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Oscillograph measurements of field patterns near lightning strokes on Mount San Salvatore

K. BERGER

Bull. ASE. Vol. 64, No. 3, pp. 120-136, (3 Feb. 1973)

Abstract

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1. Introduction

Oscillograms of field distribution in the vicinity of, and at a distance from, the lightning for a period prior to, during and after the lightning flash provide valuable information on the nature of the physical process which leads to a strike.

For making such determinations, the Research Commission for High Voltage Problems (FKH) built, in 1967, a so-called classical "field mill" and installed it in the lightning measurement tower on the top of Mount San Salvatore. A description of this instrument and a report of the first results obtained will be found in a report to CIGRE 1968 (Bib. 1). The upper limiting frequency of the instrument is about 1,200 Hz, so that it was impossible to record changes of field strength occurring within a millisecond. To extend the range of frequencies and to reduce the air raid siren noise of the first field mill, a new type of field mill was constructed in 1969 with the financial assistance of the Swiss National Fund in accordance with a proposal by E. Vogelsanger. The results and evaluation of new field measurements in relation to downward strokes will be described below.

2. Installation of the field mills

The new field mills built in 1969 were mounted in the same manner as the classical field mill of 1967 with a measuring plate facing downward so that it was protected from rain. Whereas the "old" field mill was arranged at the side of Tower 1, the four new instruments were erected on a tripod each 2.5 to 3 m above ground level as Figs. 2-5 show. The sites are shown in the map, Fig. 1, as follows:

Point 1: Sanatorium Agra, as shown in Fig. 2;

Point 2: Gemmo switching station, as shown in Fig. 3;

Point 3: Pugerna Customs House, shown in Fig. 4;

Point 4: Viewing platform on San Salvatore, shown in Fig. 5;

Point 5 is a reference point for measurement of the fine weather field, without a field mill.

3. Measuring instruments

The schedule of field measurements has already been described (Bib. 2) as have the measuring instruments on Mount San Salvatore in the years 1963-1971. The equipment was supplemented in 1971 by a highly sensitive pre-strike current measuring device at the insulated top of Tower 1. For this purpose the current limiting device was tapped at two points for continuous recording of the glow current so that two sensitive current ranges were obtained for pre-strike current measurements. Storage on a closed magnetic tape with a cycle time of 5 s allowed currents of the magnitude of 1 mA preceding the lightning flash to be recorded on the same time scale as the electric field, with a limiting frequency of 4 kHz.

A first measuring range was selected in such a manner that recording was linear up to about 7 mA with about 30 mm deflection in the original oscillogram (Code i_7). For greater currents the deflection is limited to about 40 mm.

A second measuring range included currents from 1 A with about 15 mm linearly in the original and greater currents non-linearly, with a maximum of about 27 mm. By the action of the series gap on the tower the current is limited to about 4 A. The maximum measured value is 1.3 A. The variation of the preliminary current curves shows that displacement currents were involved in the first instance which occurred during the rapid increase and sudden collapse of the field.

Current at the top of the tower frequently started extraordinarily rapidly. Its variation formed the most sensitive indication of rapid changes of field prior to and during the lightning flash and, consequently, for the entire duration of the visible and invisible lightning process.

4. Oscillogram examples

Reported below are exclusively results of field-mill measurements during the thunderstorm period of 1971, because all field mills were only ready for service in the summer of 1971. For 16 downward strokes on Mount San Salvatore the field was recorded simultaneously on Mount San Salvatore and at the three outstations together with the lightning-current recording on the mountain. Eleven examples of field distribution as recorded via the magnetic memory are shown in Figs. 6a-6l. The oscillograms were numbered as follows: 17, 33, 107, 115, 116, 139, 141, 142, 148, 167 and 168. In these:

A = the field distribution with zero line at Agra, scale A in part 10 kV/m, in part 30 kV/m

G = field distribution with zero line for Gemmo, scale G partly 10 kV/m, partly 30 kV/m

P = field distribution with zero line at Pugerna, scale P partly 10 kV/m, partly 30 kV/m

S1 = field distribution with zero line at San Salvatore, viewing platform on the church roof, scale S1 = 100 kV/m

S2 = field distribution and zero line at San Salvatore, side of tower, scale S2 (band width) = 100 kV/m, frequency about 1,150 Hz

The time scale of all oscillograms follows from the above frequency and it amounts in the original to about 1-1.2 ms/mm.

5. Tables showing field strengths measured

Table I reproduces a numerical evaluation of the 16 downward strokes already mentioned. For every oscillogram number, the table provides the following information:

a) Lightning current peak i and total charge Q of a flash at the measuring towers, in accordance with evaluation of the current oscillograms.

b_1) Static field strength prior to the beginning of field strength fluctuations of lightning pre-discharge or, in abbreviated form, "field strength prior to flash" measured in kV/m (the figures that go with a), b) and c) are shown one below the other in Table I)

b_2) In the columns relating to "San Salvatore", the maximum field strength during the lightning stroke, in kV/m. (Figures for a) b) c) one below the other Table I)

b_3) Stationary field strength after termination of field strength fluctuations of the flash or, in short, "field strength after flash", in kV/m. (Figures for a) b) c) one below the other, Table I)

c) Field strength jumps at all 5 measuring sites (Agra, Gemmo Pugerna, San Salvatore 1 and 2) are due to lightning striking San Salvatore or more precisely, due to the current impulses of strokes which in negative flashes occur invariably and, in the case of positive flashes as a rule, within 1 ms. Consequently, what is shown is the mean $\Delta E/\Delta t$ for the duration of 1 ms (kV/m/ms).

d) Duration of pre-discharge prior to lightning strokes; in the case of multiple flashes, duration up to the first pre-discharge plus the time interval up to the second stroke.

e) Duration of the leaders which can be determined from the field strength fluctuations.

f) Total duration of a lightning flash determined from field strength fluctuations.

6. Sign convention and sensitivity

Concerning the sign convention, it should be pointed out that as in the previous reports the following applies:

Current flowing from a negatively charged cloud to the ground is given a negative sign, and is consequently considered to be a negative current. In the same way the field strength E on the surface of the ground under a negative cloud is given the negative sign and is therefore considered to be a negative field strength. Conversely, a positive discharge from a cloud generates a positive current to ground and a positive field strength on the surface of the ground. Consequently, in this system, all signs are determined by the polarity of the cloud charge.

Under a negatively-charged cloud the top of the tower constitutes the positive electrode with an upwardly directed field strength which in accordance with the above definition is given the negative sign. Under a positive cloud the tower forms the negative electrode with discharge phenomena corresponding to a negative electrode.

The sensitivity of the external field mills is so adjusted that with oscillogram deflections of 1 mm it is possible to record either E values greater than 1 kV/m or than 3.5 kV/m, depending on whether transmission channel 1 or 2 has been selected. Difficulties due to signal saturation resulted in the use of the less sensitive channel in some cases which, as experience showed, made the evaluation of the relationship between lightning charge and field-strength jumps impossible. The time scale of the oscillograms corresponds to about 1 mm per ms in the original so that considering the limiting frequency of transmission and of the oscillograph (about 4 kHz) the millisecond (ms) can still be reliably evaluated.

All the field strengths shown in the table represent the field strengths directly in front of the measuring plate of the field mills. These devices can be calibrated by subjecting a large metal plate in front of the field mill to direct or alternating voltage of known magnitude. Conversion of these field-strength data to a plane environment must be done by means of the field pattern e.g. by evaluation in an electrolytic tank.

7. Discussion of field oscillograms, 4 examples

Examination of the oscillograms of field variation on Mount San Salvatore, reveals two fundamentally different types of lightning formation:

a) Lightning whose leader suddenly starts from a field that is constant at least for several seconds, and which strikes after 5-50 ms. Examples of this are oscillograms 116, 139, 140, 141, 142, 148, 166, 167, 168.

b) Lightning whose leader starts in the course of irregular field fluctuations evidently caused by discharges within the clouds. Examples of this are in particular the oscillograms 33 and 107, less definitely oscillograms 02, 17, 115, 161, 165.

The first group corresponds to our ideal picture of lightning suddenly striking from "out of the blue". As a rule, the field strength preceding these flashes is negative, i.e. corresponds to a negative cloud charge.

The second group contains flashes with more or less prolonged pre-discharges occurring inside the clouds so that they are not visible in photographs of lightning. Very frequently they cause a change of polarity, so that an initially negative field as a rule becomes a positive field which persists for some time and may become negative once more just before striking. Some oscillograms will be described briefly below.

To allow the oscillograms to be read more easily, it should be mentioned that the sequence of field curves is always the same, i.e., from top to bottom, Agra-Gemmo-Pugerna-San Salvatore 1 (new field mill on the church roof) - San Salvatore 2 (old field mill at the side of the tower, readily identified by the 1,150 Hz curve the band width of which corresponds to the field strength). These are followed by curves for i_7 (7 mA) and, in the case of oscillograms from Number 139, for i_1 (1 A) also. The flickering and overshooting curves are invariably associated with i_7.

Oscillogram 116, as an example of the first group, shows, at (1), a first strike to Tower 1, which is followed by a second rise of field to which there is no corresponding tower current. Evidently this second rise with sudden field collapse signifies a stroke in the direction of Agra because a greater change of field occurs there. After about 0.1 s, there is a third field jump, after about 0.3 s a fourth and after another 0.2 s a fifth field jump, the courses of which were reproduced after the oscillogram of the first three strokes (oscillograms 116a and b). Only the first stroke affected Tower 1, the later "strokes" must have struck elsewhere, the fourth, presumably, in the Gemmo area, where there was a considerable change of field.

Oscillogram 33 is an example of the second group of lightning flashes, those with pre-discharges. Since the steady-state field was constant and negative for a long time prior to the lightning flash, then rose a little for 0.15 s, it decreases at the beginning of the oscillogram 33a for about 30 ms, passes through zero at Point N1, becomes positive, and increases, for a further 30 ms, to figures of about +300 kV/m on the church roof (S1) and about 400 kV/m at the side of the tower (S2) without lightning occurring. The positive field is then gradually reduced for about 0.3 s, as can be seen at the start of oscillogram 33b. At N2 it passes very rapidly through zero and attains after about 5 ms a negative value of about -315 kV/m, at which point the lightning starts. A second stroke occurs after about 0.1 s at considerably lower field str ength.

The oscillogram (33) shows considerable periodical fluctuations of field strength curves at a frequency of about 100 Hz. It was recorded on 28 May 1971 during a violent thunderstorm. Evidently this reduced unevenly the insulation of the three measuring sectors of the field mills, so that the summation of the three visible voltages no longer provides a constant figure. The fluctuations indicate that summary evaluation is no longer reliable either. It was found that in rain, fine conductive bridges formed on the sectors. With subsequent periodical inspection of the state of insulation, in particular of the fine filaments of dust, this measuring error disappeared.

Oscillogram 107 is a further example of the second group, lightning striking with a positive field after a prolonged pre-discharge. In the seconds prior to the strike there is, as usual, a negative field, which can be seen at the start of the oscillogram. The field passes through zero at N and becomes positive. After just under one tenth of a second it reaches a level of about +350 kV/m at the field mill on the church roof (curve S1) and about +390 kV/m at the field mill in the tower (S2). The lightning current starts at Point 1 during this gradual increase in the field. In accordance with a current

~~osci~~llogram not reproduced in this paper it reaches a level of +400 A after about 20 ms and then suddenly jumps to an impulse of +11 kA (Point 2). The short impulse is followed by a positive after-current of about 2 kA, which decays in 0.13 s. After this the field strength again remains constant at a considerable positive level during further recording.

This example shows that the investigation of downward and upward strokes is not straightforward. The gradual increase of a relatively small current would at first suggest an upward stroke. However, the subsequent sudden increase of current to 11 kA during about 1 ms suggests that an already charged channel has been reached which can only discharge suddenly via the upward channel. A much larger charge is equalised than that supplied to the upward channel. It is therefore logical to describe this as a downward stroke and the linearly increasing pre-discharge as a connecting streamer.

Oscillogram 17 records the field pattern when lightning struck at the hitherto highest measured current amplitude of about +270 kA (highest since 1943). From a weak positive field there occurs at first a rapid field reversal at Point N1, and after a further 20 ms a second field reversal at N2 which is followed by a rapid increase of the positive field, and Tower 1 was struck after about 5 ms. The oscillogram clearly shows that as early as the first passage through zero a marked positive field increase occurred at Gemmo also, and a negative rise at Pugerna. After the second passage through zero at San Salvatore there was a rapid positive field increase simultaneously at Gemmo and San Salvatore which resulted in the lightning striking Tower 1.

The oscillogram shows that in the first instance discharge of a cloud dipole was involved which manifested itself as a change of field with reversed sign between Gemmo and Pugerna. The lightning striking San Salvatore was caused by this latter discharge.

Unfortunately this lightning caused a flashover at the shunt of Tower 1 which rendered further measurement of current and charge with the KO impossible fortunately not before the peak value had been stored in the loop oscillograph (SO). Field measurement remained undisturbed. Since the measuring equipment had previously been designed for maximum currents of 200 kA, the oscillogram deflections partly exceeded the measuring ranges; moreover it is sometimes difficult in such extreme cases to distinguish clearly between the oscillogram curves.

