Novel Observations on Lightning Discharges: Results of Research on Mount San Salvatore

by K. BERGER

Eidg. Technische Hochschule and High Voltage Research Committee Zürich, Switzerland

I. Introduction and Brief Description of the Lightning Research Station

Some new theories about lightning strokes to and from the earth are discussed, in this paper based on observations from Mount San Salvatore (near Lugano), Switzerland (**1–4**).

A geographical map of the area around Mount San Salvatore is shown in Fig. 1. The photograph of Fig. 2 was taken at Lugano. Lake Lugano is 275 m above sea level; the peak of Mount San Salvatore is 915 m a.s.l., or 640 m above Lake Lugano. This site is on the southern border of the Alps where the majority of thunderstorms and rain clouds come from the Mediterranean, *i.e.*, the southwest.

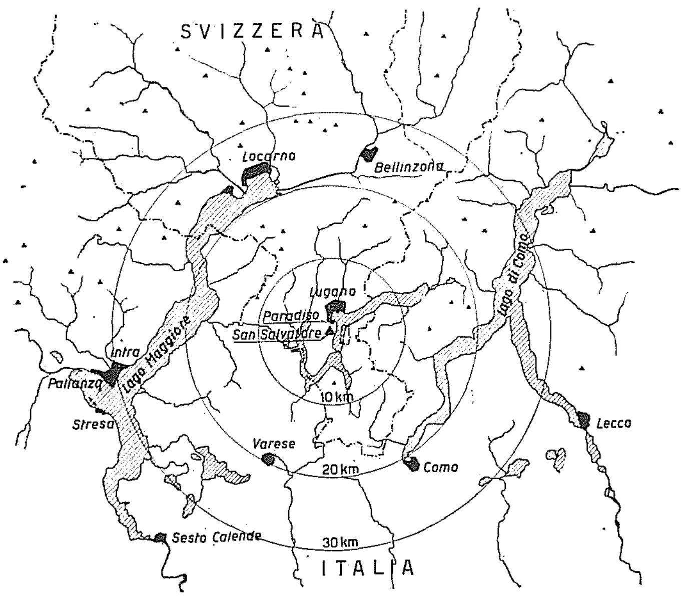


FIG. 1. Geographical map of Mount San Salvatore with surroundings; △, peak of mountain 915 m a.s.l.

FIG. 2. View towards Mount San Salvatore from Lugano.

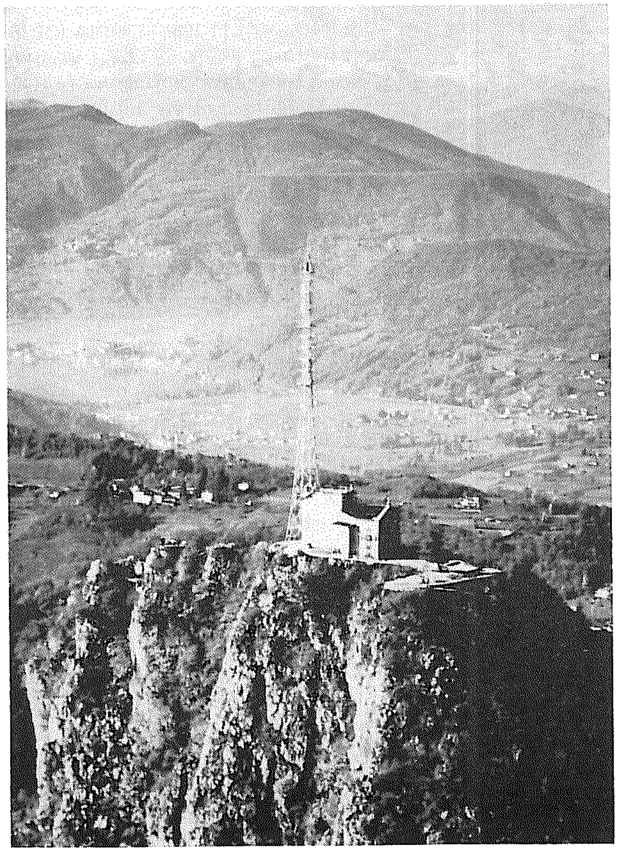


FIG. 3. Aerial view of peak San Salvatore with lightning tower 1 (TV-tower) and church (photo-lab). The shunt for lightning current measurements is just above the TV-antenna-supporting structure, and below the 10 m lightning rod

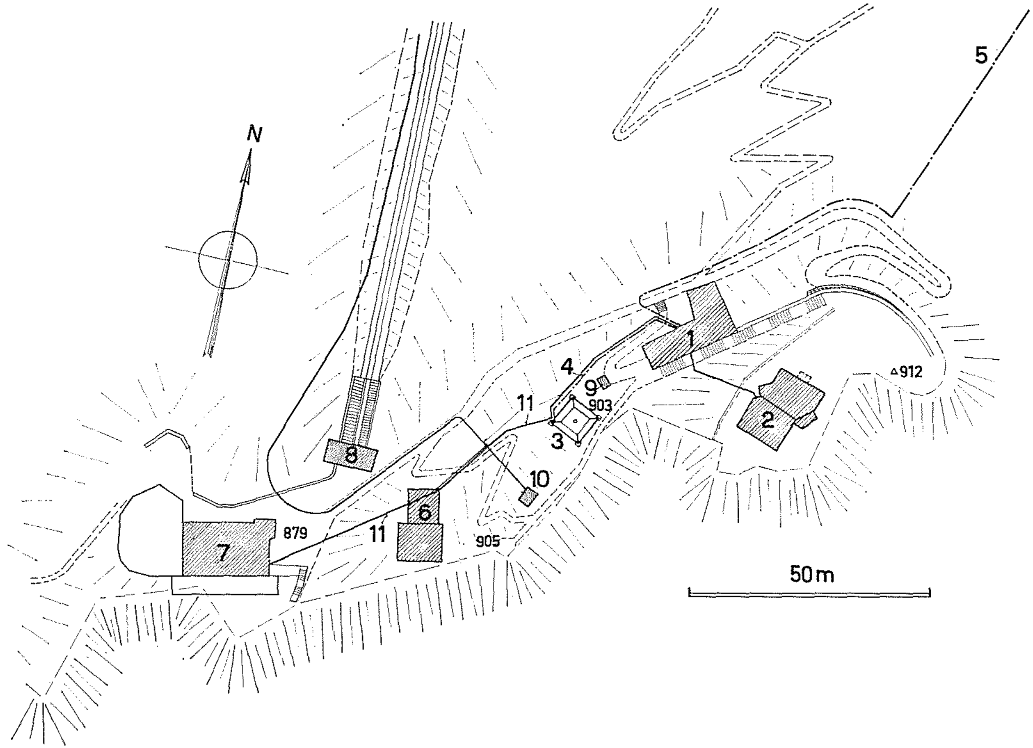


FIG. 4. Locality of Mount San Salvatore: 1) lightning measuring station; 2) church with photographic laboratory; 3) lightning tower 1 (TV-tower); 4) measuring cable from tower 1; 5) measuring cable from tower 2; 6) TV-station of the Swiss PTT; 7) Hotel San Salvatore Vetta; 8) terminal of funicular from Lugano-Paradiso; 9, 10) water tanks; 11) water pipes.

Since 1950, two towers have been used for lightning research. The first was erected in 1943 on the highest peak of the mountain specifically for lightning research. This was replaced in 1958 by a new construction which simultaneously serves as a lightning research station and as a radio and television tower (Fig. 3). Figure 4 shows the site arrangement.

The second tower, erected in 1950, is used exclusively for lightning research. It is situated on a secondary peak, at a distance of about 400 m from tower 1, and its top is some 47 m lower than that of tower 1 (Fig. 5). Each tower is 70 m high, including the steel needle which acts as a lightning rod. The lightning research covers both electrical and photographic aspects. Lightning currents to a tower as a function of time are recorded by electromagnetic and cathode ray oscillographs (c.r.o.) which are housed in a very old building (Fig. 4). The building also contains instruments (mA-meters) which continuously register the corona currents to both towers during the thunderstorm season. Lightning currents are measured by means of a two-stage shunt just below the needle of each tower. A schematic circuit diagram for one tower is shown in Fig. 6. For an accurate measurement of the current steepness a multilayer tubular shunt of

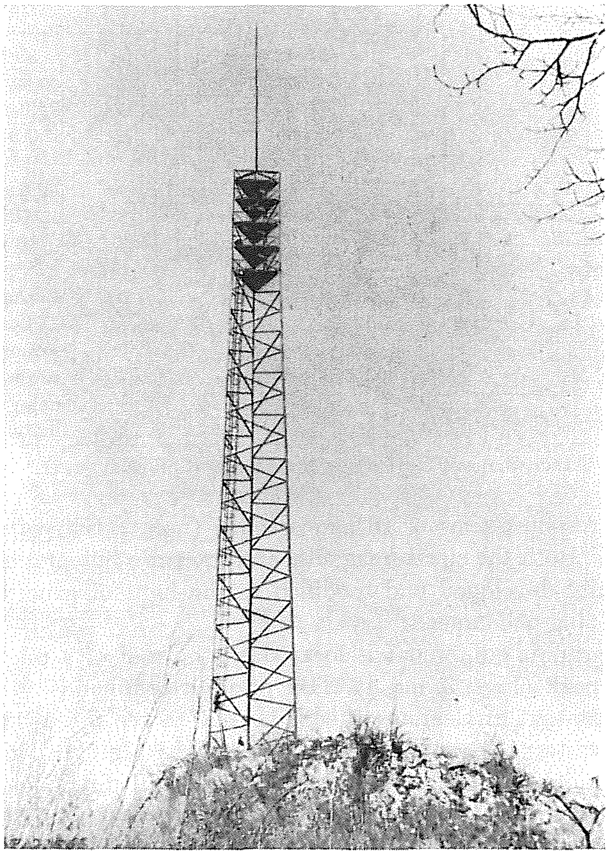
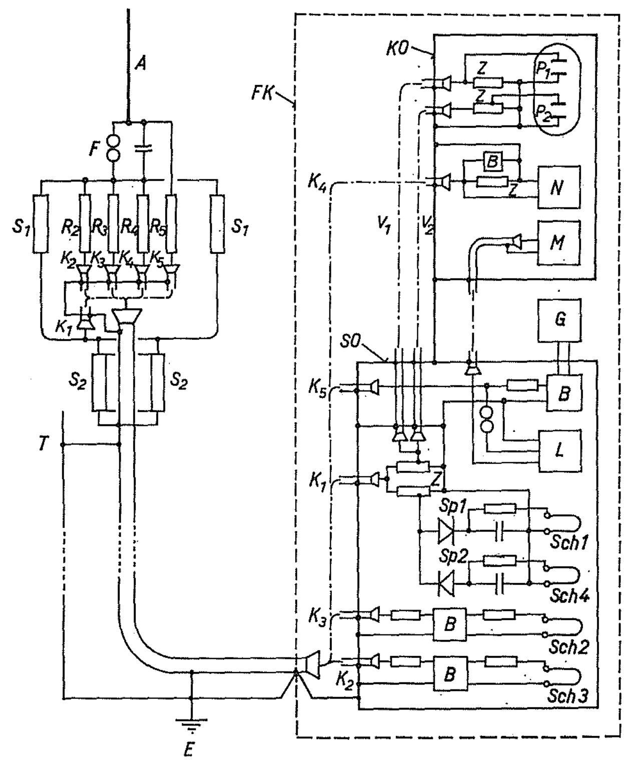


FIG. 5. Photograph of lightning tower 2. The shunt is on top of the metallic structure.



A	lightning rod or needle
B	voltage limiting devices
E	grounding system
F	tripping gap for the oscillographs, and separating gap to enable permanent registration of small corona currents at the tower.
G	corona registration mA-meter
FK	Faraday-cage
K	measuring cables
KO	cathode ray oscillograph (c.r.o.)
L	galvanometer lamp
M	tripping device for low-speed c.r.o.
N	tripping device for high-speed c.r.o.
P_1P_2	measuring plates 65 and 200 kA
R	resistors
S_1	lightning current shunt 0.8 Ω (tower 1) and 0.56 Ω (tower 2)
S_2	lightning current shunt 0.05 Ω, response-time 16 nanosec.
Sch	galvanometers
Sp	storage capacities for ±current-peak measurement
T	tower structure
V	delay cables
Z	matching resistors

FIG. 6. Circuit diagram for current measurement on each tower.

0.05 Ω with a response time of 16 nanoseconds (nsec) (IEC-value) is used, as shown in Fig. 7. Both the electromagnetic and the c.r. oscillographs are of special design, gradually developed and modified in the light of experience gained in recording lightning phenomena.

The photographic equipment is located on the roof of a pilgrim church on the mountain peak (Figs. 3 and 4). This position commands an excellent view in all directions, and in clear weather it is easy to see the 4500 m high snow peaks of the western Alps about 80 km away (see Fig. 3). This allows us to photograph at night lightning strokes to earth in all directions and makes it possible to determine their points of impact in many cases, unless these points are hidden by mountains.

Eight normal cameras have been used since 1950 for this purpose in order to

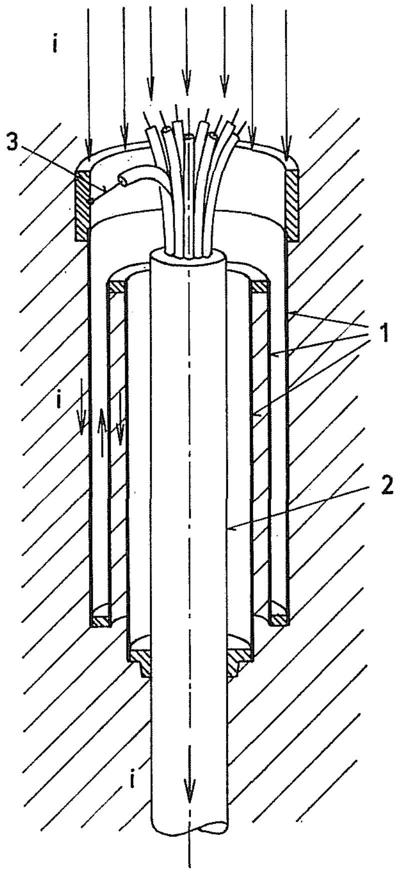


FIG. 7. Cross section of 0.05Ω-shunt: 1) Cylinder of Konstantan-sheet, 2) measuring cable, 3) screened measuring wire from 0.05 Ω shunt lightning, *i* current; other screened wires correspond to cables *K* in Fig. 6.

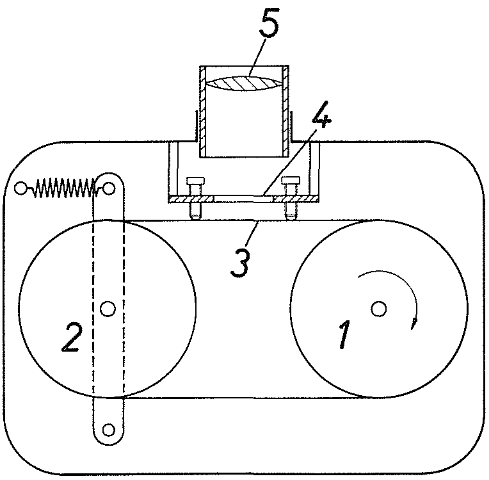


FIG. 8. Design of camera with fast-moving film: 1) motor-driven pulley, 2) movable pulley with spring, 3) film running at about 27 m/sec, 4) window with film guide, 5) lens.

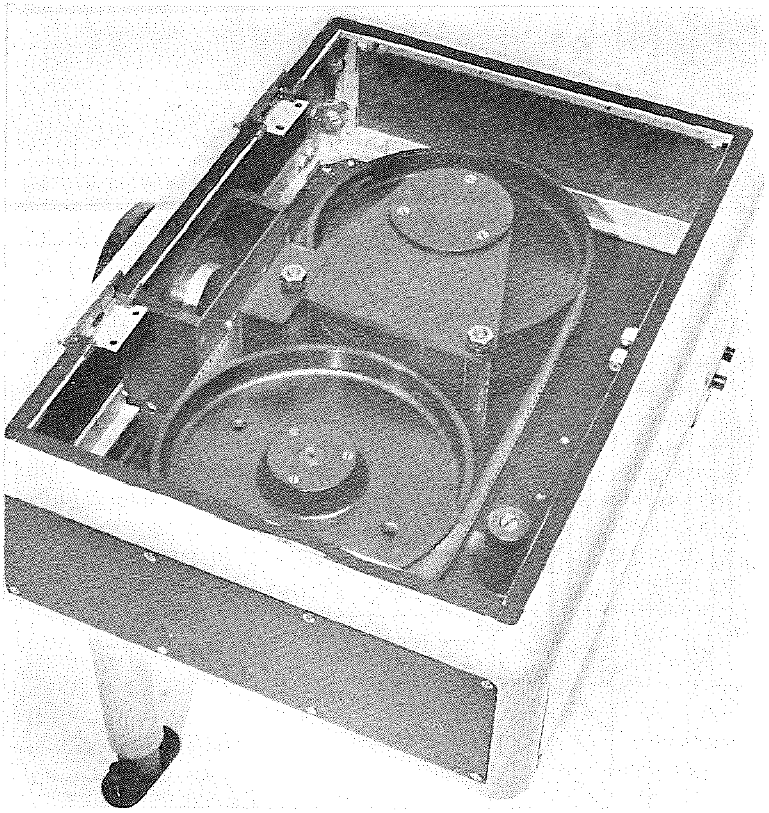


FIG. 9. Camera with fast-moving film.

cover the entire horizon. In addition, special cameras with fast moving film (developed by Boys–Schonland–Malan) obtained photographs of the development and the progression of leader strokes. Initially, we used two film speeds of about 3 and 50 m/sec. Now we use only one speed of about 27 m/sec. Figure 8 shows the design, and Fig. 9, a photograph of the fast-moving film camera which uses the construction devised by Malan (**5**).

