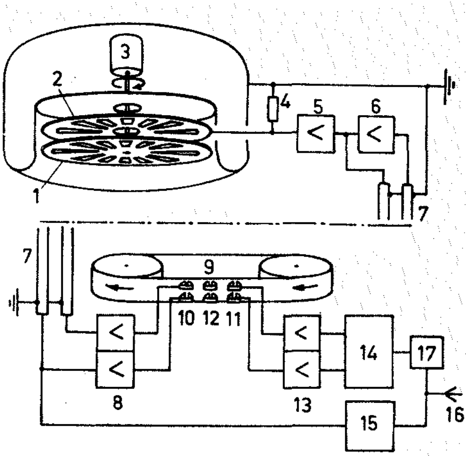


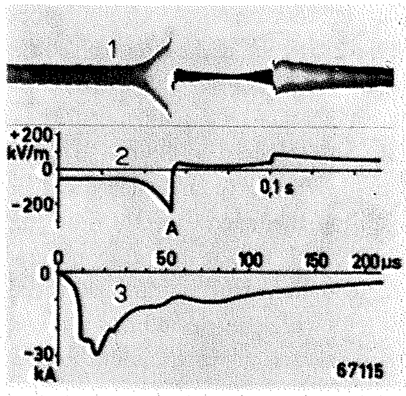
FIGURE 9 Schematic representation of the whole set of equipment used for recording the field

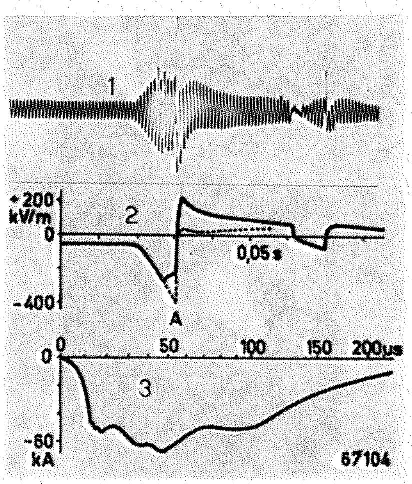
1 = rotating, earthed slotted plate; 2 = stationary slotted plate for measuring the displacement current; 3 = drive motor; 4 = resistor; 5/6 = amplifiers; 7 = cable from the "field mill" to the measuring room; 8 = input amplifier of tape recorder; 9 = tape recorder; 10 = recorder head; 11 = reader head; 12 = erasing head; 13 = output amplifier of tape recorder; 14 = magnetic oscillograph; 15 = cathode-ray oscillograph; 16 = pulse triggering the oscillographs; 17 = adjustable delay element

The triggering of this oscillograph is coupled with that of the oscillograph for recording the lightning current in such a way that the interesting part of the field trace before and during the lightning stroke is recorded. The measuring voltage of one channel is also applied to the cathode-ray oscillograph 15 used to record the lightning current, in parallel with the input amplifier of the tape recorder. The shape of the field can then only be recorded from the moment when a lightning current triggers the latter oscillograph. Nevertheless, this record is important, on the one hand because it shows the coordination in time of current and field strength, and on the other hand because it allows the checking of the accuracy of the tape storage in the recorded range. By storing the field strength, it is also possible to plot the variation of the field produced by lightning strokes between clouds, in which case the recording is triggered by hand.

Naturally, the device described records the local field at the measuring surface of the "field mill". In order to determine the mean field strength between cloud and earth from this result, it is necessary to perform comparative measurements in the electrolytic tank. Hitherto, only approximate, informatory measurements were performed. As a rough result, the relationship between the mean field cloud/earth and the local field at the "field mill" may be about 1 : 10. From the field oscillograms the direction, i.e. the polarity, of the field cannot be determined. But it is possible to determine when the field reverses its direction. In order to fill this gap, it is necessary, at the present moment, to rely on the trace of the corona current recorder which, in the period between two lightning strokes, records the corona current at the top of the tower, and its direction or polarity. Current and field strength, as in previous reports, are always referred to the downward direction, i.e. positively charged clouds give rise to a positive current and a positive field.