The oscillograms 33 and 107 represent two downward strokes of the year 1971 which were preceded by pre-discharge in the clouds lasting for several tenths of seconds. The reversal of sign of field strength was typical of the pre-discharges. Lightning eventually struck after two zero passes at negative field strength (oscillogram 33) or after the first zero pass in a positive field (oscillograms 107 and 17). In the period 1963 to 1971 as in earlier measurements the positive lightning flashes (lightning flashes from positively charged clouds) are the strong and dangerous flashes both as regards the peak current and the current square impulse.

8. Field patterns on Mount San Salvatore during lightning flashes

Oscillograms show the field increase leading to a strike with a time resolution of about 0.5 ms. It is partly exponential, partly somewhat linear. The following mean propagation velocities can be calculated for a leader of a mean length 3 km:

For 5 ms duration of the leader 3,000: 5 = 600 m/ms = 2 per 1,000 of the velocity of light

For 50 ms duration of the leader 3,000; 50 = 60 m/ms = 0,2 per 1,000 of the velocity of light

These velocities are in fairly good agreement with the photographically determined mean velocities i.e. 0.2-2 per 1,000 of the velocity of light.

The field strength at the field mills on San Salvatore attained the following maxima:

+335 - +350 kV/m)
) on the church roof (S1)
-290 - -320 kV/m).

+390 - +450 kV/m)
) at the tower (S2)
-300 - -350 kV/m)

By far the largest number of data were between -230 and -290 kV/m.

Field collapse due to lightning as a rule occurs within 1 ms. Because of the limitations of time resolution it cannot be determined more accurately than as a mean for 1 ms. The highest values of the field jump ΔE or the mean velocity of change in 1 ms amounted to:

+520 and -450 kV/m/ms on the church roof (S1)

+650 and -450 kV/m/ms at the tower (S2)

No essential difference could be seen between the first and the following lightning strokes. Unfortunately the number of determinations was too small to allow statistically significant evaluation.

9. The relation between lightning current or lightning impulse charge and maximum field strength on the Mount San Salvatore

A striking feature was that the scatter of highest field strengths on San Salvatore when lightning struck was much smaller than the scatter of current and charge quantities of individual strokes. This is attributable to the fact that even at currents and charges of any magnitude the field strength at the tower cannot rise higher than the figure necessary for flashover between tower and leader head. Whereas the mean field strength required for flashover across a fairly large distance is known to be smaller than for small flashover distances local field strength at the top ofthe tower probably shows no such relationship. Because the length of the flashover distance in accordance with the present-day theory of the space protected by a lightning conductor is connected directly with the amplitude of the lightning current impulse (Bib. 3, 4) this also means that the maximum field strength measured on San Salvatore materially depends neither upon the length ofthe connecting streamer nor on the amplitude of the lightning current. This conclusion is confirmed by measurements.

10. A comparison of field strengths on the church roof and at the tower on Mount San Salvatore

For the ideal case of an infinitely extended charged cloud with a uniform charge distribution (surface charge) a constant ratio would have to exist between the maximum field strength on the church roof and at the tower or somewhere in the vicinity, if lightning always struck at the same point, for example a measuring tower.

Comparison of the two field strengths is shown in Table I in the columns marked San Salvatore. The following transpires;

In all oscillogram examples 139 - 168 of Table I, the ratio of the two field strengths (S1:S2) is between 0.71 and 1.20 and the ratio of the two field jumps (S1:S2) between 0.81 and 1.30. In the oscillograms 02 and 116, Table I, the ratio of the two field strengths, exceptionally, amounts, for the first stroke, to 2.55 and 3.4 and the ratio of the two field jumps for the second stroke, is 2.3 and 3.8. At these highest ratios, field strength on the church roof is therefore disproportionately greater than at the tower.

It was impossible to elucidate the causes of this phenomenon. Possibly in the oscillograms 02 and 116, the insufficient insulation of the old field mill was to blame under the prevailing wet weather conditions. The minor differences that can be seen in most of the oscillograms can be attributed to the fact that the charge cloud was not always in the same position above San Salvatore or above Lake Lugano in relation to the tower.

11. Remote effects of lightning on Mount San Salvatore in the surrounding Area (3 km)

Table I lists for the three outstations Agra, Gemmo and Pugerna, three sets of figures, i.e. the two field strengths E prior to and after the lightning stroke, and the field strength jump $\Delta E/\Delta t$ caused by short duration lightning current impulses (impulse current) within 1 ms or by the corresponding channel charge at the outstations. The lightning current impulse of the more frequent negative lightning flash invariably lasts less than 1 ms, so that the field strength jump as a rule also occurs within 1 ms. The limited time resolution in the measuring system (about 1 mm/1ms) permits no accurate time measurement below 1 ms. Consequently Table II indicates for all changes within 1 ms the mean values of the field jump within 1 ms. For example, 31/1 indicates a jump ΔE of 31 kV/m within 1 ms.

As we know the formula below represents the relation between an alteration of the cloud charge ΔQ stored in the leader and the change it produces in the field strength ΔE across an infinitely extended plane.

$$\Delta E = \frac{18\ H \times \Delta Q}{(d^2 + H^2)^{3/2}}$$

providing the following units are used:

- ΔE Change in field strength or jump within 1 ms (kV/m);
- ΔQ Compensated electrical charge of lightning current impulse within 1 ms (channel charge) (As);
- H Mean altitude of channel charge above the plane (km);
- D Horizontal distance between the measuring point and the channel charge (km).

The figures given for the $\Delta E/\Delta Q$ ratio in Table II apply to the three outstations.

Using these figures we can calculate for the ideal case of a charge above an infinitely extended plane the field strength jumps given in Table III which also shows the $\Delta E/\Delta t$ figures determined from the oscillograms.

In order to allow comparison of the calculated and measured field strength data of Table III, account must in the first instance be taken of the fact that the calculated figures indicate field strengths above an infinitely extended plane. The measured data on the other hand signify field strengths at the field mills or their measuring sectors. This result must therefore be reduced for comparison to the corresponding value above an extended plane. This can be done by comparative measurement in the field, for example using radioactive probes to measure steady state fine weather field strengths in the vicinity of the field mills, and then comparing them with the field strengths at the field mills. Alternatively comparative determinations can be made in an electrolytic tank which would also provide the ratio of the two field strength figures. Such determinations were done at Agra and Gemmo and at the new field mill on the church roof of San Salvatore. A separate report on this investigation has been written by Hans Berkes (Report on Investigations of the Field Mills Model 1969). The figures below are taken from this report:

Agra: E (field mill): E (plain) $\approx$ 2.37

Gemmo: E (field mill): E (plain) $\approx$ 3.0

No measurements of this kind were carried out at Pugerna. The figures given are based on the two methods mentioned (for measurements in the field and on the model). Table III also lists the field strength data at Agra and Gemmo converted to a plain in accordance with this investigation. This allows the calculated and measured values to be compared, and the result of comparison is as follows:

a) The figures measured at the field mills are of the same order of magnitude as those calculated for a plain, assuming charge altitudes H of about 3 km. By contrast the measured data reduced to a plain will then be about 3 times lower than the calculated values.

b) The difference between measurement and calculation is reduced if the charge altitude H is assumed to be only 0.5 km (see Table III). If we remember that the charge density presumably increases in a downward direction in the leader or lightning channel, this assumption cannot be rejected out of hand particularly in the case of short negative flashes. In the case of linear charge distribution increasing in a downward direction it would correspond to a maximum charge concentration at about 1/3 of the length of the lightning flash. Ramifications of the lightning channel which are discharged together with the first stroke, may shift charge concentration altitude H in an upward or downward direction. The great difference between the current curves of the first flash and those of all consecutive flashes points to the significance of these ramifications because they no longer appear in the consecutive strokes which evidently explains the considerable simplicity and regularity of the current curves of consecutive strokes.

c) A further contribution to the clarification of the measured field strength jump data which are lower than those calculated is that all the field mills at the outstations were situated some 500 m lower than the top of the mountain. This causes partial screening by the mountain.

d) Deviations from calculation are bound to be caused by the fact that the lightning channel does not run absolutely vertically so that the maximum channel charge is not situated exactly above the point at which lightning strikes San Salvatore.

In addition to the field jumps caused by the impulse-type discharge of the lightning channel which have been discussed, considerably greater but relatively slow field changes occur in the oscillograms of the outstations which must be ascribed to the known long-duration lightning current components whose charge is greater by a whole order of magnitude, but also to charge displacements inside charged clouds in the vicinity. These effects are important for optimum dimensioning of lightning flash counters.

12. Remote effects of lightning at considerable distances, atmospherics

A striking feature is that the frequency range of the lightning current is fairly low and that very high frequencies (MHz) occur only in small amplitudes (Bib. 2). In contrast with this, as we know, frequencies of the MHz order of magnitude are still strongly represented in the remote "Sferics". The cause of this apparent contradiction will be found first in the propagation law according to which the field strength E of any dipole disturbance consists of three terms (static, electromagnetic and radiation field strength):

$$E = E_1 + E_2 + E_3 = M \frac{1}{cD^3} + \frac{dM}{dt} \times \frac{1}{c^2D^2} + \frac{d^2M}{dt^2} \times \frac{1}{c^3D}$$

In the event of lightning striking the ground, M, as a result of the mirroring of the field on the ground, means twice the amount of the electrical dipole moment (QH) of the charge Q at a height H above ground. In the vicinity of the lightning flash, the first two terms are involved, and the last two at great distances; i.e. at a great distance D the rapid changes appear to be relatively stronger.

A second reason for this Sferics phenomenon becomes evident from the oscillograms of the field pattern and in particular of field variations. The curves of current i_7 (in the 7 mA range) reveal a multitude of relatively rapid field changes (dE/dt) which do not appear in the high voltage ranges nor in field strength oscillograms already described, because the fluctuations ΔE are small in relation to the high E values.

The simultaneous recording of the field strength E and of the current i_7 $i_7 \approx dE/dt$ which is essentially a displacement current indicates that the Sferics, at a considerable distance from the flash, are the result not so much of lightning current propagation on the surface of the earth as of rapid field strength fluctuations dE/dt which are caused by a large number of local relatively weak and extremely short-lived discharges inside the charged cloud. Examples of this are the oscillograms 141, 142, 116, 33. This observation is in agreement with field measurements carried out by D. Müller-Hillebrand in the vicinity of Mount San Salvatore (Bib. 5), and also with measurements in the GHz region by Luis L. Oh (Bib. 6).

In so far as it is intended to examine the connection between atmospherics and the lightning currents that cause them, it is advisable to record not only the variation of lightning current and field strength on the ground, but also the rapid fluctuations dE/dt which can be done in a simple manner by oscillographic measurement of the displacement current at the lightning aerial (current i_7 with measuring ranges between about 1 mA and 1M on a sufficiently sensitive time scale).

13. Examination of downward strokes based on field and current measurements

Records of field variation in the immediate vicinity of the place where the lightning strikes together with records of the lightning current prior to and during the lightning flash, allow a more accurate idea of the origin of the flash to be obtained. For example, there are two kinds of downward flashes:

First, the sudden lightning flash from a negative cloud charge to the ground which occurs during a fequently weak field on the ground. The time of formation in this case is the duration of the leader which as a rule is between 5 and 50 ms.

Secondly, the lightning flash to the ground which is formed in the cloud in the course of pre-discharges. These pre-discharges may last from a few hundredths of seconds to about 1 second. With these clashes, too, the leader is clearly manifested by the mostly exponential, and more rarely linear, field increase which occurs in the vicinity of the flash. The pre-discharges frequently start very suddenly; their onset can be traced very clearly by measurement of the displacement current of the lightning current aerial on a sensitive current range (mA) without amplifiers. In the course of the pre-discharges, field polarity changes are common. In the no-currrent intervals of the lightning current measured on the earth surface the pre-discharges persist. Even after cessation of the lightning current recorded on the ground they continue to exist, frequently for many tenths of seconds ("post discharges").

The true "lightning duration" determined from the pre-discharges and post discharges of the lightning within the charged clouds is considerably greater than the lightning duration recorded on the strength of lightning current measurements on the ground; as a rule it is somewhere between 0.3 and 1 second.

The measured field strengths of about 300 to 400 kV/m peak at the field mills on Mount San Salvatore explain the formation of connecting streamers and brush discharges on wires or other pointed objects prior to the occurrence of the "return strokes".

The remote effect of lightning striking San Salvatore at a distance of about 3 km can only be made to agree to some extent with calculations if the point of maximum concentration of the channel charge equalised by the first stroke is assumed to occur at a relatively low altitude H above the mountain e.g. 0.5 km.

The explanation of the considerable difference in the shape of the current curves of the first and subsequent strokes is to be found in associated subsidiary discharge of the flash. With the first stroke, the discharge of the lightning channel also discharges the latter. In the consecutive strokes, only the main channel discharges to the cloud which is confirmed by photography. Consequently the current curves of the consecutive strokes are invariably very simple and similar to a RC discharge.

The ground field strengths measured prior to lightning striking San Salvatore are as a rule negative and surprisingly low. They are much smaller than the figures calculated from cloud charges of 100 As. The ground field strength rapidly increases when lightning strikes in the vicinity and frequently ends up at higher values than prior to the strike. This also explains the acoustic effects of a slight detonation and the subsequent hissing noise above the measuring tower. It must be assumed that there is above the ground under the cloud charge a layer of positive space charges which partly screen off the static cloud field. Evidently this layer is due to the fact that as a result of negative lower cloud charges the ground field strength is sufficient for ionisation of the air above tree tops and other pointed objects, so that there is automatic limitation of ground field strength. A formally similar phenomenon occurs in the fine weather field when the continuous ion stream of positive carriers to earth manifests itself above the ground as a space charge (Bib. 7).