II. Isoceraunic Level, Lightning Frequency and Corona Currents

The southern (Italian speaking) part of Switzerland has the greatest amount of rain and lightning storms. The isoceraunic level, according to its international definition, is given in detail in Table I for the period 1947 to 1963.

A second figure for the number of thunderstorm days has been determined from corona-current registrations (see Table II). This method is limited to counting lightning strokes within about 10 km. These numbers are collected in Table II for the same period, 1947 to 1963. The mean value of Table II is 40, compared with 51 of Table I. Both values are higher than the Italian meteorological values which are 15 to 30, [see Bossolasco: *Energia Elettrica*, 1949 or (**2**)]. This is readily understandable in view of the exposed observation point on

TABLE I

Number of thunderstorm-days
Base: At least one clap of thunder audible in a day
(Isoceraunic level)

Year	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Total	Period of Observation
1955	—	0	6	10	17	10	6	2	51	5.4–18.10
1956	—	4	3	8	13	15	4	2	49	16.4–6.10
1957	0	2	5	20	9	11	4	1	52	21.3–14.11
1958	0	2	3	4	9	9	3	2	34	17.3–8.10
1959	—	0	10	14	12	11	1	—	48	20.4–23.9
1960	—	1	7	13	9	11	5	0	46	26.4–22.12
1961	0	8	10	13	11	5	0	—	47	19.3–13.9
1962	—	3	5	8	17	10	5	0	48	2.4–3.10
1963	1	12	14	16	17	13	8	2	83	18.3–21.10
Mean values:										
1955–63	0.1	3.5	7	12	12.7	10.5	4	1	50.8	
1947–54	—	4	9.6	11.8	10.1	10.4	4.5	0.5	51	
1947–63	0.06	3.8	8.2	11.9	11.5	10.5	4.2	0.8	51	

TABLE II

Number of thunderstorm days counted by sudden field changes on Mount San Salvatore

Year	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Total	Period of Observation
1955	—	0	4	6	12	7	8	0	37	5.4–18.10
1956	—	4	3	6	9	14	4	0	38	16.4–6.10
1957	0	2	5	18	9	8	4	0	46	21.3–14.11
1958	0	0	1	5	9	6	2	0	23	17.3–8.10
1959	—	0	3	11	12	9	0	—	35	20.4–23.9
1960	—	0	11	14	6	9	6	0	46	26.4–22.12
1961	0	6	7	12	11	2	0	—	34	19.3–13.9
1962	—	2	7	5	5	8	4	0	31	2.4–3.10
1963	0	3	10	14	13	10	11	0	61	18.3–21.10
Mean values:										
1955–63	0	1.9	5.7	10.1	9.6	8.1	4.3	0	39	
1947–54	0	2.7	7.1	10.1	7.9	8.9	4.0	0.2	41	
1947–63	0	2.3	6.4	10.1	8.7	8.5	4.2	0.1	40	

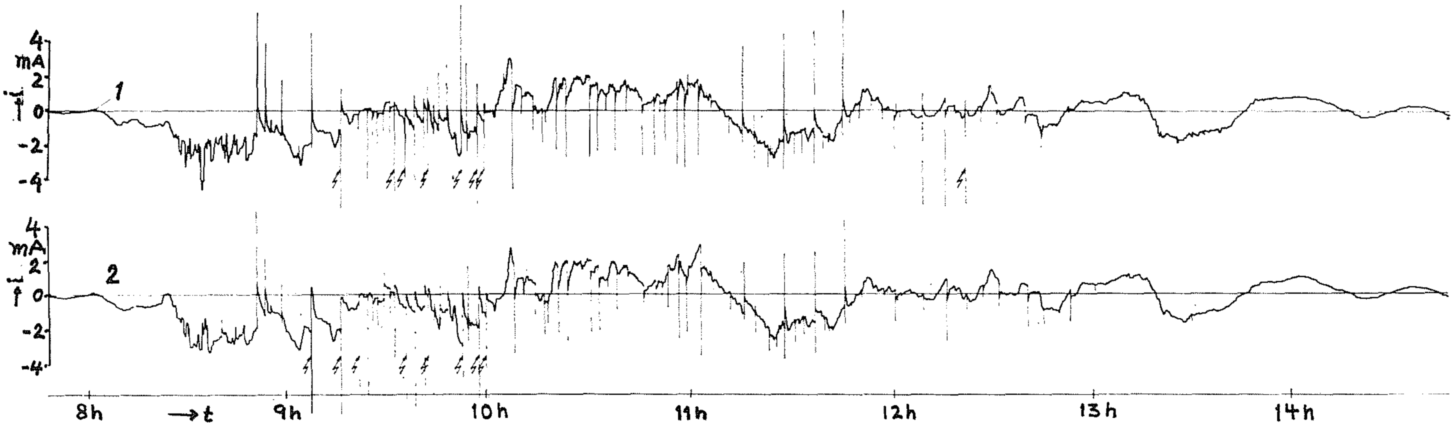


FIG. 10. Example of corona-current registration, thunderstorm of May 3, 1963. 1) Corona current in tower 1; 2) corona current in tower 2. Lightning discharges to the towers are marked by arrows.

Mount San Salvatore and the continuous readiness of its observer throughout the day and night.

The *frequency of lightning strokes* cannot be derived from the "isoceraunic level" but can be estimated from the continuous registration of currents to the towers. Nearby strokes produce rapid field changes and therefore capacitive current impulses from tower to ground. These current impulses are counted if they exceed a certain minimum. An example is given in Fig. 10. The comparison of corona currents in both towers is of special interest. Usually corona currents of less than 4 mA have the same shape and similar amplitude and, if there is no stroke to either tower, the same polarity of impulses. However, when one tower is struck, the other tower shows an impulse of opposite polarity. These corona currents give an approximate measure of the *electric field* near the towers, is their variation with time is slow. Fast field changes produce current impulses as may be seen from Fig. 10, but there is no proof that these impulses are due exclusively to capacitive current pulses. On the occurrence of a nearby stroke a very distinct and typical sound impulse, like a weak shot, is audible from the needles. The audible impression is exactly the same as the well known impulse corona on high voltage lines during the propagation of overvoltage impulses. This leads to the conclusion that the short impulses indicated by the corona-registration curves are due to a sudden increase in the electric field rather than to the capacitive current alone. This observation will be discussed later in connection with the mechanism of the stroke. In these corona-current curves (Fig. 10) the sudden field changes caused by nearby strokes are clearly visible, as are the times required to reestablish the original current or field value. Frequently this reestablishment of the electrostatic field shows an exponential shape with a time constant of one or more minutes.

The continuous registration of corona currents throughout the lightning season allows the total electric charge which has flowed from the clouds to the earth to be evaluated. The results of this integration for the years 1960 and 1963 are shown in Table III; currents below 0.1 mA are neglected. This table

TABLE III

Integrated corona charges from towers 1 and 2 for years 1960 and 1963 and comparison with electric charges by lightning

	Year	Tower	Q^+ C	Q^- C	T h
Corona currents	1960	1	34	43	150
		2	28	38	150
	1963	1	52	100	240
		2	50	82	240
Lightning currents	1960	1	255	430	
		2	735	350	
	1963	1	730	1305	
		2	360	675	

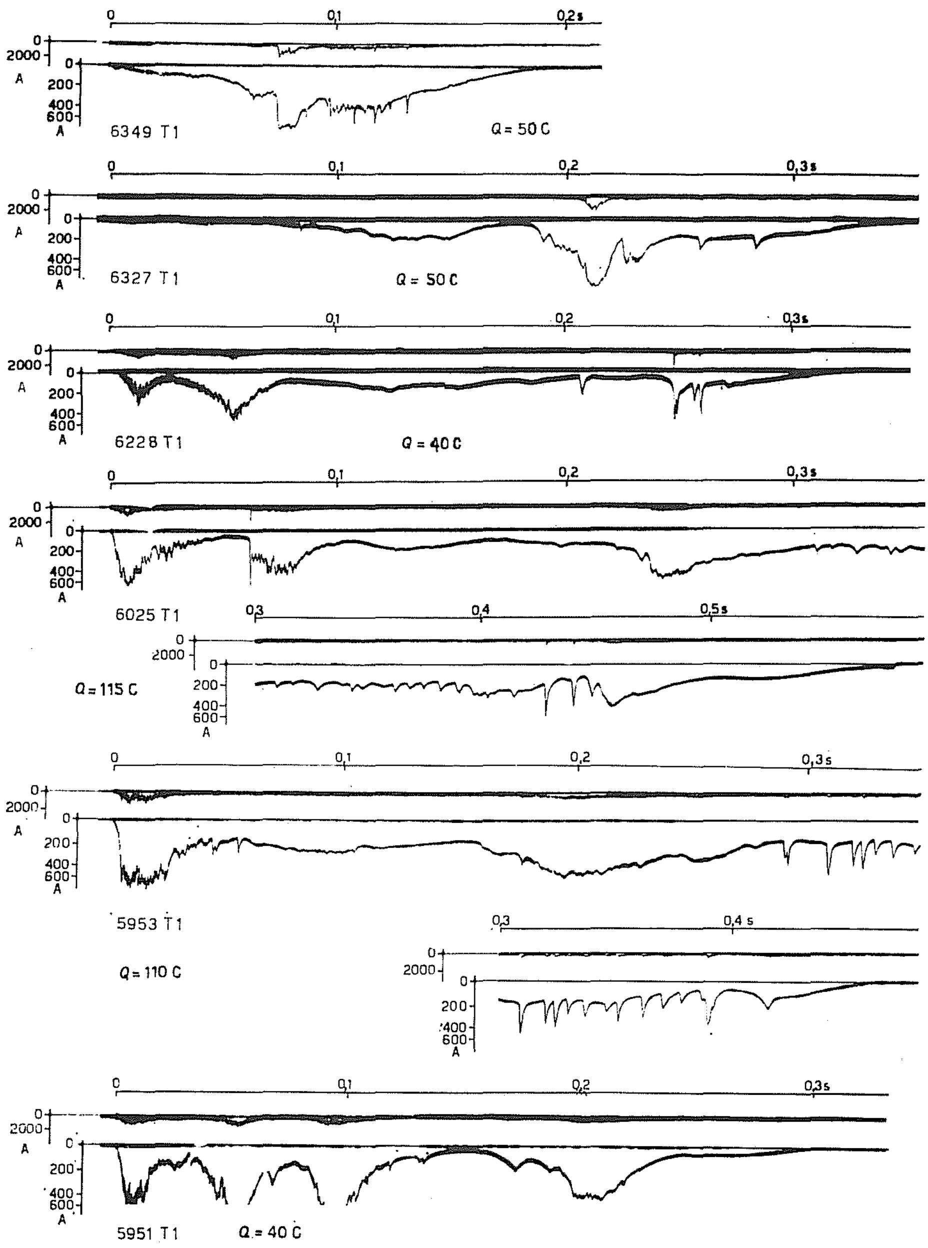


FIG. 11. Examples of current oscillograms from upward strokes with continuing current only.

also gives the total electric charge carried by lightning strokes to towers 1 and 2 in 1960 and 1963. Separate values are given for positive and negative polarities. Table III makes it clear that the total corona charge emitted by one tower in a lightning season is 7 to 25 times smaller than the charge of all strokes during the same season into or from this tower. This observation is interesting in connec-

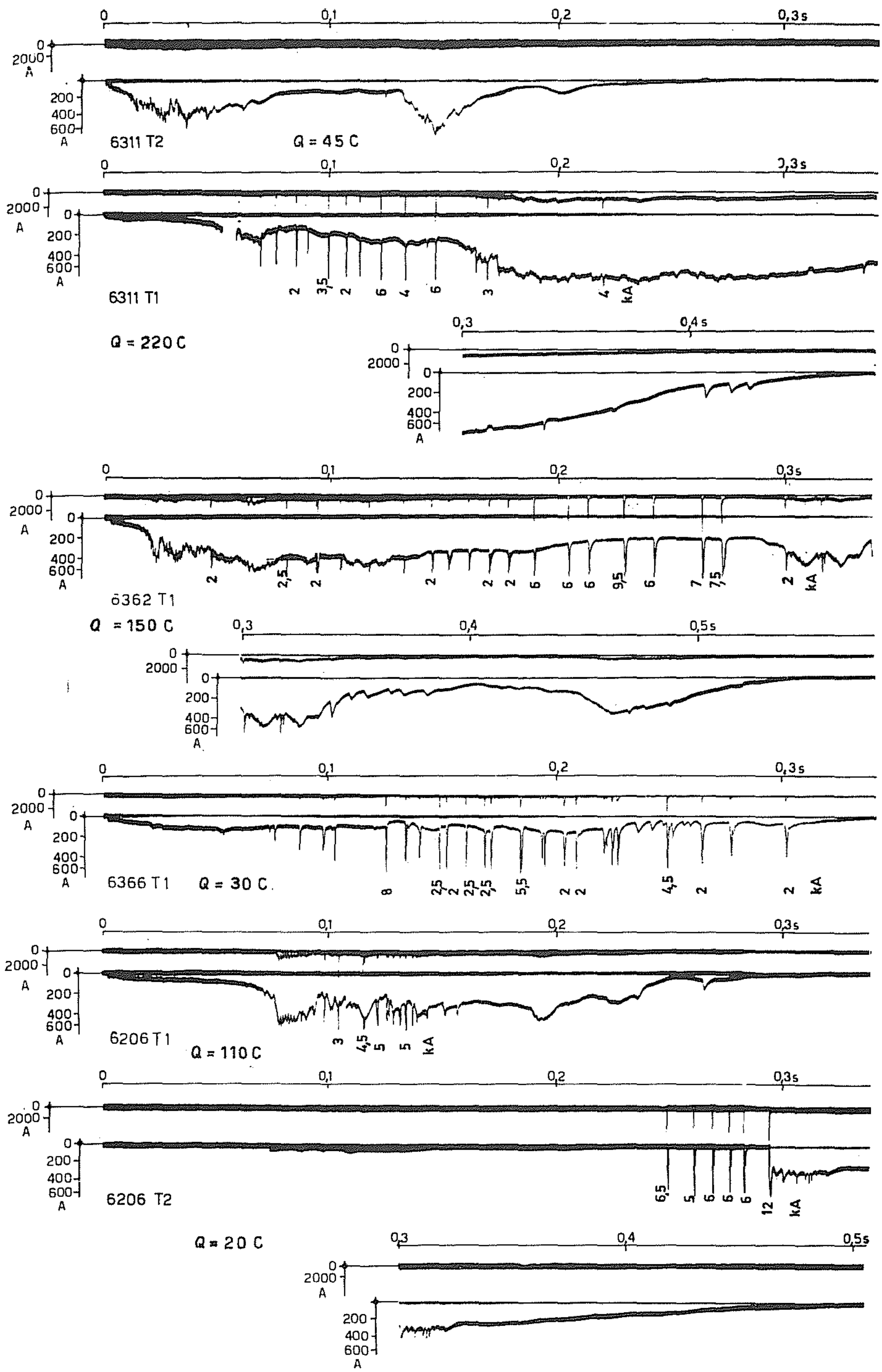


FIG. 12. Examples of current oscillograms from upward strokes with continuing currents and superimposed impulses.