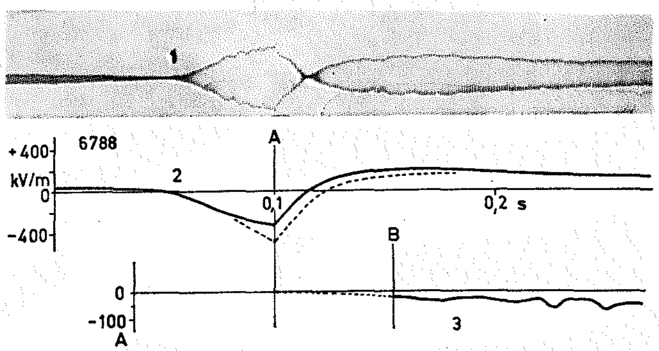
To illustrate the field strengths measured, Figures 10 to 15 show some representative oscillograms. They only depict the results obtained during the early part of the 1967 thunderstorm season. In each case the oscillogram of the insensitive measuring channel was selected (partly obliterated by the sensitive channel). Below this oscillogram the derived field curve, whose polarity is given by the corona recorder, was plotted. The curve of the corresponding lightning current is also shown. Admittedly, the field oscillograms should be treated with some care as the question of possible effects of disturbance by space charges still has to be clarified. Especially the field curves of upward lightning strokes (Figures 12–15) create this impression. It is rather striking that the polarity of the field usually does not coincide with that of the current flowing at the same time. With negative clouds, for instance, the direction of the field from the cloud towards the tower is negative at first. If a lightning stroke occurs in the upward direction with negative current (considered from atmosphere to tower), the measured field strength changes direction in a short space of time and assumes a relatively high, positive value (likewise considered from atmosphere to tower). Although it is in principle feasible for a field to build up in the oppo-

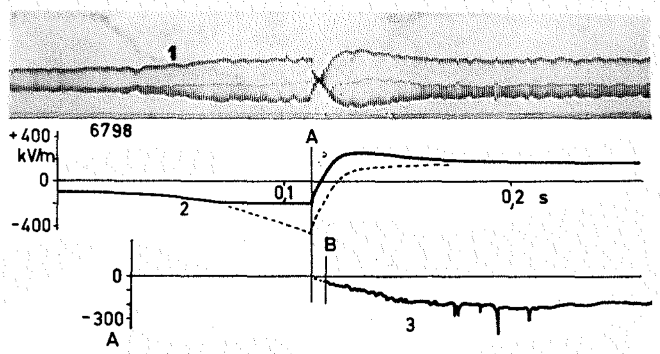




FIGURES 10 and 11 Curves of field strength and current during downward strokes from negative clouds

1 = field oscillogram; 2 = field curve plotted according to oscillogram (full line) and with correction, taking into account a possible influence of space charges (dotted line); 3 = curve of lightning current which begins at point A on the field oscillogram

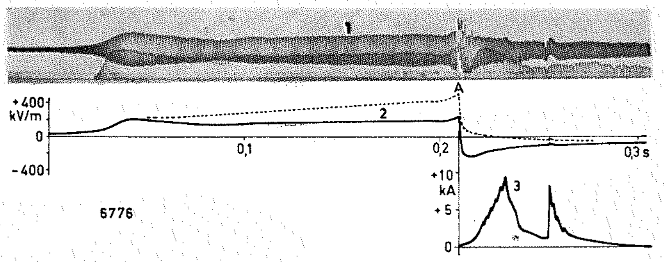


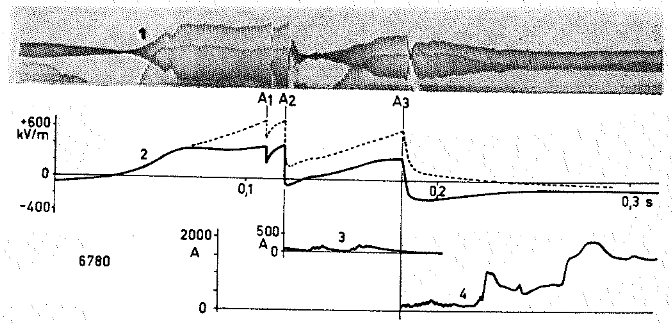


FIGURES 12 and 13 Curves of field strength and current during upward strokes from the PTT tower to negative clouds

1, 2—see Figures 10/11; 3 = simultaneous current in the PTT tower; A = start of upward discharge; B = current oscillogram triggered

site direction to the current, the values measured for these field components do appear rather high. It is suspected that at the relatively high field strength before the upward stroke occurs, space charges are produced which first lower the value measured at the "mill". When the field breaks down due to the upward stroke, these space charges—for the short time until they vanish—can give the impression of a field of opposite direction, or if an opposing field does in fact occur, they can cause its amplitude to appear higher than it really was. The effect of the space charges is particularly pronounced when the field strength increases relatively slowly to the point where the upward stroke occurs, so that there is sufficient time for a large space charge to be produced at the "field mill". This is evident in the oscillograms. In





FIGURES 14 and 15 Curves of current and field strength during upward strokes towards positive clouds

1, 2—see Figures 10/11; 3 = Simultaneous current in PTT tower; 4 = simultaneous current in tower 400 m away; A_1 = brief discharge at one tower, without current oscillogram; A_2 = start of the upward stroke on the PTT tower; A_3 = start of the upward stroke on the tower 400 m away

Figure 11–15, therefore, a dotted line indicates roughly where the field curve could be if the distrurbing effect of the suspected space charges were subtracted.