Still obscure is the origin of individual rapid field jumps between strokes at San Salvatore, e.g. in the oscillograms 115, 116, 148. They succeed one another at intervals of a few hundredths of seconds and are less high than the jumps, Table I, which occur when the mountain is struck. Conceivably, they are caused by strikes at distant points. If this is the case, their relatively rapid succession would, however, be surprising. Perhaps compensating processes between previously separate lightning channels are involved. These would have to be triggered by field changes due to one or several strokes to San Salvatore in the clouds in such a manner that starting from an as yet intact cloud charge they propagate in the direction of the existing lightning channel and suddenly discharge into this using it as it were as a connecting streamer. This hypothesis was first put forward by Schonland, but was later disputed. It has not as yet been possible to settle the question. Without doubt it forms a major problem in the design of lightning flash counters for counting ground flashes only.

The lightning striking the ground must be considered as part of a greater discharge which can probably only be recorded by field measurement under the cloud and in its vicinity and by oscillograms of the brightness of the cloud. The measurements available provide reliable information about the field variation up to ms, and the current distribution up to µs. They allow assessment to be made of the behaviour of lightning flash counters and all kinds of thunderstorm monitors.

From the theoretical point of view it would be attractive to examine the discharge of the charged leader in the "return stroke" mathematically as a discharge of a conductor subject to losses of a special kind. The losses are caused by the radial glow discharges in relation to the channel, and in the voltage drop of the channel which is like an electric arc.

Measurement of the voltage drop in sparks of any short duration with any small charge, and in a discharge corresponding to the propagation of the leader presents a further, as yet unsolved, theoretically and experimentally attractive problem.

14. Photographer of lightning

During the period under review a total of about 3,000 flashes were photographed at night from Mount San Salvatore using a conventional camera and ordinary film. In addition to this some photographs were taken on rapidly moving film which show the propagation of the lightning channel. Figs. 7 and 8 are examples of this. In negatively charged channels, the clearly marked stages were confirmed. It is impossible for lack of space to discuss details here. In contrast with this it should be mentioned that among all these photographs there is not a single one which would suggest a more or less point-shaped or spherical or in any other way mysterious light phenomenon persisting for several seconds or even minutes ("ball lightning"). But so-called "beading lightning" was recorded during the extinction of the arc of vigorous long-duration flashes by cinematography. In conclusion, a few beautiful photographs of lightning are reproduced which were selected from a special album of such photographs (Figs. 9-17).

Lightning photography has made a major contribution to our understanding of the lightning process. Associated subsidiary discharges of the lightning channel are the best means of identifying the location of space charges, at least underneath the cloud layer. It would be welcome if these fine ramifications could also be recorded inside the non-transparent cloud. Although the lightning problem may have been solved satisfactorily for the assessment of lightning conductors, detailed physical problems remain to fascinate the researcher on lightning.

The work described was made possible mainly by the financial assistance of the Swiss National Fund for scientific research and by subsidies from FKH and the Swiss Institute for the Promotion of the Swiss national economy. The measurements were done and the photographs of lightning on Mount San Salvatore were taken by H and H. Binz, and members of the High Voltage Laboratory of ETH and FKH, Dipl.-Ing. H. Kröninger from Pretoria and Dupl.-Ing. H. Berkes, helped with evaluation.

Table I: The field strength E and variation of field strength $\Delta E/\Delta t$ within 1 ms as a result of downward strokes on Mount San Salvatore.

1 = San Salvatore "new"

2 = San Salvatore "old"

3 = Duration of pre-discharge

4 = Duration of "leader"

5 = Duration of lightning flash

6 = Comments

7 = Connecting streamer

Comments:

1 µs shunt defective

2) Negative-positive field, no discharge at +290 kV/m, followed by a rapid field change positive to negative with discharge.

3) Gradual rise of positive field resulting in a positive flash (connecting streamer)

4) Traces of lightning current at Tower 2

5) Presumably lightning struck Tower 2 below the shunt

6) These oscillograms are not shown in Fig. 6

Table 1: (continued)

Feldstärke E und Feldänderung ΔE/Δt innert 1 ms infolge von Abwärtsblitzen zum Monte San Salvatore

Tabelle I

Oszillo-gramm Nr.	I_{kA}	Q total As	Agra E kV/m	Agra ΔE/Δt kV/m·ms	Gemmo E kV/m	Gemmo ΔE/Δt kV/m·ms	Pugerna E kV/m	Pugerna ΔE/Δt kV/m·ms	1) San Salvatore «neu» E kV/m	1) San Salvatore «neu» ΔE/Δt kV/m·ms	2) San Salvatore «alt» E kV/m	2) San Salvatore «alt» ΔE/Δt kV/m·ms	Dauer 3) der Vor-entladung ms	Dauer 4) des «leaders» ms	Dauer 5) des Gesamt-blitzes ms	6) Bemer-kungen
02	− 53	− 13	− 5 + 3,5	4,5/1	− 5 + 1,3	3,6/1	− 2,5 < 1	6/1	− 42 − 230 + 42	320/1	− 17 − 90 + 28	140/1	100	32	690	6)
17	+ 270	+ 65	0 − 30 0	35/1	− 2,3 + 26 + 6,3	31/1	+ 2 +10−15 + 7	25/1	+ 7 + 335 − 20	520/1	+ 22 + 450 − 73	650/1,5	35	6	410	1)
33 (1) T 2	− 26	− 8,5	0 0	< 1	− 4,7 + 6	5/1	+ 5,5 + 17	2/1	− 50 − 320 0	380/1	− 110 − 190 − 45	200/1	670	7,5	790	2)
33 (2)	− 15	+ 7,5	0 0	< 1	+ 5 + 5	2,6/1	+ 16 + 13	< 1	+ 14 − 62 − 31	85/1	− 53 − 190 − 17	170/1	670 + 125	4		
107 (1)	+ 2 7) Fangentladung zu (2)	−	− 8 0	< 3	− 4,7 + 40	< 3	− 6,6 + 23	< 3	− 63 + 350 + 210	140/1	− 56 + 390 + 325	70/1	380	≈ 0	700	3)
107 (2)	+ 11	+ 72	+ 16 + 25	< 3	+ 40 + 14	< 3	+ 26 + 10	< 3	+ 260 0 + 75	200/1,5	+ 340 − + 87	170/1	380 + 20	−		
115 T 2	− 38	− 12	0 0	< 3	< 3 − 3	12/1	0 0	< 3	− 55 − 170 0	250/1	0 − 190 + 17	220/1	110	30	0 730	4)
116 (1)	− 27	− 4	− 2,5 − 3	3/1	− 1 − 2,5	2,3/1	− 1,5 − 2,5	1,5/1	+ 14 − 290 0	375/1	0 − 170 + 17	185/1	38	38	1100	
116 (2)	−	−	− 8 0	6/1	− 4 − 1,5	2,3/1	− 4 − 4	2,2/1	0 − 190 − 40	190/1	0 − 56 − 10	50/1	38 + 80	29		
139 (1) T 2	± − 4?	−	0 0	6/1	0 + 3	3/1	− 1,5 0	3,3/1	− 28 − 200 0	220/1	− 53 − 280 0	270/1	25	25	850	5)
139 (2)	−	−	0 0	4,5/1	+ 1,5 + 6	< 3	0 − 1	2,2/1	0 − 300 + 7	400/1	0 − 335 0	360/1	25 + 84			
140 T 2	− 50	− 6,5	− 3 0	< 3	0 − 23	< 3	− 18 − 15	3/1	− 28 − 280 − 20	390/1	− 56 − 310 − 53	340/1	38	38	610	6)
141 (1) T 1 und T 2	− 55	− 8	− 3 0	6/1	0 + 3	3/1	− 22 − 18	3,6/1	− 42 − 290 0	375/1	− 56 − 350 0	450/1	53	53	610	
T 2 (2)	klein	klein	− 3 0	3/1	+ 3 + 3	3/1	− 18 < 1	2/1	0 − 290 − 28	390/1	0 − 300 − 25	340/1	53 + 113	19		
142 T 2	− 65	?	− 6 − 1,5	6/1	− 1 < 3	3/1	< 1 0	4,5/1	− 28 − 280 < 10	450/1	− 56 − 340 − 17	430/1	56	56	660	
148 (1)	− 2	?	0 0	< 3	0 < 1	< 3	0 < 1	< 1	0 − 280 + 70	380/1	−	−	41	41	800	
148 (2)	− 33	− 5,5	0 0	< 3	0 + 4,5	< 3	0 0	< 1	− 14 − 280 0	350/1	−	−	41 + 102	7,5		
161	− 13	− 0,6	< 1 < 1	< 1	− 1 0	< 1	< 1 + 3,3	< 1	− 14 − 250 − 42	200/1	− 23 − 285 − 50	160/1	41	15	480	6)
165	− 30	− 5	0 < 3	< 3	0 0	6/1	− 1,8 0	1,8/1	− 21 − 265 0	290/1	− 20 − 250 − 11	290/1	106	31	380	6)
166	− 38	− 5,5	0 0	< 3	0 0	< 3	− 1,8 < 1	2,2/1	− 21 − 265 − 28	335/1	− 23 − 250 − 32	290/1	51	51	250	6)
167 (1)	Spur	?	0 0	< 3	0 + 3	< 3	− 3 < 1	2,5/1	− 21 − 240 < 10	290/1	− 28 − 225 < 10	260/1	22	22	150	
167 (2)	− 27	?	0 0	< 3	+ 3 + 6	3/1	− 2,5 0	3,3/1	0 − 280 < 10	400/1	0 − 260 < 10	380/1	22 + 51	30		
168 (1)	− 27	?	0 0	< 3	+ 14 + 16	< 3	− 1 0	3,3/1	− 14 − 225 + 55	280/1	− 17 − 240 − 22	270/1	19	19	500	
168 (2)	−	−	0 + 3	< 3	+ 16 0	< 3	0 < 1	2,2/1	0 − 240 − 15	310/1	0 − 200 − 22	240/1	19 + 39	19		

Bemerkungen:

1) Defekt des μs-Shuntes.
2) Negatives-positives Feld, bei + 290 kV/m keine Entladung, dann rasche Feldänderung positiv-negativ mit Entladung.
3) Langsamer Anstieg des positiven Feldes führt zu einem positiven Blitz (Fangentladung).
4) Spuren von Blitzstrom im Turm 2.
5) Vermutlich Blitzschlag zu Turm 2 unterhalb des Shuntes.
6) Diese Oszillogramme sind in Fig. 6 nicht aufgeführt.

Table II: Figures of the ratio ΔE/ΔQ

1 = Site of measurement

2 = Distance D from San Salvatore in km

3 = Figures ΔE/ΔQ for an assumed altitude of channel charge above San Salvatore of H =

Tabelle I.

1 Messort	2 Distanz D vom San Salvatore km	3 Werte ΔE/ΔQ bei einer angenommenen Höhe der Kanalladung über dem San Salvatore von H =			
		0.5 km	1 km	3 km	5 km
Agra	3,30	0,24	0,44	0,61	0,42
Gemmo	3,45	0,21	0,39	0,56	0,40
Pugerna	2,52	0,53	0,96	0,20	0,51

Table III: Field strength jumps ΔE at the outstations in 1 ms caused by 12 lightning current impulses at Mount San Salvatore.

1 = Oscillogram

2 = Impulse

3 = Approximate calculated figures above the plain

4 = Figures measured at the field mills

5 = Data reduced to plain

6 = Could not be evaluated, shunt defective

7 = Not determined

Tabelle II.

			3 Approximative Rechenwerte über Ebene												4 Messwerte an den Feldmühlen			5 Reduzierte Messwerte auf Ebene		
1 Oszillogramm Nr.	I kA	2 ΔQ Impuls As	Agra kV/m bei H = km				Gemmo kV/m bei H = km				Pugerna kV/m bei H = km				Agra	Gemmo	Pugerna	Agra	Gemmo	Pugerna
			0,5	1	3	5	0,5	1	3	5	0,5	1	3	5	kV/m	kV/m	kV/m	kV/m	kV/m	kV/m
02	− 53	− 13	3,1	5,7	8,0	5,5	2,7	5,1	7,3	5,2	6,8	12	12	6,6	4,5	3,6	6	1,9	1,2	—
17	+ 270	?1)	?	—	—	—	?	—	—	—	?	—	—	—	35	31	25	14,8	10	—
33(1)	− 26	− 7,5	1,8	3,3	4,6	3,2	1,6	2,9	4,2	3,0	4,0	6,8	6,8	3,8	< 1	5	2	< 0,5	1,7	—
33(2)	− 15	− 3	0,72	1,3	1,8	1,25	0,63	1,2	1,7	1,2	1,6	2,7	2,7	1,5	< 1	2,6	< 1	< 0,5	0,9	—
107	+ 11	+ 2,5	0,60	1,1	1,5	1,05	0,53	1,0	1,4	1,0	1,3	2,25	2,25	1,25	< 3	< 3	< 3	< 1,3	< 1	—
115	− 38	− 12	2,9	5,3	7,3	5,0	2,5	4,7	6,7	4,8	6,4	11	11	6,1	< 3	12	< 3	< 1,3	4	—
116	− 27	− 4	0,96	1,75	2,5	1,7	0,84	1,55	2,2	1,6	2,1	3,6	3,6	2,05	3	2,3	1,5	1,3	0,8	—
140	− 50	− 6,5	1,6	2,9	4,0	2,7	1,4	2,5	3,7	2,6	3,5	6	6	3,3	< 3	< 3	3	< 1,3	< 1	—
141	− 55	− 8	1,9	3,5	5,0	3,3	1,7	3,1	4,5	3,2	4,3	7,2	7,2	4,1	6	3	3,6	2,5	1	—
142	− 65														6	3	4,5	2,5	1	—
148	− 33	− 5,5	1,3	2,4	3,4	2,3	1,15	2,1	3,1	2,2	2,9	5	5	2,8	< 3	< 3	< 1	< 1,3	< 1	—
165	− 30	− 5	1,2	2,2	3,0	2,1	1,05	1,9	2,8	2,0	2,65	4,5	4,5	2,6	< 3	6	2	< 1,3	2	—

unbestimmt 7

6 1) nicht auswertbar, Shunt defekt.