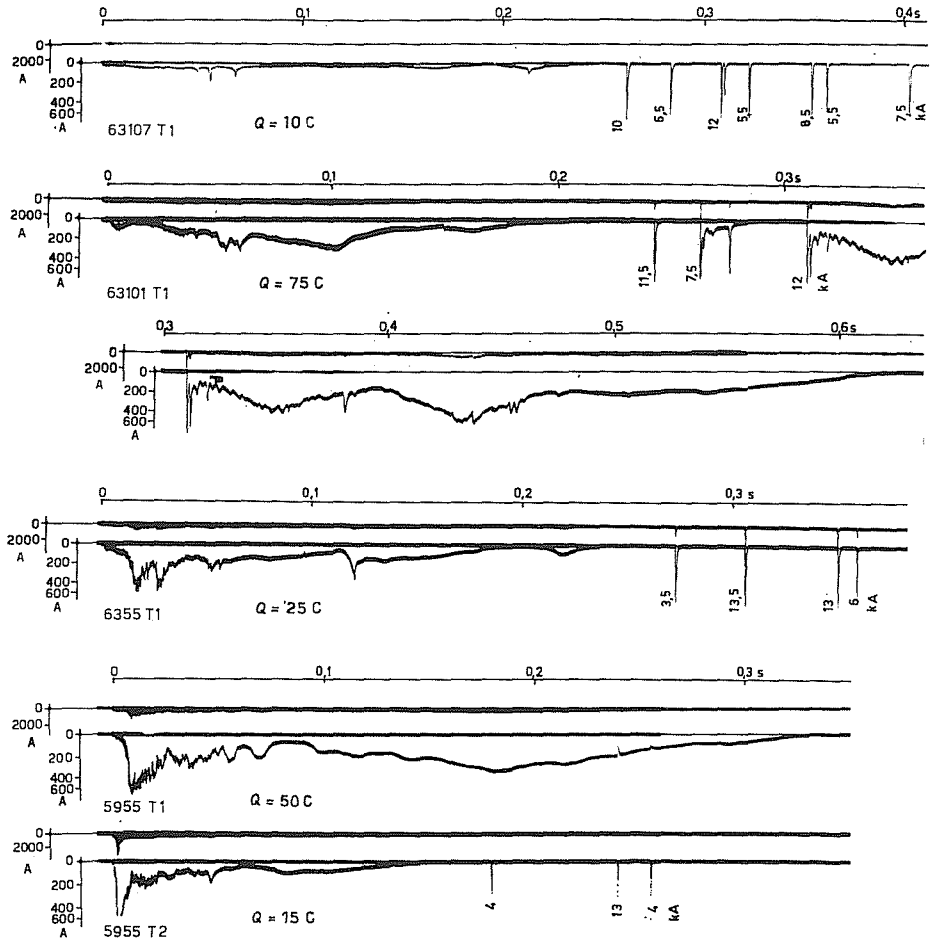


FIG. 13. Same as Fig. 12, except impulses are not superimposed, but follow first continuing currents.

tion with the idea expressed by Franklin that corona currents from sharp-pointed objects might be so strong as to discharge clouds and, hence, avoid lightning strokes. The figures obtained on San Salvatore as well as the existence of so many strokes to the towers prove that, even in the case of towers being on top of a mountain, the corona-distributed charge is always much smaller than that of a lightning stroke and that, even in this case, it is not possible to avoid strokes by preceding static currents of a few mA or less.

III. General Observations About Lightning Currents to the Earth

It should be clearly noted that all currents are measured at the earth end of lightning strokes.

a) Since the beginning of oscillographic observations in 1943, the most impressive observations concern a principal difference in current oscillograms. One

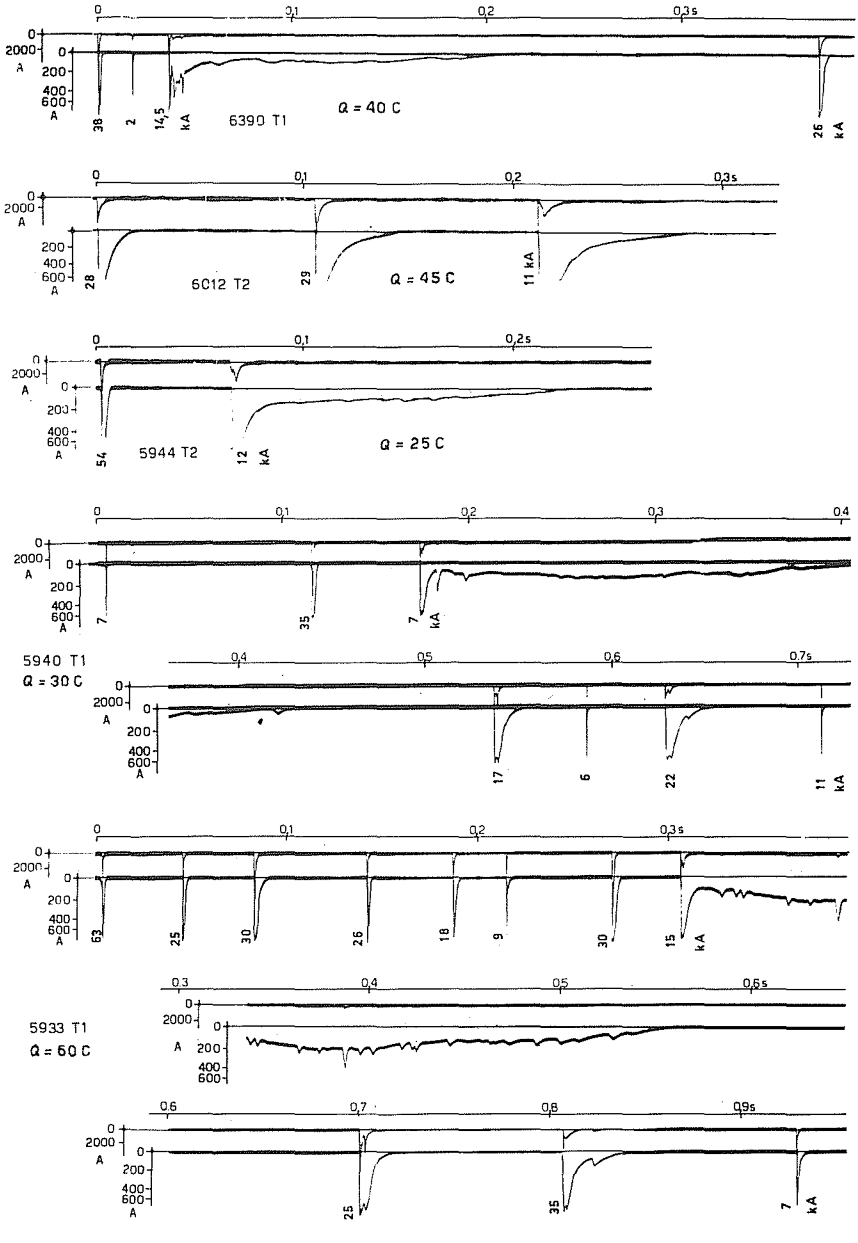


FIG. 14. Examples of currents from downward multiple strokes with some long current tails.

type of oscillogram shows a current impulse with a steep front at its origin. Another type of oscillogram, on the other hand, begins with a low current of the order of 100 A lasting a few hundredths or one tenth of a second. Only after simultaneous observations were begun using fast-moving film was it possible to prove the existence of *downward and upward growing lightning strokes* and to

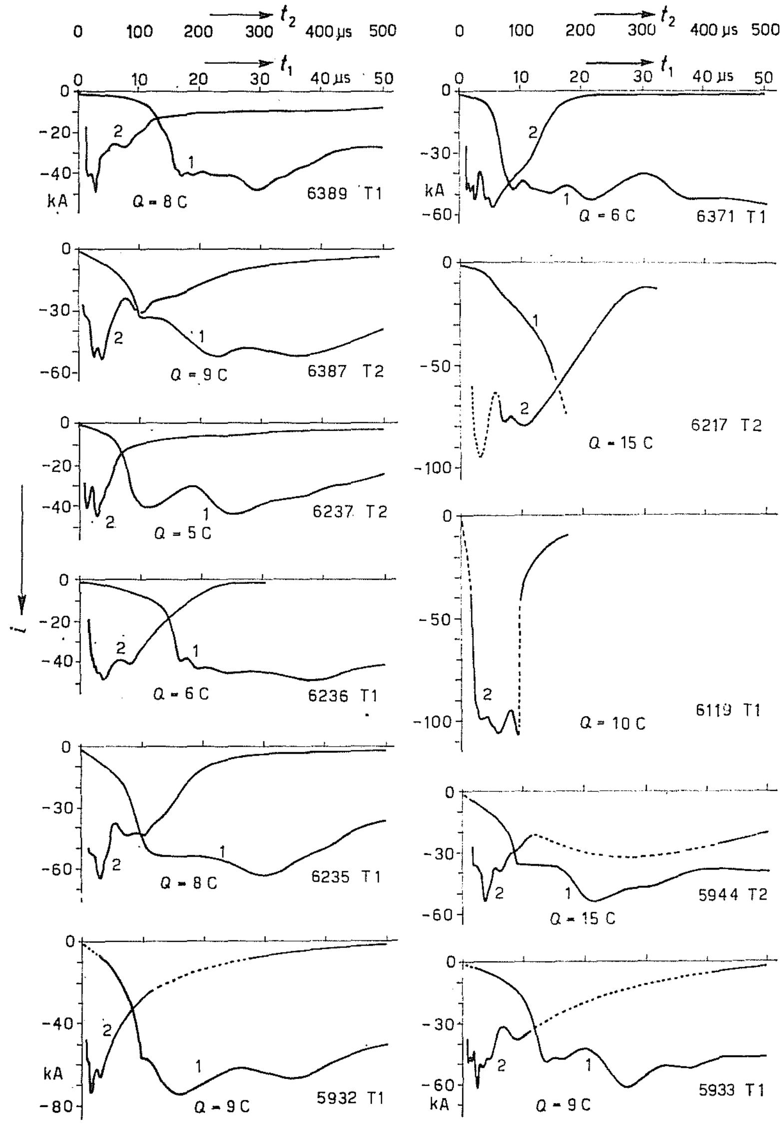


FIG. 15. Current oscillograms from single strokes or first downward strokes. 1) Fast time-scale t_1; 2) Slow time-scale t_2. In osc. No. 6119 TI, chopping may be caused by a flashover in the measuring equipment.

establish a correlation between photographic records and the two types of current oscillograms.

b) Another general observation is the well known existence of *multiple strokes*. According to Schonland, a multiple stroke is called a *flash*, which is composed of several *strokes* (6–9). (In German these definitions expressed as "Gesamtblitz" and "Teilblitz," are less arbitrary).

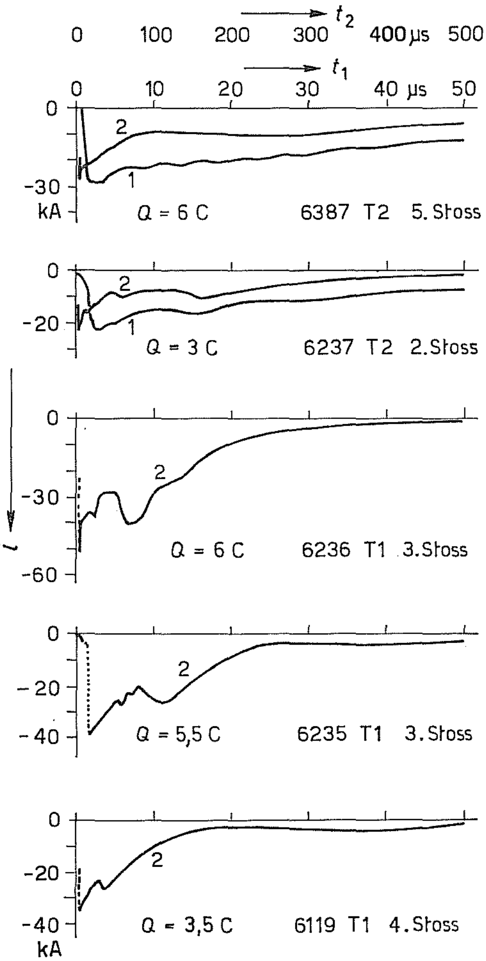


FIG. 16. Examples of strong subsequent strokes. Currents are recorded on time-scales t_1 and t_2.

In the following, we use Schonlands' definitions for *flash* and *stroke* and, in cases of doubt, we also use the term *partial stroke* as a distinct part of a *total stroke* or *flash*. In contrast to a multiple stroke there is the *single-stroke flash* or *single stroke*.

c) Two further definitions are introduced in order to describe clearly the shapes of lightning currents, i.e., *current impulses* and *continuing currents*. Current impulses are well known to high voltage engineers. Steepfronted current impulses of high amplitudes occur not only at the beginning of downward strokes but may happen anywhere in the course of a total stroke or flash.

They appear either abruptedly after current pauses (Figs. 13 and 14) or are superimposed on continuing currents (Fig. 12). In both of these cases we speak of *current impulses* or *current peaks* if their duration is short, *e.g.*, less than 500 µsec for negative or 2000 µsec for positive currents.

The long duration currents of small amplitudes (less than several 100 A) are defined as *continuing currents.* Their duration amounts to hundredths or tenths of a second. They may occur in the form of a tail to an impulse current or separately as the first stroke (upward stroke). The wave shapes of lightning currents are both complex and variable. In the next section some examples are given. *Partial strokes* are normally separated by very pronounced *current pauses.* Measurements during the first years of observation showed that, during this current pause, the lightning current is less than 1 A. *Subsequent strokes* are always initiated by an impulse current.

d) Another term to be clarified is *polarity.* There is no problem about the polarity of *cloud charges*, but the polarity of *lightning currents* must be defined.

In this paper, a positive cloud charge is deemed to produce a positive lightning current; this means that the current is counted "positive" in the downward direction. The same definition will be applied to the electric field in the atmosphere. In the current year of 1967, oscillographic measurements will be undertaken for the first time of the electric field near one tower on Mount San Salvatore, before, during and after a stroke to that tower. It is logical, then, to define a *positive field* as a field between a positively charged cloud and ground. This matter had to be settled because of ambiquities in the literature of meteorology. Our definitions mean that a positive cloud charge produces both a positive electric field to ground and positive lightning currents.

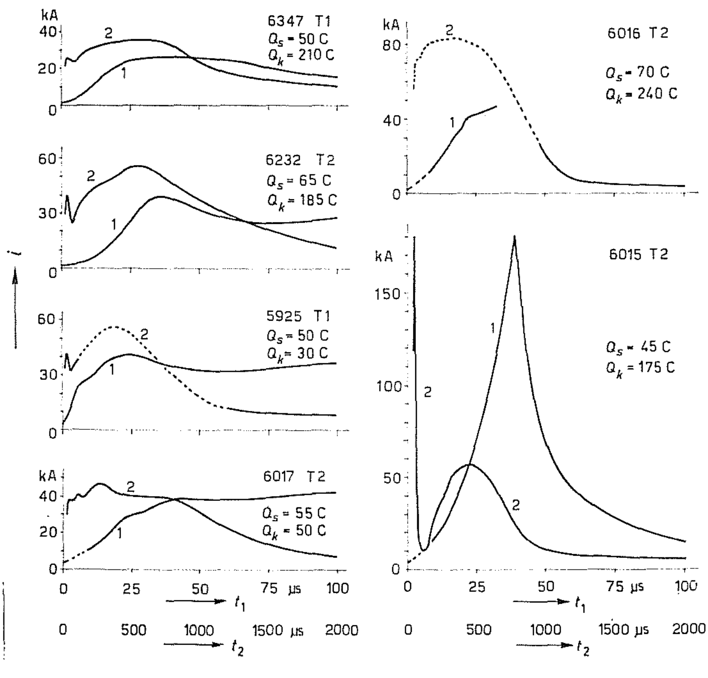


FIG. 17. Examples of strong positive strokes. Currents are recorded on time-scales t_1 and t_2; Q_s Electric charge (Coulombs) within 2 msec from the origin; Q_k Electric charge (Coulombs) in the continuing current after 2 msec.

TABLE IV

Analysis of strokes to towers 1 and 2 during the period 1955 to 1963, regarding polarity of strokes and leader progression

										1955–1963	
Year	1955	1956	1957	1958	1959	1960	1961	1962	1963	Total	Mean
Number of oscillograms	30	20	28	9	46	37	18	36	92	316	35.1
Strokes to both towers simultaneously	3	7	2	1	14	5	0	5	26	63	7.0
Sum of evaluated strokes to tower 1 or tower 2	33	27	30	10	60	42	18	41	118	379	42.1
Strokes to tower 1	21	15	14	7	35	24	13	23	70	222	24.7
Downward strokes	5	4	3	1	9	1	7	11	11	52	5.8
Upward strokes	16	11	11	6	26	23	6	12	59	170	18.9
Strokes to tower 2	12	12	16	3	25	18	5	18	48	157	17.4
Downward strokes	7	3	4	1	3	7	2	6	14	47	5.2
Upward strokes	5	9	12	2	22	11	3	12	34	110	12.2
Positive currents	3	5	12	0	4	8	0	4	10	46	5.1
Downward strokes	2	1	4	0	2	3	0	2	4	18	2.0
Upward strokes	1	4	8	0	2	5	0	2	6	28	3.1
Negative currents	30	22	16	9	54	34	18	37	104	324	36.0
Downward strokes	10	6	3	2	10	5	9	15	21	81	9.0
of these with continuing current	4	4	3	1	5	2	4	3	2	28	3.1
Upward strokes	20	16	13	7	44	29	9	22	83	243	27.0
of these with impulses	4	2	6	2	15	12	5	15	25	86	9.5
Bipolar strokes (only upward strokes)	0	0	2	1	2	0	0	0	4	9	1.0
Percentage of strokes with positive currents %	9.1	18.5	46.7	10.0	10.0	19.0	0	9.8	11.9	14.5	
Percentage of downward strokes %	36.4	26.0	20.0	23.3	20.0	19.0	50.0	41.5	21.2	26.1	

IV. Examples of Lightning-Current Oscillograms

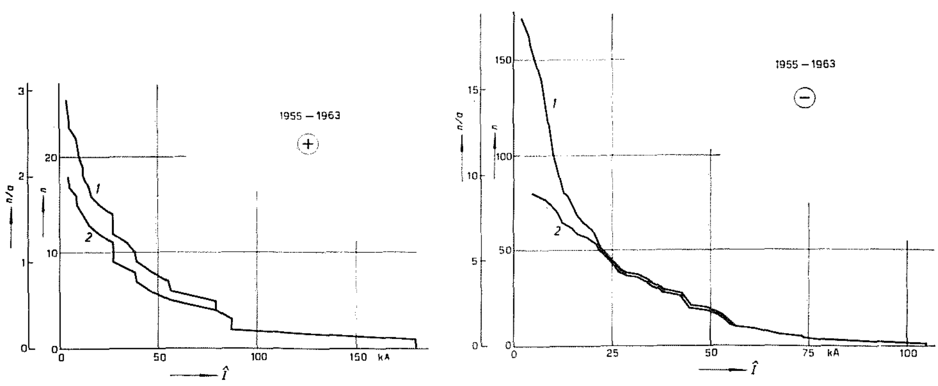
Figures 11 to 14 show some typical current oscillograms of single or multiple strokes. In these oscillograms, which were produced by the electromagnetic oscillograph, two different current scales are employed and these are adjusted to the amplitudes of continuing currents. The total flash duration amounts up to 0.7 sec. in these examples, and up to 1.8 as the maximum of all registrations.

