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Triggered Lightning Strokes Originating in Clear Air

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During the 1978 campaign of the triggered lightning program at Saint-Privat d'Allier (France), simultaneous data from a movie camera, a coaxial shunt amperometer, a network of electric field mills, and a weather radar, were collected during the initial phase of a particular triggered event. These data are shown to exhibit a high degree of consistency, leading to the conclusion that charges totaling several coulombs were present in cloudfree air in the vicinity of a stormy area.

INTRODUCTION

During the 1973–1978 period a series of summer experiments near Saint-Privat d'Allier, in Massif Central (France), has been conducted to study scientific and applied aspects of lightning [*Saint-Privat d'Allier Research Group,* 1978]. While some attention in 1978 was given to natural lightning, most of the research was focused on the study of rocket-triggered flashes. The experimental setup in 1978 included optical, acoustical, electromagnetic, and electrostatic measurements, as well as a direct recording of the triggered lightning current and weather radar observations. Several technical descriptions and preliminary results are given by *Hubert* [1978], *Boulay and Laroche* [1979], *Chauzy et al.* [1979], and *Waldteufel and Metzger* [1978]. In terms of triggering attempts the 1978 campaign was quite successful: 13 hits were recorded out of 14 rockets which were fired within three distinct stormy events. As a general rule, optical observations were difficult to exploit, since most of the time lightning channels were imbedded in rainy or foggy zones. In one occurrence, however, the bottom of the discharge could be observed with excellent visibility, allowing a detailed comparison between several measurements, at least during the initial phase. The relative location of relevant equipment is displayed in Figure 1.

OBSERVATIONS

On August 23, 1978, the meteorological situation over western Europe featured a nearly homogeneous pressure field; winds were weak, and they blew from the northwest. The air mass was rather humid and conditionally unstable. Convection was triggered by orographic lifting as the air was advected over Massif Central mountains and was further enhanced by a local divergence of the upper tropospheric flow above central France. From aerological soundings, cloud base and cloud top altitudes were estimated around 1800 m and 6000 m (msl), respectively.

In the early afternoon the *S* band radar began to detect a series of cells which appeared in the northern sector, 80–120 km away. These cells exhibited roughly conical shapes with base diameters in the 6- to 10-km range and top altitudes around 5 km M.S.L. They moved south-southeastward at approximately 7 m s^{-1}.

A rocket was fired at 1538 LT, when the electric field at the firing station had reached -13.3 kV m^{-1} and stayed near this high magnitude for several tens of seconds. A flash, referred to below as 7813, was triggered when the rocket reached an altitude of about 230 m above the station.

At that time the radar indicated the presence of a convective cell centered about 12 km southwest of the radar. Echo contours in the horizontal plane 1.3 km above the firing site near the time of the 7813 flash are plotted in Figure 1. The radar calibration was unreliable that day: The contoured reflectivity lied in the 15–25 dBZ range. The distance of the echoes to the firing site was never less than 6.5 km (8.5 km at launching time). This particular cell had been tracked by the radar for more than 40 min; its trajectory was almost a straight line, to the extent that the radar operator had (correctly) forecast its bypassing the firing site by a fairly large distance and concluded (wrongly) to a very weak probability of successful triggering attempts.

A preliminary analysis of the 7813 flash has been presented by *Boulay et al.* [1979]. This flash did not follow the metal wire; that is, it was an example of 'anomalous triggering' such as was described by *Fieux and Hubert* [1976] and discussed by *Fieux et al.* [1978]. Nevertheless it struck the instrumented tower, a fortuitous circumstance which allowed accurate current measurements.

At the beginning the current recorded through the coaxial shunt (see Figure 2*a*) exhibits a behavior typical of anomalous triggering. First, a slow pulse of low intensity current ($I_{max} \simeq$ 50 A) lasting about 10 ms vaporizes the wire (phase A). This is followed by a 30-ms pause. As a general rule the main flash of triggered lightnings begins with a continuous component. The 7813 flash was an exception in this respect, since a series of discrete, negative strokes were observed first (phase B). Next comes the continuous discharge, which lasts about 450 ms, with reversed polarity during the ultimate 70 ms (phases C and C').