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FIGURE CAPTIONS

(Illustrations are reproduced by an economical method which is adequate for most purposes. If greater definition is required, please refer to the original document obtainable from the Library

Fig. 1 Geographical location of the measuring points with new field mills

1 Agra

2 Gemmo

3 Pugerna

4 Mount San Salvatore

Fig. 2 Field mill on the roof of Agra Sanatorium

Fig. 3 Field mill on the roof of Gemmo switching station
Massagno Power Station

Fig. 4 Field mill in the garden of Pugerna Customs House

Fig. 5 Field mill on the viewing platform on San Salvatore.

Looking East

Fig. 6 Sample oscillogram of field variation with lightning strokes on Mount San Salvatore

Legend:

A	=	Agra
G	=	Gemmo
P	=	Pugerna
S1	=	San Salvatore (church roof)
S2	=	San Salvatore (tower)
N	=	Current Zero
i_7	=	Pre-discharge current, 7 mA range
i_1	=	Pre-discharge current, 1 A range

Top: Calibration frequency 100 Hz

Frequency of S2, approximately 1,150 Hz

The scales are valid for E = 10/30/100 kV/m

The figures noted in the Diagram A-G-P-S1-S2 indicate field strength scales for 10, 30, or 100 kV/m

Fig. 7 An example of the propagation of a downward stroke from a negatively charged cloud. Time interval about 3 ms

Fig. 8 Example of the propagation of a flash from the top of the tower to a positively charged cloud. Time interval shown: about 2 ms.

Fig. 9 Upward stroke

Fig.10 Upward stroke

Fig.11 Upward stroke

Fig.12 Upward stroke

Fig.13 Downward strokes

Fig.14 Downward strokes

Fig.15 Downward strokes

Fig.16 Downward strokes.

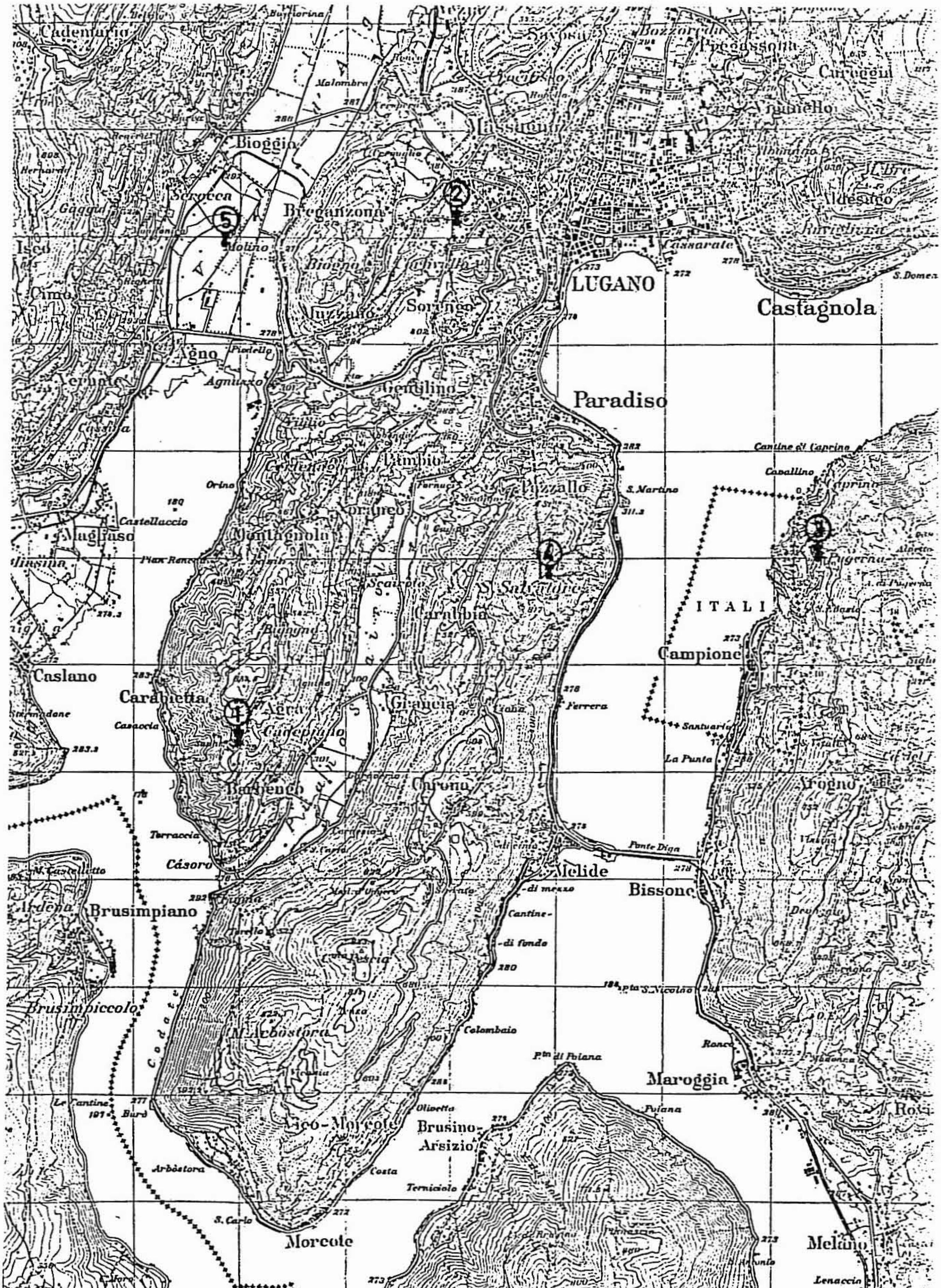


Fig. 1
Geographische Lage der Messpunkte mit neuen Feldmühlen

1 Agra *3* Pugerna
2 Gemmo *4* Monte San Salvatore

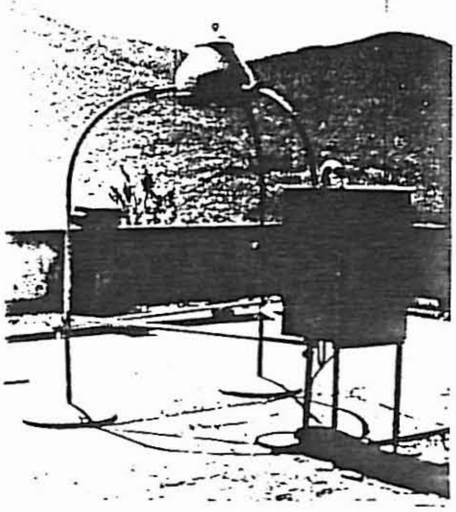


Fig. 2
Einbau der Feldmühle auf dem Dach des Sanatoriums Agra

[3]) Die Zahlenwerte zu a), b), c) sind in der Tabelle I untereinander gesetzt.

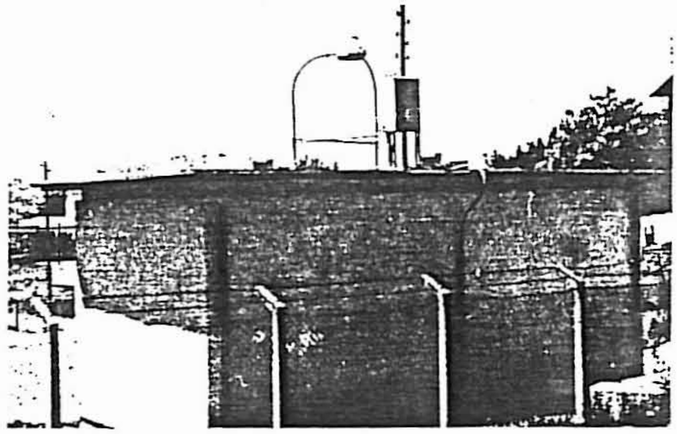


Fig. 3
Einbau der Feldmühle auf dem Dach der Schaltkabine Gemmo des Elektrizitätswerkes Massagno

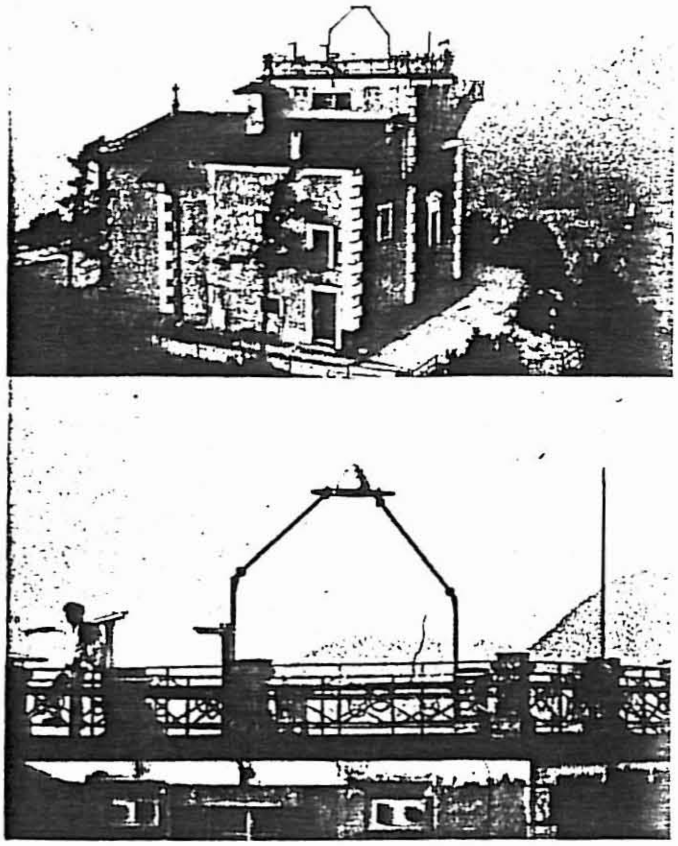


Fig. 5
Einbau der Feldmühle auf der Aussichtsterrasse auf dem San Salvatore
Blickrichtung nach Osten

Fig. 4
Einbau der Feldmühle im Garten des Zollhauses Pugerna

Fig. 6

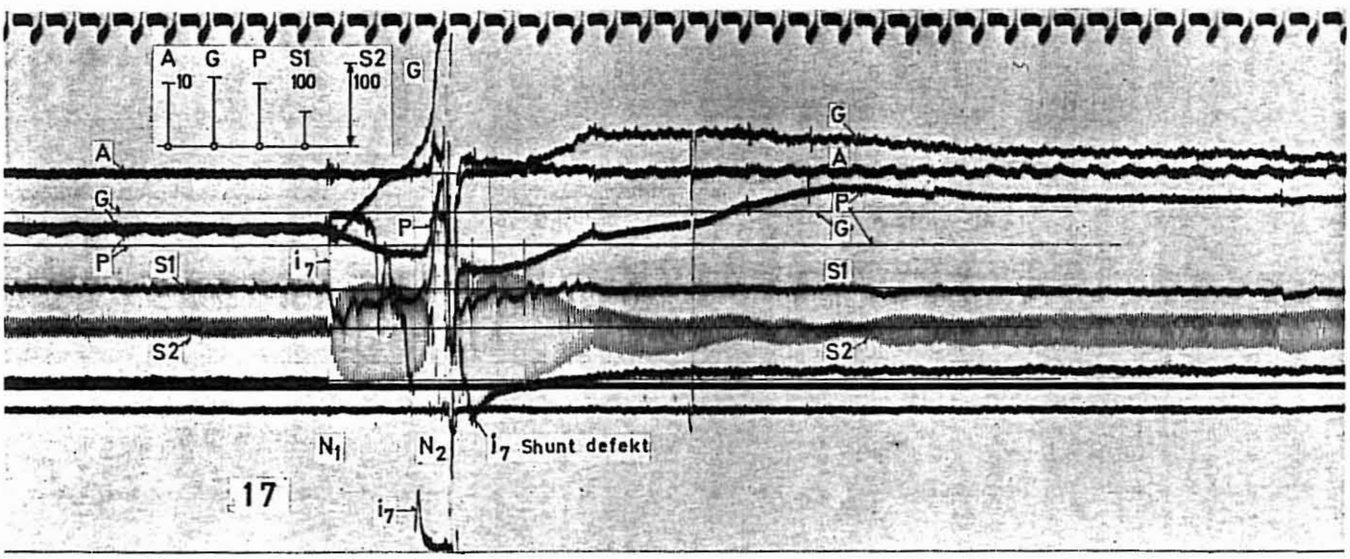
Oszillogramm-Beispiele des Feldverlaufs bei Blitzeinschlägen am Monte San Salvatore