The impulse currents are recorded by the c.r. osc. Their peak values, in kA, are indicated by small numbers near the slow-speed curves in Figs. 11 to 14.

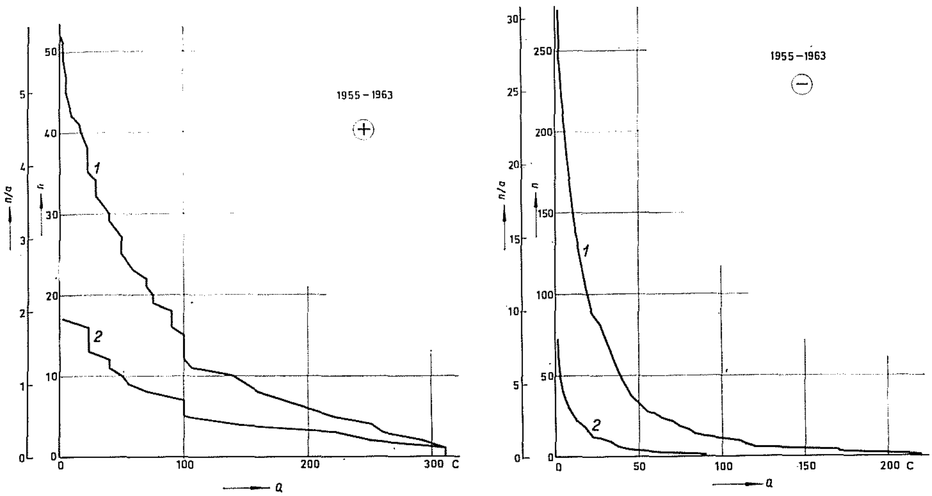
Figures 15 to 17 are reproductions of negative and positive impulse currents. They are recorded on two time-scales obtained by two cathode beams with different time-scales. The first scale is adapted to the current front, the second to the whole impulse duration.

Comparing Figs. 15 and 16, it is obvious that the front durations of subsequent partial strokes are shorter than those of first strokes. Furthermore, the current curve of the first stroke has a concave shape which is in contrast to the wave shape standardized by IEC. Its steepest part has a duration of a few μsec; the total front duration corresponding to IEC straight line through 10 per cent and 90 per cent of the peak is of the order of magnitude of 10 μsec; with a 30/90 per cent definition, the front duration would be about 5 μsec. The tails of the first partial strokes greatly differ in shape. On the other hand, subsequent strokes always have very short fronts of about 1 μsec duration. From the existing oscillograms and time scales, shorter durations cannot be measured accurately. The current shapes of these subsequent impulses are rather regular and smooth. If they are of small amplitude, *i.e.*, less than 10 kA, their tails resemble an exponential curve; all subsequent strokes frequently have exactly the same shapes and durations of impulse currents.

FIGS. 18 to 31. Integrated frequency curves of several lightning-current parameters; n number of lightning flashes measured within the period indicated against each curve, with parameters at least equal to the abscissa value; n/a number as above, but per annum (mean value). Polarities are indicated against each curve. 1) All flashes; 2) Only downward flashes. For bipolar flashes, positive and negative strokes are counted separately.



FIGS. 18 and 19. Î Peak values of currents in a flash.



FIGS. 20 and 21. Q Electric charges (Coulombs) in a flash.

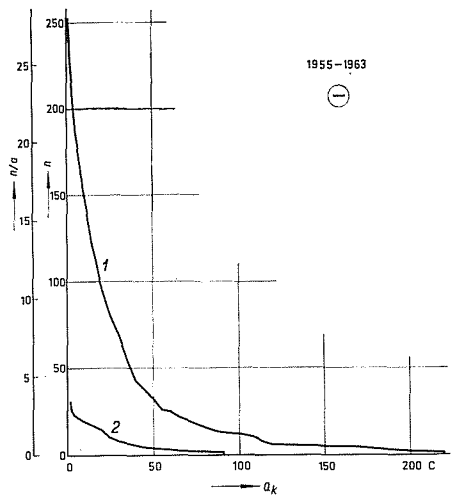


FIG. 22. Q_k Electric charges in continuing currents.

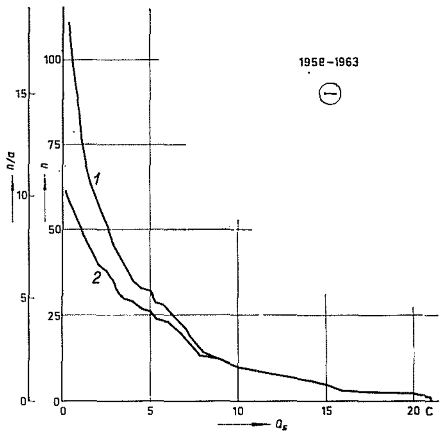


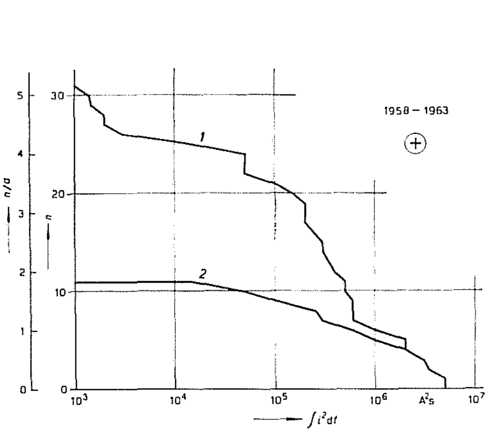
FIG. 23. Q_s Electric charges in impulse currents.

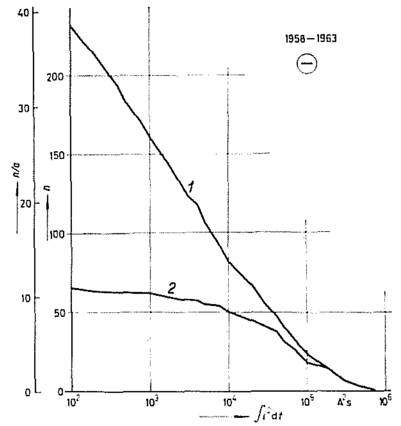
V. Statistical Data on Lightning Parameters.

Table IV contains a subdivision of lightning current oscillograms obtained during the period 1955 to 1963 with regard to polarity and direction of propagation of strokes to towers 1 and 2.

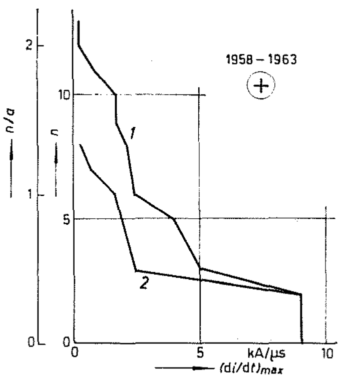
Statistical frequency distributions of some interesting parameters of lightning currents, such as their peak values, electric charges, $\int i^2 dt$, steepnesses, durations and number of partial strokes are given in Figs. 18 to 31.

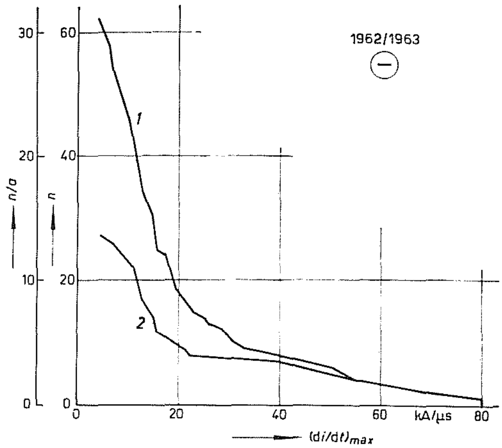
a) Each figure shows two curves; one refers to all flashes, the other only to downward flashes. It is believed that curve 2 (downward flashes) may be valid not only for Mount San Salvatore but also for the plains of southern Switzer-





FIGS. 24 and 25. $\int i^2 dt$ calculated values (A^2 sec) for a flash.

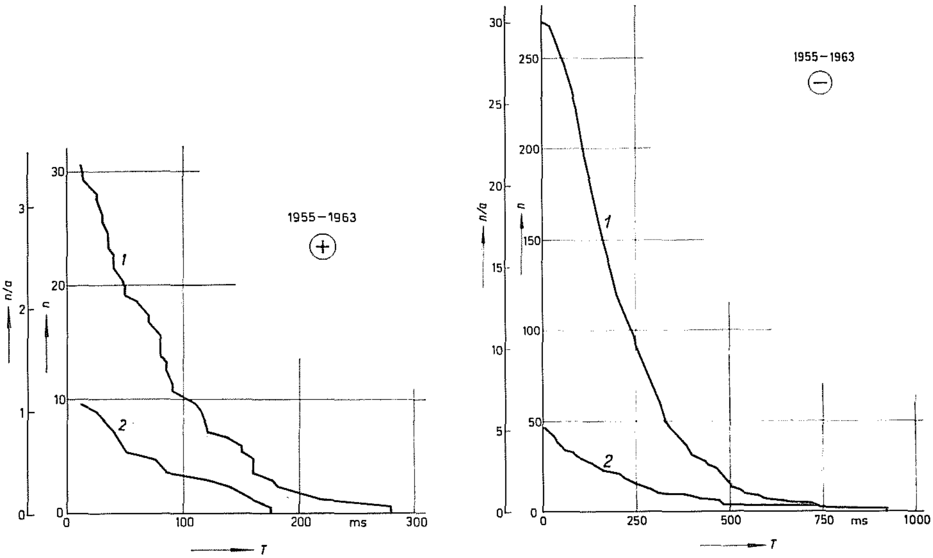




FIGS. 26 and 27. $(di/dt)_{max}$ highest current steepness (kA/μ*sec*).

land (southern border of the Alps). Regarding steepness, it is important to note that the values listed were calculated from the steepest tangent to the current curve. It is interesting to note the differences between *positive and negative current steepnesses*. This phenomenon will be discussed further in connection with the optical research (section VII).

b) Another interesting phenomenon is the much greater *value* of $\int i^2 dt$ for positive lightning currents, see Figs. 24 and 25. This integral determines the heating effect of metallic conductors and electro-dynamic forces. In fact, all cases of damage to the lightning current shunts until now were caused by positive currents. As seen from Fig. 25, all measured values of $\int i^2 dt$ are below 10^7 A^2 sec. On the basis of this value, it is easy to calculate the temperature rise, *e.g.* one copper wire of 6 mm diameter, which will be below 100°C. Two steel wires, each of 6 mm diameter, will be heated to 140° in an extreme and very rare case. Such wires are thus capable of conducting very heavy lightning cur-



FIGS. 28 and 29. T total duration of a flash (ms).

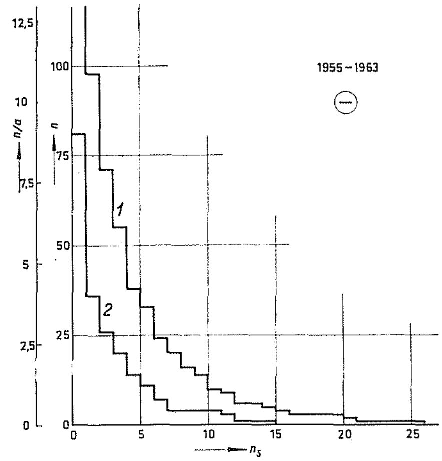


FIG. 30. n_s number of impulses >2 kA in one flash.

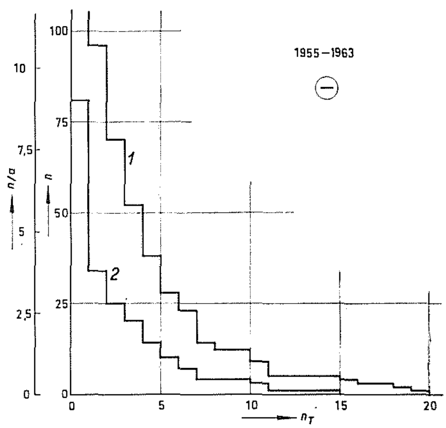


FIG. 31. n_T number of strokes in one flash.

rents. If difficulties arise in practical installations, they are caused by badly welded connectors between the wires.

c) A further notable fact is the difference in the *number of strokes* in positive and negative flashes. During the period 1946 to 1954, from 57 positive flashes, only 2 were observed to have 2 strokes; 55 were single strokes (**2**). In the period 1955 to 1963, the same observation was made. This phenomenon will be discussed later.

d) A comparison of Figs. 30 and 31 shows little difference between the numbers of current impulses and partial strokes. This means that the great

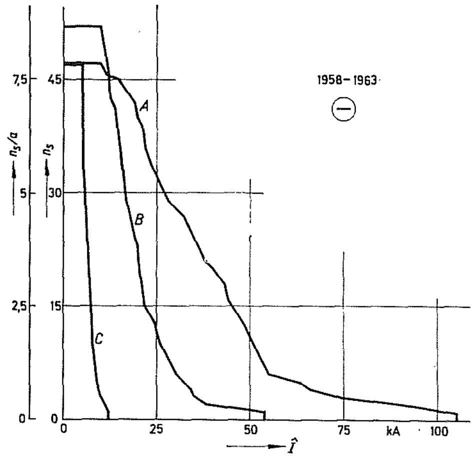


Fig. 32. Î Current peak.

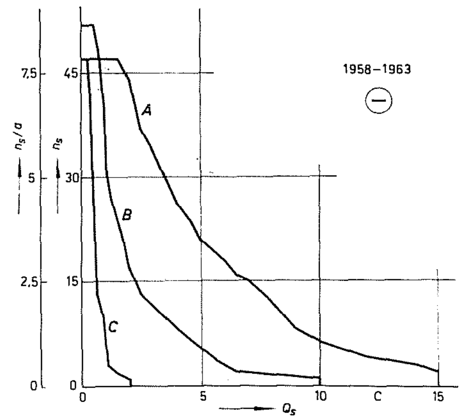


Fig. 33. Q Electric charge.

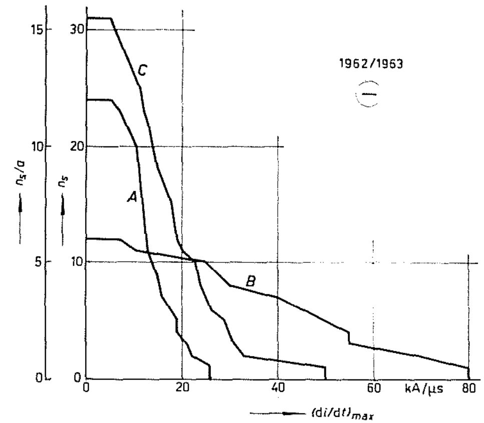


Fig. 34. $(di/dt)_{max}$ Highest current steepness (tangent).

Figs. 32 to 34. Integrated frequencies of parameters of negative current impulses: n_s and n_s/a, as in Figs. 18 to 31, n and n/a; A Impulse currents of downward first strokes; B Impulse currents of subsequent downward strokes; C Impulse currents in upward strokes; A to C only currents with 10 kA peak or more are counted.

majority of impulses occur at the beginning of partial strokes. Only a relatively small number of impulses are superimposed on continuing currents. Indeed, all subsequent strokes, *i.e.*, strokes which occur after a current pause in a multiple stroke, are steep-fronted impulses with or without long tails.

e) The highest current steepnesses occur in negative subsequent strokes (Fig. 34) which always progress downward.

f) The annual electric charge which was transported to earth by lightning strokes during the period from 1955 to 1963 is shown in Table V. From this table it appears that the widespread assumption that lightning carries more negative than positive charges to the ground may be erroneous for downward flashes, while it holds for upward flashes. In fact, downward flashes to the towers brought greater positive than negative charges to earth between 1955 and 1963. However, this may be too short a period to allow general conclusions to be drawn.