The analysis and discussion presented below concern mainly the strokes recorded during the first 54 ms of the main flash (phase B). Figure 2*b* is a field mill record of nearby electric field variation. A comparison of Figures 2*a* and 2*b* reveals an

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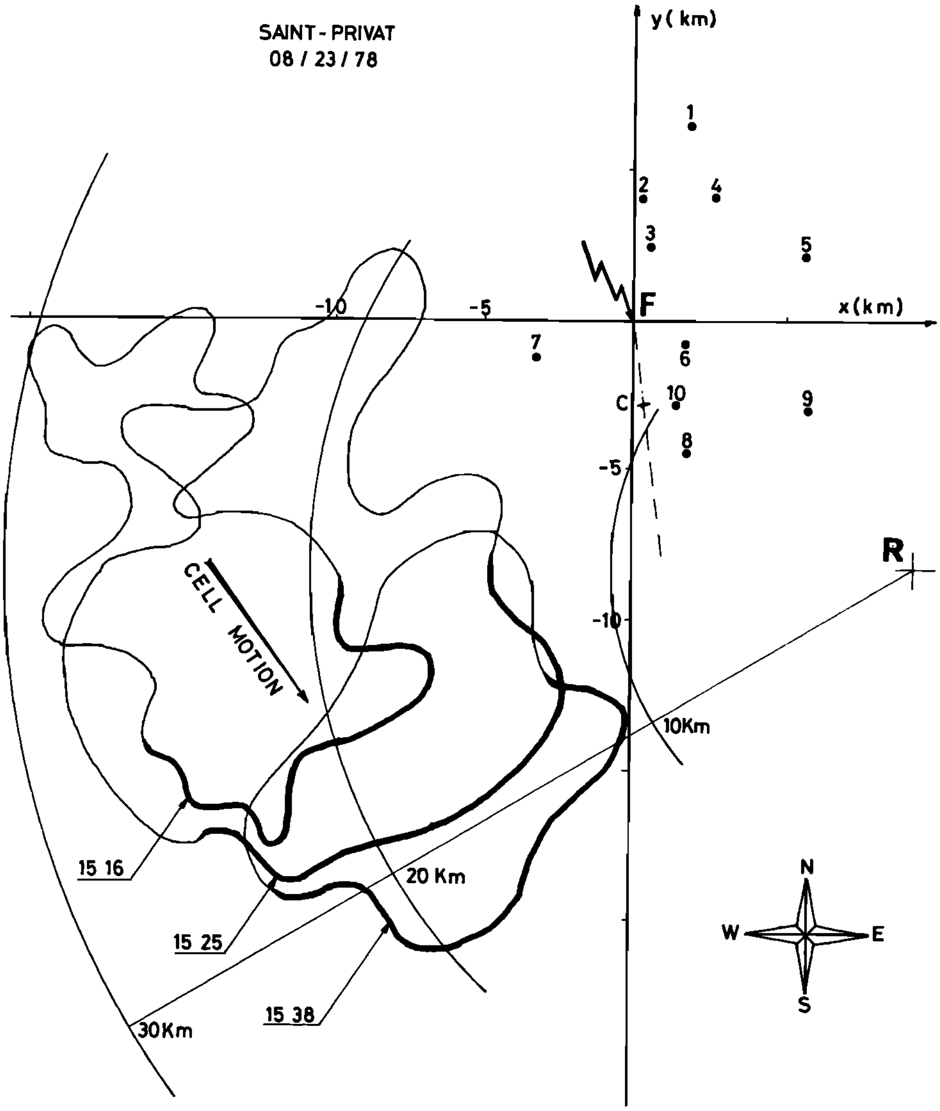

Fig. 1. Geometry of measuring equipment on the Saint-Privat site in 1978. F denotes the firing site (1100 m msl), including coaxial shunt. The dots numbered 1-10 denote elements of the field mill network. C denotes the high-speed movie camera. R denotes the weather radar (1420 m msl). Also shown are the contours of echoes detected by the radar on a horizontal plane 1.3 km above F, during three successive scans around the time the 7813 flash was triggered.

excellent correspondance between current pulses and electric field steps.