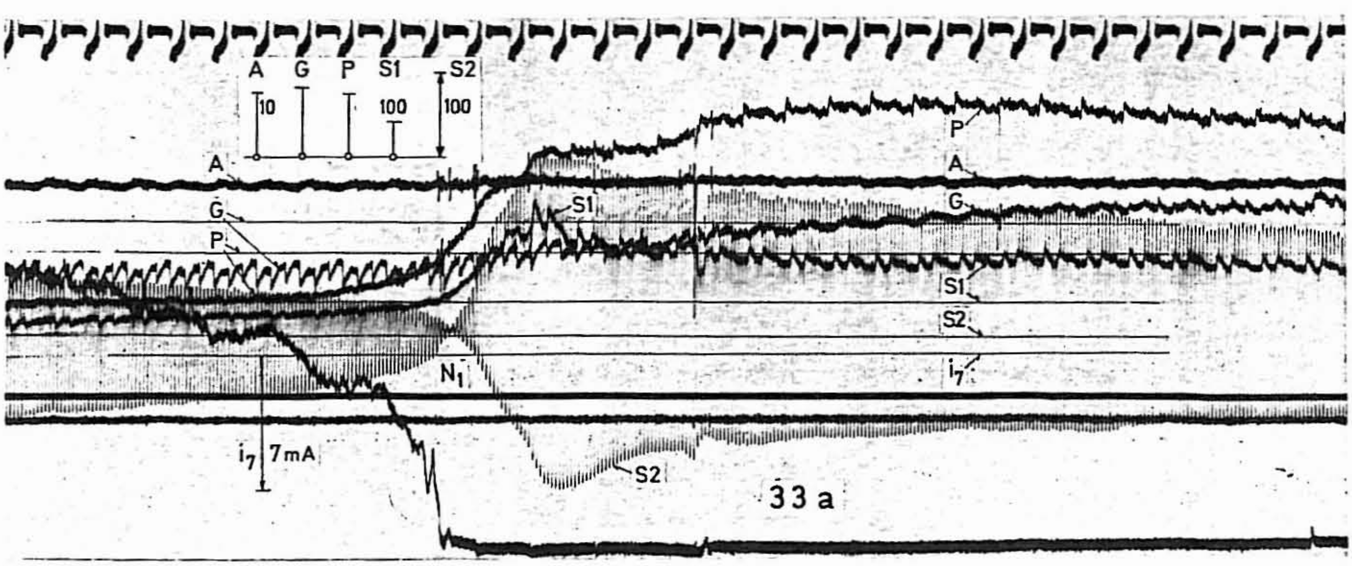
Bezeichnungen:

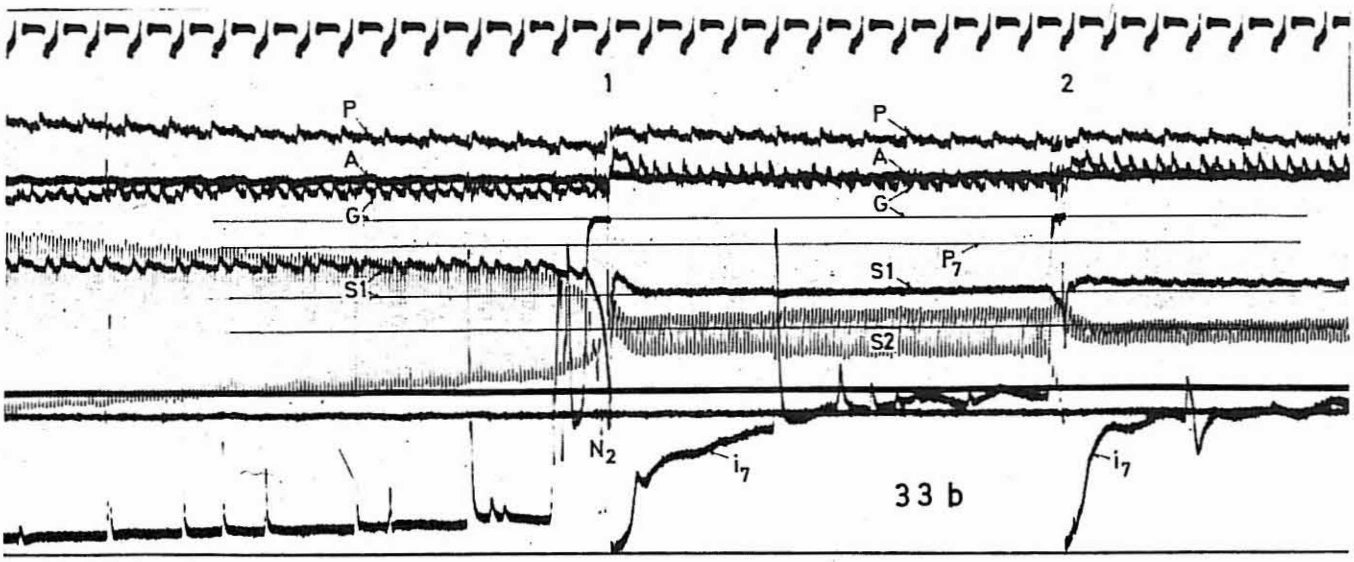
A	Agra	*N*	Nulldurchgang
G	Gemmo	i_7	Vorentladungsstrom, Bereich 7 mA
P	Pugerna	i_1	Vorentladungsstrom, Bereich 1 A
S1	San Salvatore (Kirchendach)	*Oben:*	Eichfrequenz 100 Hz
S2	San Salvatore (Turmflanke)		Frequenz von S2 ca. 1150 Hz

Maßstabstrecken gelten für $E = 10 / 30 / 100$ kV/m

Die beim Strecken-Schema A – G – P – S1 – S2 notierten Zahlen bedeuten die Feldstärke-Maßstäbe für 10, 30 oder 100 kV/m

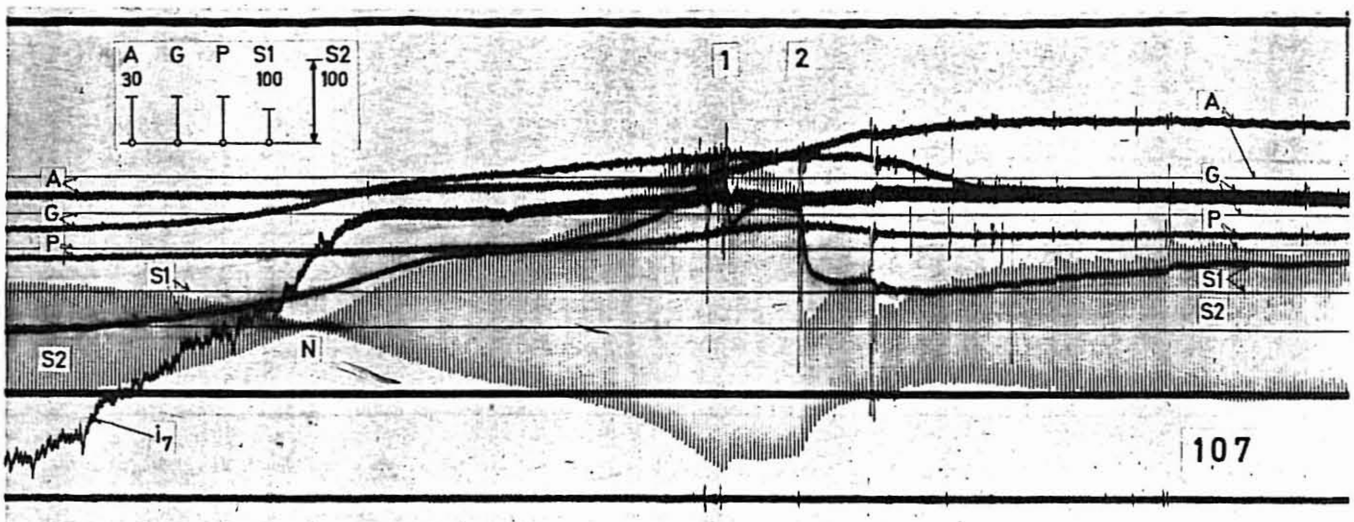






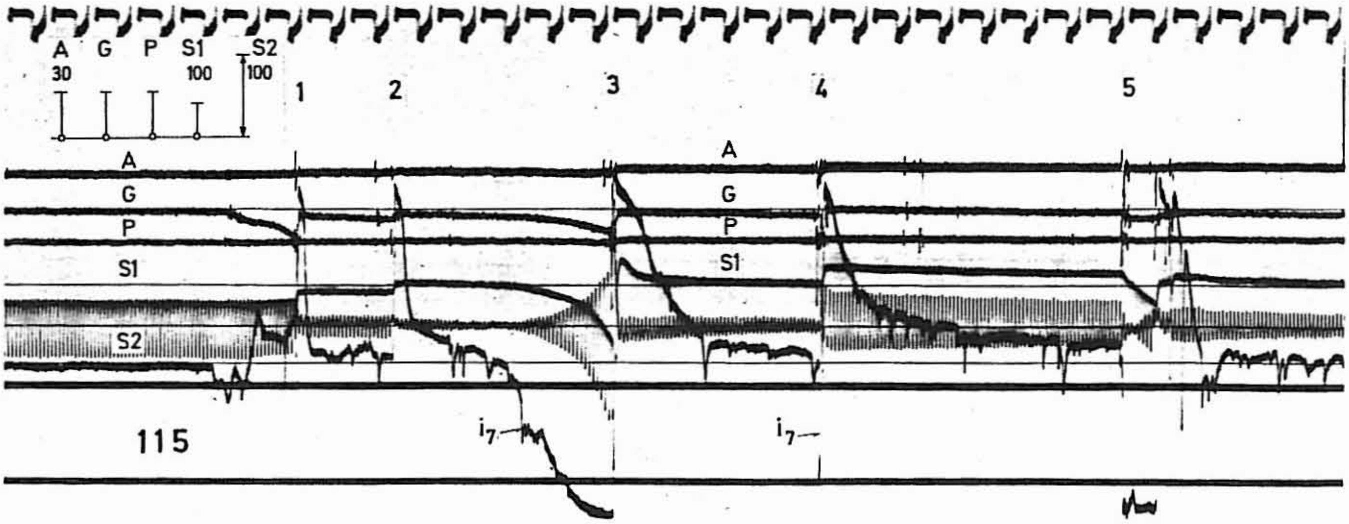
1
2
P
A
G
S1
S2
P7
N2
i7

33 b



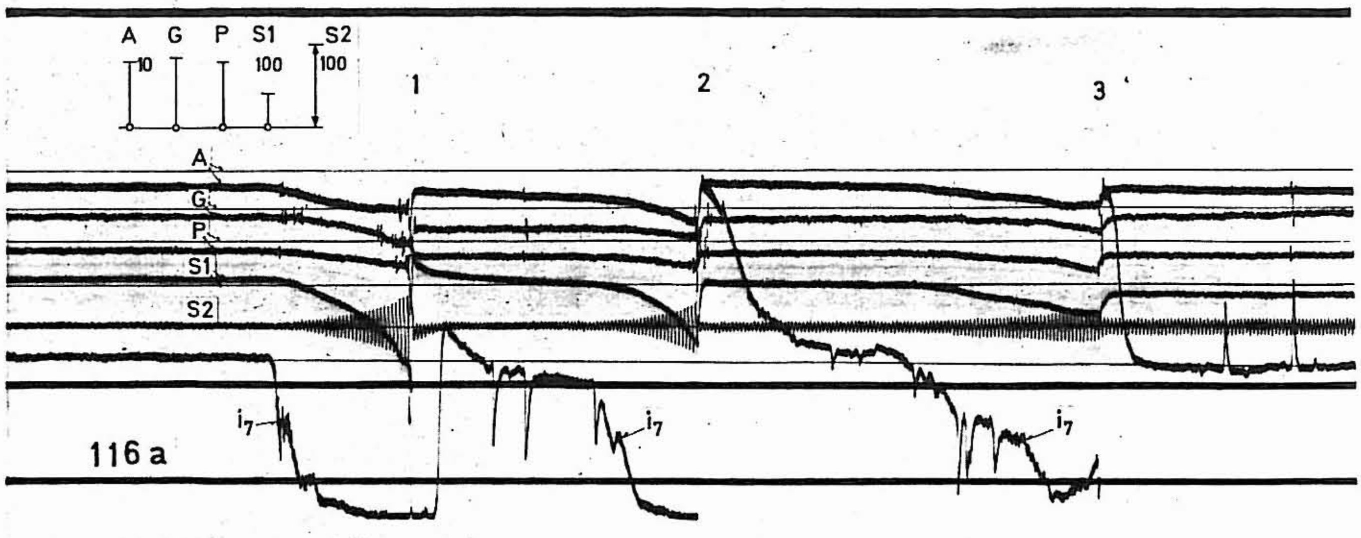
A G P S1 S2
30 100 100
1
2
A
G
P
S1
S2
N
i7