TABLE V

Integrated electric charges (Coulombs) transported by lightning strokes from clouds to the towers during the period 1955–1963

Year	Downward strokes		Upward strokes		Total	
	+	−	+	−	+	−
1955*	20	130	50	660	70	790
1956*	20	30	50	220	70	250
1957*	280	80	480	420	760	500
1958	0	30	200	220	200	250
1959	130	150	240	990	370	1140
1960	630	50	360	730	990	780
1961	0	100	0	70	0	170
1962	300	100	100	530	400	630
1963	190	220	900	1760	1090	1980
Total 1955* to 1963	1570	890	2380	5600	3950	6490
Mean values 1955* to 1963	174	99	264	622	438	721
Mean values 1958 to 1963	208	108	300	716	508	824

* 1955–1957 without charges in current impulses.

VI. Purposes of Lightning Photography on Mount San Salvatore

Photography on Mount San Salvatore has three purposes: a) Research on the development of lightning strokes, together with current oscillograms; b) Registration of all points struck by lightning in the surrounding areas of San Salvatore; c) Contribution from a), to the problem of the "protective area" of lightning rods (towers). These three purposes will now be discussed.

VII. Development of the Lightning Stroke

a. General Remarks about Lightning Photography

The first unusual observation on Mount San Salvatore was the surprisingly high number of *upward-growing strokes*. To prove their existence, it was necessary to combine current measurements with photographic observations especially by using the method of fast moving film, described in section I. From the oscillograms, we were led to conclude that current curves which begin with a slow-fronted continuing current were caused by upward-growing strokes. This was indeed proved by photographs taken on fast moving film. Another result of the comparison of current curves and photography concerns *branching* of the channel of lightning strokes. When branching is observed, branches always point in the direction of the propagation of the lightning stroke, independently of the polarity of the stroke.

Another observation is this: *by no means do all strokes clearly show leaders.* The reason for this statement was found only by the careful analysis of many photographs of strokes and their corresponding current oscillograms. In other words, we have to distinguish between *four types* of leaders, with respect to both polarities and both directions of progression, see Fig. 35. It is necessary

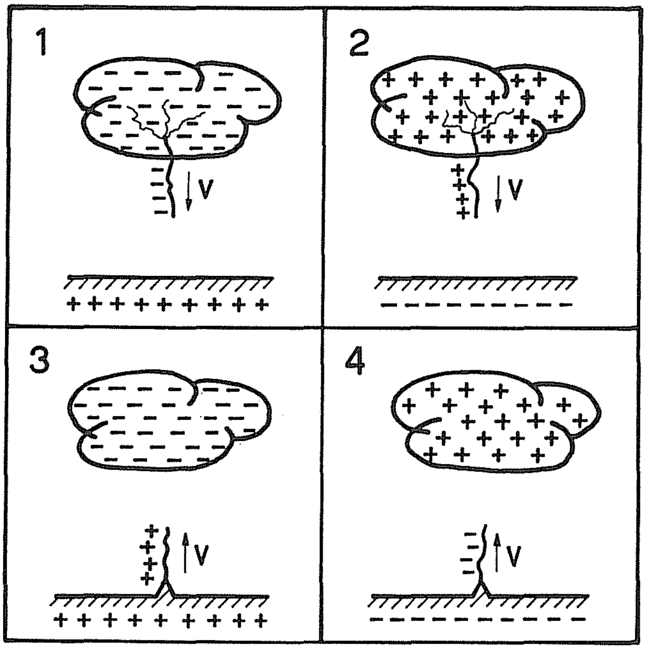


FIG. 35. The four types of lightning stroke: 1) Negative downward stroke (negative charge) negative current. 2) Positive downward stroke (positive charge) positive current. 3) Positive upward stroke (positive charge) negative current. 4) Negative upward stroke (negative charge) positive current. v) Direction of stroke propagation.

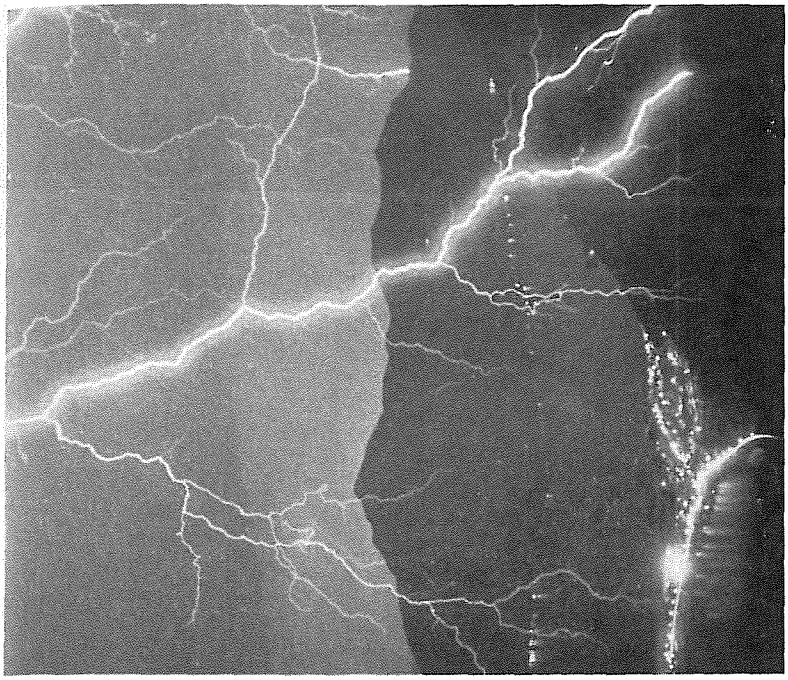


Fig. 37. Downward flash near Ciona.

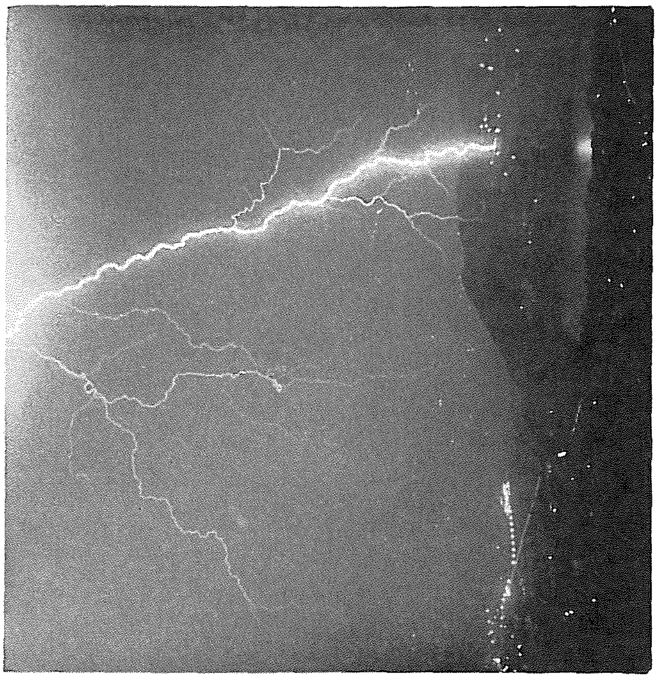


Fig. 36. Downward flash to Biogno.

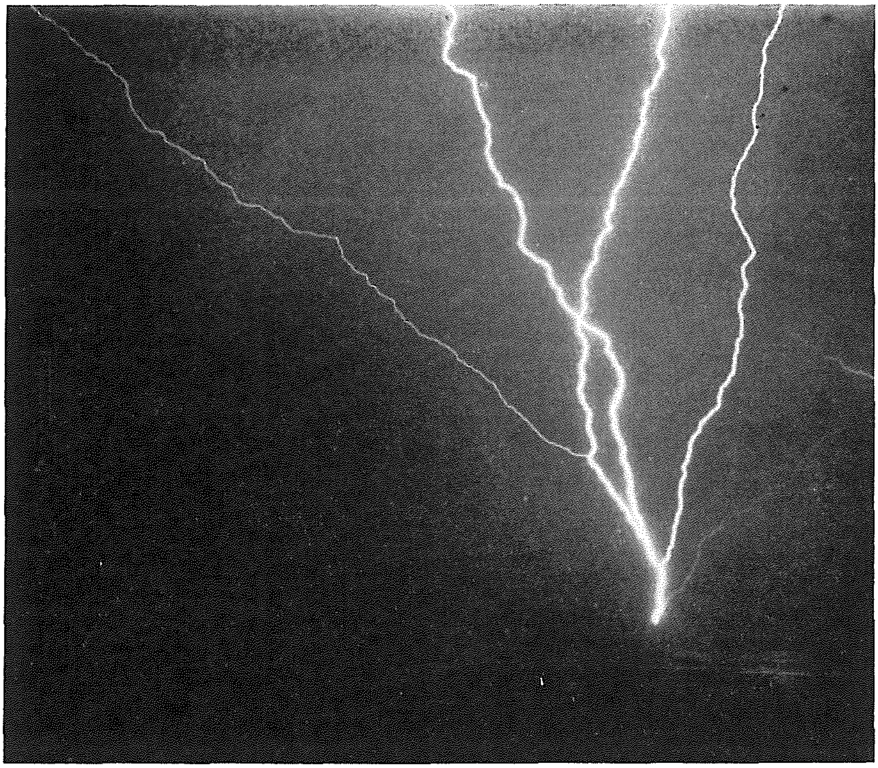


FIG. 38. Upward flash from tower 2.

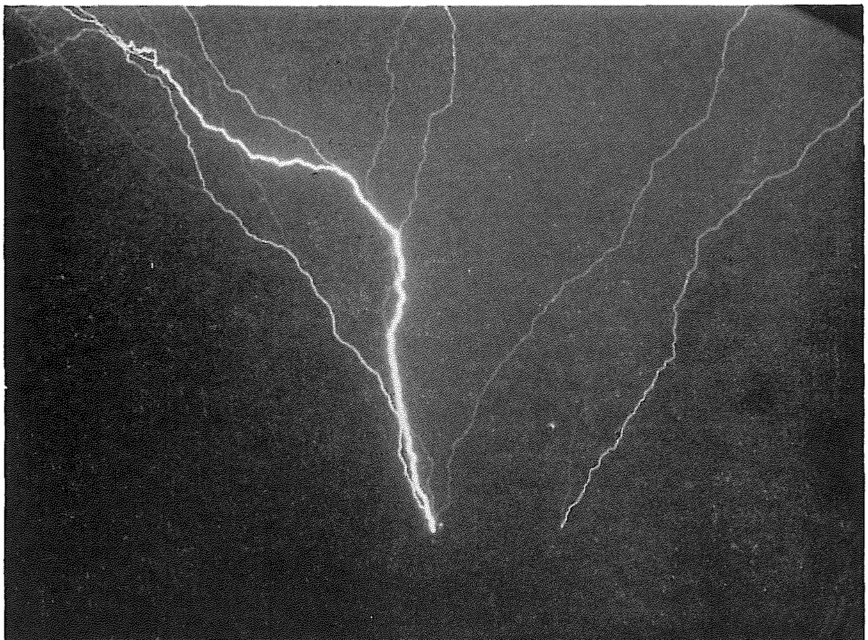
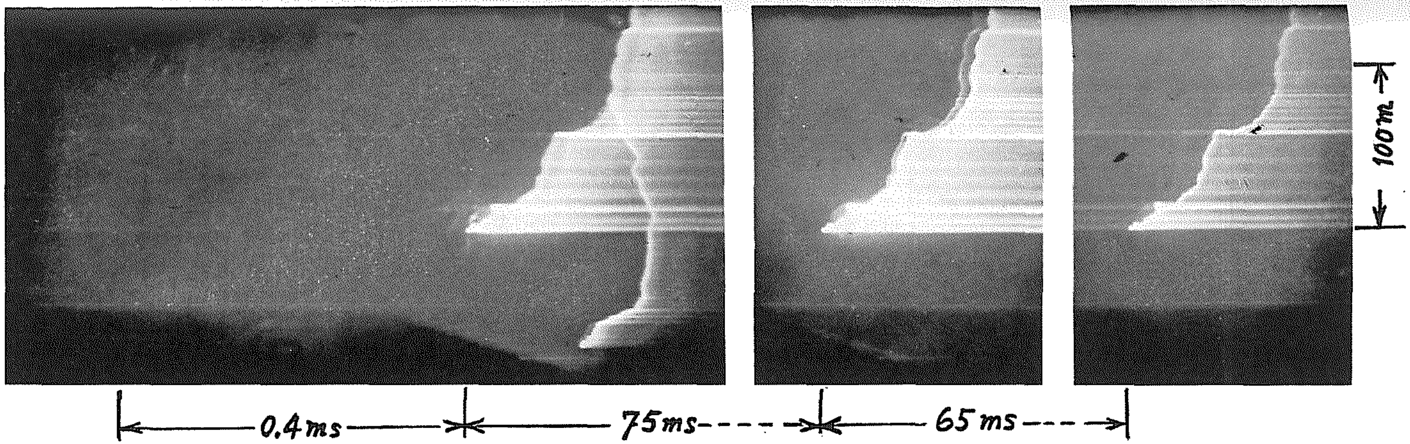


FIG. 39. Upward flashes from towers 1 and 2.

(a)



(b)

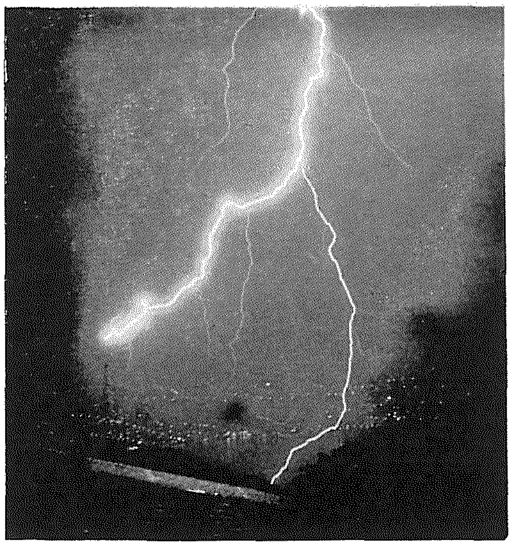


FIG. 40. Downward flash with 3 strokes to tower 2. First stroke shows stepped leader. Subsequent strokes show dart leaders.

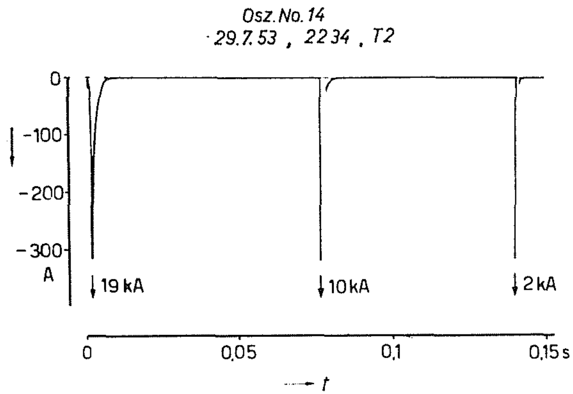
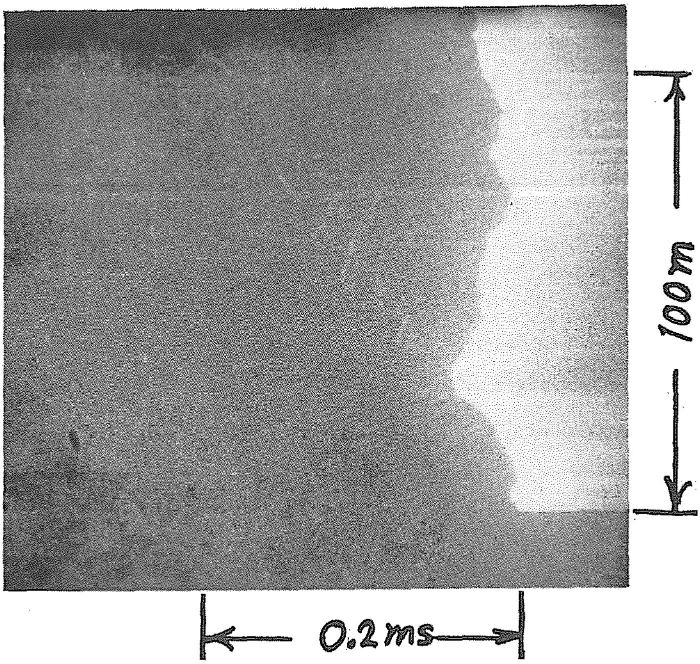
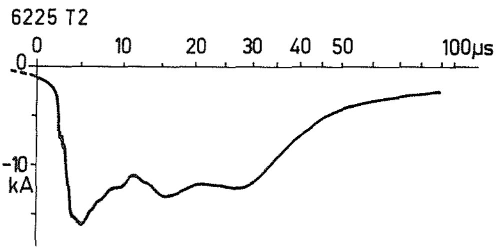


FIG. 41. Lightning current oscillogram of Fig. 40.