A movie was taken during the 7813 flash by a high-speed (730 frames/s), color, 16-mm movie camera operated by Electricité de France 2.7 km south of the site (point noted C on Figure 1). Enlarged photographs of frames corresponding to the strokes are presented in Figures 3*a*–3*i*. Most of the sky was clear. Low-altitude clouds in the background on the right side were distinctly seen. Note the sharpness of channel tips, and recall that the neighboring rain cell was in the southwest, behind the camera. This cell, visually observed from the radar, was isolated at low levels but apparently was connected, at higher altitudes, to a broken layer consisting of altocumulus and altrostratus clouds. The local presence of an upper cloud layer was recorded by firing site operators and was further confirmed through still photographs.

DATA PROCESSING

Every observation relevant to the initial strokes was first synchronized with reference to current data. This was easy for the field mill recordings, where only minute differences in acquisition rate had to be accounted for. As for the movie camera observations, allowances had to be made for the fact that the camera shutter was open only 2.5% of the time; consequently, it is very likely that most of the strokes were seen during the afterglow. Since the afterglow duration was of the order of a few hundred microseconds (see, e.g., *Orville* [1977]), as compared to a 1.3-ms period between successive frames, some strokes may have partly or totally escaped optical detection. For example, stroke 8 was present only through very faint traces aloft, while stroke 7 could not be seen at all. The observed lightning channels have been drawn schematically in Figure 3*j*, where the x and z scales correspond to the vertical $y = 0$ plane, nearly perpendicular to the camera axis. The sequence clearly indicates that the lightning channels developed upward along approximately three main branches (which we shall call the left, center, and right branches, according to the way they appear when projected on the $y = 0$ plane).

Still photographs were taken from nearby locations during the 7813 lightning. Owing to the cumulative exposure, no distinction between strokes could be made. The center channel

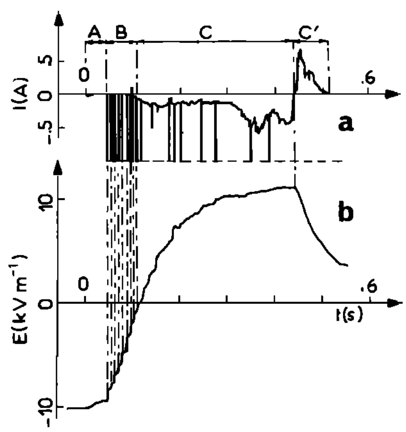

Fig. 2. The 7813 flash as was detected by (*a*) current through the coaxial shunt and (*b*) a typical field mill record (location 3 on Figure 1). Peak values of stroke currents (clipped on the drawing) were of the order of 10 kA. The three main phases of the flash (A, B, C, and C′) are indicated. A number of strokes occurring during phase C have been omitted for clarity: 32 current pulses in excess of 1 kA were detected during this flash. Field values are counted positive when directed upward.

was by far the brightest, and the other branches could hardly be seen (indeed, the center channel carried to ground most of the charges during later phases of 7813). A photogrammetric analysis of these photographs, including the movie camera data, indicated that this channel was approximately vertical for at least 2.5 km above ground.

The current recording was integrated to yield grounded charge values for each stroke. The integration process is deemed to be accurate to ±25–30%. As for the field mills, their time resolution was 0.33 ms. While *Krehbiel et al.* [1979] point out that leader changes may be present and may contaminate field step estimations, we found very little evidence for sizable leader effects in the field mill records, and we decided, accordingly, to use the best time resolution available. Therefore the field changes associated to each stroke event were read directly with no interpolation and were processed by a nonlinear least squares adjustment assuming a monopole charge distribution [*Jacobson and Krider,* 1976; *Krehbiel el al.,* 1979; *Boulay and Laroche,* 1979]. Digitizing step and relative estimated accuracy for the field measurements are 15 V m^{-1} and 1.5%, respectively; the mean square resulting errors on each retrieved parameter (i.e., the charge Q and coordinates X, Y, Z) have been estimated in the course of the least squares adjustment.

RESULTS

Experimental field changes and adjusted results (including the estimated errors and reduced χ^2 figure) are given in Table 1.