107

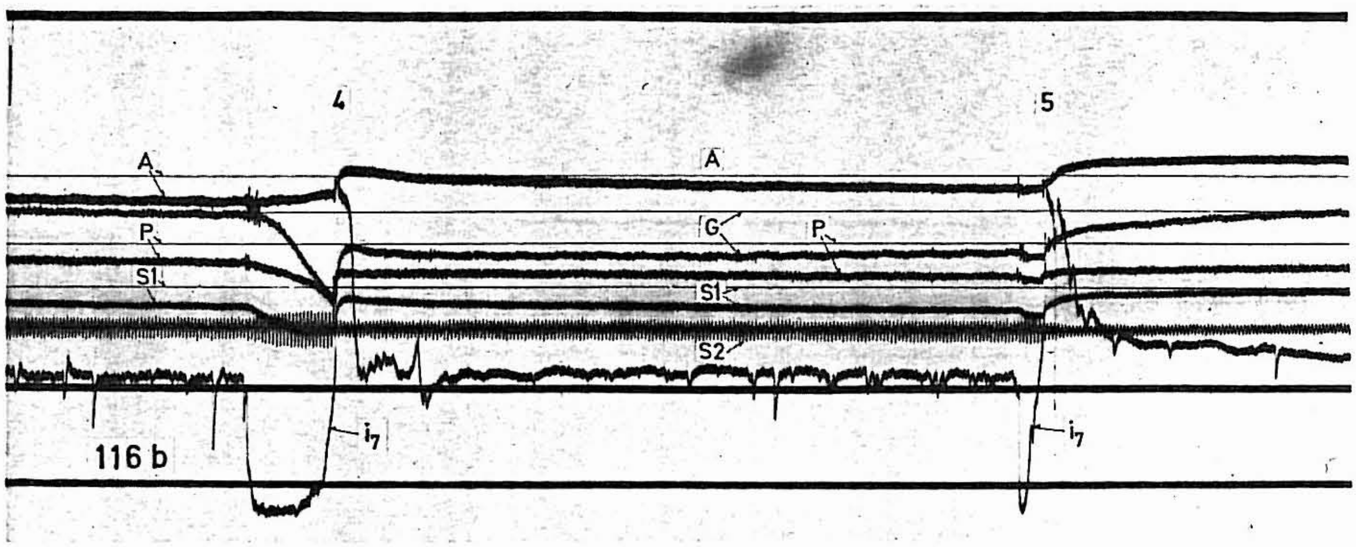


A G P S1 S2
30 100 100
1
2
3
4
5
A
G
P
S1
S2
i7

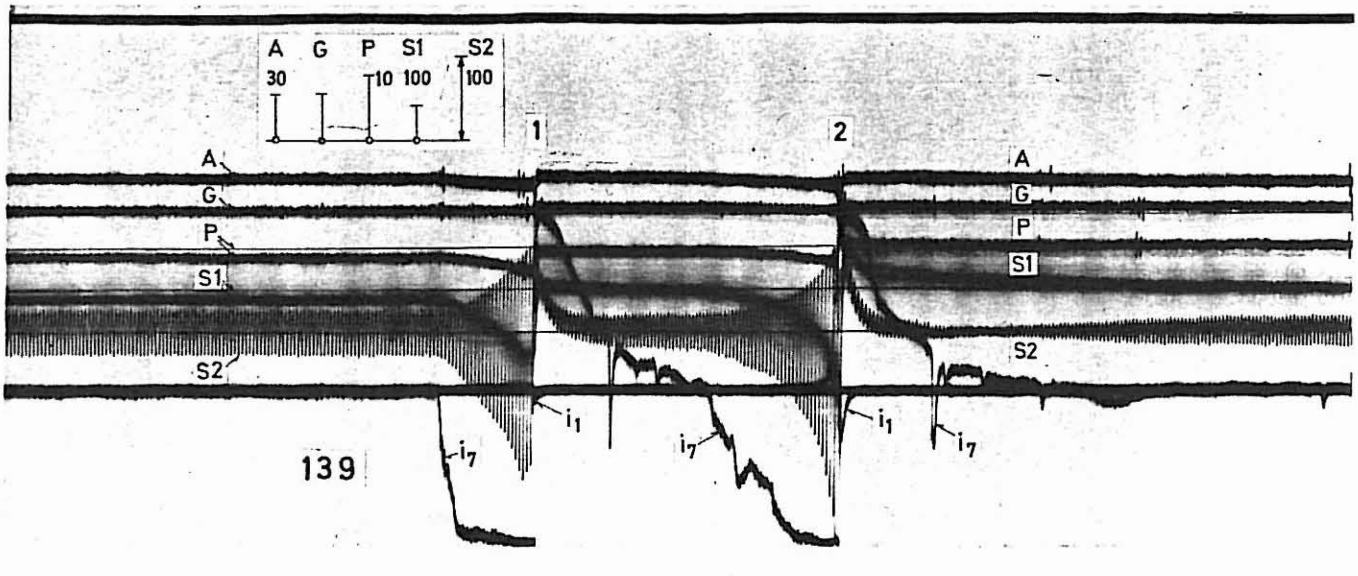
115



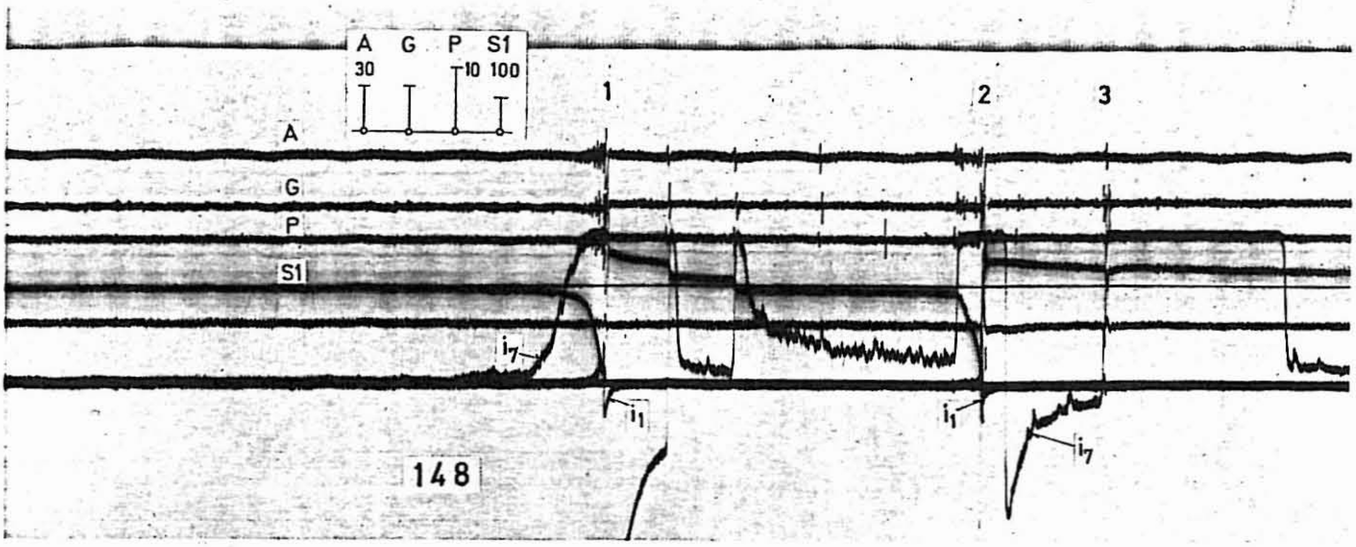
116 a

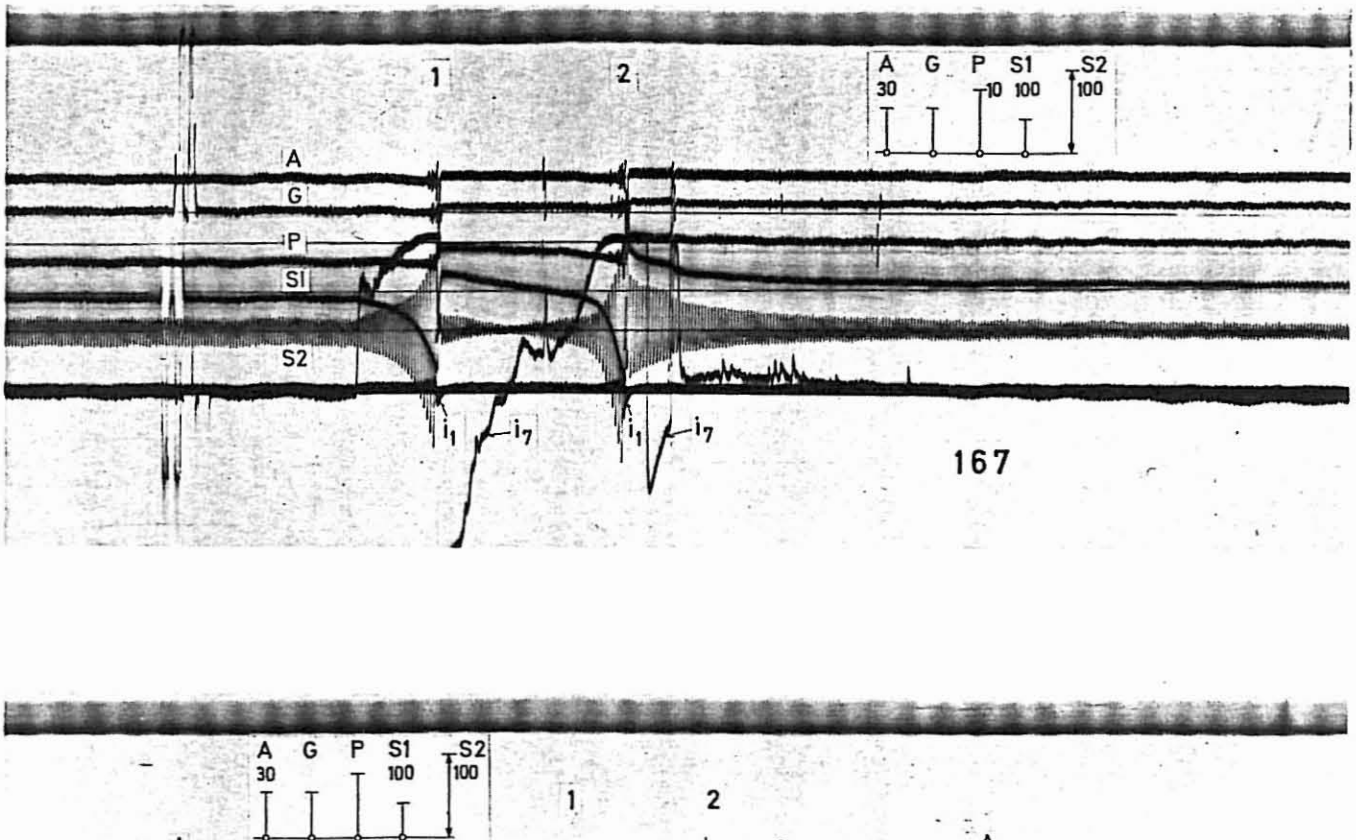


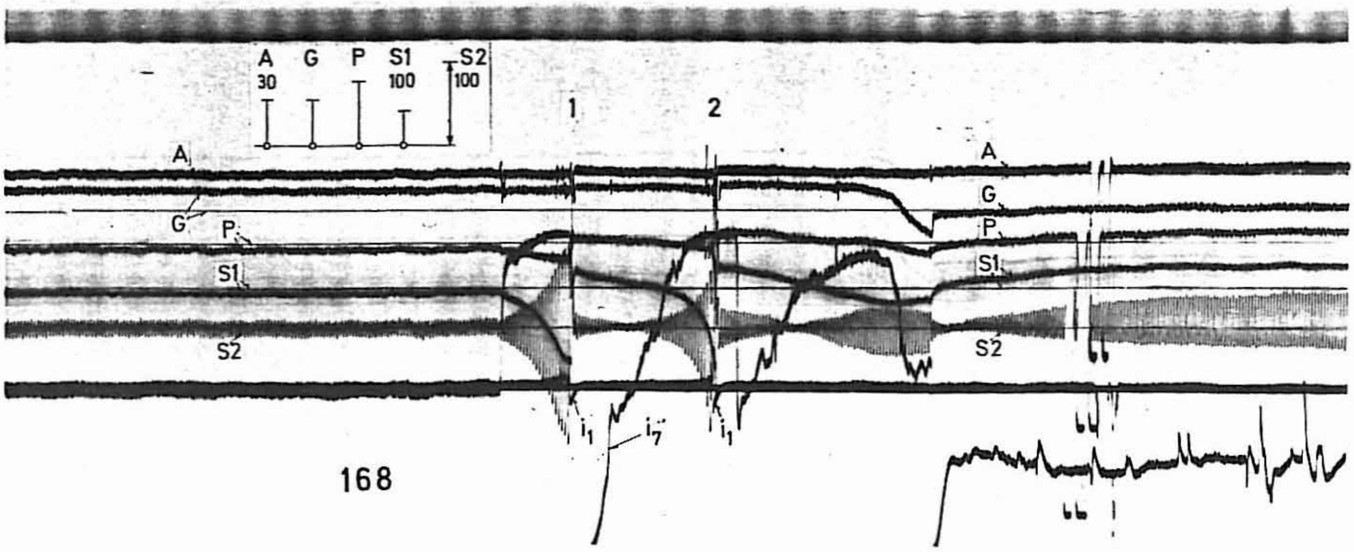
116 b

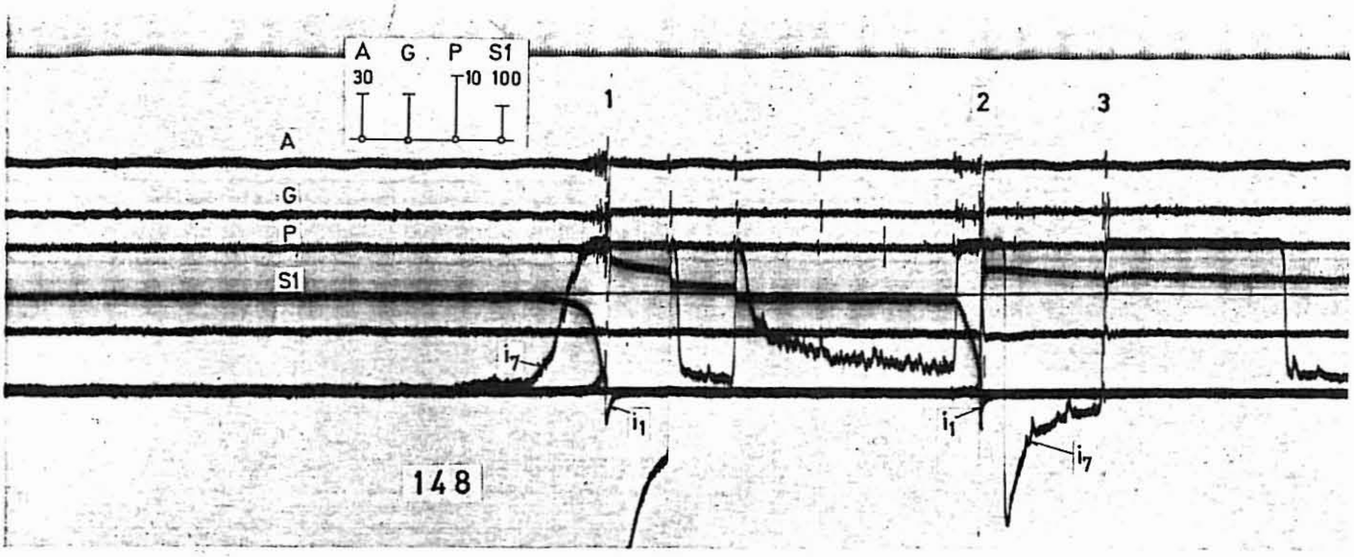


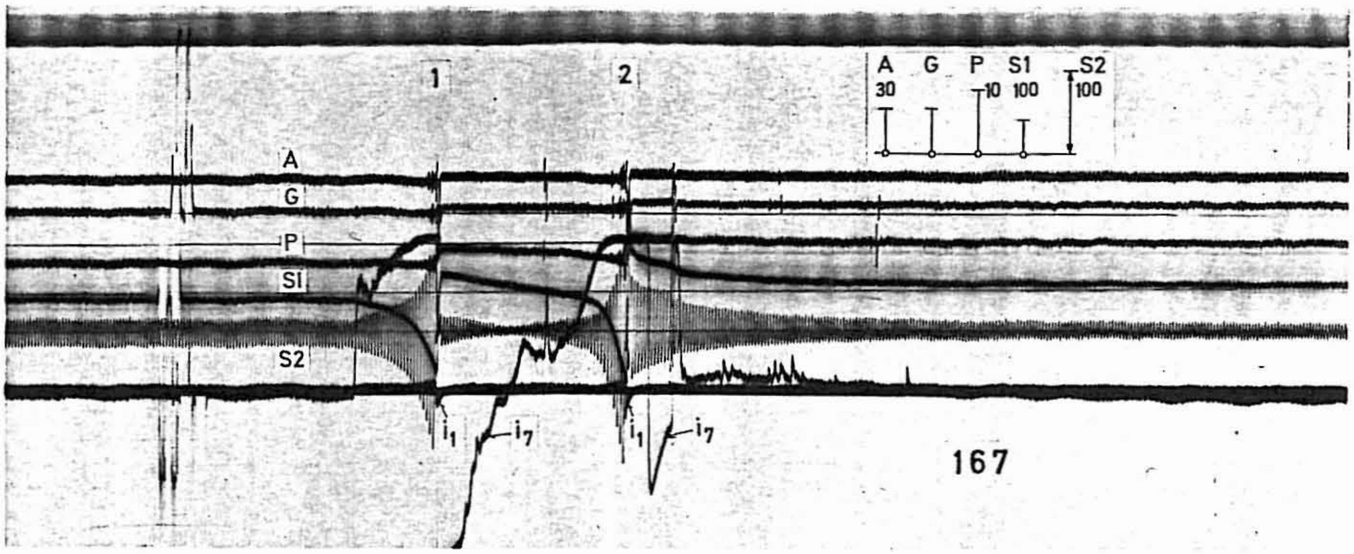
139

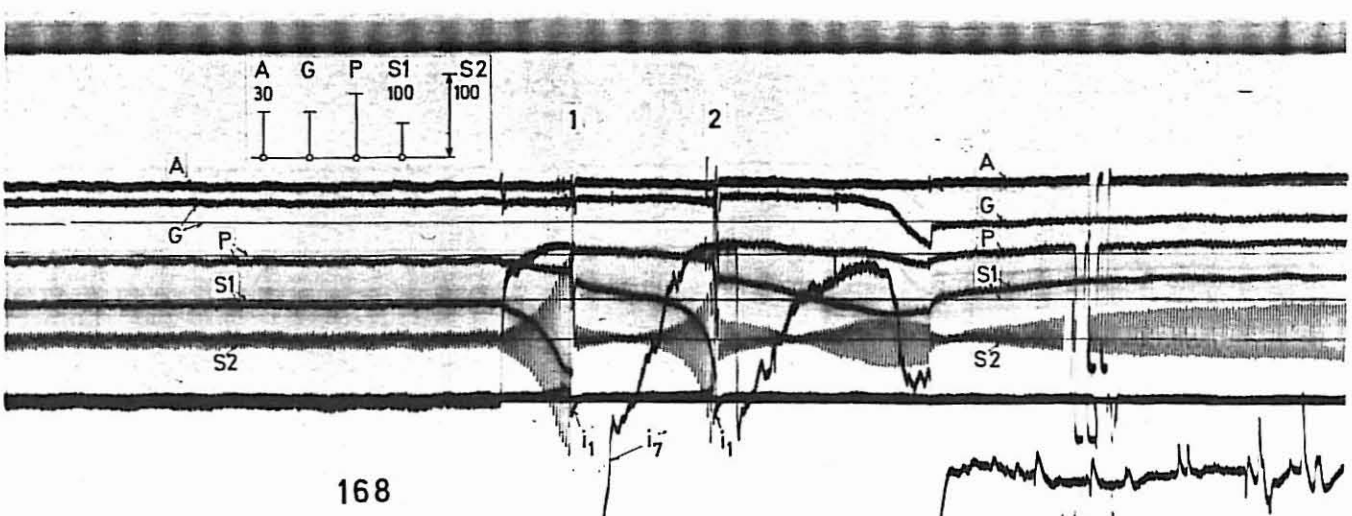

A G P S1
30 10 100
1 2 3
A
G
P
S1
i_7
i_1
i_1
i_7
148


1 2
A G P S1 S2
30 10 100 100
A
G
P
S1
S2
i_1 i_7
i_1 i_7
167


A G P S1 S2
30 100 100