(a)



(b)

FIG. 42. Downward negative stroke to tower 2. a) Photograph from mountain peak on fast moving film. b) Current oscillogram (impulse current).

to define the polarity of a leader. A positive leader shall be a leader which carries a positive electric charge; correspondingly, a negative leader is a leader with a negative charge. *Positive clouds* produce *positive leaders* (if they propagate downwards) or *negative leaders* (if they propagate upwards from the towers). In the same way *negative clouds* produce negative (downward) or positive (upward) leaders.

The following examples show that *only negative leaders, i.e., leaders with a negative charge, exhibit a very distinct and bright stepping.* Positively charged leaders show a very faint or weak luminosity and less clear, or no stepping. Often this luminosity is so weak that it cannot be observed even on a fast moving film.

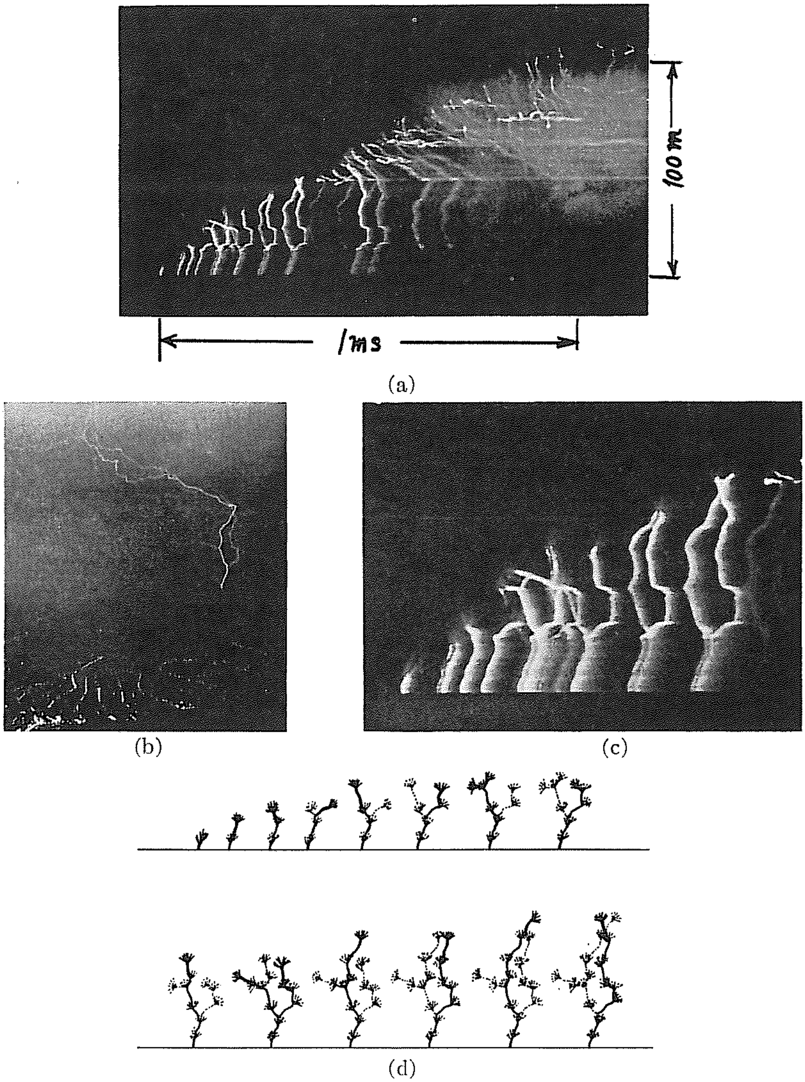


FIG. 43. Upward stroke from tower 2 (tower is the negative electrode). a) Photograph on fast-moving film from mountain peak. b) Photograph on still film. c) Enlargement of a) to show corona-envelopes at the tips of the negative leader. d) Stages of development of leader designed from original c). Full lines are just visible. Dotted lines indicate former discharges. Time intervals between steps do not correspond to c).

b. Examples of Lightning Stroke Photographs

Figures 36 and 37 show two strokes with downward branching, while Figs. 38 and 39 show two strokes with upward branching from the towers on Mount San Salvatore. These photographs (Figs. 36–39) were taken with normal cameras (Leica) using still film. Their shutters were left open at night time for several minutes.

The next photographs give examples obtained on fast moving film at a speed of about 27 m/sec.

Figure 40 shows a *downward negative stroke* to tower 2 which contacts the tower not at its tip (lightning rod) but just below, at the steel framework. The main stroke current did not therefore pass through the measuring shunt. The corresponding oscillogram, Fig. 41, shows three short current pips caused probably by the streamer which is visible in the photograph from the tip of the lightning rod in a vertical direction. The first stroke shows stepped leaders in both branches simultaneously. The second and third strokes, as usual, are not stepped, but have dart leaders. Only the branch to the tower exists in these strokes.

Figure 42 is another example of a downward *negative* stroke to tower 2, representing the stepped leader and the corresponding current oscillograms.

Figure 43 shows an *upward* stepped leader from tower 2. This leader contains *negative* charge, *viz.*, the tower represents the negative electrode. The current is therefore positive, corresponding to the definition in Fig. 35. The enlarged photograph shows not only the distinct and very luminous streamers but also the corona region in front of the tip of each streamer.

Figure 44 is a similar stroke with a negative leader from tower 2 towards the clouds, hence, with positive current, showing distinct streamer steps with a corona envelope in front of the tip of each streamer.

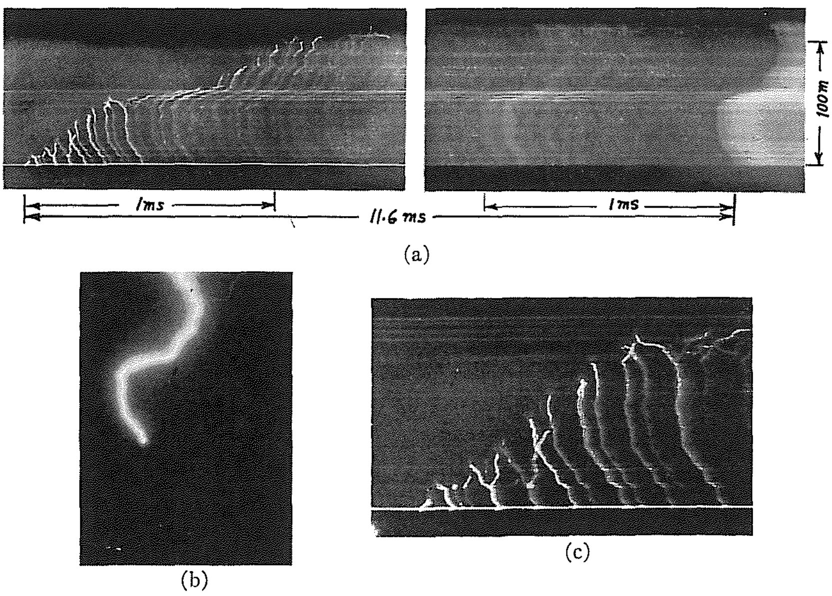


FIG. 44. Upward stroke from negative tower 2. a) Photograph on fast-moving film from peak of mountain. b) Photograph on still film. c) Enlargement of a) shows corona envelopes at the tip of the negative leader. A bright illumination is visible 11.6 msec after start of the leader. The oscillogram shows at that instant an impulse of 27 kA. This proves that this "leader" is in reality an extremely long "upward connecting streamer" to a positive downward stroke.

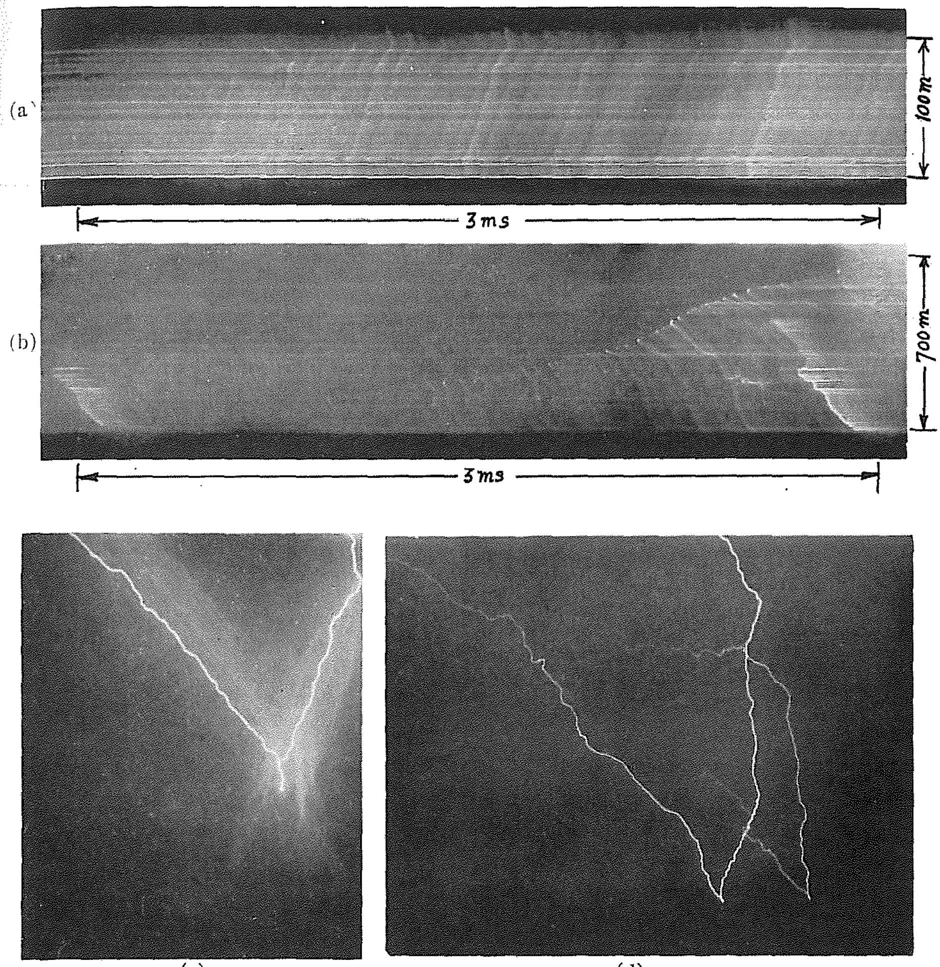


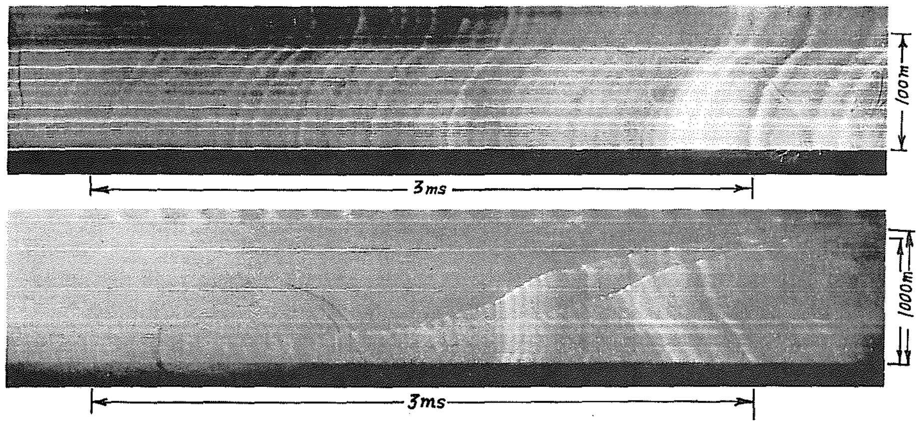
FIG. 45. Upward stroke from positive tower 2. a) Photograph on fast moving film from peak of mountain. b) Photograph on fast moving film from Breganzona. c) Photograph on still film from mountain peak. d) Photograph on still film from Breganzona shows another stroke from tower 1 (at right).

Very different from these upward or downward negative leaders are leaders with *positive electric charge*, as shown in the following examples (Figs. 45 to 47).

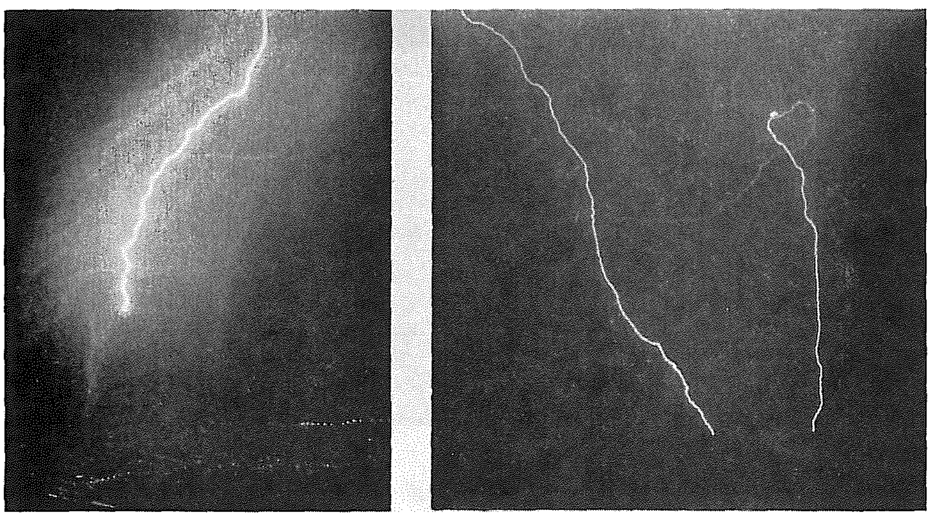
Figures 45 and 46 are strokes from both towers 1 and 2 with upward leaders. Both leaders (from towers 1 and 2) are visible from Breganzona [Fig. 45(b) and (d)]. In Fig. 45(b) one first leader corresponds to a branch at tower 2, a second leader begins about 3 msec later on tower 1. In Fig. 45(a) and (c) which were taken from the top of the mountain, tower 1 cannot be seen. A faint indication of branching leaders is visible in Fig. 45(a).

In Fig. 46(b) the first leader is from tower 1 [right on photograph 46(d)] and the second from tower 2 [left on Fig. 46(d)], less than 1 msec later. The

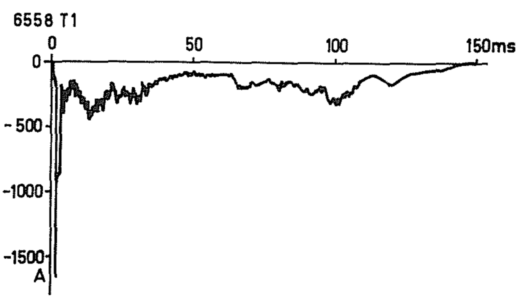
(a)



(b)



(c) (d)



(e)

FIG. 46. Upward stroke from positive towers. a) Photograph on fast moving film from mountain peak. b) Photograph on fast moving film from Breganzona. (Fast scale for tower 1, slow scale for tower 2). c) Photograph on still film from mountain peak toward tower 2. d) Photograph on still film from Breganzona (tower 2 at left, tower 1 at right). e) Current oscillogram tower 1.

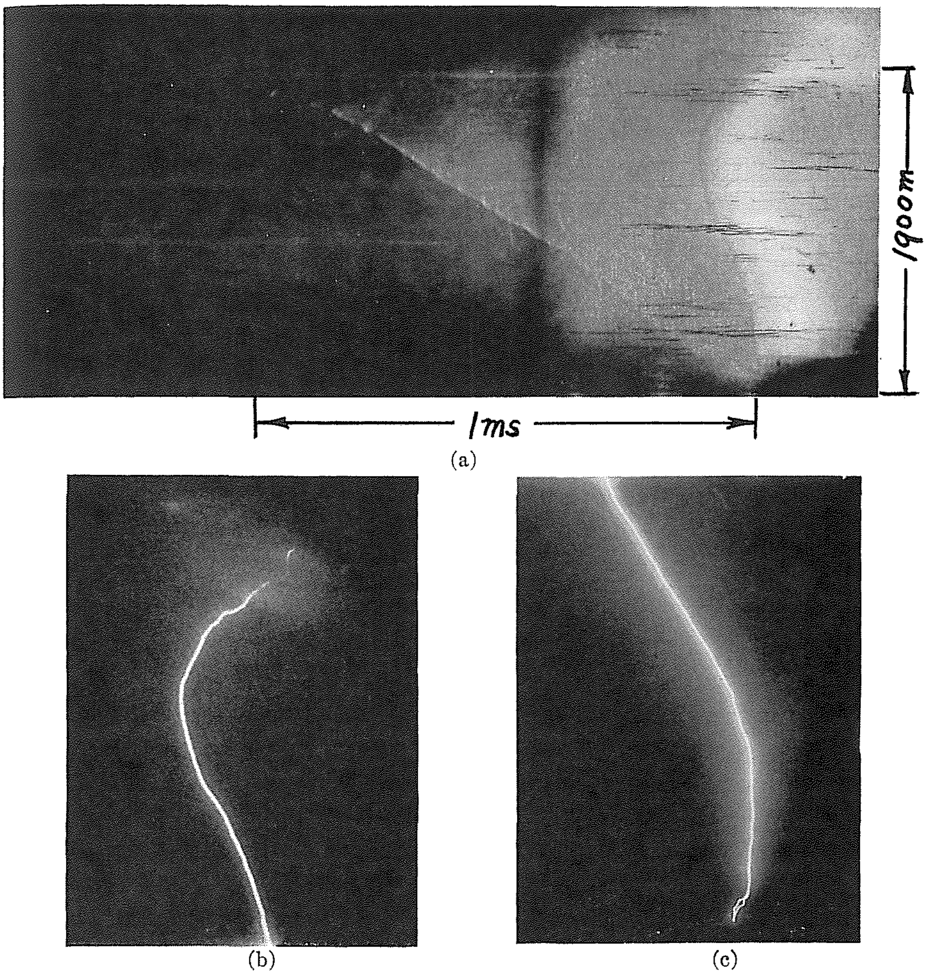


FIG. 47. Downward (probably positive) stroke to Campione. a) Photograph on fast-moving film from Breganzona. Leader does not show real stepping. b) Photograph on still film from Breganzona. c) Photograph on still film from peak of mountain. See the loop caused by a "streamer discharge" joining the downward stroke just above Campione.