The charges retrieved from the field mill network are compared in Figure 4*a* to those obtained by integrating the lightning current separately for each of the first 10 strokes of lightning 7813. In view of accuracies estimated for each measurements, the agreement is quite satisfactory. The main features of the evolution throughout the stroke sequence are consistent. Note, in particular, how both methods yield relatively higher charge values for strokes 6 and 7. A fair agreement between field mill retrieved charges and directly recorded lightning currents has already been reported by *Boulay et al.* [1979] for two continuous component periods This is confirmed here for a series of discrete strokes.

The altitudes z_c estimated by adjustment to a monopole charge model are given in Figure 4*b*. On the average this altitude increases with time. Looking back to Figure 3, the z_c values are seen to be broadly consistent with the evolution of channel tips: The mean altitude above ground lies near 1 km for the first few strokes and then increases until the last channel (number 10) reaches above 2 km. The altitude of a particular point P, the coordinates of which were estimated photogrammetrically, is also indicated in Figure 4*b*. It agrees very well with the altitude retrieved for stroke 2; indeed, inspection of the movie camera frames shows that it was the location of a channel tip for stroke 2.

The location of each charge in the horizontal plane is illustrated in Figure 5, together with estimated mean square errors. These errors generally lie in the ±100- to 300-m range. They are consistently largest along the x axis. This is so because, with respect to the firing station F, the field mill network offers a balanced coverage along the y axis, whereas most of the stations are located on the east side and only one on the west side of F.

We have also indicated for each stroke, through appropriate symbols, the basic geometry of illuminated channels as was observed by the movie camera. Again, the consistency here is good: in every case, charge locations are compatible with optical observations. This is particularly clear in four cases when only one branch is seen to be illuminated and the adjusted horizontal location is found on the same side with respect to the movie camera viewing axis.

The charge retrieved from field mill data for the first stroke is more than twice the value found by current integration. At the same time the mean square uncertainty is very large. This is because the altitude is rather low in such a way that for all field mills, possible errors on the charge magnitude may be nearly compensated by an altitude error. To a lesser extent this is also true for stroke 3.

On the other hand, since several distinct channels are often illuminated for a single stroke, the monopole model may not always be satisfactory. A case in point is the first stroke with four channels (see Figure 3). We have found through trial and error that it was easy, introducing several charges in agreement with the visible channels, to reconstruct accurately the observed electrostatic field map with a total charge less than half the value found by the monopole model (see Figure 4).

An inspection of high time resolution data recorded by the shunt amperometer and the magnetic captors indicates that generally the current strokes have a fine structure. The initial (and most vigorous) pulse lasts of the order of 100 μs and is often multiple peaked; it is sometimes followed, several hundred microseconds later, by further, less intense events. It is worth noting that such secondary pulses did not occur for strokes 3, 4, 5, 6, and 9, including those strokes specifically (4, 5, 6, and 9) for which only one illuminated channel was observed by the movie camera. The total duration and complexity were particularly noticeable for strokes 1, 7, and 10; this should be kept in mind when looking at the reduced χ^2 figures in Table 1, which indicate a good overall quality of the adjustment, with the exception of strokes 7 and 10. Note that for stroke 10 the total duration was of the order of 5–600 μs, that is, substantially larger than the time resolution of the field mills.

DISCUSSION

Although we have been mentioning negative charges in the previous sections, every observation reported and analyzed so

Fig. 3*a*

Fig. 3*b*

Fig. 3*c*

Fig. 3*d*

Fig. 3*e*

Fig. 3*f*

Fig. 3. Illuminated channels seen by the high-speed movie camera for strokes 1(*a*, *b*), 2(*c*), 3(*d*), 4(*e*), 5(*f*), 6(*g*), 9(*h*), and 10(*i*).