1 2
A
G
P
S1
S2
A
G
P
S1
S2
i_1 i_7 i_1
168


A G P S1
30 10 100
1
2
3
A
G
P
S1
i_7
i_1
i_1
i_7
148


1
2
A G P S1 S2
30 10 100 100
A
G
P
S1
S2
i_1
i_7
i_1
i_7
167


A G P S1 S2
30 100 100
1
2
A
G
P
S1
S2
A
G
P
S1
S2
i_1
i_7
i_1
168

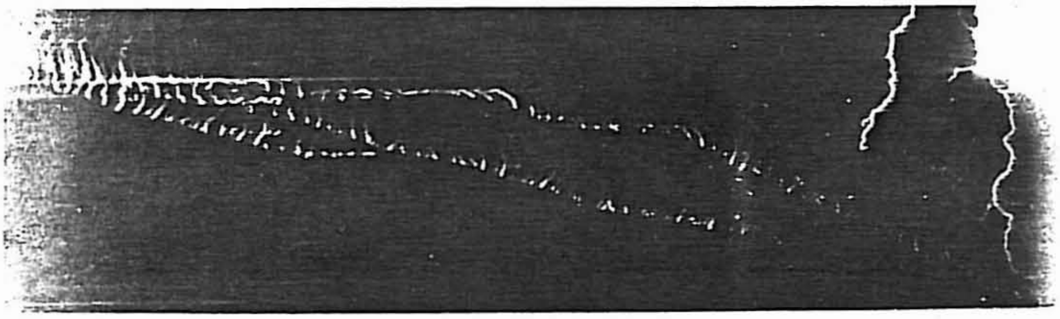


Fig. 7

Beispiel für das Vorwachsen eines Abwärtsblitzes aus einer negativen Ladungswolke

Dargestelltes Zeitintervall ca. 3 ms

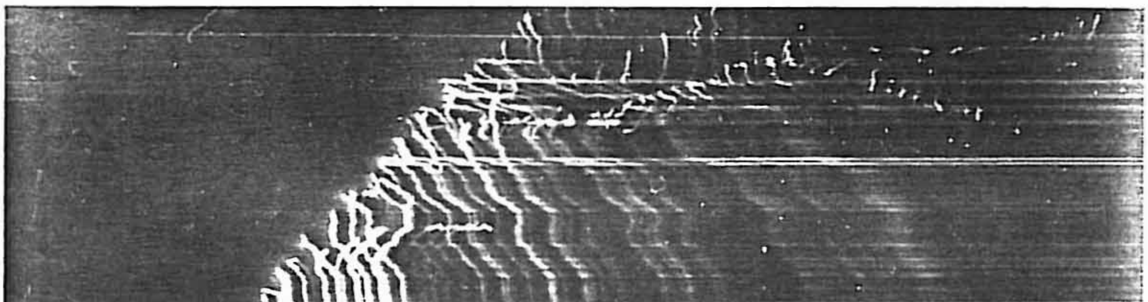


Fig. 8

Beispiel für das Vorwachsen eines Blitzes aus der Turmspitze nach einer positiven Ladungswolke