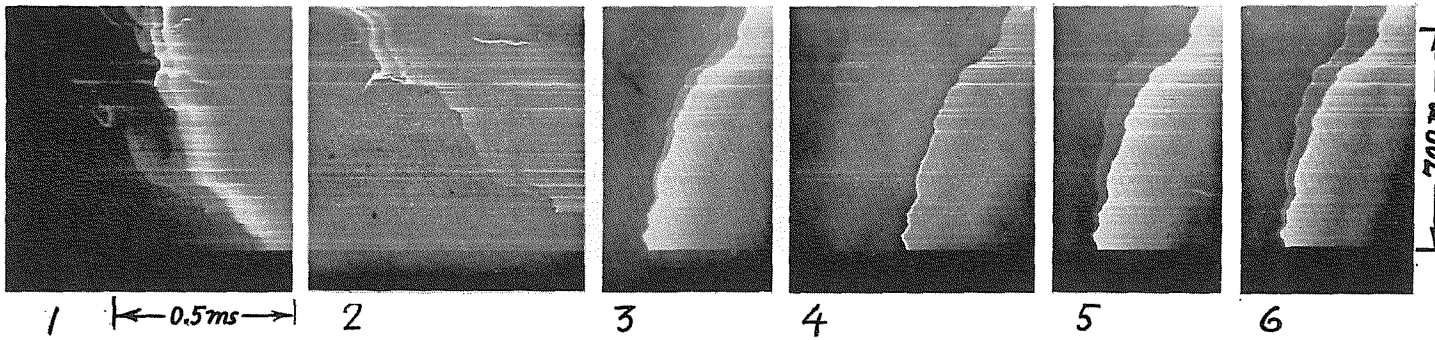
very short time interval between the leader formations on both towers is extremely interesting.

Figure 47 shows a downward leader to the shore of Lake Lugano (Campione). By examining the photograph it is obvious that this is a positive leader.

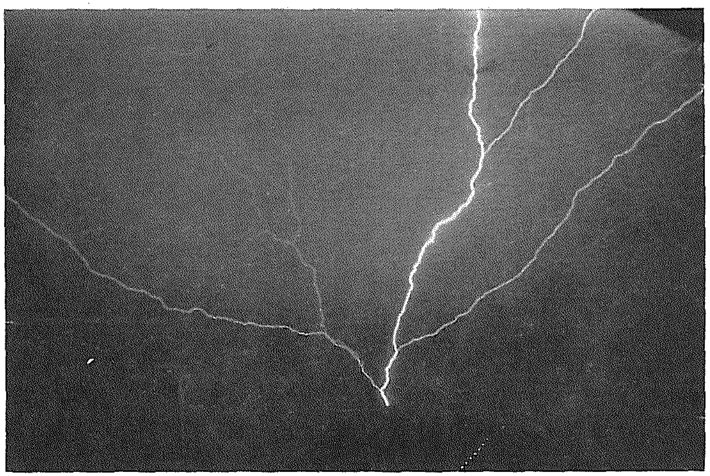
Figure 47(c) taken from San Salvatore shows an example of a loop in the lightning channel above Campione which can be explained as an upward "streamer discharge."[1]

Another example of a positive leader from tower 2 is given in Fig. 48. From the oscillogram it is obvious that the leader was growing upward and, as in

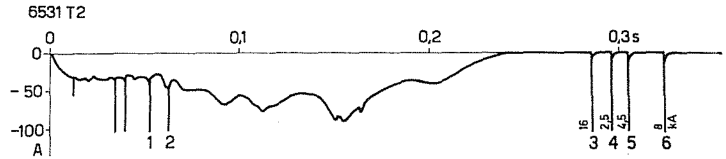
[1] This term is explained in the following subsection (d).



(a)



(b)



(c)

Fig. 48. Upward flash from positive tower 2 with subsequent strokes. a) Photograph on fast-moving film from Breganzona. b) Photograph on still film from Breganzona. c) Current oscillogram, points 1 to 6 correspond to photographs a-1 to a-6. The first upward leader from tower 2 (positive electrode) is not visible.

most cases with positive leaders, it could not be photographed. Instead, the superimposed current peaks 1 to 6 show downward negative dart leaders, 1 and 2 in one branch and 3 to 6 in another branch. Both branches are clearly visible in Fig. 48(b), a still film photograph.

Summarizing, it is interesting to note the great differences in appearance between leaders with negative charges and those having positive charges. The first class of leader shows very well defined luminous lines with bright tips, sometimes even with the corona envelope visible in front of the tips. The second class of leader does not show distinct streamers but only faint bands which could better be described as an irregularly oscillating, weak luminosity with somewhat brighter local tips. These tips sometimes produce a rather continuing trace, as in Fig. 47, which proves that there are no real steps.

TABLE VI

Evaluation of leaders

No.	P_q	P_i	Type of stroke	n	H m	v m/sec	T_{St} μsec	H_{St} m
1	−	−	Negative downward strokes to towers	4	0–100	185–220	40–52	8–10
2	−	−	Negative downward strokes to earth	14	0–1300	85–440	29–47	3–17
					0–1750	65		
				1	1750–2000	700	41	29
					2000–2350	1060	47	50
3	−	+	Upward strokes from negative towers	8	0–110	120–190	33–50	4.5–8
				3	250–1200	110–450	40–47	5–18
				1	20–110	870–1150	4–6.5	3.5–7.5
4	−	+	Streamers from negative towers	6	0–55	85–140	34–47	3–6
5	−	+	Upward strokes from Mt. Sighignola (4 steps)	1	540–900	2200	55	120
6	+	−	Upward strokes from positive towers	4	40–110	40–75	65–110	4–8
				7	110–500	130–490	45–115	8–27
					500–1150	105–970	40–115	12–40
7	+	+	Positive downward stroke	1	320–920	2400	—	—
					920–1660	1700	—	—
					1660–1870	360	—	—

P_q Polarity of leader charge q i
P_i Polarity of stroke-current i
n Number of evaluations within range of heights H
H Height above tower or above earth
v Vertical velocity of leader } Mean values over 5–30 steps
T_{st} Time-interval between steps } Mean values over 5–30 steps
H_{st} Vertical length of steps

c. Photographic Evidence on Lightning Progression

Table VI shows the results of a very laborious evaluation of leaders which was carried out by E. Vogelsanger. It is not possible to discuss here all the details which were published in (4). Of special interest is the small percentage of upward leaders from the positive towers which could be photographed (7 out of 46, column 6). Most positive leaders are too weak to produce an image on photographic film. The table shows a wide range in the lengths of steps (H_{st}). The limits are 3 and 50 m, with one exceptional value of 120 m. The mean velocities of progression (vertical component) are within 40 and 2200 m/msec or km/sec, or within about 0.01 and 0.7 per cent of the velocity of light.

Subsequent strokes in multiple strokes exhibit much higher leader velocities than first leaders. They lie within 0.4 to 30 m/μsec, or about 0.13 to 10 per cent of the velocity of light. This is about 10 times the velocity of the first (stepped) leader. It is interesting to note that an inverse relation exists in the front durations of stepped and dart leaders (first strokes and subsequent strokes), which is about 5 to 10 μsec to 0.5 to 1 μsec. It would be of theoretical and practical interest to determine whether some correlation exists between the length of steps and the current amplitude of the lightning stroke. Unfortunately, the number of leader photographs with corresponding current oscillograms is not large enough yet to answer this question.

The smallest dispersion is found in the *time interval between* two steps (T_{st}). This time is between 29 and 55 μsec for negative leaders, and should be compared with the period of light-intensity variation, which is 40 to 110 μsec for positive leaders. One exception of only 4 to 6.5 μsec exists for one negative leader.

d. Establishment of the Electrical "Bridge" between the Downward Progressing Leader and the Earth

The photographic records on fast moving film prove the existence of upward streamers[2] developing not only from earth towards visible leader strokes, but also from earth towards already existing but invisible lightning channels in the clouds. The occurrence of these discharges is electrically proven by the impulse currents which are superimposed on the continuing current of upward leaders (Fig. 48). These upward connecting streamers greatly differ in length; they often are not longer than a few steps of the downcoming leader (Fig. 42) yet, in other cases, they may reach astonishing lengths. The upper limit may be several kilometers, as is shown in Table VII. For short "bridges" or "breakdown distances" between leader tip and earth the "bridge" formation may be regarded as a "breakdown," similar to a laboratory breakdown. For breakdown distances exceeding a

[2] The term "streamer" is intended to denote a discharge which develops from earth or from an earthed structure and which finishes in mid-air or which continues to extend until it effects contact with a downward leader stroke from a cloud; in this latter case it may be termed an "upward connecting streamer." (German expression is "Fangentladung.")

TABLE VII

Characteristics of some "upward connecting streamers" to 6 downward positive strokes (tower is negative electrode)

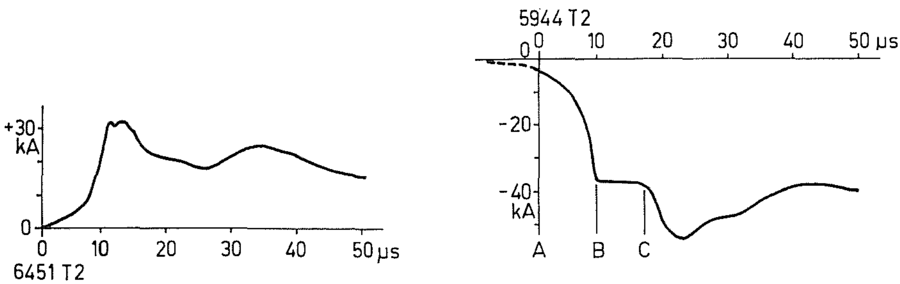
Oscill. No.	Tower No.	T msec	H m	Q C	$\hat{\imath}$ kA	$(di/dt)_{max}$ kA/μsec
6451	2	0	0	30	32	17
6527	1	3.0	500	12	22	4.5
6572	2	6.1	1000	62	77	3
6232	2	8.7	1200	65	56	2
6520	2	11.6	1150	35	27	1
6422	2	14	1800	130	106	2

T Time from start of upward leader until beginning of impulse current i
H Vertical length of upward leader up to its arrival at the existing lightning channel into the cloud (velocity is considered to be constant above this length)
Q Charge of impulse current within 2 msec after start of the impulse
$\hat{\imath}$ Impulse current (peak value)
$(di/dt)_{max}$ Steepness (tangent to the current-time curve) of the impulse current

few steps in length the "bridge" formation assumes the form of an upward leader with its own steps.

e. Steepness of Positive and Negative Lightning Currents and its Correlation with "Connecting Streamers"

From the statistical curves shown in Figs. 26 and 27 it is seen that negative currents are in general much steeper than positive currents. From Table VII it is obvious that the steepness of positive lightning currents depends on the length of the "connecting streamer." The only case without or with only a very short "streamer" (first line in Table VII) shows a steepness which, with



(a) (b)

FIG. 49. Comparison of steepnesses of usual negative strokes with a positive downward stroke without connecting streamer. a) Downward positive stroke without connecting streamer. b) Usual downward negative stroke. A) Up to this point formation of the very faint "streamer discharges" from the positive tower. AB) Formation of highly conducting bridge between downcoming and upward growing "streamer discharge." C) Secondary current initiation from branching.

TABLE VIII

Highest values of current, electric charge and $\int i^2dt$ in positive and negative flashes during the period 1955–1963

Year	Current kA		El. Charge C		$\int i^2dt$ A^2s	
	+	−	+	−	+	−
1955	5	79	50*	110*		
1956	20	45	23*	65*		
1957	87	57	160*	70*		
1958	10	20	200	170	3×10^5	1.5×10^5
1959	55	74	90	110	6×10^5	4×10^5
1960	180	29	310	120	5×10^6	2×10^5
1961	0	105	0	35	0	7×10^5
1962	56	95	250	110	3×10^6	4×10^5
1963	36	55	290	220	2×10^6	3×10^5

* 1955–1957 without charges in current impulses.

17 kA/μsec, is similar to those of negative strokes. Figure 49 shows a comparison of the current oscillograms of the stroke designated in Table VII, (line one) *which showed no streamer* and of a usual oscillogram of a negative stroke. There is no essential difference between both current fronts in this case.

Table VIII shows the highest values of some lightning-flash characteristics during the period 1955–1963.

VIII. Short Review of Unsolved Lightning-Stroke Problems

There still remain several questions and a few unsolved problems about the physical nature of lightning strokes. Some of these are new, resulting from the observations described in this paper, others revert to the classical observations of Schonland. It is not the purpose of this paper to offer theoretical explanations for our observations; instead, we confine ourselves to examining several problems which seem to be of special interest for the physics of long sparks:

a) What is the origin of the high electric field which is necessary to develop an upward stroke? Or more precisely: are upward strokes always "secondary" strokes, *i.e.*, caused by a primary distant stroke?

b) Why do multiple strokes occur only with negative lightning currents, *i.e.*, from negatively charged clouds?

c) Why are streamer discharges from a negative tower tip much longer than those from a positive tower? This observation is in contradiction with experience on long sparks in rod plane gaps in high-voltage laboratories.

d) Are modern theories about the propagation of leaders and of multiple-stroke formation capable of explaining the phenomena described in this paper?

Regarding question a: Upward Strokes = Secondary Strokes?

The observations about very long streamer discharges raise the question whether possibly *all* upward strokes are caused by distant primary flashes and their field variations near the towers. Very often a sharp noise is audible at the tower tops at the instant of a distant flash, as with the well-known impulse corona. Field impulses may then cause the development of upward leaders. If they are long enough to effect contact with primary strokes, they are called *connecting streamer discharges*. If they do not reach distant primary strokes, we shall call them *secondary strokes*. Normally upward strokes have negative current. This means that the tower normally is the positive electrode. The positive leader of the secondary stroke is very faint and very often not visible on fast moving film. Yet, the secondary stroke is clearly visible on a normal photograph with still film. We hope to be able to answer this question about the origin of secondary strokes by using a "field-mill" which will registrate with good time resolution the field variation near tower 1 before and during strokes to this tower.

Regarding question b: Multiple-stroke Formation.

The following hypothesis is suggested:

Multiple strokes occur exclusively in the discharge of negative clouds to earth. This phenomenon may be explained by the different mobilities of ions and free electrons. During the discharge of a negative cloud the electric field to earth decreases. On the other hand, with decreasing current the voltage drop in the lightning channel (main return stroke) increases. This involves acceleration of all existing free electrons in the plasma channel towards earth, with or without new ionization effects. What remains is a positive charge in the channel. The electric field at its earthed end is now the difference of the field produced by the remaining negative cloud charge and the positive channel charge. When the field reaches zero, the current is chopped at the earth but not in the upper part of the channel, which continues to be charged by the cloud streamers. When the upper part of the channel is again charged to an adequate potential, a dart leader travels down along the still hot channel.

For positive clouds, the fields due to the cloud and to the positive charge in the channel are additive. The electric field at the earthed end of the channel does not fall to zero until the cloud is completely discharged. This suggested mechanism agrees with observations.

Regarding question c): Polarity Effects in Leaders from the Tower Top.

When comparing leaders of lightning strokes with leaders of long laboratory sparks it is most surprising to note that very long leader strokes develop upwards from *negative* towers to meet downcoming positive leaders. Laboratory sparks, on the contrary, always show much longer predischarges (leaders) from *positive* points or rods (**10**).

Regarding luminosity, leaders to lightning strokes are quite similar to laboratory predischarges or sparks. In both cases light emission is much higher in front of a negative point or rod electrode than in front of a positive one (**10**). This would suggest the existence of much longer positive lightning leaders than we can observe by photography. This, however, is in contradiction to the observation of only short *positive* connecting streamers from the tower to downcoming negative leaders. This problem of very long *negative* connecting streamers from the tower remains, therefore, open to future explanation.

Regarding question d): Stepped Leader and Pilot Leader.