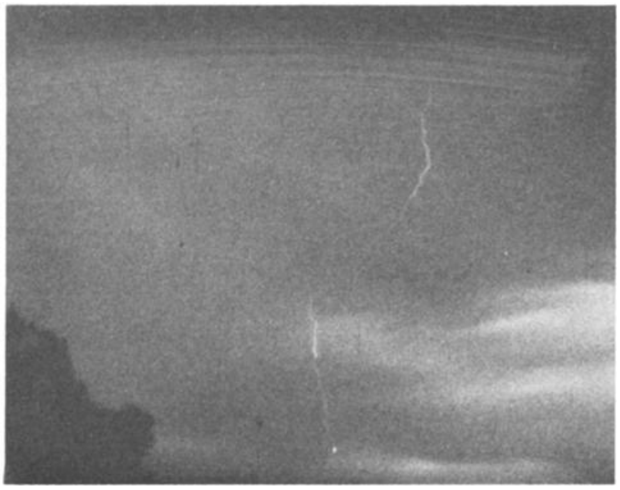

Fig. 3*g*

Fig. 3*h*

Fig. 3*i*

far is compatible with an interpretation in terms of a positive stepped leader progressing slowly upward under the attraction of negative charges situated above (e.g., in the cloudy volume outside the camera field of view). Indeed, such a mechanism would yield the observed polarity for both the current pulses and the electric field variations.

Besides the fact that most of the charge in the upper cloud is probably positive (see below), such a possibility can actually be excluded for two main reasons.

First, every current pulse has a steep front (rise time $\tau_F \sim 1$ μs for the first stroke and $\tau_F \leq 0.3$ μs for subsequent ones); this is typical of a regular 'stepped leader-return stroke-dart leader-return stroke' sequence.

Second, an electro-optical device designed for the measurement of stroke velocities was implemented by one of us [*Hubert and Mouget,* 1979]. This device, which consists of two horizontal slits fitted with photodiodes, aimed at neighboring elevations on the vertical of the firing station, unambiguously detected downward-going events with velocities of the order of magnitude to be expected for a stepped leader (first stroke) and for dart leaders (subsequent strokes). Each of these events was followed by light pulses propagating upward with a velocity of the order of 10^8 m s^{-1}.

While no streak camera record was available for the 7813 flash, members of the Saint-Privat group have obtained, during previous observations of triggered lightning exhibiting fast rising current pulses, streak camera pictures which are quite consistent with the classical dart leader-return stroke sequence [*Fieux et al.,* 1978].

Consequently, there are firm grounds for our conclusion that negative charges, neutralized by each stroke, preexisted at the location corresponding to the extremity of each return stroke channel.

Now, the combined observations presented above show that indeed the regions neighboring the tops of lightning branches seen by the movie camera correspond well to the location of these charges; hence, they were present in clear air.

It is well known that space charges can exist in the absence of clouds (see, e.g., *Israël* [1973]). Although most of these charges are detected near the ground, some haze layers aloft have been observed to be charged.

These observations [e.g., *Vonnegut and Blume,* 1955] were made in fair weather conditions. Also, the maximum negative charge density was found to be of the order of -10^{-2} C km^{-3}, which is 2 orders of magnitude lower than what is observed here (a total of about -4 C was brought to the ground from a volume of about 4–6 km^3). However, in a recent paper, *Winn et al.* [1978] report the presence of a layer carrying approximately -0.15 C km^{-3}, at 0.42 km above ground, below the base of a weakly active thundercloud. Obviously, we cannot consider our observations otherwise than in the context of the surrounding cloud structure.

The later period (phases C and C′ on Figure 2) of the 7813 flash has been investigated by adjusting a monopole charge model to field changes observed during successive time slices of the continuous component, which brought in turn to ground about -80 C and $+20$ C total charges. While the quality of the adjustments is not always good, they indicate clearly that positive charges are located in the upper cloudy region above the firing site, while negative charges are found quite near (and sometimes inside) the radar echo region southward.

It does not seem impossible that the charges in clear air originated in this middle cloud region itself. Cloud elements are continuously detrained and dispersed. After some evapo-