Dargestelltes Zeitintervall ca. 2 ms

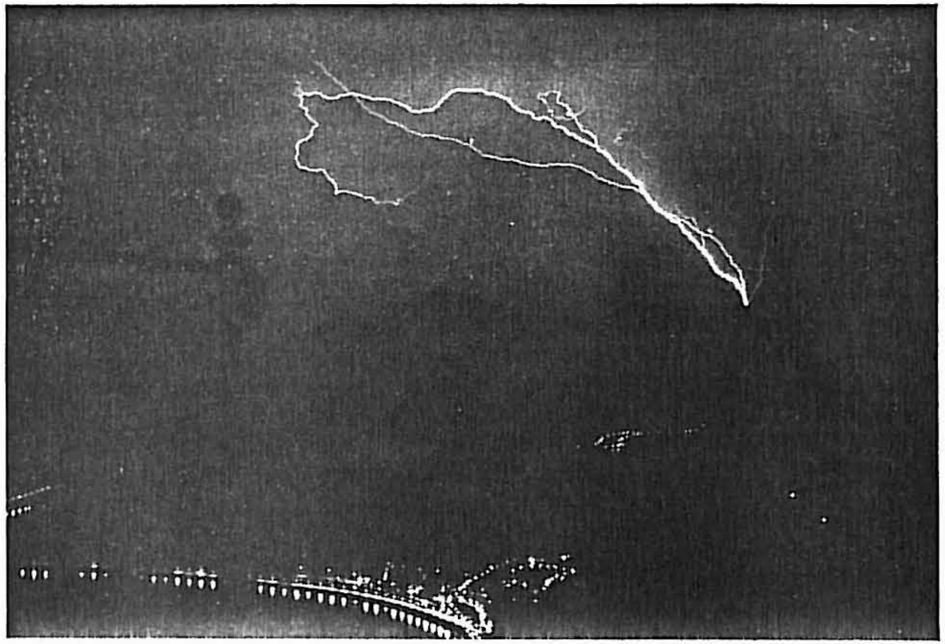


Fig. 9 **Aufwärtsblitz**

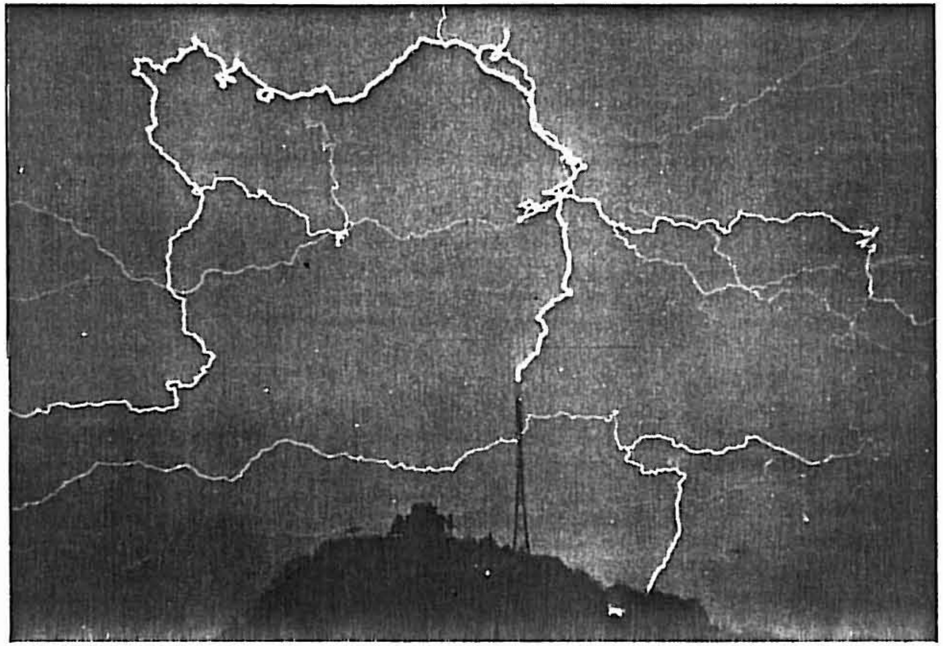


Fig. 10 **Aufwärtsblitz**

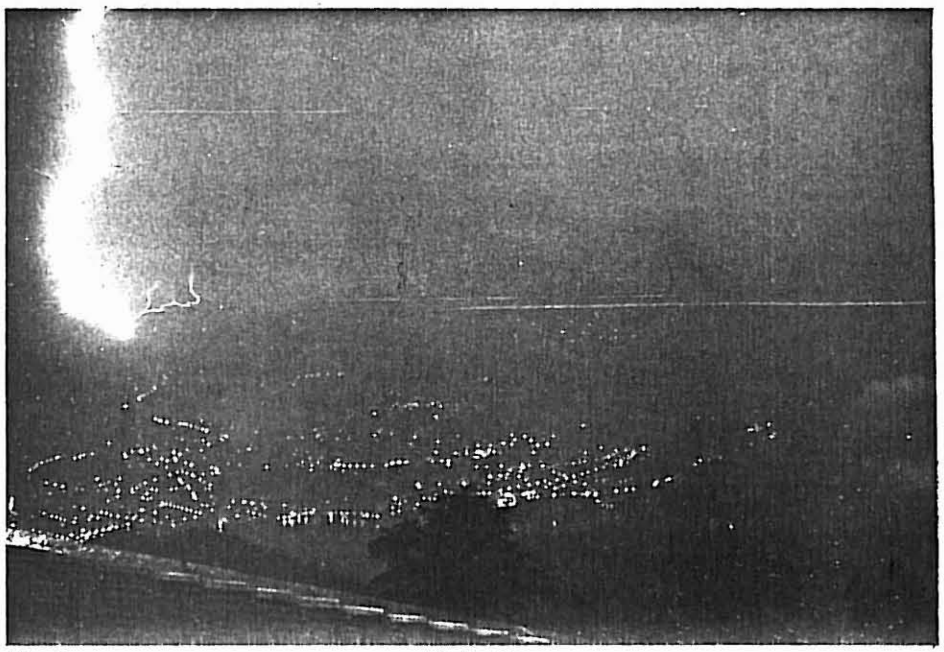


Fig. 11 **Aufwärtsblitz**

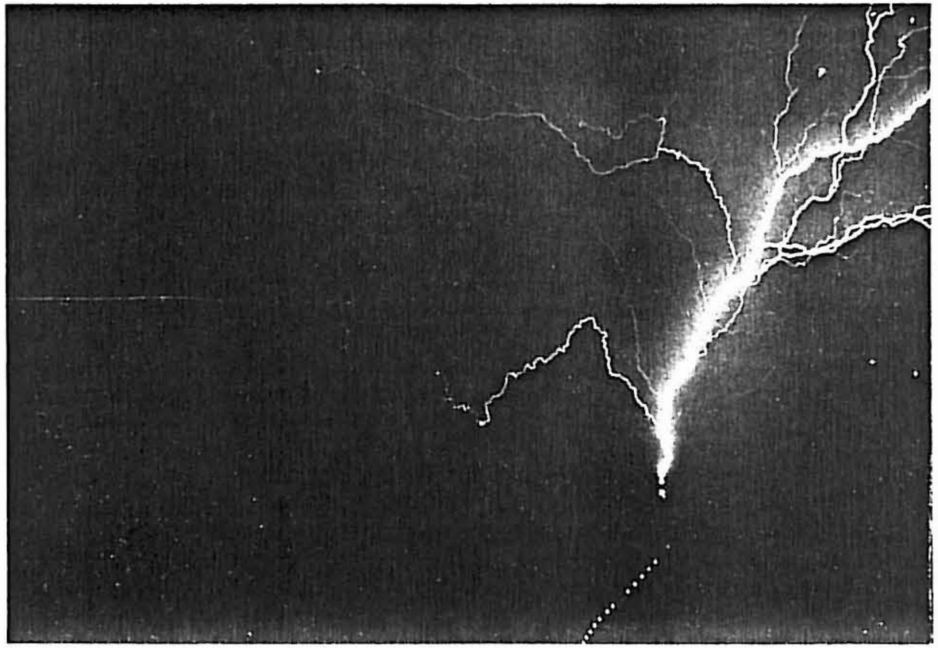


Fig. 12 **Aufwärtsblitz**

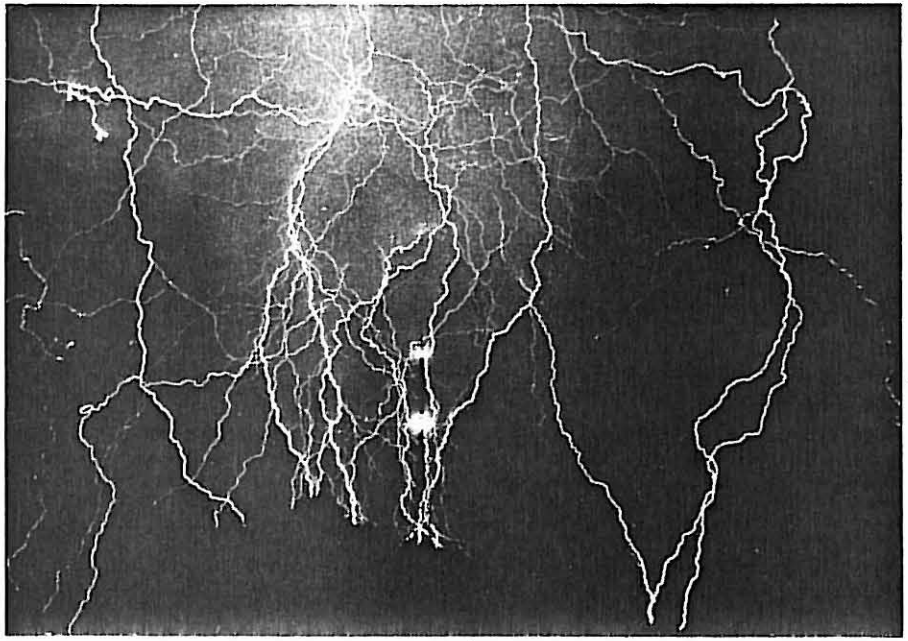


Fig. 13 Abwärtsblitze

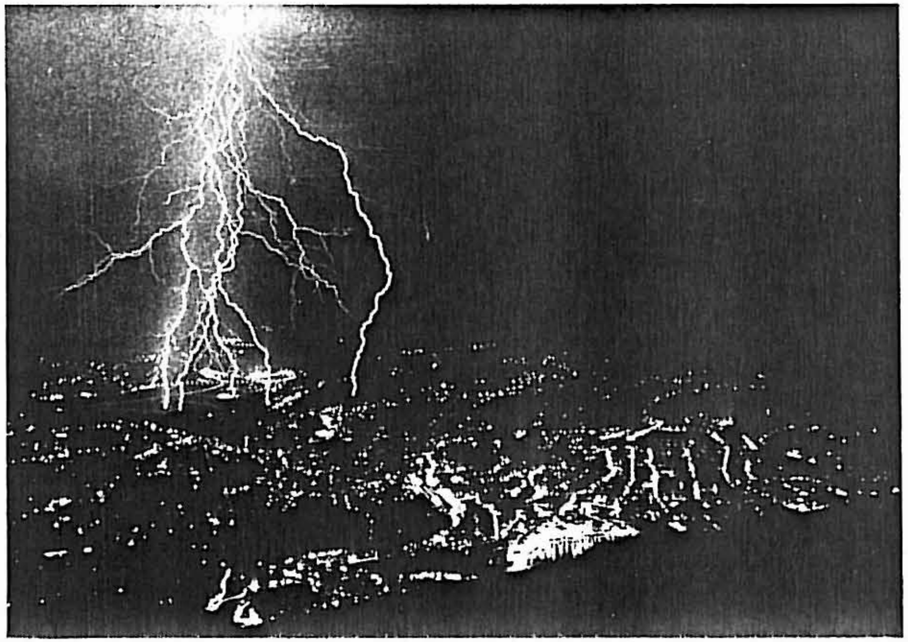


Fig. 14 Abwärtsblitze

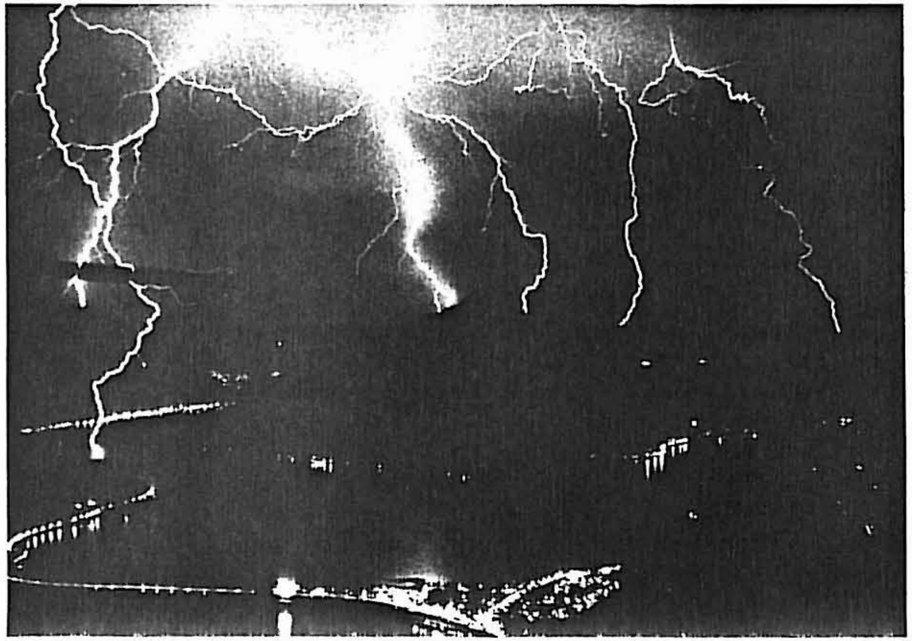


Fig. 15 Abwärtsblitze

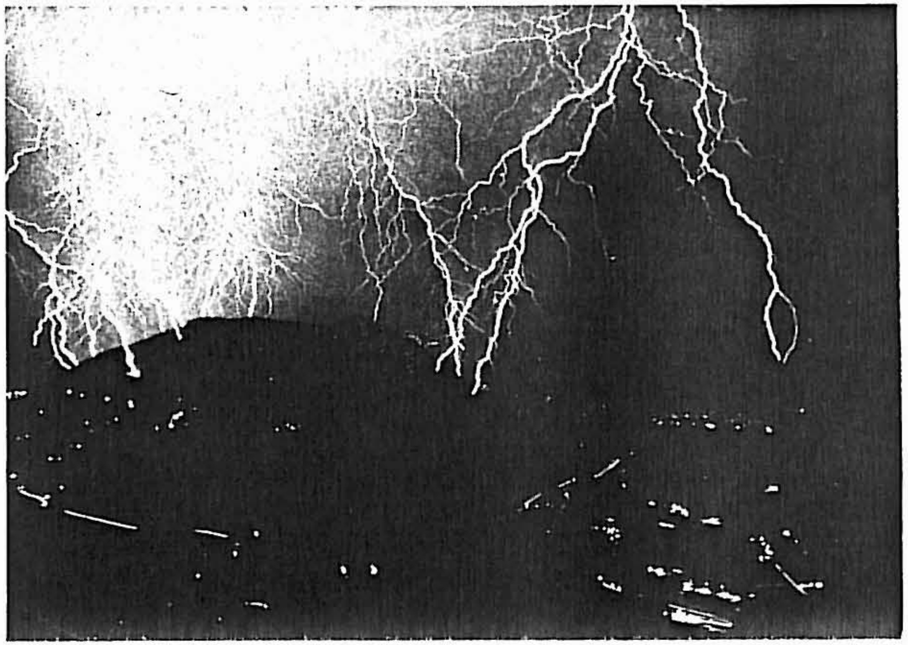


Fig. 16 Abwärtsblitze