Schonland has suggested a regularly progressing and invisible pilot leader which prepares the steps of the negative leader. The photographs of negative upward leaders from the towers show a very faint corona-envelope at the end of each leader tip [Fig. 43(d)]. This proves the existence of a strong ionization at this point.

Step formation has constituted a fundamental problem since about 1900 when M. Töpler in Dresden predicated their occurrence with remarkable foresight from his famous experiments about "gliding discharges" and especially "electrodeless gliding discharges" which are a special form of Lichtenberg figures (**11–14**). Fundamental research on these phenomena was done in the decade of 1930 by McEachron (**15, 16, 17**), Allibone (**10, 18**), Loeb (**19**), Meek (**18, 19**), Raether (**20, 21**), and Stekolnikov (**22–24**). A survey of the literature before World War II is given by Goodlet (**25**), and by Bruce and Golde (**26**) who cite many references.

After World War II, fundamental research on discharges in air was resumed in several countries (**27**). Pertinent references are given in some papers by Loeb (**28, 29**). A theoretical study of the lightning channel in comparison with long laboratory-sparks is given by Wagner and Hilemann (**30**).

Stepped leaders and the pilot leader pose some fundamental and rather complicated physical problems. From the large amount of physical investigations it is clear that solutions are not easy to find and, in the author's opinion, not yet complete.

IX. Points of Impact of Lightning Strokes near San Salvatore

From the many photographs we have taken of lightning strokes in the surrounding areas of Mount San Salvatore, the visible points of impact are indicated on a geographic map (Fig. 50) where the results are given for the period 1955–1965. Figure 50(a) represents downward strokes; Fig. 50(b), upward strokes. In the shaded areas in Fig. 50(a) the ground is not visible from the peak of San Salvatore; therefore, only the number of strokes into this area is noted. Mount San Salvatore is marked by a cross in both figures. A comparison of the points of strike for different years clearly shows enormous variations. Figure 50(a) forms a basis for statistical information on the local distribution of strokes. Figure 50(b) is of special interest because it shows that

(a)

FIG. 50. Map of surroundings of Mount San Salvatore with photographed points of lightning strikes. *a*) Downward strokes during the lightning seasons: ×, 1955; □, 1956; ○, 1957; ★, 1959; ●, 1960; ✳, 1961; △, 1962; *, 1963; ▲, 1964; ■, 1965 (1958 no photos of strokes). Where the ground is not visible from the peak of San Salvatore, the total number of strokes to these shaded areas are noted. *b*) Upward strokes from San Salvatore, Monte Generoso, Monte Bré, Monte Sighignola and Biogno (Monte Ceneri is not on the map).


LUGANO
Castagnola
Paradiso
Gandria
Campione
ITALIA
Bissone
Melide
Maroggia
Brusino Arsizio
Morcote
Porto Ceresio
Ponte Tresa
Lavena
Brusimpiano
Marzio
Val Marchirolo
Agno
Magliaso
Caslano
Figino
Carabietta
Barbengo
Grancia
Carona
Capolago
Melano
Rovio
Arogno
Lanzo
Caprino
Cadempino
Comano
Porza
Massagno
Sorengo
Muzzano
Bioggio
Bosco
Cademario
Aranno
Breno
Fescoggia
Mugena
Arosio
Bedano
Gravesano
Manno
Cureglia
Canobbio
Davesco
Soragno
Origlio
Tesserete
Sala
Sigirino
Villa
Cadro
Sonvico
Bidogno
Riva S. Vitale
Meride
Vernate
Curio
Miglieglia
Bedigliora

FIG. 50 (b)

upward strokes occur only on mountain peaks with metal structures, such as towers or masts. The lowest position from which an upward stroke has been observed until now was at Biogno near Breganzona, about 3 km northwest of Mount San Salvatore. Figure 51(a) is a photograph of the stroke; Fig. 51(b) shows the church and its steeple as well as the lightning rod, which had been hit. This example proves the occurrence of upward strokes from relatively low hills with a steeple of 8 to 10 m high; the church is about 250 m above the level of Lake Lugano.

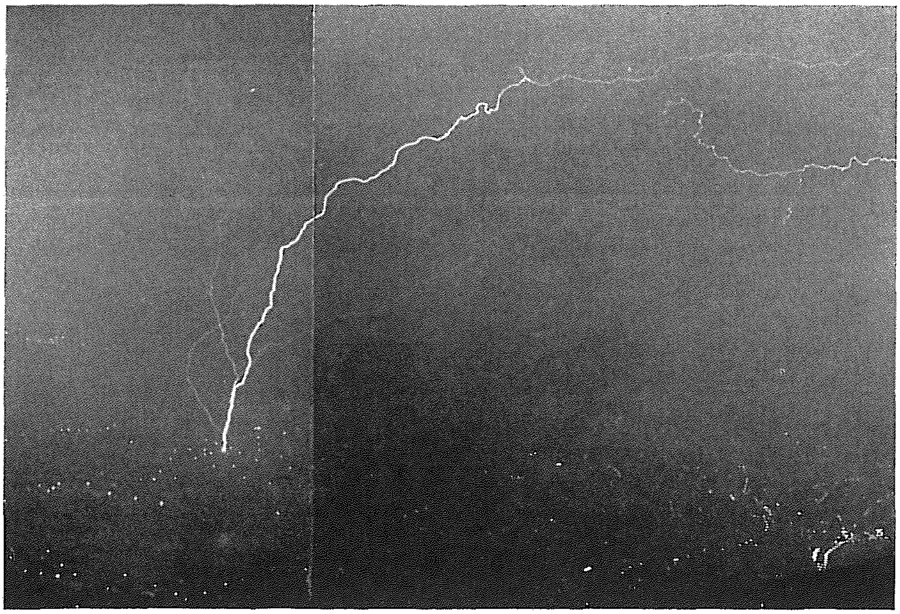
As seen on the map of Fig. 50(a), the frequency of lightning strokes per year and per square kilometers can be estimated. Within 2.5 km from San Salvatore, the mean value of photographed strokes is 1.1 strokes per year and km^2. Considering that only about one quarter of all strokes occur at night, when the photographs were taken, a frequency of about 4 strokes per annum and km^2 may be an approximate value.

If this period of observation spans at least 10 years, the resulting map indicates that strikes may occur practically anywhere, including the lake. No direct evidence exists of any preferential points of strike. Therefore, we may conclude that the paths of downward lightning strokes are guided by the very irregular and variable distribution of space charges in the thunderstorm atmosphere which is influenced by topography and wind direction, but probably not by conductivity of soil. Obviously, then this space charge is the reason why so many downward strokes penetrate deep into valleys between fairly high mountains.

X. *Consequences of Leader Development with Respect to the "Protective Area" of Lightning Rods and to Lightning Accidents*

Undoubtedly, in the case of *upward strokes*, long lightning rods may concentrate lightning discharges to themselves in a measure which is not essentially different from that produced in a high voltage laboratory. The reason is that this type of discharge is determined by the more or less static field near the lightning rod, taking into account possible space charges around the lightning rod. It may be possible to visualize a model test for upward strokes.

When we began measurements on Mount San Salvatore in 1943, we wondered whether upward strokes would develop from the many mountain peaks near San Salvatore. Observations clearly showed that the surrounding mountain peaks did not produce upward strokes if they were not equipped with a tower or electrically conducting mast. However, a steel mast of not more than 13 m was the cause of many upward strokes on nearby Mount Sighignola where no lightning strokes were ever observed before its erection. This observation of upward strokes on mountain tops may be compared to the observations at the Empire State Building, with its exceptional height of 400 m (**16**). In such cases, it may be justified to speak of a protective area. This area is associated exclusively with the initiation of a discharge which is an electrostatic problem between lightning rods and charged clouds.



(a)

(b)

FIG. 51. Upward stroke from the steeple of Biogno. a) Photograph on still film from San Salvatore. b) Photograph of the church of Biogno from below.

The situation is different for *downward strokes*. The tip of the downward leader has a certain electric potential. If the tip approaches earth or an earthed tower, the electric field is similar to that of a point-plane or point-point gap, if space charges are neglected.

From laboratory research work, it is well known that d.c. voltages or switching surges of 2 MV or more may occasionally cause abnormally long sparks. For higher voltages it seems very difficult to correlate discharge and spark distance. This is the principal objection to the theories which connect leader voltages and lengths of the ultimate "striking" distance to earth. Until more knowledge is available for d.c. voltages of at least several MV and on the influence of free space charges near the discharge, it will not be possible to justify those theories about protective areas.

The problem seems to be less complicated if a secondary discharge is caused by a far flash. This secondary discharge takes the form of an upward streamer discussed in item d of section VII. In this case, long rods may produce a protective area which is defined by electrostatics, taking into account near space charges.

This philosophy leads to two consequences: One is that lightning protection methods on mountains should partly be based on different considerations from those on flat land. Long lightning rods may be useful in the mountains as a means of producing greater protective areas. The second consequence is that secondary discharges may occur at the same instant on many pointed objects, *i.e.*, on mountains and on flat land. This may explain the many instances when people have felt strong electric shocks resulting from lightning strokes but were not hit directly. In the future we hope to obtain more information about the "protective areas" from the results of "field mill" records, together with pertinent photographs and oscillograms.

XI. New Observations on Lightning

Briefly summarizing some new observations, we mention the following points:

1. On Mount San Salvatore all *four forms of lightning strokes* appear: both polarities and both directions of progression (downward and upward strokes).
2. *Upward and downward strokes* can be distinguished by three methods.
   a) Fast moving film (Boys–Schonland–Malan-Camera).
   b) Oscillogram of stroke current: *Upward strokes* begin with continuing currents of about 100 A during hundredths of a second (leader current); *Downward strokes* begin with a steep-fronted impulse current (return-stroke current).
   c) Observation of branching in the normal lightning photograph with still film. Branching always points in the direction of progression of a leader. The equivalence of these three methods has been proved by comparison.

3. *Negative first leaders* show very distinct steps. This is true for both downward and upward leaders. Upward leaders from a tower top sometimes even show the very faint corona-envelope at the tip of the leader. The duration of one step is between 29 and 55 μsec which agrees quite well with Schonland's value of 50 μsec.

4. *Positive leaders* have very low luminosity and, in general, have no distinct steps but show rather a periodic variation in light intensity. The duration of two maxima of light intensity is between 40 and 110 μsec, or twice the value of step formation in negative leaders.

5. Until now we have not succeeded in proving the existence or nonexistence of current pips which would correspond to the steps of upward leaders from a tower.

6. Most interesting is the so-called *connecting streamer discharge.* Such a discharge is caused by a downward progressing leader. It starts at the tower, contacts the downward leader and therefore initiates the main return stroke by bridging the last remaining gap to earth. With the usual *downward negative* leader (from a negative cloud) the upward "connecting streamer" (from the positive tower top) is very faint, and generally not longer than a few steps of the downward leader. This agrees with the general observation of item 4.

For the comparatively rare *downward positive* leader (from a positive cloud) the streamer discharge (from the negative tower top) is clearly visible and reaches astonishing lengths of more than 1 km. It then takes the form of a usual negative upward leader. The high luminosity agrees with item 3. The steepness of the current impulse is reduced by these long "connecting streamer discharges."

7. *Special streamer discharges* may occur which do not reach the lightning channel, but which are produced above the towers by the very pronounced and audible field impulse at the instant of a distant lightning flash. Such incomplete upward discharges may be regarded as *secondary strokes* that follow a distant primary flash. The question is therefore justified whether all upward strokes could be such secondary strokes.

Upward strokes normally develop from the tower as a positive electrode. Their luminosity is very low and their length is considerable. This agrees well with the experiences of high voltage laboratories where long sparks result from positive point electrodes. Future research using a "field-mill" should shed some light on this phenomenon.

Acknowledgment

This research was made possible through the support of the Swiss High Voltage Research Committee and the Swiss National Research Foundation to whom the author expresses his appreciation. He is also indebted to his many co-workers for their invaluable assistance, and especially to Mr. E. Vogelsanger for his careful evaluation and discussion of the results, and also to Mr. H. Binz for installing and surveying the measuring equipment as well as recording the many lightning strokes with camera and oscillograph.

Bibliography

(1) K. Berger, "Die Messeinrichtungen für die Blitzforschung auf dem Monte San Salvatore," *Bull. SEV*, No. 5, pp. 193–232, 1955.

(2) K. Berger, "Resultate der Blitzmessungen der Jahre 1947–1954 auf dem Monte San Salvatore," *Bull. SEV.* No. 9, pp. 405–456, 1955.
(3) K. Berger and E. Vogelsanger, "Messungen und Resultate der Blitzforschung der Jahre 1955–1963 auf dem Monte San Salvatore," *Bull. SEV*, Bd. 56, No. 1, pp. 2-22, 1965.
(4) K. Berger and E. Vogelsanger, "Photografische Blitzuntersuchungen der Jahre 1955–1965 auf dem Monte San Salvatore," *Bull. SEV*, Bd. 57, No. 13, 1966.
(5) D. J. Malan, "The Theory of Lightning-Photography and a Camera of New Design," *Geofisica pura e applicata, Milano*, Vol. 38, pp. 250–260, 1957.
(6) B. F. J. Schonland and H. Collens, "Progressive Lightning 1," *Proc. Roy. Soc.*, Vol. 143A, p. 654, 1934.
(7) B. F. J. Schonland, D. J. Maaln, and H. Collens, "Progressive Lightning 2," *Proc. Roy. Soc.*, Vol. 152A, p. 595, 1935.
(8) B. F. J. Schonland, "Progressive Lightning 4, The Discharge Mechanism," *ibid.*, 164A, pp. 132–150, 1938.
(9) B. F. J. Schonland, "The Lightning Discharge," Handbuch der Physik, Vol. 22, Berlin, Springer, 1956.
(10) T. E. Allibone, "The Mechanism of the Long Spark," *Jour. IEE London*, Vol. 82, No. 497, 1938.
(11) M. Töpler, "Gewitter and Blitze," Vortrag vom 22.2.1917, Verlag: Ernst H. Meyer, Dresden, Germany.
(12) M. Töpler, "Elektrodenlose Gleitfiguren," *Phys. Zeitschrift*, Vol. 22, p. 59, 1921.
(13) M. Töpler, "Ueber den innern Aufbau von Gleitbündeln und die Gesetze ihrer Leuchtfäden," *Annalen der Physik*, Bd. 53, pp. 217–234, Tafeln I and II, 1917.
(14) M. Töpler, "Ueber Blitzbildung und Blitzschläge," Vortrag vom 24.10.1932, Berichte von der Sondertagung über Blitzschutzfragen, mit Literaturangaben, Verlag: Sächsische Elektrizitätswerke, Dresden, Germany.
(15) K. B. McEachron, and McMorris, *Gen. El. Rev.*, Vol. 54, p. 487, 1936.
(16) K. B. McEachron, "Lightning to the Empire State Building, N. Y.," *Jour. Frank. Inst.*, Vol. 227, p. 149, 1939.
(17) K. B. McEachron, *Elec. World*, Vol. 113, p. 56, 1940.
(18) T. E. Allibone, "The Development of the Spark Discharge I and II," *Proc. Roy. Soc. London*, Vol. 166A, No. 924, p. 97–126, May 1938; and *Proc. Roy. Soc. London*, Vol. 169A, No. 937, p. 246–268, Dec. 1938.
(19) L. B. Loeb and John M. Meek, "The Mechanism of Spark Discharge in Air at Atmospheric Pressure," I and II, *Jour. Appl. Phys.*, Vol. 11, pp. 438–447, June 1940; and pp. 459–474, July 1940.
(20) H. Raether, Erg. Exkt., *Nature*, Bd. 22, p. 73, 1949.
(21) H. Raether, "Electron Avalanches & Breakdown in Gases," London, Butterworth, 1964.
(22) I. S. Stekolnikov, *Elektrichestvo*, No. 1, p. 32, 1939.
(23) I. S. Stekolnikov and C. Valeev, *Cigre*, No. 330, 1937.
(24) I. S. Stekolnikov and A. A. Landon, *Elektrichestvo*, No. 5, p. 29, 1938.
(25) B. L. Goodlet, "Lightning," *Jour. IEE London*, Vol. 81, No. 487.
(26) C. E. R. Bruce and R. H. Golde, "The Mechanism of the Lightning Discharge and Its Effect on Transmission Lines," Tech. Rept. S/T 18, British El. & All. Ind. Res. Assn. (E.R.A.) 1940.
(27) I. S. Stekolnikov, "Gas Discharges and Electric Supply Industry," London, Butterworth, 1962.
(28) L. B. Loeb, "Ionizing Waves of Potential Gradient," *Science*, Vol. 148, No. 3676, pp. 1417–26, 1965.
(29) L. B. Loeb, "The Mechanism of Stepped and Dart Leaders in Cloud-to-Ground Lightning Strokes," *Jour. Geophys. Res.*, Vol. 71, Oct. 1966.
(30) C. F. Wagner and A. R. Hilemann, "Mechanism of Breakdown of Laboratory Gaps," Meeting *AIEE* Power and Apparatus, Paper 61–489, New Orleans, La , April 1961.