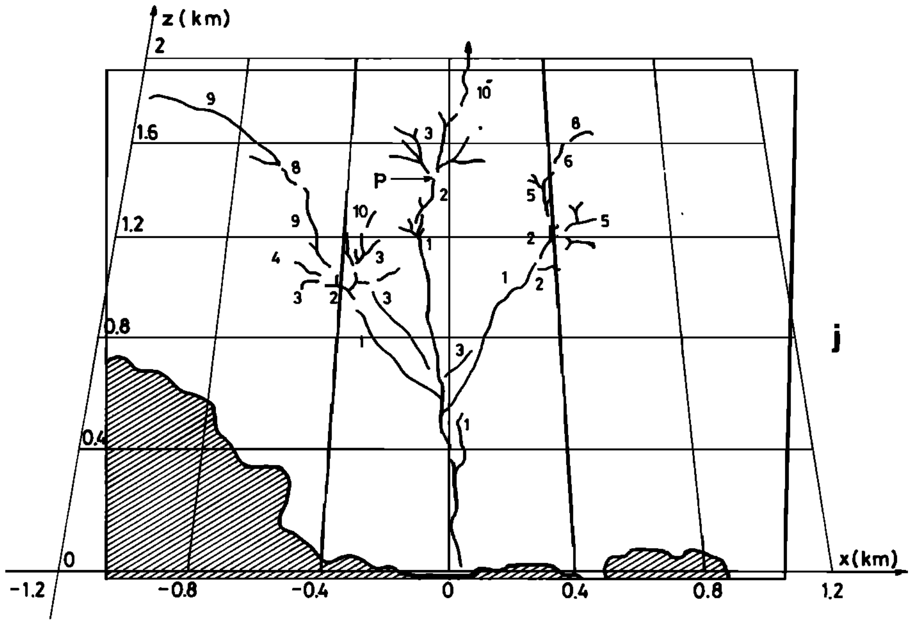

Fig. 3*j*. Schematic composite plot of observed lightning channels for the 10 first strokes. The *x* and *z* coordinates are given in the $y = 0$ plane (see Figure 1). Coordinates of point P (reached during stroke 2) have been estimated by photogrammetry. The channel drawings have been interrupted deliberately between distinct strokes.