The following comments may be made about the oscillograms reproduced. The fields in Figures 10 and 11 belong to *downward* strokes from *negative* clouds. The stroke in Figure 10 is shown as it appeared in Figure 3. It struck the tower 400 m away, whereas that in Figure 11 struck the PTT tower. The sudden rise in field strength is obviously due to the approach of the downward-growing streamer. At the moment the latter discharges to earth, the field collapses. The steady value before the rise, as measured at the "field mill", was only about 50 kV/m in both cases, which, according to the foregoing, ought to represent an average field strength of only 5 kV/m between cloud and earth.

Figures 12 and 13 show the shape of the field in the case of *upward* strokes from the PTT tower to *negative* clouds. In both cases it may be assumed that the decrease in field strength that begins at point *A* was caused by an upward stroke beginning with a weak current, whereas the current oscillogram begins only in point *B*, when the current has reached the level of 20 A needed for triggering and recording. These traces show that the field rises to the strength required to trigger the stroke within a few hundredths to tenths of a second. It is thus clearly due to rearrangement of charges by cloud strokes. Sometimes the field changes direction before it rises. The field strength at the "mill" at the instant an upward stroke begins is of the order of 200–300 kV/m, corresponding to an average field strength between cloud and earth of about 25 kV/m. That the field before the "field mill" should be weakened by space charges, so that in reality it would amount to something like 400–500 kV/m (dotted curve), is, at present, mere conjecture.

Figure 14 and 15 show the phenomena in the case of *upward* strokes to *positive* clouds. The difference to negative clouds is that the field collapses almost instantaneously when the discharge strikes. Attention may also be drawn to the following detail in Figure 15. At point A_1 a short discharge to the tower evidently occurred, which only set off the cathode-ray oscillograph (without visible deflection). At point A_2 the relatively low positive current at the PTT tower began, causing the field to decrease briefly. Not until the powerful current began at the tower 400 m away (point A_3), did the field finally collapse altogether and change to negative values.

CONCLUSIONS

Sparks produced hitherto in the laboratory were seldom longer than about 10 m. Only lightning enables investigations to be carried out on discharges several kilometers in length. In the course of these, fundamental differences become obvious. Whereas with laboratory discharges the initial low-current strings of the corona discharge fill the entire space between the electrodes in a very short space of time (10^{-6} s), and the time for the discharge to build up is largely determined by the time taken by the current to concentrate on one of these strings and for it to change from high to low resistance, in the case of lightning a low-resistance current streamer develops at a measurable velocity of progression from one "electrode" to the other, or two streamers grow towards one another from the "electrodes". Here the non-conducting clouds act to a certain extent as electrodes by virtue of their charged drops of water. Marked differences in the appearance of positive and negative paths may then be observed. These differences were in fact qualitatively predicted by Toepler some 50 years ago in the light of his observations of "gliding" discharges on the surface of insulators.

The results of field measurements obtained so far permit the assumption that simultaneous measurement of lightning current and field variation before and during a stroke will render a valuable addition to our knowledge of lightning phenomena. At present it may be roughly estimated that the streamer of a downward stroke, when it has reached a certain length, only requires an average field strength of about 5 kV/m to continue growing. In contrast, the average field strengths needed to produce the longest d.c. discharges in the laboratory are in the region of 300 kV/m. If the field remains homogeneous from earth to the edge of the cloud at a height of, say, 2 km, the voltage of this layer relative to earth only amounts to about 10 MV. Of course, the field strength must increase to the breakdown level of air at the point where the lightning starts (usually in the dipole field inside the cloud). The voltage of the resultant streamer to earth will then probably be several times 10 MV. For the formation of upward-growing strokes the same estimate gives an average field strength of about 50 kV/m. This field is not produced slowly by the build-up of the static charge in the cloud, but quickly as a result of the displacement of charges during strokes between clouds.

Special attention must be paid to the heavy charges and long upward connection streamers of positive downward strokes. They permit us to suspect that these strokes occur between the uppermost positive layer and the negative layer below it, and that they are fed from the heavy positive charges of the uppermost layers. On account of the heavy charges involved, the positive strokes are of primary importance in relation to protection against lightning.

In conclusion, it may be said that, even after 25 years' work on Monte San Salvatore, lightning still presents many unsolved problems to stimulate research.