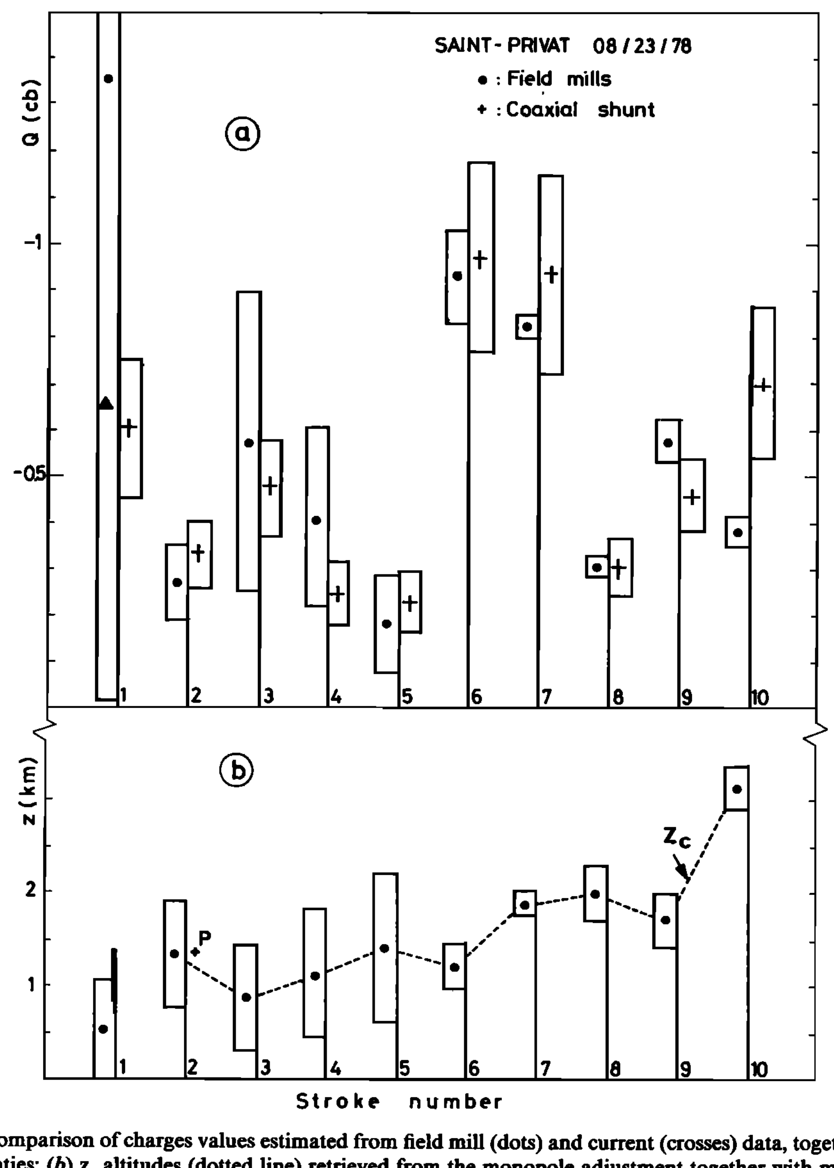

Fig. 4. (*a*) Comparison of charges values estimated from field mill (dots) and current (crosses) data, together with mean square uncertainties; (*b*) z_c altitudes (dotted line) retrieved from the monopole adjustment together with mean square incertainties. The triangle on (*a*) and thick line on (*b*) for stroke 1 indicate total value and attitude range of distributed charges adjusted by trial and error (see text).

TABLE 1. Electric Field Change Data and Adjusted Results for the First 10 Strokes of 7813 Lightning, Using a Monopole Charge Model

Stroke Number	Observed Field Change,* $kV\ m^{-1}$									Adjusted Results				Reduced
	1	2	3	4	5	6	7	8	9	X (ΔX)	Y (ΔY)	Z (ΔZ)	Q (ΔQ)	χ^2
1	0.06	0.14	1.02	0.09	0.06	0.96	0.29	0.13	0.05	−457 (91)	158 (44)	503 (686)	1.39 (1.28)	1.44
2	0.02	0.05	0.42	0.05	0.05	0.49	0.10	0.08	0.02	−42 (275)	213 (123)	1305 (617)	0.27 (0.08)	0.99
3	0.04	0.11	0.63	0.06	0.03	0.57	0.19	0.09	0.04	−502 (137)	171 (59)	849 (547)	0.58 (0.32)	0.43
4	0.02	0.08	0.35	0.05	0.02	0.34	0.19	0.06	0.02	−820 (148)	−25 (67)	1079 (678)	0.39 (0.19)	0.06
5	0.04	0.09	0.44	0.03	0.03	0.45	0.06	0.03	0.03	24 (301)	347 (164)	1335 (810)	0.28 (0.11)	0.49
6	0.07	0.20	0.89	0.14	0.06	1.21	0.51	0.18	0.05	−477 (58)	−153 (24)	1193 (326)	0.93 (0.10)	0.48
7	0.08	0.32	0.46	0.23	0.10	1.53	0.89	0.30	0.09	−52 (47)	−952 (27)	1800 (136)	0.82 (0.03)	13.5
8	0.02	0.06	0.22	0.05	0.01	0.55	0.29	0.12	0.07	−61 (123)	−802 (63)	1952 (303)	0.30 (0.02)	0.53
9	0.06	0.19	0.60	0.11	0.03	0.63	0.36	0.10	0.04	−731 (83)	−48 (42)	1694 (327)	0.58 (0.05)	0.50
10	0.07	0.23	0.54	0.15	0.07	0.23	0.12	0.17	0.07	−732 (544)	1200 (132)	3087 (223)	0.37 (0.03)	4.76

*Station 10 was out of order.

ration, air parcels still containing charged aerosols or small droplets might thus be carried away from the cloud. The charge density noted above ($\sim$1 C km^{-3}) is typical of precipitating clouds rather than clear air, mist, or nonprecipitating clouds.

Whether or not such an hypothesis is correct, the fact that these charges were present in the immediate vicinity of the launching site and were neutralized as the channels extended upward leads us to think that their role was important in making the triggering attempt successful. In this respect, note that during the first stroke one of the channels (never seen later) extended only up to a 450- to 500-m altitude. Since the rocket reached about 230 m before triggering, the presence of even a rather small charge immediately above is obviously favorable to a local growth of the electric field toward the breakdown range.

CONCLUDING REMARKS

Most of the evidence available so far from field mill networks supports the idea that electric charges are located inside precipitating zones. For example, *Krehbiel et al.* [1979] carry out a detailed analysis of four multiple stroke flashes to ground and conclude that 'the discharges developed through the full horizontal extent of the precipitating region and appeared to be bounded within this extent.'

On the other hand, a few cases of lightning channels ending in clear air have been reported in the past. Photographs of the Surtsey volcano eruption [*Lane,* 1963] show a clear example of such phenomena. In statistics presented by *Mackerras* [1974], 4% of the flashes are termed 'air discharges.' Most re-

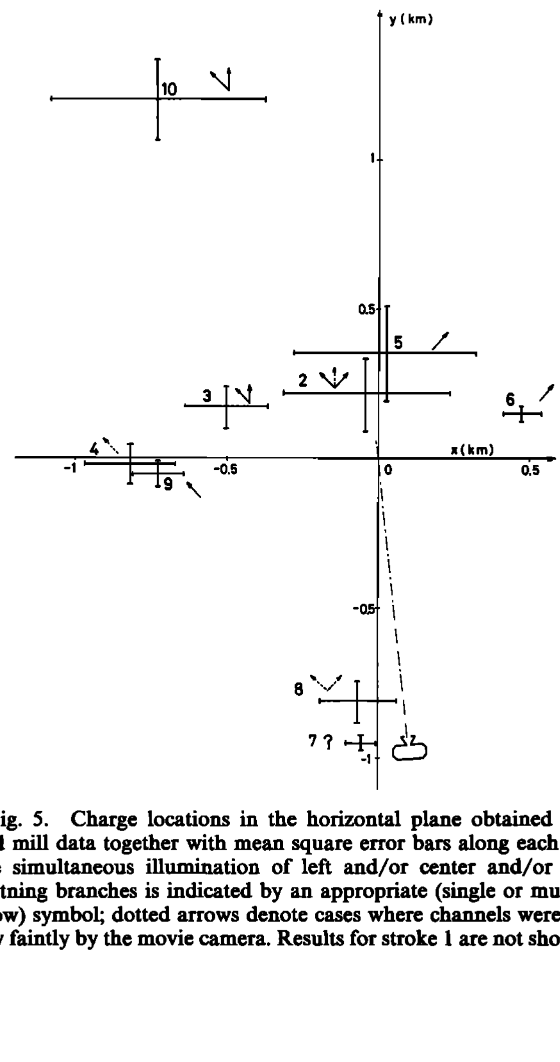

Fig. 5. Charge locations in the horizontal plane obtained from field mill data together with mean square error bars along each axis. The simultaneous illumination of left and/or center and/or right lightning branches is indicated by an appropriate (single or multiple arrow) symbol; dotted arrows denote cases where channels were seen very faintly by the movie camera. Results for stroke 1 are not shown.

ports so far are consistent with a picture where negative charges embedded in clouds are neutralized by positive space charges in clear air [*Malan,* 1963]. An observation reported by *Krider* [1974] deals with a case where the entire discharge apparently took place outside the cloud. The channels propagated with an estimated speed in the range of 1–4 10^4 m s^{-1}.

Conversely, the set of simultaneous measurements presented in the present study shows with a high degree of consistency the existence of 'air discharges' which neutralize negative space charges by bringing them to the earth. In our case, while the velocity in individual strokes measured by *Hubert and Mouget* [1979] was $(1 \pm 0.5) \times 10^8$ m s^{-1}, the ascent velocity of lightning channels over a 54-ms period was of the order of 3 10^4 m s^{-1}, in the same range as estimated by *Krider* [1974]. Comparable values also are found for equivalent propagating velocities within thunderclouds determined at Saint-Privat for other triggered lightnings.

Triggered lightning experiments undoubtedly offer, owing to the direct measurement of current and also the focusing of many instruments on restricted periods and locations, an excellent opportunity to detect and to study the distribution of such charges in space. On the other hand, it may be suspected that charges drifting at low altitude outside the cloudy or rainy areas indeed are not infrequent. While the triggering procedure is particularly likely to bring such charges to ground, their existence might more generally play a role in discharges initiated with upgoing leaders, such as those which originate often from elevated structures [*Uman,* 1969].

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